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Master Thesis

In-Beam Gamma-Ray Spectroscopy of Neutron-Rich Actinides after Multi-Nucleon Transfer Reactions



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# Abstract

Excited states in neutron-rich actinides and nuclei in the Te-Ba region were investigated after multi-nucleon transfer reactions employing the AGATA demonstrator and PRISMA setup at the Laboratori Nazionali di Legnaro (INFN, Italy). A primary 1 GeV <sup>136</sup>Xe beam from the Tandem-ALPI accelerator impinging on a <sup>238</sup>U target was used to produce the nuclei of interest. Beam-like reaction products of Te, I, Xe, Cs and Ba isotopes after multinucleon transfer were identified and selected with the PRISMA spectrometer. Kinematic coincidences between the binary reaction products, i.e. beam-like and target-like nuclei, were exploited. The target-like particles were tagged inside the scattering chamber by MCP detectors covering a range around the grazing angle. The high fission background can be reduced significantly with this technique, allowing cleaner conditions for in-beam  $\gamma$ -ray spectroscopy.  $\gamma$  rays from excited states in both beam- and target-like particles were measured with the position-sensitive AGATA HPGe detector array. Small Doppler broadening and the high quality of the  $\gamma$ -ray spectra are based on the novel  $\gamma$ -ray tracking technique which was successfully exploited. The analysis of the mass spectrometer PRISMA delivers mass yields for the  ${}^{136}Xe + {}^{238}U$  multi-nucleon transfer reaction channels. Results on  $\gamma$ -ray spectra of high-spin states in neutron-rich barium nuclei are presented. Neutronrich actinide nuclei are located far away from shell closures and are characterized by effects of strong collectivity. Collective properties of hard-to-reach neutron-rich <sup>236</sup>Th candidates are discussed.

# Zusammenfassung

Am AGATA/PRISMA-Aufbau des INFN Legnaro wurde ein Experiment zur Messung angeregter Zustände neutronenreicher Aktinide nach Multinukleonentransfer-Reaktionen durchgeführt. Hierfür wurde ein <sup>136</sup>Xe-Strahl mit einer Energie von 1 GeV auf ein <sup>238</sup>U-Target geschossen. Die strahlähnlichen Reaktionsprodukte der Elemente Te, I, Xe, Cs and Ba wurden mit dem PRISMA-Massenspektrometer identifiziert und für die weitere Analyse ausgewählt. DANTE-MCPs, die in der Strahlkammer am Grazing-Winkel angebracht waren, detektierten targetähnliche Teilchen. Kinematische Koinzidenzen zwischen den strahl- und targetähnlichen Reaktionsprodukten erlauben eine erhebliche Reduktion des Spaltuntergrunds. Hierdurch können auch die im Massenspektrometer PRISMA undetektierten targetähnlichen Teilchen mit dem AGATA-HPGe-Array per In-Beam-Gammaspektroskopie untersucht werden. Die  $\gamma$ -Spektren werden mit der neuen Methode des Gamma-Ray-Trackings erstellt. Für die strahl- und targetähnlichen Kerne werden verschiedene Dopplerkorrekturen durchgeführt. Die Analyse des PRISMA-Spektrometers liefert Massenverteilungen für die Multinukleontransfer-Reaktion  $^{136}$ Xe $+^{238}$ U. In der vorliegenden Arbeit werden  $\gamma$ -Spektren neutronenreicher Barium-Kerne präsentiert. Neutronenreiche Aktinide befinden sich weitab von Schalenabschlüssen und sind daher durch Effekte starker Kollektivität charakterisiert. Kollektive Eigenschaften des schwer zugänglichen neutronenreichen Isotops<sup>236</sup>Th werden diskutiert.

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# 1 Multi-Nucleon Transfer Reactions and Neutron-Rich Actinides

The actinide series comprises the elements with  $89 \leq Z \leq 103$  following the element actinium  $_{89}$ Ac. All isotopes are unstable, yet  $^{238}$ U,  $^{235}$ U,  $^{232}$ Th and  $^{244}$ Pu have long enough lifetimes above  $10^8$  years to show natural abundance in nature. Neutron-rich actinide nuclei are far away from shell closures. Therefore, they are of high interest since neutron excess leads to interesting phenomena such as modified shell structure and effects of strong collectivity. Those nuclei show a variety of shapes in the ground state and at higher excitation energies.

Neutron-deficient nuclei can be easily produced in experiments exploiting fusion-evaporation or incomplete-fusion reactions. Here, nuclear spectroscopic information is obtainable even close to the proton drip line. In contrast, neutron-rich nuclei are difficult to produce, particularly for the excitation of high-spin states. Neutron-rich heavy nuclei were only accessible by decay studies for a long time [1].

Spectroscopic studies in the neutron-rich actinide region are very elaborate and challenging due to the narrow choice of target materials for stable-beam experiments. In order to populate a wide range of neutron-rich isotopes in the Th-Pu region, <sup>238</sup>U is an applicable stable low-radioactive target material. Nonetheless, there is always a significant background contribution from induced actinide fission that dominates all other desired nuclear reaction channels with excitation energies high above the fission barrier. The fission barrier height of <sup>238</sup>U is in the order of  $\approx 6$  MeV [2].

Multi-nucleon transfer reactions (MNT reactions) are a suitable tool and a more recent approach to populate neutron-rich actinide nuclei and to study them at high-spin excitations. These reactions are direct reactions in which one or more nucleons are exchanged between two nuclei [3, 4]. Like every other direct reaction, MNT reactions are considered as fast processes within a timescale of  $t \sim 10^{-22}$  s and can be described by the transit of nucleons of Fermi momentum through the nuclear diameter. Direct processes only show minimum rearrangement processes within the nuclei, in contrast to indirect reaction processes like

the slower compound nucleus reactions, in which equilibrium-reaching intermediate systems are formed and subsequently decay in various independent decays channels. The resulting angular distributions are asymmetric since forward directions are advantageous for the reaction. If nucleons are transferred from the projectile to the target, the transfer is called *stripping*, while the projectile receives a nucleon by the target nucleus in a so-called *pickup* reaction.



Figure 1: Scheme of an example multi-nucleon transfer reaction in the experiment without fission contribution. The impinging beam particle <sup>136</sup>Xe (1) undergoes multi-nucleon transfer (2) with a <sup>238</sup>U target particle. Highly excited highspin states of beam- and target-like fragments are populated (4). Nucleon evaporation has to be taken into account (3). The large number of excited reaction products emit  $\gamma$  radiation to be measured with a  $\gamma$ -ray detector array. The beam-like fragments have to be carefully selected out of the various reaction products with a high-resolution mass spectrometer to discriminate desired spectroscopic information from the huge fission background.

Theoretical model descriptions of multi-nucleon transfer processes are based on a direct reaction picture such as the GRAZING model [5] or complex WKB approximation calculations (CWKB) [6]. Here, multi-nucleon transfer processes are treated in a statistical manner by using multiple successive single-nucleon transfer probabilities calculated in first-order perturbation theory. Nucleons can be transferred either simultaneously or sequentially in a multi-step reaction process [3]. The number of transfer possibilities obviously increases with an increasing number of transferred nucleons. A microscopic approach based on timedependent Hartree-Fock calculations (TDHF) is available as well [7]. Reaction mechanisms and many other features of multi-nucleon transfer reactions are very complex and subject of current research [3, 4, 8, 9]. Multi-nucleon transfer reactions often produce dozens of nuclei in the exit channels. These various reaction products are excited over a broad range of spin and excitation energies. Each of them emits  $\gamma$  radiation and contributes to a  $\gamma$ -ray spectrum of extreme complexity. For this reason, an unambiguous identification of the beam-like reaction product from the multitude of reaction products with a high efficiency is necessary in order to discriminate the interesting reaction fragments from the huge fission background contribution. This demands on the one hand a careful selection of the various reaction products with a high-resolution mass spectrometer together with ancillary heavy-ion detectors. On the other hand, large high-efficiency  $\gamma$ -ray multi-detector arrays with a good spacial resolving power to Doppler-correct and analyze the high-statistics multifold  $\gamma$ -ray coincidence data have to be employed. The main challenges are given by the extremely low cross sections for the production of neutron-rich actinides and the possibility of neutron evaporation in the reactions.

For energies high above the Coulomb barrier, MNT reactions favor the equilibration between the N/Z ratios of the two final products [10]. The process of charge equilibration is quite complex and issue of ongoing studies. A summary is given by Freiesleben and Kratz [11]. Swiatecki [12] describes the process as a minimization of the liquid drop energy of two touching spherical nuclei. Królas *et al.* [13] explained the process with two distant, non-touching nuclei. Sekizawa and Yabana [7] studied various N/Z transfer processes for different impact parameters. For different N/Z ratios of both projectile and target, fast transfer processes of a few nucleons towards the charge equilibrium of the initial system occur at large impact parameters. As the impact parameter decreases, neck formation between the two reaction partners is mainly responsible for the transfer of protons and neutrons in the same direction after neck breakup.

As a result, reactions of neutron-poor projectiles and heavy target nuclei favor proton stripping and neutron pick-up. By using neutron-rich projectiles, proton pick-up and neutronstripping channels are possible as well. Consequently, the selection of both neutron-rich nuclei as beam and target enables the production of a variety of hard-to-reach isotopes located in the neutron-rich regions in the Segré chart for both beam- and target-like particles. In the case of a <sup>238</sup>U target and a <sup>136</sup>Xe beam, the N/Z ratios are:

$$\frac{N}{Z}\Big|_{\substack{238\\92}} = \frac{146}{92} \approx 1,587 \qquad \frac{N}{Z}\Big|_{\substack{136\\54}} = \frac{80}{54} \approx 1,519$$

Therefore, one would expect the population of neutron-rich I, Te and Sb isotopes to be

favored. Since both values are close together, the +1, 2p nuclei Cs and Ba are produced in the same way, corresponding to neutron-rich Pa and Th isotopes in the -1, 2p target-like channels. The stable nucleus <sup>136</sup>Xe is a preeminent candidate to populate neutron-rich  $N \sim 82$  nuclei in the Te-Ba region, because the N/Z equilibrium line points into neutron-rich regions for both proton-stripping and pickup channels.

Since the beam-like reaction fragments produced after multiple neutron and proton exchange are excited over a broad range of energy and spin, the scarcely known high-spin states as well as the yrast-state population of neutron-rich nuclei in the Te-Ba region may be analyzed. Table 1 lists an overview of the beam-like fragments of interest and their corresponding binary reaction partners in the target. An overview on the two regions of interest is presented in figure 2.

**Table 1:** Nuclear charge Z of beam-like fragments of interest and their correspondence in<br/>the target. By demanding kinematic coincidences after multi-nucleon transfer,<br/>there might be a corresponding recoil fragment for every ejectile fragment. The<br/>beam-target combination is marked in bold letters.

Ejectile $Z$	Corresponding $Z$ in the target
Z = 52: Tellurium <sub>52</sub> Te	Plutonium <sub>94</sub> Pu
Z = 53: Iodine <sub>53</sub> I	Neptunium <sub>93</sub> Np
Z = 54: Xenon <sub>54</sub> Xe	Uranium $_{92}$ U
Z = 55: Caesium <sub>55</sub> Cs	Protactinium <sub>91</sub> Pa
Z = 56: Barium <sub>56</sub> Ba	Thorium <sub>90</sub> Th

Aiming for a spectroscopic study of neutron-rich actinide nuclei in the Th-U region [14] as well as high-spin states in the Te-Ba region, the experiment LNL 11.22 was conducted at the Laboratori Nazionali di Legnaro (LNL) in Italy in October 2011 employing the AGATA demonstrator [15] and the magnetic spectrometer PRISMA [16] in combination. A 1 GeV <sup>136</sup>Xe beam was accelerated by the Tandem-ALPI accelerator impinging onto a <sup>238</sup>U target in order to produce highly excited neutron-rich actinides in the Th-U region via multi-nucleon transfer reactions. A sketch of the reaction mechanism employed in the present analysis is depicted in figure 1. The beam-like particles are detected and identified with the PRISMA mass spectrometer. To make use of kinematic coincidences between the binary reaction products, i.e. beam-like and target-like nuclei, DANTE multi-channel plate detectors were installed inside the scattering chamber. Fission background is successfully

suppressed by this method. To select in-beam high-resolution AGATA  $\gamma$ -ray spectra of the required hard-to-reach actinide nuclei, a Doppler correction for the target-like nuclei has to be applied. The experimental setup is described in more detail in chapter 3. The results of the analysis of the experiment will be shown in chapter 4.



Figure 2: Segré chart showing the regions of interest in the present study. The different colors mark the various decay modes of the ground states. The Te-Ba region around the neutron magic number N = 82 as well as the nuclei of interest in the neutron-rich Th-U region are marked and shown separately.

# 2 Collective Properties of Actinide Nuclei

### 2.1 Collective Model

Complementary to the picture of individual nucleons changing orbits to create excited states of the nucleus as described by the Nuclear Shell Model, there exist also nuclear transitions involving many or all nucleons. Since these nucleons are acting together, the resulting properties and transitions of the nucleus are called *collective* and the nuclear structure may be described by a so called Collective Model [17, 18].

Two types of collective effects may be distinguished, on the one hand nuclear deformation leading to collective modes of excitation and on the other hand collective oscillations and rotations. Nuclei of high mass have low-lying excited states that are associated to vibrations and rotations of non-spherical nuclei, comparable to vibrations and rotations of a liquid drop. Indeed, the Liquid-Drop Model gives a first satisfactory description of collective excitations of nuclei. The interior structure of the nucleus, thus, the existence of individual nucleons, is neglected in favor of the picture of homogeneous fluid-like nuclear matter. Collective Models combine both the liquid drop and the shell model with the assumption of a net nuclear potential due to a filled core shell, in which nucleons of unfilled shells are moving. That potential may not necessarily be of spherical symmetry, it can be deformed. Nuclei showing collective properties usually hold many valence nucleons, thus, proton or neutron numbers are far from closed shells. This is the case for neutron-rich actinide nuclei.

#### 2.2 Nuclear Rotations

In the Nuclear Shell Model, the inert core is always at rest and only the valence nucleons rotate. If the nucleus is deformed, both core and valence nucleons rotate collectively. A classical rotor can rotate about any of its axes. In a quantum mechanical description, this premise has to be modified for the case that the nucleus has rotational symmetries. In simple models, the nucleus is assumed to have no internal structure. A spherical nucleus cannot rotate since any rotation leaves the surface invariant, leaving the quantum mechanical state unchanged. The Hamiltonian  $\mathcal{H}_{rot}$  of a nuclear rigid rotor with moments of inertia  $\mathscr{I}$  separates into a rotational and an intrinsic part:

$$\mathcal{H} = \mathcal{H}_{\rm rot} + \mathcal{H}_{\rm intr} \tag{2.1}$$

In general, the rotational angular momentum operator  $\hat{J}'$  is not equal to the total angular momentum operator  $\hat{J}$ . Instead, it is given by the difference

$$\hat{J}' = \hat{J} - \hat{J}_{\text{intr.}} \tag{2.2}$$

 $\hat{J}_{intr.}$  is the intrinsic angular momentum operator. This relationship is shown geometrically in figure 3. Since J is rather than J' a good quantum number, it is reasonable to expand  $\mathcal{H}_{rot}$  [18]:

$$\mathcal{H}_{\rm rot} = \sum_{i=1}^{3} \frac{\hbar^2 \left(\hat{J}_i - \hat{J}_i^{\rm intr.}\right)^2}{2\mathscr{I}_i} = \underbrace{\sum_{i=1}^{3} \frac{\hbar^2 \hat{J}_i^2}{2\mathscr{I}_i}}_{\mathcal{H}_{\rm rot}} - \underbrace{\sum_{i=1}^{3} \frac{\hbar^2 \hat{J}_i \hat{J}_i^{\rm intr.}}_{\mathscr{I}_i}}_{\mathcal{H}_{\rm coupling}} + \underbrace{\sum_{i=1}^{3} \frac{\hbar^2 \left(\hat{J}_i^{\rm intr.}\right)^2}{2\mathscr{I}_i}}_{\mathcal{H}_{\rm intrinsic}}$$
(2.3)

The last term only acts on the intrinsic coordinates and may be incorporated into  $\mathcal{H}_{intr.}$ . This model's premise is that the nucleus rotates as a whole with collective degrees of freedom, while the nucleons move independently inside a deformed potential with intrinsic degrees of freedom. That adiabatic approximation is justified since the nucleonic motion is much faster than that of the rotation.  $\mathcal{H}_{coup.}$  denotes the Coriolis interaction that couples both rotational and intrinsic motion and can be neglected under the assumption that rotational energies are small in contrast to intrinsic excitation energies. Centrifugal stretching is neglected here as well.

As a consequence of the adiabatic assumption, the wave function of a collective nuclear state can be written in the form  $\Psi^J_{MK}(\theta_i) = \Phi(\theta_i) \chi$  where  $\Phi$  depends only on the collective coordinates in Euler angles  $\theta_i$ , describing the motion of the deformed potential, and where  $\chi$  describes the motion of the particles with respect to this deformed potential in the intrinsic coordinates. In the laboratory coordinate system S, the axes x, y, z are fixed in space. The intrinsic reference frame S' with the axes 1, 2, 3 coincides instantaneously with the principal axes of the deformed potential and can have any orientation with respect to the laboratory reference frame, because the orientation of nuclei can hardly be controlled in an experiment. In laboratory axes, the commutation identities read as follows:  $[\hat{J}_x, \hat{J}_y] = -i\hbar \hat{J}_z$  with its cyclic permutations and  $[\hat{J}^2, \hat{J}_i] = 0$ , i = x, y, z. In body-fixed-axes, one has



Figure 3: Illustration of the relationship between the total angular momentum  $\hat{J}$  with the rotational angular momentum  $\hat{J}'$  and the intrinsic angular momentum  $\hat{J} = \hat{J}' + \hat{J}_{intr.}$ . The eigenvalue of the  $\hat{J}_z$  component along the laboratory frame z axis is M, while the eigenvalue of  $J_3$  in the body-fixed-frame is K.

 $[\hat{J}_1, \hat{J}_2] = -i\hbar \hat{J}_3$  with its cyclic permutations,  $[\hat{J}^2, \hat{J}_i] = 0$ , i = 1, 2, 3 and  $[\hat{J}_z, \hat{J}_3] = 0$ . The intrinsic components  $\hat{J}_{1,2,3}$  commute with the external components  $\hat{J}_{x,y,z}$ , because  $\hat{J}_{1,2,3}$  are independent of the orientation of the external system. In the coordinate system S, the total angular momentum J and its z component  $J_z = M$  are constants of the motion. One may further require that the deformed potential is axially symmetric around the 3-axis. Consequently, the component  $J_3 \equiv K$  is conserved as well. K has the same range of values as  $M, K = -J, -J + 1, \ldots, +J$ . Eigenvectors  $|\Psi^J_{MK}\rangle \equiv |JMK\rangle$  of  $\mathcal{H}_{\rm rot}$  then satisfy the following identities: <sup>i</sup>

$$\hat{J}^{2} |JMK\rangle = \hbar^{2} J(J+1) |JMK\rangle \qquad \hat{J}_{z} |JMK\rangle = \hbar M |JMK\rangle \qquad (2.4)$$
$$\hat{J}_{3} |JMK\rangle = \hbar K |JMK\rangle$$

In terms of axial symmetry, one assumes  $\mathscr{I}_1 = \mathscr{I}_2 \equiv \mathscr{I} \neq \mathscr{I}_3$ . Then the Hamiltonian rewrites in terms of the third component of the rotational operator  $\hat{J}_3$  and  $\hat{J}^2$ :

$$\mathcal{H}_{\rm rot} = \sum_{i=1}^{3} \frac{\hbar^2 \hat{J}_i^2}{2\mathscr{I}_i} = \frac{\hat{J}_1^2 + \hat{J}_2^2}{2\mathscr{I}} + \frac{\hat{J}_3^2}{2\mathscr{I}_3} = \frac{\hat{J}^2 - \hat{J}_3^2}{2\mathscr{I}} + \frac{\hat{J}_3^2}{2\mathscr{I}_3}$$
(2.5)

To calculate the quantized rotational energy spectrum, the Schrödinger equation for the

$$\Psi(\theta,\xi) = \left(\frac{2J+1}{16\pi^2}\right)^{1/2} \sum_{K} a_K \left\{ \mathfrak{D}^J_{MK}(\theta)\phi^{(\theta)}(\xi) + (-1)^{J+K} \mathfrak{D}^J_{MK}(\theta) \left(\mathfrak{R}_2(-\pi)\phi^{(\theta)}_{\Omega}(\xi)\right) \right\}$$

where the functions  $\mathfrak{D}_{MK}^{J}(\theta)$  are the normalized Wigner functions,  $\theta \equiv (\alpha, \beta, \gamma)$  the Euler angles,  $\mathfrak{R}_{2}$  the rotation operator in 2-direction and  $\phi_{\Omega}^{(\theta)}(\xi)$  the eigenfunctions of  $\mathcal{H}_{intr.}$  depending only on the intrinsic coordinates  $\xi$ . The coefficients  $a_{K}$  have to be determined by diagonalization of  $\mathcal{H}_{rot}$  [18].

<sup>&</sup>lt;sup>i</sup>In fact, the rotational symmetrized wave function in the asymmetric rotor model is given by

given Hamiltonian using the identities given in equation 2.4 has to be solved:

$$\mathcal{H}_{\rm rot} |JMK\rangle = E_{\rm rot}^{JK} |JMK\rangle \quad \Rightarrow \quad E_{\rm rot}^{JK} = \frac{\hbar^2}{2\mathscr{I}} J(J+1) + \frac{\hbar^2}{2} \left(\frac{1}{\mathscr{I}_3} - \frac{1}{\mathscr{I}}\right) K^2 \quad (2.6)$$

The nucleus does not have an orientational degree of freedom with respect to the symmetry axis, thus,  $K^2/\mathscr{I}_3$  vanishes. There are no collective rotations about the symmetry axis:

$$E_{\rm rot} = \frac{\hbar^2}{2\mathscr{I}} \left( J(J+1) - K^2 \right) \tag{2.7}$$

For given J, the value of K, for which  $J(J+1)-K^2$  is a minimum, defines the lowest energy. Lowest energy states are called yrast states. In the following discussion, the  $K^2$  term is assumed to be incorporated into  $E_K^{(0)}$ . For a triaxial rotor K vanishes.<sup>ii</sup> The spectra are subsequently proportional to J(J+1) which is in reasonable agreement with experimental data. An example of a rigid rotor spectrum representing this dependence is presented in figure 4. The depicted <sup>238</sup>U  $\gamma$ -ray spectrum was obtained from the quasi-elastic Coulomb excitation channel <sup>238</sup>U(<sup>136</sup>Xe,<sup>136</sup>Xe')<sup>238</sup>U' in the present experiment [19]. The spectrum shows the ground-state rotational band of <sup>238</sup>U ranging from 4<sup>+</sup> up to 20<sup>+</sup>. The 2<sup>+</sup>  $\rightarrow$  0<sup>+</sup> transition is not visible in the spectrum since internal electron conversion prevails for such small  $\gamma$ -ray transition energies.

Because J is quantized, the *rotational bands* are characterized by a given value of the moment of inertia  $\mathscr{I}$  and a series of energy levels with a  $\Delta J$  to be specified. The parity assignment is  $(-1)^J$ , but since there is a reflection symmetry for even-even nuclei, i.e. positive parity, odd J are not acceptable here. Allowed values of J are therefore  $0, 2, 4, 6, \ldots$  with  $0^+$  the ground state. The ground-state band of even-odd and odd-even deformed nuclei consists of  $\Delta J = 1$  transitions on top of a half-integer ground state. In terms of the first excited energy,  $E_J$  for even-even nuclei can be written as

$$E_J = \frac{1}{6} J(J+1) E_{2^+}$$
(2.8)

Large deformations imply large moments of inertia  $\mathscr{I}$ , which results in low  $E_{2^+}$  values. The moment of inertia  $\mathscr{I}$  is mainly observed to be less than the value for a classical rigid

<sup>&</sup>lt;sup>ii</sup> In a triaxial symmetry, the 3-axis is fixed by the condition that it has to be the symmetry axis of the nucleus. The 1- and 2-axes can be rotated arbitrarily around the 3 axis because of the axial symmetry. Any direction perpendicular to the 3-axis is a principal axis, one has  $\Re'_2(\alpha, \beta, \gamma) = (\alpha, \beta, \gamma + \eta)$  with an arbitrary rotation angle  $\eta$ . This puts a constraint on the wave function:  $\Psi_{IMK}(\alpha, \beta, \gamma) = e^{i\eta K}\Psi_{IMK}(\alpha, \beta, \gamma)$ . For invariance, K has to be 0.



Figure 4: <sup>238</sup>U  $\gamma$ -ray spectrum [19] obtained in experiment LNL 11.22 analyzed in this thesis. The spectrum shows the ground-state rotational band from 4<sup>+</sup> up to 20<sup>+</sup>. The 2<sup>+</sup>  $\rightarrow$  0<sup>+</sup> transition is not visible in the spectrum since internal electron conversion prevails for such small  $\gamma$ -transition energies. The level energies are proportional to J(J + 1), the transition energies in the  $\gamma$ -ray spectrum have approximately same distances.

rotor:  $\mathscr{I}_{rigid} > \mathscr{I}_{nuclear} > \mathscr{I}_{fluid}$ . An interpretation of this phenomenon is that the nucleus has pairing correlations that make it analogous to a superfluid.

In the discussion above, collective rotational motion is considered to be a pure macroscopic feature. Nonetheless, there is a microscopic structure underlying the collective phenomena. The cranking model introduced by Inglis [20] assumes independent particles moving in an average potential. This potential  $V(\mathbf{r};t) = V(r,\theta,\phi-\omega t;0)$  rotates around a rotational axis  $\boldsymbol{\omega}$  of a coordinate frame fixed to the potential itself. The wavefunction transforms by means of a unitary transformation  $\hat{U} = \exp(i\omega Jt/\hbar)$ :  $\psi_r = \hat{U}\psi$ . The time-dependent Schrödinger equation then reads as follows:

$$i\hbar \frac{\partial \psi_r}{\partial t} = i\hbar \left( \hat{U} \frac{\partial \psi}{\partial t} + \frac{\partial \hat{U}}{\partial t} \psi \right) = \left( \mathcal{H}(t=0) - \boldsymbol{\omega} \cdot \mathbf{J} \right) \psi_r$$
(2.9)

The general many-body cranking-model Hamiltonian with the orientation of the rotational axis chosen to be the x-axis and  $\mathcal{H}$  the sum of the individual deformed potentials reads:

$$\mathcal{H}_{\omega} = \mathcal{H} - \omega \hat{J}_x \quad , \qquad \hat{J}_x = \sum_{i=1}^A \hat{j}_{x,i} \tag{2.10}$$

Applying perturbation theory, the energy eigenvalues in the lab system  $E(\omega)$  can be expanded in  $\omega$ .<sup>iii</sup>

$$E(\omega) = \langle \psi_{\omega} | \mathcal{H} | \psi_{\omega} \rangle = \langle \psi_{\omega} | \mathcal{H}_{\omega} | \psi_{\omega} \rangle + \omega \langle \psi_{\omega} | \hat{J}_{x} | \psi_{\omega} \rangle$$

$$\simeq E(\omega = 0) + \mathscr{I} \omega^{2} + \dots$$
(2.11)

Furthermore, one has  $J(\omega) = \mathcal{I} \omega + \mathcal{O}(\omega^3)$ .  $\omega$  can be semi-classically defined as  $\omega = \frac{dE}{dJ}$ with  $\tilde{J} = \sqrt{J(J+1)}$ . Then the expression for the rotation band energies reads as before:

$$E_J = E_0 + \frac{\hbar^2}{2\mathscr{I}} J(J+1)$$
 (2.12)

In fact, the above-mentioned concepts outline only the most basic properties in simple systems. More in-depth theoretical frameworks are required for asymmetric rotors with all three moments of inertia different, a correct treatment of coupling effects, and the inclusion of further particles in even-odd or odd-even nuclei. More detailed descriptions can be found in [18, 23–26].

### 2.3 Phenomenological Treatment of the Yrast Band

Moments of inertia of the ground state can be calculated with the transitions of the groundstate rotational band using the rotational frequency  $\omega$ . Replacing the differential definition of  $\omega$  with a quotient of differences, one gets:

$$\omega = \frac{\mathrm{d}E}{\mathrm{d}\tilde{J}} \longrightarrow \omega_{\mathrm{exp}} = \frac{\Delta E}{\Delta\sqrt{J(J+1)}} \bigg|_{J,J-2} \simeq \frac{E_J - E_{J-2}}{\sqrt{J(J+1)} - \sqrt{(J-2)(J-1)}}$$
(2.13)

The kinetic moment of inertia  $\mathcal{I}^{(1)}$  is defined by the transition energies of the ground-state rotational band [27]:

$$\mathcal{I}^{(1)} = \frac{\tilde{J}}{\omega} = \frac{1}{2} \left( \frac{\mathrm{d}E}{\mathrm{d}\tilde{J}^2} \right)^{-1} \simeq \frac{(2J-1)\hbar^2}{\Delta E_{J\to J-2}}$$
(2.14)

With these definitions,  $\omega$  and the moments of inertia for every level can be calculated. The dynamic moment of inertia  $\mathcal{I}^{(2)}$  describes the deviations in energy differences of consecutive rotational transition energies. With  $\Delta J = 2J - 1 - (2(J-2) - 1)$ , one obtains:

$$\mathcal{I}^{(2)} = \hbar^2 \frac{\Delta J}{\Delta E_{\gamma}} = \frac{4\hbar^2}{\Delta E_{J \to J-2} - \Delta E_{J-2 \to J-4}}$$
(2.15)

<sup>&</sup>lt;sup>iii</sup> Harris [21] proposed the parametrization  $E_J = \alpha \omega^2 + \beta \omega^4 + \gamma \omega^6 + \dots$  There are also other possibilities to parametrize  $E_J$ , such as the Variable Moments of Inertia (VMI) model [22] or expansions in  $[J(J+1)]^n$ .

This phenomenological model provides useful tools to extract physical information and deformation systematics from the energy spectrum of the observed nucleus, however, it has no predictive powers about the nuclear structure.

The collective band structure does not always describe the most favorable excitation energy for a given spin. Along the yrast line there is no internal excitation. However, pairing changes drastically with angular momentum. An important resulting phenomenon is the so-called backbending (compare figure 5). Viewing the moment of inertia as function of energy, one can define three zones: As  $\omega$  increases, the nucleus stretches and  $\mathscr{I}$  increases. In the second zone with higher rotational frequencies, the Coriolis force  $\boldsymbol{\omega} \cdot \mathbf{J}$  gradually breaks up pairing correlations in the nucleus. Now the nucleons tend to align their angular momenta along the axis of collective rotation instead of coupling them to zero. Other bands can become energetically lower than the original rotational ground-state band.

Figure 5: Whenever a pair of nucleons is broken up, the moment of inertia increases. When a rotational band crosses a band with a broken pair and larger moment of inertia, the bands mix near the crossing. Repulsion "pushes" them apart. The observable states along the yrast line are the lower ones for each angular momentum. The backbending effect is observed in plots of  $\omega(\mathscr{I})$ . Little changes in the angular frequency cause the rotational band to get smaller spacings. Modified reprint from [25].



### 2.4 Nuclear Vibrations

For a model of nuclear vibrations, one may consider oscillations about a spherical equilibrium shape with a time-dependent boundary surface. Since the spherical harmonic functions form a complete set of orthonormal functions and therefore an orthonormal basis of the Hilbert space of square-integrable functions, any square-integrable function on the unit sphere can be expanded as a linear combination of these. The moving nuclear surface then may be described by an expansion in spherical harmonics with time-dependent shape parameters  $\alpha^*_{\lambda\mu}(t)$  as expansion coefficients. The instantaneous coordinate R(t) of a point on the nuclear surface at  $(\theta, \varphi)$  can be written in the following way:

$$R(\theta,\varphi,t) = R_0 \left( 1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu}^*(t) Y_{\lambda\mu}(\theta\varphi) \right)$$
(2.16)

The order of the excitation is given by the parameter  $\lambda$ .  $\mu$  describes different vibration modes.  $R_0$  is the radius of the spherical nucleus. Given appropriate coefficients, the expansion characterizes rather any shape. Each contribution can in principle oscillate at a different frequency. Symmetry and quantum mechanical considerations pose restrictions on the model. For example, shapes of axial symmetry let all deformation parameters with  $\mu \neq 0$  vanish.

Vibrations are always quantized with a bosonic ladder-operator algebra resulting in the eigenvalues  $E_n = n\hbar\omega, n \in \mathbb{N}$ , so that modes of the system correspond to excitations with particular values of  $\lambda$  and  $\mu$ , associated to characteristic frequencies  $\omega$ . Transitions are mediated by particle-like so-called phonons. Consider for example the case  $\lambda = 0$ . Here, the result is  $R(\theta, \varphi) = R_0 \left(1 + \frac{\alpha_{00}^*(t)}{\sqrt{4\pi}}\right)$ . This "breathing" monopole mode leaves the nuclear surface spherical, but compresses and decompresses it. Those modes do not occur at low excitation energies due to the high incrompressibility and the constant density of nuclear matter. The dipole mode with  $\lambda = 1$  describes an overall shift in the center of mass of the nucleus which is only a translation. It occurs only at very high energies of the order 10-25 MeV. Thus, the most important nuclear collective vibrations are the  $\lambda = 2, 3, 4$  (quadrupole, octupole, hexadecapole) modes, while higher multipoles become negligible.



Figure 6: Quadrupole deformation parameter  $\beta$  describing prolate and oblate deformation (examples for  $\gamma = 0$ ). The coordinates (1, 2, 3) describe the body-fixed frame of reference.

The dominant vibration is the quadrupole vibration. For most even-even nuclei, there is a low lying state with  $J^P = 2^+$ . Quadrupole deformation may either be described by the spherical tensor  $\alpha_{2\mu}$  in the laboratory-fixed frame of reference or, alternatively, by a parameter set in intrinsic axes. The sum over the components  $|\alpha_{2\mu}|^2$  is rotationally invariant, i.e. it has the same value in the laboratory and the body-fixed axis systems [24]:

$$\sum_{\mu} |\alpha_{2\mu}|^2 = a_0^2 + 2a_2^2 \equiv \beta^2 \tag{2.17}$$

 $a_0$  and  $a_2$  can be parametrized with the parameter set  $(\beta, \gamma)$ :

$$a_0 \equiv \beta \cos \gamma \qquad a_2 \equiv \frac{1}{\sqrt{2}} \beta \sin \gamma$$
 (2.18)

At  $\gamma = 0$ , the nucleus is elongated or stretched along the 3-axis, but the 1- and 2-axes stay the same. One distinguishes between the oblate deformation ( $\beta < 0$ ) and the prolate deformation ( $\beta > 0$ ). Completely triaxial shapes have  $\gamma = 30^{\circ}$ . Figure 6 illustrates the different deformation modes. Vibrational modes interact with the rotational motion in a complex manner, a treatment of the rotation-vibration model can be found for example in [17, 23].

#### 2.5 Modern Theoretical Approaches

Several theoretical descriptions for shapes and dynamics of nuclei in the actinide region are available. Theoretical predictions for neutron-rich thorium nuclei are presented in the following compilation. Among other isotopes ranging from radium up to super heavy nuclei, Sobiczewski *et al.* make detailed predictions on the ground-state energies, first excited states and deformation parameters of highly neutron-rich even-even  $^{236-246}$ Th isotopes [28]. The calculations are based on a macroscopic-microscopic approach, taking the Yukawaplus exponential model for the macroscopic part of the energy and the Strutinski shell correction for the microscopic part. A minimum of excitation energy of the first 2<sup>+</sup> state and a maximum of deformation energy at N = 144, 146 is found exactly at the border of available experimental data.

Delaroche *et al.* [29] performed a large-scale theoretical study in the region from thorium to nobelium isotopes covering a wealth of structure properties of these heavy nuclei. Mean field and beyond mean field methods implementing the Gogny D1S force are exploited for a total of 55 nuclei. Constrained Hartree–Fock–Bogolyubov (HFB) as well as configuration mixing, blocking, and cranking HFB approaches were taken into account. Collective rotational excitations in the even–even nuclei  $^{226-236}$ Th are part of the analysis. Kinetic moments of inertia in dependence of the rotational frequency  $\omega$  are depicted in figure 7. Cranking HFB calculations are compared with calculations within a collective model and experimental data. The HFB data suggest backbending effects near  $\omega = 0.20 \,\text{MeV}/\hbar$  in <sup>236</sup>Th (compare figure 7).



Figure 7: Theoretical predictions for  $K^{\pi} = 0^+$  yrast-bands in some even-even Th nuclei from Delaroche *et al.* Kinetic moments of inertia in dependence of the rotational frequency  $\omega$  are shown. Cranking HFB calculations (black curves) are compared to calculations within a collective model in red circles and experimental data (blue stars). Modified reprint from [29].

Vrenetar, Nikšić and Ring [30] exploited a reflection asymmetric relativistic mean-field theory to investigate the shape evolution for even-even Th isotopes. A detailed summary of the method can be found in [31]. The calculations provide a unified description of particlehole and particle-particle correlations on a mean-field level. The particle-hole channel is determined by a relativistic density functional. A new separable pairing interaction is used for the particle-particle channel. Among many other results, the study predicts groundstate axial quadrupole and hexadecapole moments along the isotopic chains of Th up to <sup>236</sup>Th.

A further study by Guo *et al.* is based on a reflection-asymmetric relativistic mean-field theory and focuses on the shape evolution of even-even Th isotopes [32]. Quadrupole, octupole, and hexadecupole deformation values along the full Th chain, potential energy surfaces and matter density distributions are calculated. Guo *et al.* state that Th isotopes undergo two types of shape transition if the neutron number increases from N = 126 to the very hypothetical N = 156. The first one is a transition from spherical to octupole deformation around neutron number N = 134, whereas the second transition is predicted to occur at very hypothetical extreme neutron-rich N = 150 isotopes. Here the shape would change from a octupole to quadrupole deformation.

Nomura *et al.* [33] used a relativistic Hartree-Bogoliubov (RHB) model to calculate constrained energy surfaces for <sup>220–232</sup>Th. A *sdf* Interacting Boson Model (IBM) Hamiltonian is employed to compute spectroscopic properties associated to quadrupole and octupole deformations, e.g. the isotopic dependence of the excitation energies of the first five levels of the positive-parity ground-state band ( $K^{\pi} = 0_1^+$ ) and the lowest negative-parity band ( $K^{\pi} = 0_1^-$ ). Figure 8 shows the results compared to experimental values. Particularly experimental ground-state band excitation energies for A > 234 are sorely needed in order to confirm the predictions.



Figure 8: Isotopic dependence of the excitation energies of the first five levels of the positive-parity ground-state band  $(K^{\pi} = 0_1^+)$  and the lowest negative-parity band  $(K^{\pi} = 0_1^-)$ . Experimental values are drawn with symbols, lines denote theoretical values obtained in Interaction Boson Model (IBM) calculations. Modified from [33].

### 2.6 Previous Experimental Results for Thorium Nuclei

Thirty-two thorium isotopes ranging from A = 206 up to A = 238 have been discovered so far. According to the HFB-14 model, about 70 additional thorium isotopes could exist [1, 34]. While excited states in Th isotopes up to <sup>234</sup>Th are known, little or no information on excited states in neutron-rich Th isotopes is available beyond that mass. Figure 9 shows experimental data on the systematics of the first  $2^+$  energies of even-even actinide nuclei and reduced ground-state moments-of-inertia. This compilation illustrates the need for experimental data on the ground-state bands of neutron-rich Th isotopes, in particular beyond  $^{234}$ Th.



Figure 9: Compilation of recent studies on excitation energies and collective properties in the actinide region from Th to Fm. Especially neutron-rich actinides in the Th-U region are of high interest. Modified from [35].

Cocks *et al.* [36] investigated the high-spin structure of a wide range of Rn, Ra and Th isotopes via multi-nucleon-transfer reactions bombarding a <sup>232</sup>Th target with 833 MeV <sup>136</sup>Xe projectiles. The experiment was performed at the Lawrence Berkeley National Laboratory with the GAMMASPHERE  $\gamma$ -ray spectrometer. The experiment aimed to observe interleaving bands with opposite parities to high spin. High quality  $\gamma$ -ray spectra were obtained for <sup>218,220,222</sup>Rn, <sup>222,224,226,228</sup>Ra and <sup>228,230,234</sup>Th isotopes. A tendency from octupole vibration to deformation could be observed for Ra, Rn and Th. The potential of multi-nucleon transfer reactions for the population of highly excited neutron-rich nuclei was successfully demonstrated. Amzal *et al.* [37] populated <sup>228–234</sup>Th using multi-nucleon transfer from <sup>232</sup>Th. Level schemes have been extended and <sup>228,230–234</sup>Th were found to behave like octupole vibrators.

In 1969, Trautmann *et al.* reported the discovery of <sup>235</sup>Th. Uranyl nitrate was irradiated with 14.8 MeV neutrons produced by the Mainz cascade accelerator. <sup>235</sup>Th was formed in the reaction <sup>238</sup>U(n, $\alpha$ ) and then chemically separated to measure the  $\beta$ -decay curves. The current accepted half-life is 7.2(1) min. No data on excited states are available. The first observation of <sup>236</sup>Th was reported by Kaffrell and Trautmann in 1973. <sup>238</sup>U targets were irradiated with bremsstrahlung X-rays with a maximum energy of 140 MeV. <sup>236</sup>Th is produced via the  $(\gamma, 2p)$  reaction.  $\gamma$ -ray spectra and decay curves were measured after chemical separation. The analysis of the growth–decay curve gave a half-life of  $36 \pm 3$  min. (compare [34]) Furthermore, <sup>236</sup>Th was produced by Orth *et al.* at the Los Alamos Scientific Laboratory in 1973. The group employed a <sup>238</sup>U(p, 3p)<sup>236</sup>Th reaction using 100 MeV protons. The nuclide's half-life was determined to be  $37.5\pm1.5$  min by measuring the growth and decay of its daughter <sup>236</sup>Pa after a radiochemical separation of the Th component. [38]



Figure 10: <sup>236</sup>Th  $\gamma$ -ray spectra obtained by Ishii *et al.* employing a <sup>238</sup>U(<sup>18</sup>O, <sup>20</sup>Ne)<sup>236</sup>Th transfer reaction. By gating on different excitation energies in the residual Th isotope <sup>236</sup>Th singles spectra as well as -2n evaporation channels can be distinguished. A level scheme of the observed ground-state band transitions in <sup>236</sup>Th is shown left.

In 2005, Ishii *et al.* [35] managed to populate neutron-rich uranium and thorium nuclei via transfer reactions at the tandem booster of the Japan Atomic Energy Research facility (JAEA). A 200 MeV <sup>18</sup>O beam was shot onto an aluminum supported <sup>238</sup>U target. The recoil particles in the actinide region were either stopped in the target or in the Al backing. A Doppler shift correction was unnecessary since the  $\gamma$ -ray decay lifetimes are longer than the stopping time. Outgoing nuclei were detected with four sets of  $\Delta E$ -E silicon telescope detectors. The ejectile emitted in the transfer reaction, which corresponds to the residual nucleus <sup>236</sup>Th, is <sup>20</sup>Ne. The sum of excitation energies of both scattered and residual nuclei is approachable from the ejectile's kinetic energy. Accordingly, lower kinetic energies of <sup>20</sup>Ne correspond to higher excitation energies in the recoil nucleus. By gating on high ejectile kinetic energies, i.e. small recoil excitations, almost equally spaced transitions of 112, 169, 224 and 273 keV could be observed. The observed transition candidates can be assigned to states in the ground-state band of <sup>236</sup>Th up to spin 8 $\hbar$ . The 2<sup>+</sup>  $\rightarrow$  0<sup>+</sup>  $\gamma$ -ray transition was not observed due to large internal conversion coefficients. In the succeeding gates corresponding to higher recoil excitation energies, well known  $\gamma$ -rays from <sup>234</sup>Th appeared. The observation of <sup>234</sup>Th excited states indicates that two-neutron evaporation takes place and therefore the transition candidates are in fact excitation  $\gamma$ -rays in <sup>236</sup>Th. Moments of inertia could be deduced in the analysis. The singles spectrum of <sup>236</sup>Th, the -2n channel <sup>234</sup>Th, and a level scheme are depicted in figure 10. The cross section for the production of <sup>236</sup>Th was estimated to be very low in the order of µb.

K. Geibel [39] studied various neutron-rich actinide nuclei. Among others, neutron-rich Th isotopes could be populated. Two experiments at the CLARA-PRISMA setup at the Laboratori Nazionali di Legnaro were performed in 2007 and 2008 and analyzed with respect to the target-like reaction products. The experiments closely resemble the experiment discussed in this thesis. A 460 MeV <sup>70</sup>Zn beam and a 926 MeV <sup>136</sup>Xe beam, respectively, were shot onto <sup>238</sup>U targets. Neutron-rich actinide nuclei were populated via multi-nucleon transfer reactions. Beam-like particles were positively identified with the PRISMA mass spectrometer. Kinematic correlations between the reaction partners allowed to study excited states of the unobserved target-like reaction products employing the CLARA HPGe detector array. Besides extensions in the ground-state rotational band of <sup>240</sup>U up to the  $18^+$  state, the <sup>236</sup>Th ground-state band established by Ishii *et al.* was tentatively confirmed up to spin  $8^+$ . Singles and sum spectra are depicted in figure 11.



Figure 11: Various Th  $\gamma$ -ray spectra obtained in a CLARA/PRISMA experiment by K. Geibel [39]. Left: Singles spectrum of <sup>236</sup>Th with a cut on the total kinetic energy loss and particle coincidence. Right: Various sum spectra taking different neutron evaporation channels into account. Modified reprint from [39].

Xu *et al.* [40] investigated the <sup>236</sup>Th production cross section for <sup>18</sup>O projectiles of 60 MeV/u hitting natural uranium targets in 2006. The reaction cross section was found to be  $250 \pm$ 

50 µb. Two characteristic 642.2 and 687.6 keV  $\gamma$  rays belonging to the decay product <sup>236</sup>Pa and a peak at 229.6 keV assigned to <sup>236</sup>Th were observed.

For the nuclei <sup>237</sup>Th and <sup>238</sup>Th, only the ground-state decay properties, but no excited states are known. <sup>237</sup>Th was first populated employing the <sup>238</sup>U(n,2p)<sup>237</sup>Th reaction using a 14 MeV neutron source [41]. In 2000 Yanbing *et al.* [42] produced <sup>237</sup>Th in a multi-nucleon transfer reaction by shooting <sup>18</sup>O ions at 60 MeV/u onto a natural uranium target. The experiment took place at the Heavy Ion Research Facility in Lanzhou/China. Thorium was radiochemically separated from the mixture of uranium and reaction products and subsequently transported to a HPGe detector measuring the activity of the Th sample. Growth and decay of  $\gamma$  rays of the daughter nucleus <sup>237</sup>Pa were employed to identify <sup>237</sup>Th. Its half-life was determined to be  $4.69 \pm 0.60 \text{ min}$ . Masses of <sup>236,237</sup>Th isotopes were measured for the first time at the FRS-ESR ion-storage facility in Darmstadt/Germany employing the Schottky Mass Spectrometry method in 2012 [43].

Jianjun et al. [44] produced <sup>238</sup>Th with the same setup as used by Yanbing et al. in 1999. Again, <sup>18</sup>O ions 60 MeV/u impinging on a natural uranium target were used to produce the nucleus of interest. The half-life of <sup>238</sup>Th was measured employing the same technique, i.e. using the growth and decay of <sup>238</sup>Pa  $\gamma$  rays after a radiochemical separation of the Th component. The half-life  $T_{1/2}$  was found to be  $9.4 \pm 2.0$  min. In addition, a new  $\gamma$ -ray of  $89.0 \pm 0.3$  keV with  $T_{1/2} = 8.9 \pm 1.5$  min was found and assigned to <sup>238</sup>Th.

### 3 Experimental Setup

The experiment LNL 11.22 which is subject of this thesis was conducted from 10 to 20 October 2011 at the Laboratori Nazionali di Legnaro (LNL) in Italy. The AGATA demonstrator [15] and the magnetic spectrometer PRISMA [16, 45, 46] were employed in combination. The aim of the experiment is a spectroscopic study of neutron-rich actinide nuclei in the Th-U region [14].

The 930 MeV <sup>136</sup>Xe beam delivered by the LNL Tandem-ALPI accelerator facility [47] was shot at 0.5 and  $1 \text{ mg/cm}^2$  thick <sup>238</sup>U targets with a beam current of  $\simeq 2 \text{ pnA} = 55 \text{ enA}$ . The set of reaction parameters is summarized in table 2.

Table 2. Reaction and beam parameters of the experiment.				
Projectile	$^{136}_{54}$ Xe			
Beam energy	$1{ m GeV}$			
Beam current	$2\mathrm{pnA}\simeq55\mathrm{enA}$			
Target	$^{238}_{92}$ U			
Target angle	$45^{\circ}$			
Target thickness	$1.0 \text{ und } 2.0 \text{ mg/cm}^2$			
Backing	Nb with an effective thickness of $1.3 \mathrm{mg/cm^2}$			
Energy loss in the backing	$\sim 46{ m MeV}$			
Effektive beam time	97 hours in 94 runs			

 Table 2: Reaction and beam parameters of the experiment.

The LNL accelerator facility consists of an electrostatic Van-de-Graaf Tandem accelerator followed by the linear accelerator ALPI. Negative <sup>136</sup>Xe ions are injected by the PIAVE [48] ion injector. The Tandem accelerator operates with an accelerating voltage of up to ~ 15 MV. ALPI, consisting of Cu-Nb and Cu-Pb cavity resonators, is capable to postaccelerate the beam up to energies of 20 MeV/u in order to meet the requirements for high-energy multi-nucleon transfer reactions. After leaving the accelerator complex, the beam is magnetically dispersed, purified from contaminants by a dipole magnet, and then focused onto the target in the scattering chamber. The target was equipped with a  $0.8 \text{ mg/cm}^2$  Nb backing facing the Xe beam. The backing stabilizes the thin U foil and has very low reaction cross sections with <sup>136</sup>Xe. This guarantees a minimal energy loss of beam- and target-like nuclear reaction products leaving the target material. A picture of the used targets is presented in figure 12.



Figure 12: Left: Scheme of the <sup>238</sup>U target in the experiment. The beam-like particles are identified with the PRISMA mass spectrometer. Right top: Glossy <sup>238</sup>U coating. The U surface densities are 1.0 (mid) und 2.0 mg/cm<sup>2</sup>. Right bottom: Niobium backing after several days of beam exposure.

Direct detection of the interesting actinide particles in the high-resolution mass spectrometer PRISMA is impossible due to small recoil energies and the low penetration depth of these highly charged particles in the foils of the PRISMA detector. Therefore, the beam-like particle is identified at the reaction's grazing angle. Kinematic coincidences between the two reaction products allow clean conditions for in-beam  $\gamma$ -ray spectroscopy with the AGATA demonstrator. The surviving actinide nuclei need to be detected directly with another particle detector inside the scattering chamber. For this reason, DANTE Multi-Channel-Plate detectors are installed in the reaction plane covering the angle range which corresponds to the grazing angle for the target-like reaction product. The main advantage of this method is the suppression of fission fragments which is achieved by requiring the scattered particles of both beam- and target-like nature in narrow angle cones at the corresponding grazing angles. A sketch of the experimental method is shown in figure 12. Kinematic coincidences between the two reaction products allow the detection of the surviving heavy nuclei after multi-nucleon transfer and possible neutron evaporation from excited intermediate states.

## 3.1 The AGATA Array

The Advanced Gamma Tracking Array AGATA Demonstrator [15], equipped with five novel AGATA triple cluster (ATC) detectors was operational at the INFN Legnaro till mid 2012. It was used to observe the  $\gamma$ -rays emitted after the reaction in the <sup>238</sup>U target. Each AGATA cryostat holds three slightly different asymmetric hexagonal shaped encapsulated high-purity Germanium (HPGe) crystals that are 36-fold electrically segmented. The fully digitized read-out processes the signals from 36 segments and one core contact per HPGe crystal. Altogether, 555 channels have to be readout. The assembly of the five triple clusters around the reaction chamber is depicted in figure 13.



Figure 13: AGATA Demonstrator with five ATC detectors located near the (opened and dismounted) scattering chamber. Three HPGe crystals are encapsulated into 0.8 mm thick aluminum capsules and housed together in a common triple cryostat.

Highly-segmented high-purity germanium detectors are operated at significantly improved conditions far superior to common Ge detectors with respect to efficiency, energy and position resolution [49]. The main source of background in previous HPGe  $\gamma$ -ray detector arrays arises from true  $\gamma$  rays that are detected, but only deposit parts of their energy in the detector volume due to Compton scattering before leaving the detector. In the past, background suppression could be achieved with BGO scintillator shields placed around the HPGe detector. If  $\gamma$  rays are measured by the HPGe and a BGO detector in coincidence the event is discarded, because the  $\gamma$  ray may be scattered from the HPGe into the BGO. The disadvantage of this method is the smaller solid angle coverage of the HPGe array since the shields impose dead space and reduced solid angle coverage for a high-resolution  $\gamma$ -ray detection. The information contained in Compton-scattered  $\gamma$  rays cannot be used.

In contrast, AGATA data processing allows  $\gamma$ -ray tracking via pulse-shape analysis (PSA), as sketched in figure 14. For this purpose, position, energy, and time information of all  $\gamma$ -ray interactions in the crystal segments are measured. Instead of accepting only the  $\gamma$  rays which deposit all their energy into a crystal and to reject any  $\gamma$  rays Compton scattered from the crystal, the  $\gamma$ -ray tracking algorithm is now able to track down the path of the detected  $\gamma$  rays allowing to add each energy deposition from each interaction point in order to obtain the original full  $\gamma$ -ray energy deposition.

#### Constituents of the $\gamma$ -ray tracking chain



Figure 14: Principle of  $\gamma$ -ray tracking.

Besides energies, the emission angles of the individual  $\gamma$  rays can be disentangled from the first interaction point of the tracks as well. The precise knowledge of the position of the interaction points and their angle of impingement dramatically improves the peak-to-total ratio, the precision of the Doppler correction and the overall energy resolution [19].

#### 3.2 The PRISMA Spectrometer

PRISMA is a large acceptance magnetic ancillary particle spectrometer installed at the LNL for the tracking and identification of heavy ions. It consists of an entrance Multi-Channel-Plate Detector, a succeeding quadrupole singlet lens, a magnetic dipole and two heavy-ion detector arrays (MWPPAC and IC) in the magneto-optical system's focal plane. Coupled with the large HPGe detector array AGATA, it is capable to study moderately neutron-rich nuclei produced by grazing reactions [15]. A photography and a layout sketch is shown in figure 15. Rotating PRISMA on a steel ring around the target in an angular range from  $-30^{\circ}$  to  $130^{\circ}$  relative to the beam line allows the spectrometer to be positioned at the grazing angle of the desired nuclear reaction. PRISMA identifies the beam-like reaction products with their nuclear charge Z, atomic charge state q, mass A and their velocity  $\beta$ .





Figure 15: Top: Sketch of the experimental setup of the LNL 11.22 consisting of the AGATA  $\gamma$ -ray spectrometer, the ejectile detecting heavy ion particle spectrometer PRISMA and the recoil particle detector DANTE. Below: PRISMA spectrometer with MCP, quadrupole lens and dipole magnet, MWPPAC and ionization chamber. The spectrometer is mounted on a 160° ring enabling to position it at best angles according to the reaction kinematics.

PRISMA covers a very large solid angle of  $\simeq 80 \,\mathrm{msr}$  with  $\pm 6^{\circ}$  for  $\theta$  and  $\pm 11^{\circ}$  for  $\phi$ , a momentum acceptance of  $\Delta p/p \simeq \pm 10\%$  and a dispersion of  $\simeq 4 \,\mathrm{cm}/\%$  in momentum. The total flight distance from the start detector to the focal plane is  $\simeq 6.5 \,\mathrm{m}$ . PRISMA is designed for medium-mass heavy ions.

A physical PRISMA event is composed of the following constituents:

- 1. position at the entrance  $x_{\text{start}}, y_{\text{start}}$
- 2. position at the focal plane  $x_{\text{stop}}, y_{\text{stop}}$
- 3. time of flight  $t_{\text{TOF}}$  between the MCP and the focal plane detector
- 4. energy loss  $\Delta E$  and kinetic energy E

All ion tracks are reconstructed via software. A trajectory reconstruction algorithm uses the position, energy and the exit angle given by the MCP entrance detector plus the time of flight along the spectrometer to calculate the trajectory length of the ions and the curvature radius inside the dipole magnet. The complete kinematics of the ejectile fragments can be determined. Therefore, a very effective Doppler correction for the  $\gamma$ -ray energies is performed. The details of the settings of PRISMA are summarized in table 3.

 Table 3: PRISMA settings.

Prisma angle	50° grazing angle
Magnetic dipole field strength	$0.789272\mathrm{T}$
Magnetic quadrupole field strength	$0.857744\mathrm{T}$
IC Fill gas	Methane at $\approx 84 \mathrm{mbar}$
MWPPAC fill gas	Isobuthane

#### 3.2.1 Microchannel Plate Detector

After the beam-like fragment scatters into the entrance window of PRISMA, it is detected by a microchannel plate detector (MCP). The entrance MCP detector is placed 25 cm downstream the target ladder and provides (x, y)-information and a delayed time signal for the measurement of the time of flight  $t_{\text{TOF}}$  between entrance and focal plane of PRISMA with a precision of 400 ps. Additionally, it gives the direction and trajectory angle of the ions with an uncertainty smaller than  $0.5^{\circ}$  in the dispersion plane. The spatial resolution in x and y direction is 1 mm [50]. The MCP consists of two rectangular  $80 \times 100 \text{ cm}^2$  microchannel plates in a chevron configuration. When the produced beam-like fragments enter the detector, they pass a thin self-supporting carbon foil of  $20 \,\mu\text{g/cm}^2$  biased to  $2300 \,\text{V}$ . Secondary  $\delta$  electrons are shed from the atomic shells and accelerated backwards to the MCP by an electrostatic field. A parallel magnetic field by an external magnetic coil is applied to preserve the electron position information on the MCP. The accelerated electrons hit the MCP surface with up to  $300 \,\text{eV}$  and undergo charge amplification. The produced charge is collected by positionsensitive orthogonal anode delay lines providing two-dimensional localization. An example spectrum is shown in figure 16.



Figure 16: MCP spectrum. The shadowed cross structure originates from a plastic cross mounted above the MCP for calibration purposes.

#### 3.2.2 Dipole- and Quadrupole Magnets

The quadrupole singlet focuses the ions vertically towards the dispersion plane given by the ion optics of the following dipole magnet. Being 50 cm away from the target chamber, the quadrupole is 30 cm in diameter and has a length of 50 cm. The entrance coordinates and incidence angles of the particles flying into the quadrupole is given by the entrance MCP. The motion of the ion can be described a hyperbolic curve. The beam is focused on the vertical axis, but defocused in the horizontal dispersion plane. From the quadrupole to the dipole, the ion trajectories are supposed to be straight lines, as they are not affected by any magnetic field. The dipole magnet then bends the ions horizontally with respect to their magnetic rigidity BR given by the equation of Lorentz force  $|\vec{F}_{\text{Lorentz}}| = qvB$  and centripetal force  $|\vec{F}_{\text{centrip.}}| = \gamma mv/q$  with  $\gamma^{-1} = \sqrt{1 - \beta^2}$ :

$$\frac{\gamma m v^2}{R} = q v B \quad \Rightarrow \quad BR = \frac{\gamma m v}{q} \tag{3.1}$$

*B* is the dipole field strength and *R* the bending radius of the circular motion of the charged particle within the dipole. After exiting the dipole, the ion trajectories are again supposed to follow straight lines up to the focal plane detectors. The dipole has a gap of 20 cm, a curvature radius of 1.2 m. It causes a 60° deflection bending for the central trajectory. The maximum magnetic field is 1 T, resulting in a maximum magnetic rigidity of BR = 1.2 Tm. The dipole's longitudinal dimension is large compared with the transversal one. This ensures a weak effect of the magnetic fringing fields on aberration effects and guarantees the planarity of the trajectory.

#### 3.2.3 Focal Plane Detectors

The Multiwire Proportional Plate Avalanche Counter (MWPPAC) [51] is placed at the focal plane of PRISMA and acts as a second timing detector for the time-of-flight calculation that is crucial for the trajectory reconstruction process. Besides the timing signal, it provides position information along the x axis of the focal plane. The detector consists of 10 equal detector sections with a beam-facing surface of  $100 \times 13 \text{ cm}^2$ . The  $x_{\text{FP}}$  position spectrum is depicted in figure 17.

The ionization chamber (IC) is located 60 cm downstream of the MWPPAC detector at the focal plane [51, 52]. It consists of ten anodes in the same high-purity  $CH_4$  gas volume, each one subdivided into 4 sections for subsequent  $\Delta E$  measurements, resulting in a total amount of 40 single segments, i.e. IC read-out channels. A 1m Frisch grid electrode shields the anodes. The four IC sections perpendicular to the focal plane are labeled with A, B, C, D, beginning with A at the focal plane. The sections alongside the focal plane are given numbers from 0 to 9. Furthermore, there are 28 additional segments at the side of the chamber for veto purposes. In order to be able to stop the heavy ions, the IC has an overall length of 120 cm. The surface in front of the beam amounts to  $100 \times 25 \text{ cm}^2$ . In the IC the beam-like reaction products are stopped by the gas and deposit their energy in the segments. Each segment acts as a  $\Delta E$  section and gives a signal proportional to the energy loss of the passing fragment.


Figure 17: Position spectrum of the focal plane MWPPAC detector.

#### 3.3 The DANTE detector

DANTE (Detector Array for Multi-Nucleon Transfer Ejectiles) is a heavy-ion positionsensitive ancillary detector consisting of two MCP detectors mounted in a chevron configuration with a thin biaxial mylar entrance foil [53]. The configuration is very similar to that of the PRISMA start detector.

The detector consists of two orthogonal 100 µm thick copper anodes acting as delay lines, wrapped around a frame of plexiglas rods. After hitting the upper mylar foil, incoming heavy ions unleash a shower of secondary electrons into the DANTE MCPs. The position information is then obtained from the difference in arrival time of the signal at one end of the corresponding delay line with respect to a reference time signal given by the second MCP behind. DANTE covers a large area of  $40 \times 60 \text{ mm}^2$ . It provides the impact position (x, y) of ions within a precision of  $\Delta_{x,y} = 1 \text{ mm}$  and the time of impact with  $\Delta_t = 130 \text{ ps}$ [53]. Apart from that, it does not provide the ion velocity that has to be estimated from a two-body kinematic calculation. A Doppler correction for  $\gamma$  rays from either beam- or target-like particles can be performed using the DANTE position and a calculated velocity.

Three DANTE-MCPs were mounted on a 58° ring inside the target chamber in the experiment to detect target-like reaction products. A picture of the position within the chamber is presented in figure 18. The position information of the DANTE detectors could not be resolved in this experiment, hence, only the time information was usable for the data analysis.

#### Figure 18:

DANTE detectors in the target chamber. The three detectors are mounted on a  $58^{\circ}$  ring and are able to detect target-like reaction products. The plastic cross mounted on top can be used for position calibration purposes.



## 3.4 Data Processing, Trigger and Doppler Correction

The AGATA signals from each crystal are handled and processed in real-time. Five digitizers, one for each detector, digitize all incoming preamplifier signals with a sampling rate of 100 MHz using 14-bit analog-to-digital converters. Subsequently, the data are passed to the AGATA front-end electronics (FEE) by optical fibers. The data coming from the digitizers are reduced by a factor of 10<sup>2</sup> by selecting only relevant detector signals with a programmable trigger system. As the highly-segmented AGATA detectors and PRISMA produce a huge amount of raw data, it is necessary to introduce selective online trigger conditions. The following three trigger conditions were used in the present experimental setup:

PRISMA <sup>1</sup>MWPPAC 
$$\lor$$
 (PRISMA MCP  $\land$  <sup>2</sup>DANTE  $3 \land$  AGATA)  
 $\lor$  (DANTE  $1 \land$  DANTE  $4 \land$  AGATA)

The PRISMA (MWPPAC) trigger is the most important trigger for the experiment. Only ions reaching the focal plane of PRISMA were identified. The coincidence with AGATA was not requested in this trigger. The two other triggers are especially sensitive on recoil fragments that are tagged with DANTE.

Raw trace data, the energy deposition and a global time stamp by a 100 MHz clock are then passed to a computer farm by optical fibers. The dataflow is handled with the online data processing system Narval (Nouvelle Acquisition temps Réel Version 1.6 Avec Linux) [54, 55]. Narval receives both the AGATA data and the raw buffer information of the ancillary detectors. The data are passed online to so-called actors running as individual processes on a computer to execute the Pulse Shape Analysis, the event building including ancillary detector information and the  $\gamma$ -ray tracking. Figure 19 shows the schematic design of the front-end electronics data aquisition system.

In addition, all relevant data of the experiment are written to disk and stored on the GRID (the AGATA collaboration is represented as a virtual organization in the WLCG GRID). Approximately 7 TByte of data were collected during the experiment analyzed in this thesis. The storage of the data allows a later replay of the complete experiment, including the PSA and tracking. Further improvements on PSA and tracking algorithms can be performed this way. New trigger conditions concerning PRISMA can be set as well with the offline replay. This allows to study fully reconstructed PRISMA events without any  $\gamma$ -ray coincidence in order to quantify the elastic reaction channel which is necessary for the calculation of cross sections.



Figure 19: Data processing of AGATA and ancillary detectors. The data stream of the AGATA demonstrator is processed online with the data acquisition software Narval. After a Pulse Shape Analysis (PSA) the  $\gamma$  information is merged with ancillary detector raw buffer data to events. After that, the  $\gamma$ -ray tracking is performed. Event building and merging can also be performed offline via replay. LaBr<sub>3</sub> scitillation detectors were mounted in the setup, but not used in the analysis.

# 4 PRISMA Analysis

The collisions between the <sup>136</sup>Xe beam and the <sup>238</sup>U actinide target generate a variety of reaction products with mostly very low cross sections. The identification of heavy ions is much more difficult than that of light ions like protons, deuterons, tritons or  $\alpha$  particles emerging in direct transfer reactions. In the regime of heavy ions a broad distribution of possible atomic charge states q due to electron stripping and pick-up in foils and detector gases complicates the identification procedure. The recorded position spectra at the focal plane detector are in fact an overlap of q and mass A distributions with a variety of different energies. The dispersion on the focal plane is not sufficient to identify the reaction products unambiguously with respect to their nuclear charge Z and atomic mass number A. Moreover, one has to measure additional quantities such as the time of flight and the total kinetic energies E and partial energy losses  $\Delta E$  to positively identify the nuclear charge and the mass of the ejectile fragments.

### 4.1 Analysis Procedure and Programs

The experimental data are replayed with the emulator femul [56] which is based on the same actor user libraries as Narval [55]. The data analysis is done on a standard server machine with two CPUs, each providing 8 cores and 16 threads, and a CentOS Linux operating system. The dataset is split into 70 different runs, with those runs for calibration and test purposes excluded, which do not contribute to the statistic and do not hold valuable information for the physics to be extracted.

Problems with the ancillary detector data acquisition during the experiment could only be solved by saving the corresponding data streams separately. The data sets of ancillary and AGATA detectors have to be merged offline for these runs. The replay procedures are explained in more detail in the dissertation of B. Birkenbach [19]. The resulting data files are root [57] binary tree files which are called AGATREE. These files are then used as an input for the further analysis with the program treegen [58] developed by B. Birkenbach. treegen is written in C++ and depends on the PRISMA analysis library PrismaManager [59] by E. Farnea. The treegen code performs the calculation of the binary partner reaction kinematics, applies a Doppler correction and extracts the raw data saved in the AGATREE to provide calibrated PRISMA spectra to further identify and select the recorded ejectile fragments. Finally, all the calibrated and analyzed data from AGATA, PRISMA and DANTE are stored in one root tree, called ANATREE. The amount of data is successively scaled down. In the end only those events with identified nuclear charge and mass are stored together with their Doppler corrected  $\gamma$ -ray spectra, timing, Q-value and particle coincidence TAC information. Those root-files have a reduced size of only 27.3 GBytes. Spectra can be generated with different cuts or gates. The cut parameters are validated on an event-by-event basis.



Figure 20: The analysis procedure of is divided in three parts: First of all, the program femul [55] emulates the whole experiment to store the raw data in binary root trees called AGATREE. In a next step, treegen [58] processes the dataset and extracts meaningful physical information from AGATA and the ancillary detectors to store the data in ANATREE root files. Supplementary analysis steps such as the construction of  $\gamma$ - $\gamma$  matrices are performed with the program PostAnalysis [58].

The code PostAnalysis [58] generates mass and charge spectra, time spectra, mass-overcharge spectra for the aberration correction (see section 4.3) and many other spectra needed for the mass spectrometer analysis. Moreover, PostAnalysis extracts final  $\gamma$ -ray spectra and sorts  $\gamma$ - $\gamma$  matrices into the MFILE format readable with the  $\gamma$ -spectrum analysis and fitting programs tv [60] and hdtv [61] developed at the IKP Cologne. A sketch of the whole analysis procedure is depicted in figure 20.

Due to instabilities and shifts in the PRISMA detector system and electronics a timeconsuming problem in the data analysis occurred. The mass-over-charge ratio A/q, which is measured by the mass spectrometer, shows severe shifting as a function of the beam time. The resolution of mass spectra of small independent datasets of short beam time segments could not be reproduced in other dataset parts, nor for the full beam time. Even mixing of masses and charge states were observed after an analysis of the full dataset [62]. Calibration factors differ drastically, making a single analysis procedure impossible. Hence, the masses of the ejectile fragments can not be selected at all. Figure 21 illustrates that problem, showing the observable A/q as a function of beam time, represented by the running time stamp number of the AGATA events.



Figure 21: Shifts and instabilities in the experiment: The mass A divided by the atomic charge state q is plotted against the running time stamp number of the AGATA events which corresponds to the overall beam time. Only events between  $x_{\rm FP} = 300 \,\mathrm{mm}$  and  $400 \,\mathrm{mm}$  on the MWPPAC focal plane detector are selected. As one would expect parallel A/q stripes (like in analysis section A), the mass-over-charge ratio smears out, shifts, or in extreme cases, is not resolvable at all. The alphabetic order of the beam-time segments is given by a chronological order.

As a consequence, the analysis has to be split up into six analysis segments A,B,C,D,F,E. This assignment is only due to the original chronological order in the analysis. The short sections B and D could not be analyzed. Segment B does not contain enough events for a full analysis of all atomic charges q (see section 4.4) and a  $\gamma$ -ray identification (see section 4.4). Section D poses no possibility to extract information on q or A. Finally, the analysis sections A, C, F and E, which are stable over long periods of the measuring time, had to be treated separately by applying adapted calibration and analysis procedures. All final files containing fully analyzed binary data trees are merged or handled with a **root TChain**. The only analysis step applicable in all sections is the determination of the nuclear charge Z, which is described in the next subchapter.

#### 4.2 Identification of the Nuclear Charge

After passing the MCP, quadrupole and dipole magnet, the trajectory and the time of flight of an ejectile fragment in PRISMA are fully determined. The ions then enter the array of ionisation chambers (IC) described in 3.2.3 and deposit their kinetic energy by interactions with the filling gas  $CH_4$ . The energy loss of an impinging particle in an absorber material is governed by the Bethe-Bloch equation [63],

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Z^2 \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi N_A Z_0 \rho_0}{m_\mathrm{e}c^2 \beta^2 A_0} \cdot \left[\ln\left(\frac{2m_\mathrm{e}c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$
(4.1)

where *m* is the mass of the impinging fragment, *Z* its atomic number and E(z) its energy at a given distance.  $\beta$  is the ratio v/c,  $m_e$  the electron mass,  $N_A$  the Avogadro number and *z*,  $A_0$  and  $\rho_0$  are the atomic number, the mass number and the density of the stopping material. The energy loss of non-relativistic particles along the beam trajectory length *z* in the IC filling gas then gives:

$$\frac{\mathrm{d}E(z)}{\mathrm{d}z} \propto \frac{mZ^2}{E(z)} \ln\left(\frac{E}{m}\right) \tag{4.2}$$

The term  $E \times \frac{dE}{dz}$  is only weakly dependent on the kinetic energy E of the ion and can be used to identify the nuclear charge Z by constructing matrices with the energy loss  $\Delta E$  versus the total kinetic energy spectrum E. With E the total energy of the particle entering the IC, the range r(E) is given by

$$r(E) = \int_{0}^{E} \left(-\frac{\mathrm{d}E}{\mathrm{d}z}\right)^{-1} \mathrm{d}E$$
(4.3)

Therefore, Z is either accessible in  $\Delta E$ -E or in E-r matrices. In the present analysis the energy loss  $\Delta E$  of different fragments varies in the different IC segments. Therefore, Z selection is obtained by setting two-dimensional graphical gates on the different separated stripes standing for the different nuclear charges in  $\Delta E$ -E plots. The energy-loss matrix comprising the energy loss in the first two IC layers and the full energy deposition in the IC is utilized for a primary Z selection. Five cuts on stripes standing for tellurium, caesium, xenon, iodine and barium are drawn. Further cuts in  $\Delta E^{A}$ -E matrices are applied. Although the resolution of the energy loss in the  $\Delta E^{A}$ -E plot is not as good as that of the  $\Delta E^{AB}$ -E plot, the second Z selection is of high importance to identify low kinetic ejectile particles as well. Both used energy-loss matrices are depicted in figure 24. The relative intensity distribution of the selected elements is listed in table 4 and depicted in figure 4.2. The ejectile proton stripping channels are more populated than the pick-up channels. A more detailed treatment of the nuclear charge Z selection process and the elaborate IC calibration can be found in the author's bachelor thesis [62] and in the dissertation of B. Birkenbach [19].



Figure 22: Z distribution.

Barium	$2.34 \times 10^{6}$	17.9%
Caesium	$4.68 \times 10^6$	35.8%
Xenon	$13.09 \times 10^6$	100%
Iodine	$4.35 \times 10^6$	33.2%
Tellurium	$2.05 \times 10^6$	15.6%

Table 4: Absolute and relativeZ intensities.

Besides the intrinsic resolving power, several factors influence the energy resolution of the IC. The particles lose around 84 or 122 MeV in the Nb backing and the 1 or  $2 \text{ mg/cm}^2$  thick U targets. Moreover, kinetic energy is deposited in miscellaneous mylar foils as the particles travel through the PRISMA mass spectrometer.



Figure 23: Z resolution under different cut conditions.

To quantify the Z resolution, the  $\Delta E/E$  matrix is rotated counterclockwise by  $\alpha = 8^{\circ}$  using

$$E' = E\cos(\alpha) - \Delta E\sin(\alpha)$$
  $\Delta E' = E\sin(\alpha) + \Delta E\cos(\alpha)$ 

It is then projected onto the abscissa and calibrated to fit the selected nuclear charges. By applying a multi-Gaussian fit, a Z resolution can be determined. The overall resolution

of the ionization chambers is sufficient to guarantee an (inverse) resolution  $Z/\Delta Z$  of  $\approx 52.7 \pm 0.1$ , which is adequate for the experiment. The software routines of PrismaManager do not use only energy depositions in successive IC pads. On the contrary, the angle of the impinging particle at the focal plane is also considered to select all relevant IC pads along the ion's flight path through the ionization chamber. If a straight ion path in successive IC pads is demanded instead, one obtains a slightly better Z resolution of  $Z/\Delta Z = 58.0 \pm 0.1$ , showing that the Z reconstruction routines work reasonably well. The Z projections are depicted in figure 23.

Evaluating the  $\gamma$ -ray spectra, it becomes obvious that the  $\pm 1p$  and -1p reaction channels overlap Xe fractions. The element yields will be discussed in more detail by investigating the X-ray fractions of Z-gated  $\gamma$ -ray spectra in chapter 6.1. The Z selection is the bottleneck for the quality and cleanliness of the  $\gamma$ -ray spectra to be selected. However, xenon-free spectra can only be expected in the  $\pm 2p$  reaction channels.

## 4.3 Ray Tracing and Aberration Corrections

The identification of the reaction products in PRISMA is based on an iterative software reconstruction of the ion trajectories following measurements of the position, time and total energy signals at the entrance and at the focal plane.

First of all, the total flight path  $L(\theta, \phi)$  and the curvature bending radius  $R(\theta, \phi)$  of each particle are reconstructed iteratively using the ray-tracing algorithm of the **PrismaManager** software. The motion of a charged particle inside the quadrupole and the dipole is fully determined by its corresponding magnetic rigidities BR and by the maximum magnetic fields. The trajectory is reasonably simplified as a straight line from the target to the quadrupole entrance, followed by the motion in the quadrupole up to its exit, a straight line to the dipole entrance, a following arc of circumference in the horizontal plane to the dipole exit and a subsequent straight line in the horizontal plane up to the focal plane. The iterative calculation to match with the measured MCP start-, MWPPAC stop- and time-of-flight values starts with a value of R = 120 cm corresponding to an ideal central trajectory. The iteration ends, if the calculated point in the focal plane lies within 1 mm from the measured MWPPAC hit. The ejectile fragment's velocity  $\beta = L/t_{\text{TOF}}$  can now be deduced precisely. The required fine matching and removal of global and relative TOF offsets are described extensively in [19].



Figure 24: Energy loss matrices. (Top) The energy loss in the first two IC layers plotted against the full energy deposition in the IC. Five Z are selected (Tellurium, Caesium, Xenon, Iodine, Barium). (Bottom) To select low kinetic particles further cuts in  $\Delta E^{A}$ -E matrices are set. Selected events are colored proportional to the number of events in the corresponding matrix bins. Excluded events are shaded grey.

Since the PRISMA dipole magnet acts as a magneto-optical imaging system, incoming ejectile ions are transmitted and dispersed by the mass-over-charge ratio A/q from the start detector to the imaging system's focal plane  $x_{\rm FP}$ . The Lorentz equations of motion of a non-relativistic particle of charge q in an electromagnetic field are

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \tag{4.4}$$

As the force on the particle is perpendicular to the motion, the magnetic field exercises no work on the particle, and so its momentum magnitude is constant. Therefore the particle has constant speed  $\beta$ , but the flight direction may change. Considering  $\mathbf{E} = 0$  and  $\mathbf{B}$  an uniform constant magnetic field, equation 4.4 describes the motion of the charged particle in the following way:

$$m \frac{\mathrm{d}^2 \mathbf{r}}{\mathrm{d}t^2} = q \mathbf{v} \times \mathbf{B} \tag{4.5}$$

 $|d\mathbf{v}/dt|$  equals the Lorentz acceleration  $v^2/R$ . *m* may be identified as the nuclear mass *A*. The velocity can be written as  $v = L(\theta, \phi)/t_{\text{TOF}}$ . It follows:

$$\frac{v^2}{R} = \frac{qvB}{m} \quad \Rightarrow \quad \frac{m}{q} \equiv \frac{A}{q} = \frac{BR}{\beta c} = BR \frac{t_{\text{TOF}}}{L(\theta, \phi)} \tag{4.6}$$

Therefore, a precise determination of the entity A/q requires a well calibrated time of flight and a well determined trajectory length  $L(\theta, \phi)$ . Above all the magnetic field mapping has to be understood in-depth. Unlike an ideal instrument, real mass spectroscopy systems are initially always misaligned and suffer from inaccuracies and inhomogeneous magnetization of the pole pieces. These static effects cause non-linearities and aberrations of any order, visible in systematic dependencies between A/q and the position coordinates of both the entrance MCP and the focal plane MWPPAC. Most of the magneto-optical aberration effects are compensated via the software-based reconstruction of the ion trajectories with ray-tracing codes. Effects of the magnetic fringe fields are partly reabsorbed with an effective quadrupole length, different than the real geometrical quadrupole size.

For each of the five selected nuclear charges Z and for each of the four analysis segments an aberration correction has to be conducted in order to correct for the remaining nonlinearities and to separate the different mass-over-charge ratios in a one-dimensional A/qprojection. For this purpose three matrices are of interest: A/q plotted against the x and y coordinate of the MCP start detector and against the x coordinate of the MWPPAC focal plane detector. For an ideal ion optic one would expect clearly resolved A/q bands, representing several masses for different charged states shifted against each other. The projection onto the A/q axis should result in a series of resolved Gaussian peaks. Instead, only an unresolved Gaussian envelope is visible before any aberration correction is applied. This A/q spectrum poses no possibility to identify nor construct final masses. Curvatures and contortions in varying degrees are seen in the three two-dimensional  $A/q \rightarrow x_i$  matrices. The A/q distortion in the  $x_{\text{MCP}}$  and  $x_{\text{FP}}$  is a concave curvature of positive slope, while the A/q bands in the plot against  $y_{\text{MCP}}$  are of a convex parabolic nature.



Figure 25: Example set of polynomial fits for aberration correction in analysis segment C, Z = 56. 7th order polynomials F(x) are fitted into plots of A/q versus  $x_{\text{MCP}}$ ,  $y_{\text{MCP}}$  and  $x_{\text{FP}}$  to correct the non-linearities visible in the diagrams.

For the correction root TCut gates are drawn around a single A/q stripe. Then a custom root fit macro is applied to all events located in the gate to extract a one-dimensional curve shape. With gnuplot [64] the resulting points are fitted with a 7th order polynomial  $F(\chi)$ :

$$F(\chi) = \sum_{i=0}^{7} a_i x^i$$
,  $\chi = x_{\rm MCP}, y_{\rm MCP}, x_{\rm FP}$  (4.7)

In some cases additional points were added at the fit boundaries to eliminate boundary effects. This elaborate procedure has to be done carefully one after the other, starting with the  $A/q \rightarrow x_{\rm MCP}$  and  $A/q \rightarrow y_{\rm MCP}$  diagrams and ending with a final correction for the focal plane coordinate. Example data points and the corresponding polynomial fit functions are shown in figure 25. Examples of pre- and post-corrected 2D and 1D spectra are presented in figure 26. The final effect on the A/q spectra can be best seen in a one-dimensional projection.



Figure 26: Results of the software-based aberration correction on the non-linear distortions in the two-dimensional matrices A/q against  $x_{\text{MCP}}$ ,  $y_{\text{MCP}}$  and  $x_{\text{FP}}$ . The corrections are best visible in the one-dimensional projection.

#### 4.4 Charge State q

In order to obtain the mass A from the mass-over-charge ratio A/q, further information on the atomic charge q is needed. Since the ejectile ions pass through target material, the target backing, several mylar foils and detector gases, parts of the atomic electron shell are stripped off. This results in a broad charge-state distribution.

In order to access and identify the atomic charge state, three relations between the time of flight  $t_{\text{TOF}}$ , the total kinetic energy  $E_{\text{IC}}$  given by the  $\Delta E/E$  measurements in the ionization chamber and the particle motion in the magnetic field within the dipole are used:

$$t_{\rm TOF} = \frac{L(\theta, \phi)}{\beta c} \qquad E_{\rm IC} \simeq \frac{1}{2}mv^2 \qquad B R(\theta, \phi) = A \frac{\beta c}{q}$$
(4.8)

Let  $R(\theta, \phi)$  be the dipole bending radius for a given ray curvature,  $\beta = v/c$  the relative particle velocity, *B* the magnetic field strength and  $L(\theta, \phi)$  the ray trace length. Then it follows:

$$E_{\rm IC} \simeq \frac{1}{2} m v^2 = \frac{1}{2} q B \frac{L(\theta, \phi) R(\theta, \phi)}{t_{\rm TOF}} = \frac{1}{2} q B R \beta c = \text{const} \cdot q R \beta$$
(4.9)

As a result, one gets:

$$\frac{E_{\rm IC}}{R(\theta,\phi)\,\beta} \propto q \tag{4.10}$$

The different charge states can therefore be separated in a plot of  $E_{\rm IC}$  against  $R\beta$ . They are selected by bi-dimensional polygonal gates, depicted in figure 27. The extracted atomic charge distributions for the different nuclear charges are shown in figure 28.

A direct measurement of the atomic charge state is not possible, since  $E_{\rm IC}$  is not given in absolute values. In fact, it is not needed to identify absolute values for q, since A/q is given in arbitrary units as well and the final mass distributions have to be calibrated to center at integer mass values.

The charge state selection is crucial for the quality of A/q spectra as well. Misidentified events are responsible for spurious unresolved parts in the A/q distributions for a given qor contribute to the uniform background in the final mass spectra. This problem depends entirely on the energy resolution of the ionization chamber due to the fact, that there are substantial energy losses of particles in various mylar foils throughout the PRIMSA detector. The effect is most critical for heavy masses and low energies.



Atomic charge state selection for  ${}_{56}Ba$ 

Figure 27: Charge state separation in  $E/R\beta$  matrices shown for the  ${}_{56}Ba$  reaction channel. Each line represents one charge state. Events selected with charge cuts are shown with a color scheme. Events outside the charge gates are plotted in grey. The amount of events lost in this analysis step is negligible. The accumulation of unselectable events in the right originates from particles only detected in IC segments 0 and 1. They are probably fission fragments entering PRISMA.



Figure 28: Atomic charge distributions for all analyzed Z channels. The broad charge distributions, characteristic for heavy ions, do not depend on the isotope.

#### 4.5 Mass A

At this step of the analysis, both nuclear and atomic charge and the mass-over-charge ratio A/q are known. The mass A could be assigned event-by-event by simply calculating  $A = A/q \cdot q$ . This method has a significant disadvantage. The atomic charges and the final mass value have to be calibrated independently, requiring two independent analysis steps to obtain a sufficient mass resolution. Moreover, one would have to assign non-integer q values for calibration purposes. Instead, the several unaligned charge-state-gated A/qdistributions, which are randomly unaligned as shown in figure 29(a), are calibrated to integer mass values by a two-parameter fit and then subsequently summed up. In this way, the calibration function is depending on scale factors  $a_i$  and offsets  $b_i$ :

$$A = a_i \cdot \left. \frac{A}{q} \right|_{q_i} + b_i \tag{4.11}$$

All q-gated  $A/q|_{q_i}$  spectra are created with PostAnalysis as a hdtv-readable spc file. Multi-Gaussian fits are applied to each mass spectrum. An example is shown in figure 29(c). All Z channels and analysis sections have to be performed individually. Together they yield approximately 600 fitted centroids. Calibrated mass spectra are obtained by assigning the correct mass values in terms of atomic mass units to the corresponding peaks in the  $A/q|_{q_i}$  spectra still given in arbitrary units. The masses are finally determined by inspecting the characteristic  $\gamma$ -ray signature of different high-statistic  $\gamma$ -ray transitions in coincidence with the various mass peaks.

For this purpose,  $A/q |_{q_i}$  is plotted versus the  $\gamma$ -ray energy Doppler corrected for the ejectile reaction fragments. An example plot (nevertheless successfully calibrated) showing the general appearance of such a diagram is depicted later on in figure 31. This allows careful inspections of possible leakages of identified events into neighboring reaction channels due to a false calibration. For the barium reaction channel, the <sup>140</sup>Ba 2<sup>+</sup> (602.4 keV) and 4<sup>+</sup> (528.3 keV) transitions as well as the <sup>137</sup>Ba (19/2) (274.4 keV) transition are used for mass identification. In the tellurium channel, the 15/2<sup>-</sup> (697.4 keV) and 19/2<sup>-</sup> (678.2 keV) transitions show a strong intensity in the identification matrix.

Several python [65] based programs organized by a bash [66] script produce text files filled with the Gaussian fit centroids and the corresponding identified integer mass numbers. Linear fits then give the desired calibration factors  $a_i$  and  $b_i$ . An example fit result is



Figure 29: Mass alignment examples for the Barium analysis. (a): Different unaligned and unshifted q-gated  $A/q|_{q_i}$  spectra. (b): Example linear mass calibration fit. (c): Example fit of the A/q distribution for q = 26.

shown in figure 29(b). Finally, all  $A/q \Big|_{q_i}$  distributions are shifted and summed up. The final mass yield is depicted in both linear and logarithmic scales in figure 33. In this way, the assignment of the correct mass A can be obtained for every previous selected charge state (see section 4.4). The assignment of correct mass values may be difficult for weak reaction channels and charge gates with only low statistics.



Figure 30: Mass A plotted against the focal plane position coordinate  $x_{\text{FP}}$ . Twodimensional graphical cuts are set for further event selection.

The aberration correction improved the A/q spectra in a way that, finally, a mass determination with a high resolution is possible. Nevertheless, there is a strong relationship between the extracted mass values and the position in the focal plane. This can be observed in all four spectra in figure 30, in which the ejectile mass is plotted against the focal plane position  $x_{\rm FP}$ . The MWPPAC section between 400 and 500 mm does not work properly, the mass spectra in the corresponding areas smear out and are distorted. This inaccuracy is a potential source of background in the one-dimensional A projections. Therefore, it is reasonable to extract all events in the respecting section for the determination of the mass resolving power, since the mass selection is done via graphical two-dimensional cuts.

Z = 52: <sup>129</sup> Te		$Z = 53: \ ^{132}$ I			
Z = 52	$m/\Delta m$	FWHM [amu]	Z = 53	$m/\Delta m$	FWHM [amu]
A C E F	$\begin{array}{c} 258.3 \pm 1.0 \\ 259.5 \pm 1.5 \\ 255.9 \pm 1.2 \\ 222.1 \pm 1.2 \end{array}$	$\begin{array}{c} 0.4995 \pm 0.0019 \\ 0.4972 \pm 0.0028 \\ 0.5041 \pm 0.0024 \\ 0.5807 \pm 0.0032 \end{array}$	A C E F	$219.8 \pm 0.7 218.9 \pm 0.9 215.5 \pm 0.8 205.3 \pm 0.8 $	$\begin{array}{c} 0.6006 \pm 0.0018 \\ 0.6030 \pm 0.0024 \\ 0.6127 \pm 0.0023 \\ 0.6429 \pm 0.0026 \end{array}$
All $261.5 \pm 0.6  0.4934 \pm 0.0011$ $Z = 55:  {}^{136}Cs$		All $215.2 \pm 0.5$ $0.0135 \pm 0.0013$ Z = 56: <sup>138</sup> Ba			
	Z = 55:	<sup>136</sup> Cs		Z = 56: <sup>1</sup>	<sup>.38</sup> Ba
Z = 55	Z = 55:	<sup>136</sup> Cs FWHM [amu]	Z = 56	$Z = 56: \ ^{1}$ $m/\Delta m$	<sup>38</sup> Ba FWHM [amu]
	$Z = 55:$ $m/\Delta m$ $274.0 \pm 0.2$ $249.7 \pm 0.8$ $260.0 \pm 0.6$ $206.5 \pm 0.8$	$\begin{array}{c} ^{136}\mathrm{Cs} \\ \hline \mathrm{FWHM} \ [\mathrm{amu}] \\ 0.4965 \pm 0.0005 \\ 0.5447 \pm 0.0017 \\ 0.5232 \pm 0.0013 \\ 0.6587 \pm 0.0027 \end{array}$	Z = 56 A C E F	$Z = 56: \ ^{1}$ $m/\Delta m$ $293.5 \pm 0.4$ $268.2 \pm 0.1$ $259.7 \pm 0.1$ $265.0 \pm 0.5$	$\begin{array}{c} {}^{38}\text{Ba} \\ \hline \text{FWHM [amu]} \\ 0.4701 \pm 0.0006 \\ 0.5146 \pm 0.0002 \\ 0.5313 \pm 0.0002 \\ 0.5207 \pm 0.0009 \end{array}$

Z = 52: <sup>129</sup>Te

**Table 5:** Mass resolution values for the strongest mass channels: <sup>129</sup>Te, <sup>132</sup>I, <sup>136</sup>Cs and<sup>138</sup>Ba including all events for four different measuring periods A, C, E, F.

Z = 52: <sup>129</sup> Te			$Z = 53: \ ^{132}$ I			
Z = 52	$m/\Delta m$	FWHM [amu]	-	Z = 53	$m/\Delta m$	FWHM [amu]
A C E F	$\begin{array}{c} 276.6 \pm 1.1 \\ 276.5 \pm 1.6 \\ 270.0 \pm 1.4 \\ 232.4 \pm 1.4 \end{array}$	$\begin{array}{c} 0.4664 \pm 0.0018 \\ 0.4666 \pm 0.0027 \\ 0.4779 \pm 0.0025 \\ 0.5549 \pm 0.0033 \end{array}$	-	A C E F	$\begin{array}{c} 236.9 \pm 0.6 \\ 251.9 \pm 1.0 \\ 232.3 \pm 1.1 \\ 232.2 \pm 1.1 \end{array}$	$\begin{array}{c} 0.5573 \pm 0.0013 \\ 0.5241 \pm 0.0020 \\ 0.5685 \pm 0.0028 \\ 0.5685 \pm 0.0026 \end{array}$
All	$262.4 \pm 0.6$	$0.4916 \pm 0.0012$	-	All	$219.4 \pm 1.1$	$0.6016 \pm 0.0031$
	Z = 55:	$^{136}Cs$			Z = 56: <sup>1</sup>	<sup>38</sup> Ba
Z = 55	$Z = 55:$ $m/\Delta m$	<sup>136</sup> Cs FWHM [amu]	-	Z = 56	$Z = 56: \ ^{1}$ $m/\Delta m$	<sup>38</sup> Ba FWHM [amu]
Z = 55 A C E F	$Z = 55:$ $m/\Delta m$ $305.3 \pm 0.7$ $275.6 \pm 0.9$ $288.1 \pm 0.9$ $253.3 \pm 1.0$	$\begin{array}{c} ^{136}\mathrm{Cs} \\ \hline \mathrm{FWHM} \ [\mathrm{amu}] \\ \hline 0.4454 \pm 0.0010 \\ 0.4935 \pm 0.0017 \\ 0.4721 \pm 0.0014 \\ 0.5368 \pm 0.0021 \end{array}$	-	Z = 56 A C E F	$Z = 56: \ ^{1}$ $m/\Delta m$ $339.7 \pm 1.3$ $296.8 \pm 1.6$ $283.3 \pm 1.1$ $269.3 \pm 1.6$	$\begin{tabular}{ c c c c c c c } \hline & & & & & & & & & & & & & & & & & & $

Table 6: Mass resolution values for the strongest mass channels: <sup>129</sup>Te, <sup>132</sup>I, <sup>136</sup>Cs and  $^{138}$ Ba excluding the broken MWPPAC section 4.

In the PRISMA collaboration, the mass resolving power is defined as  $\Delta m/m$ , taking the full width at half maximum (FWHM) as  $\Delta m$  and the fit centroid as m [8, 67]. The mass resolutions for the strongest mass peaks in all analyzed Z channels are shown in the tables 5 for all events in the MWPPAC and in tables 6 for all events in the MWPPAC, excluding section 4. Although PRISMA works at its specified limits with a <sup>136</sup>Xe beam, the final mass resolution is remarkably good. Figure 31 shows the ejectile masses for Z = 56plotted against the ejectile Doppler corrected  $\gamma$ -ray energy. All mass channels show a clean separation in terms of the  $\gamma$ -ray spectra analysis. There is no leakage or contamination of events in neighboring mass channels.



Figure 31: Identified ejectile masses for Z = 56 plotted against the ejectile Doppler corrected  $\gamma$ -ray energy. The clean separation in terms of the  $\gamma$ -ray analysis is visible. There is no leakage of events into neighboring mass channels.

Figure 33 shows the final mass distribution of all analyzed Z channels. The mass yields reveal typical characteristics of multi-nucleon transfer reactions. As described in chapter 1, it is expected for multi-nucleon transfer reactions that the lighter projectile tends to strip protons and to pick up some neutrons. This tendency is confirmed for the proton transfer, the -1, 2p channels Te and I are higher populated than the +1, 2p channels Cs and Ba. The high overall intensities of the Cs and Ba channels is worth to be noted. The tendency to pick up neutrons in the -1, 2p channels only occurs to a limited extent. The distribution of the Te mass spectrum is limited by <sup>136</sup>Te. Hence, the neutron-pickup reactions are strongly suppressed. Neutron pick-up in the proton pick-up channels is hindered as well. The highest populated channels are <sup>136</sup>Cs and <sup>138</sup>Ba which are +1p-1n respective +2p transfer reactions. Figure 32 shows a Segré-chart-like representation of the mass yields.



Figure 32: Two-dimensional representation of the mass yields given in figure 33. Only channels with > 5000 counts are shown. Here, the proton number is not plotted against the mass, but the neutron number N = A - Z in the style of the Segré chart. The maximum channels are marked with the corresponding mass number for each Z.

In the quasi-elastic channel neutron pick-up is not favored either. The intensities of the neutron pick-up peaks in the Xe mass spectra drop rapidly. For  $^{139}$ Xe only a fraction of 0.6%with respect to the beam isotope  $^{136}$ Xe were identified. In contrast, the -8n channel  $^{128}$ Xe still contains 2.1% of the beam intensity. For the first picked-up neutron the Xe mass yield drops by a factor of  $\sim 3.5$ . The second neutron-pick-up accounts for a further drop by a factor of  $\sim 2.8$ . The drop factor for successive neutron stripping is constant with  $\sim 1.6$ . The intensity of the one-neutron transfer channel with  $9.33 \times 10^5$  counts is much larger than the one-proton transfer channel with only  $5.69 \times 10^5$  (Xe contaminated) counts. For few-nucleon transfers in the quasi-elastic channel, the reaction cross sections are strongly determined by the Q = -TKEL values. The mass spectra envelopes of the  $\pm 1, 2p$  multi-nucleon transfer channels are broader and more Gaussian-like. Furthermore, those yields are distributed over more masses. The pure proton transfer channels without neutron exchange become less favorable as more protons are transferred in the reaction. Concomitant neutron stripping is favored here. When more protons are stripped off the ejectile fragment in the multi-nucleon transfer reaction, the centroid of the mass distributions shifts to lower neutron numbers. This effect on the isotopic distribution may be mostly influenced by neutron evaporation from the primary reaction fragments as indicated in figure 1, because the fragments are produced "hot" at quite high excitation energies. Recent studies on multi-nucleon transfer reaction employing PRISMA show similar systematics [4, 9].



Figure 33: Mass spectra for identified ejectile masses in the reaction  $^{136}$ Xe (1 GeV) on  $^{238}$ U. The beam mass is labeled with a dotted line.

Evaluating figure 33, it becomes obvious that the difficulty in populating extremely neutronrich nuclei far away from the valley of stability via multi-nucleon transfer reactions lies not only in the vanishing low production cross sections, but also in the fact that, as more protons are stripped from the beam projectile, *Q*-values get more negative and neutron evaporation effects modify the final mass yields significantly.

#### 4.6 TKEL

In a magnetic mass spectrometer the magnetic rigidity, together with the energy information given by an ionization chamber, gives the correct energy of an impinging reaction fragment directly. The total kinetic energy loss (TKEL) for the reaction, defined as the difference between the ingoing and the outgoing kinetic energies, can then be simply deduced [68]. The three-dimensional momentum vectors are reconstructed with the knowledge of mass, velocity and the entrance angle at the PRISMA MCP. Neglecting the momentum of the target atoms moving with only thermal energies,  $p_T = 0$ , the relativistically correct expression for the conservation of momentum in the reaction process is

$$\mathbf{p}_R = \mathbf{p}_E - \mathbf{p}_B \tag{4.12}$$

 $\mathbf{p}_R$  stands for the momentum of the target-like recoil particle,  $\mathbf{p}_E$  for the ejectile fragment momentum and  $\mathbf{p}_B$  for the initial momentum of the impinging beam. It follows:

$$p_R^2 = p_E^2 + p_B^2 - 2p_B p_E \cos\theta$$
(4.13)

 $\theta$  is the angle of emission of the ejectile fragment with respect to the direction of the incoming beam particle. At this point, it is reasonable to employ the non-relativistic energy relation between kinetic energy K and momentum  $\mathbf{p}$ ,  $E = \frac{p^2}{2m}$ , because  $E \gg m_0 c^2$ . m is the mass of the particle. Substituting  $p = \sqrt{2Em}$  in 4.13, one obtains:

$$E_R = \frac{m_B}{m_R} E_B + \frac{m_E}{m_R} E_E - 2\sqrt{m_B m_E E_B E_E} \cos\theta \qquad (4.14)$$

The Q value is defined as the difference between the initial kinetic energy  $E_i$  of the projectile and the final kinetic energy  $E_f$  after the reaction. The intrinsic excitation energies  $E_E^*$  and  $E_R^*$  of the two nuclei produced after the collision are included.

$$-Q = \text{TKEL} = E_i - E_f = E_B - (E_E + E_R)$$

$$= (m_R + m_E - (m_B + m_T))c^2 + E_E^* + E_R^*$$
(4.15)

 $Q_{gg} = (m_R + m_E - m_B - m_T) c^2$  describes the so-called ground state Q-value which corresponds to the TKEL of a reaction leading to the recoil and ejectile fragments in the ground state. It follows:

$$Q = \frac{m_R + m_E}{2m_R m_E} p_E^2 - \frac{m_R - m_B}{m_R} E_B - \frac{1}{m_R} \sqrt{2m_B E_B} \, p_E \cos\left(\theta_{\rm MCP}\right) \tag{4.16}$$

Therefore, the Q value fully depends on the measured momentum vector of the ejectile and  $\theta_{\text{MCP}}$ . The analysis library **PrismaManager** calculates the effective Q value in this way and corrects for the energy losses of the ions through the target material and the mylar windows in PRISMA as well. Figure 34 shows two example Q-value distributions, one for the quasi-elastic channel <sup>136</sup>Xe and one for the multi-nucleon transfer channel <sup>136</sup>Ba. The quasi-elastic channel has a superimposed contribution of events around Q = 0, caused by the elastic reaction part. As expected, this contribution is completely missing in the multi-nucleon transfer channel.



Figure 34: Q-value distributions for quasi-elastic and multi-nucleon transfer channels. The quasi-elastic channel shows an elastic contribution around Q = 0, whereas the multi-nucleon transfer channel is evenly distributed.

By gating on the Q value in the analysis of  $\gamma$ -ray spectra Doppler corrected for target-like nuclei, the total excitation energy can be restricted. This yields a suppression of neutron evaporation channels in the actinide spectra. Especially, events with a small Q value are more likely reaction products with a lower excitation energy and therefore reduced neutron evaporation. The disadvantage of this method is the fact that one does not know how the TKEL is shared between the two reaction product and one may not distinguish to which amount beam- and target-like fragments are individually excited. Nonetheless, the Q-value cut parameters have to be adjusted for each reaction channel. A detailed analysis of the behavior of spectra under Q-value cuts can be found in [19].

## 4.7 Cross sections

Additionally to the analysis of the  $\gamma$ -ray spectra, cross sections for the various multi-nucleon transfer channels will be extracted in the near future. The determination of cross sections  $\sigma$  actually requires the measurement of both beam and elastic channel intensities. The differential cross section  $\frac{d\sigma}{d\Omega}$  can be determined directly by  $N_s$  the number of interactions in the target,  $N_b$  the number of impinging particles and  $\rho_t$  the target-area density. In the present experiment, the beam intensity was not measured accurately, therefore, a relative measurement will be applied. A prospective approach is the study of the elastic component accessible via the total kinetic energy loss (TKEL) spectra measured in PRISMA. This method is described in detail by Szilner *et al.* [3] and Montanari [8]. The elastic cross section at forward angles is given by the Rutherford scattering formula. The identification of the pure elastic contribution allows to correlate the elastic counts to the well known Rutherford cross sections and to calculate conversion factors between counts and differential cross sections in mb/sr. These factors can then be used to determine relative cross sections for other inelastic reaction products.

For this purpose, several TKEL spectra are already constructed. In a new replay of the complete dataset, any forced coincidences between PRISMA and AGATA have to be deactivated in order to obtain a dataset including elastically scattered events which do not contain  $\gamma$ -rays measured with AGATA. The first TKEL distribution comprises all events, only with a cut on the quasi-elastic channel <sup>136</sup>Xe selected by PRISMA. A second TKEL distribution is constructed with a cut on an AGATA-array multiplicity greater than zero and a total hit energy of less than 100 keV to exclude X-rays. The efficiency of AGATA is taken into account by normalizing both spectra in the inelastic tail region.

The intensity of the pure elastic scattering can then be determined by subtracting both normalized TKEL spectra from each other. This procedure has to be performed for various scattering angles  $\theta_{\text{PRISMA}}$  over the complete angular acceptance  $\Omega(\theta, \phi)$  of the PRISMA entrance window, for example in steps of 1°. PRISMA has a scattering angle coverage of 12° with a range of 6° around the calculated grazing angle of 50°. Figure 35 shows the process with example TKEL spectra for  $\theta_{\text{PRISMA}} \in [5^\circ, 6^\circ]$ . The blue line shows all events including elastic scattering, the green line shows all events with an additional cut on AGATA hits normalized to the tail region and finally the bell-shaped red line the difference of the blue and green shaded distributions, standing for the pure elastic contribution.



Figure 35: Extraction of the elastic component via subtraction of different TKEL spectra for  $\theta_{\text{PRISMA}} \in [5^\circ, 6^\circ]$ . Blue: TKEL spectrum of all events positively identified as <sup>136</sup>Xe. Green: Same spectrum with an additional request on a  $\gamma$ -ray coincidence, normalized to the inelastic tail region of the blue distribution. The red spectrum is the subtraction of the two spectra and represents the elastic scattering component of <sup>136</sup>Xe on <sup>238</sup>U. Arbitrary arising peak structures on top of the TKEL distributions are generated by erroneous ray-tracing in PRISMA. The corresponding event accumulations are observed in both MCP as MWPPAC spectra.

The number N of elastically scattered <sup>136</sup>Xe ions is obtained by integrating over the subtracted TKEL distributions. The ratio of  $N(\theta)$  with the Rutherford cross section  $\sigma_{\text{Rutherford}}(\theta)$  can now be compared with predictions of the semi-classical model GRAZ-ING [69]. This ratio allows to calculate the normalization factor C, [C] = mb/sr that is then used to estimate the cross sections of the various multi-nucleon transfer reaction products. To extract the true elastic cross section, the experimentally obtained total number of counts in the elastic peak have to be corrected by a response function  $f(E, \theta, \phi)$  of the PRISMA spectrometer.  $f(E, \theta, \phi)$  must be introduced to correct for inaccuracies in the magnetic systems and ion transport effects. Finally, it follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{N f(\theta_{\mathrm{lab}}, \phi_{\mathrm{lab}}, E)}{C} \tag{4.17}$$

The integrated cross section  $\sigma_{\text{tot}}$  over the angular acceptance of PRISMA can be obtained by the summation over all differential cross sections in the laboratory system calculated for the  $\Delta \theta = 1^{\circ}$  steps in the angular acceptance region  $\Delta \Omega$ :

$$\sigma = \int \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \mathrm{d}\Omega \simeq \sum_{i} \left(\frac{\Delta\sigma}{\Delta\Omega}\right)_{i} \Delta\Omega = \sum_{i} \left(\frac{\Delta\sigma}{\Delta\Omega}\right)_{i} 2\pi \Delta \cos\left(\theta_{\mathrm{lab},i}\right) \quad i \in \{42,\ldots,56\} \quad (4.18)$$

 $\Delta \cos(\theta_{\text{lab},i})$  gives the integration over  $\theta_{\text{lab}}$ , while the factor  $2\pi$  results from the integration over the polar angle  $\phi_{\text{lab}}$ , to which transfer reactions are symmetric.

For the determination of the PRISMA response function a GEANT4 [70] based Monte-Carlo simulation has to be performed. At first, an uniform input event distribution is created for  $E_{\rm kin}$ ,  $\theta$  and  $\phi$ . Those events are then transported event by event with a simulation code [71] based on the ray-tracing code provided by the PRISMA analysis library.

The magnetic fields and the gas pressures in the focal plane detectors are tuned in the same way like in the real experiment. In the second step, the uniform distribution is transported via the PRISMA ray-tracing algorithm. The response function of PRISMA is then defined as as the ratio between the output distribution of events detected at the focal plane and the uniform input distribution at the MCP:

$$f(E, \theta, \phi) = \frac{\# \text{INPUT events at MCP}(E, \theta, \phi)}{\# \text{OUTPUT events at Focal Plane}(E, \theta, \phi)}$$
(4.19)

Applied to the data detected at the focal plane,  $f(E, \theta, \phi)$  gives the real input event distribution. The corrected experimental cross sections are:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{\mathrm{exp}} \times f(E,\theta,\phi) \tag{4.20}$$

Figure 36 shows a visualization of 100 events transported by the PRISMA simulation code through the simulated spectrometer. The simulation code delivers ASCII files with all relevant PRISMA information, such as the ion's radius of curvature inside the dipole, the trajectory length, time of flight or energy losses in the ionization chamber. This data may be branched into **root** trees and can be treated with the described analysis programs and

procedures. A complete PRISMA analysis has to be performed again to extract the response function.



Figure 36: PRISMA Geant4 simulation to obtain the response function. This OpenGL visualization shows the first 100 events transported by the PRISMA simulation code through the spectrometer.

All these future analysis steps require a careful implemented simulation of the PRISMA setup with fine tuned parameters such as the magnetic field strengths and the pressures in the gas-filled detectors.

## 4.8 Coincidence requirements

Three different coincidence signals were recorded in the experiment. Figure 37 sketches the complete setup with all employed coincidence signal measurements. The HPGe ar-



Figure 37: Coincidence measurements in the experiment. A particle coincidence signal is recorded for the combinations DANTE-PRISMA as well as DANTE-DANTE. The prompt time signal describes the coincidence between AGATA and PRISMA.

ray AGATA measures the  $\gamma$  rays nearly instantaneously, while the ancillary signal of the PRISMA focal plane detector is delayed. Coincidence events are therefore measured by the time difference between a signal from the ancillary detectors and the different germanium detectors employing time-over-amplitude converters (TAC). The corresponding time spectrum with the so-called prompt peak is shown in figure 38.



Figure 38: Prompt peak: Time difference between PRISMA's MWPPAC signal AGATA hits. A cut on the prompt peak reduces the fission background in the  $\gamma$ -ray spectra.

All contributions in the prompt peak arise from  $\gamma$  rays in coincidence with their corresponding particles, from where they were emitted. By gating on the prompt  $\gamma$ -ray peak, all other uncorrelated particles are excluded. Prompt peak cuts are always applied as condition for the following  $\gamma$ -ray spectra. The data have been corrected by the time of flight of the ions entering the mass spectrometer [19] to sharp the prompt peak in coincidence with PRISMA. The time resolution connected to the FWHM of the prompt peak accounts to 15.9(1) ns for the barium channel.

In addition, the time differences between PRISMA's MCP entrance detector and the recoiltagging DANTE MCP detectors in the reaction chamber were recorded. The TAC1 time spectrum denotes the coincidence relationship between PRISMA and DANTE, TAC2 between two DANTE detectors. As described in section 3.3, one DANTE detector was mounted at the opposite position of the PRISMA entrance MCP, two other DANTE detectors were placed side by side on a ring in the target chamber but rotated around the beam axis. Both time spectra, TAC1 and TAC2, are shown in figure 39. The time difference spectra of both detector pairs now allow to gate on coincident particles hitting the detectors. The TAC2 coincidence is not applicable on the data since there are only  $\approx 5 \times 10^3$  events in the left peak for Z = 56. This poses no possibility for a further analysis of  $\gamma$ -ray spectra with that cut applied. The recoil  $\gamma$ -ray spectra analysis using TAC1 cuts is described in detail in chapter 6.



Figure 39: TAC particle coincidence time spectra. The time spectrum on the left shows the coincidence between PRISMA's entrance detector and a recoil-tagging DANTE MCP detector in the reaction chamber for the complete dataset and identified Ba isotopes. The right hand side shows the DANTE-DANTE coincidence spectra.

Two separated peaks can be observed in both TAC spectra. Gating on the different peaks, there is no difference visible concerning the nuclear charge Z, mass A, velocity distribution  $\beta$  and even the ejectile Doppler corrected  $\gamma$ -ray spectra. By analyzing for target-like particles, a gate on the right TAC peak yield only a flat background spectrum without any peaks except X-ray contributions. Therefore, it is reasonable to assume that the right peak originates from either random background contributions triggered by a corrupt electronic module or from fission fragments produced in reactions like  $^{136}$ Xe( $^{136}$ Xe,  $f\gamma$ ) $^{136}$ Xe'. Here one of the two fission fragments, which are radiated uniformly in all directions over the full solid angle in the center-of-mass system, cause a signal in the DANTE detector. There is a significant time delay due to the high kinetic energy and therefore high  $\beta$  of the fission products. In general, fission products have a much shorter time correlation due to the additional high kinetic energy from the energy release after the fission process. The remaining fission fragment angular correlation and the fission fragment kinematics in the laboratory frame also disfavors misidentification of fragments as reaction products.

Table 7 lists the absolute and relative statistics of the dataset for the different analysis procedures applied during the analysis. The total raw dataset after replay without any coincidence requirements comprise  $3.272 \times 10^8$  events. For the PRISMA analysis only events

with a coincidence between AGATA and PRISMA were used. For example, elastically scattered beam nuclei without any  $\gamma$ -ray hit in AGATA are excluded in this reduction step. This amount of data corresponds to 60.8% of the original raw data. Compact **root** trees consisting of events with identified nuclear charges and mass numbers are created after applying all analysis steps described in this chapter. With a further cut on a  $\gamma$ -ray multiplicity of  $n_{\gamma} \geq 1$  they contain only 8.09% of the PRISMA data. Asking for a further cut on the PRISMA-DANTE particle coincidence, only  $\approx 0.03\%$  of the analyzed data remain for the Th channel. This is a total of  $\sim 50600$  events.

**Table 7:** Summary of the statistics of the dataset taken in experiment LNL 11.22 for the different analysis procedures applied. For the analysis of ejectile  $\gamma$ -ray spectra  $\sim 8.1\%$  of the analyzed dataset is available. The Th channel contains only  $\sim 0.03\%$  of the analyzed data.

Procedure	Statistics [events]	Relative intensity
Raw data (total)	$3.272 \times 10^{8}$	-
Forced coincidence between AGATA and PRISMA	$1.990 \times 10^{8}$	100.00%
Identified $\gamma$ -rays	$1.582 \times 10^{8}$	79.51%
Correct trajectory in PRISMA	$6.209 \times 10^{7}$	31.20%
Identified $Z$	$2.284 \times 10^{7}$	11.48%
Identified $q$	$1.967 \times 10^{7}$	9.88%
Identified $A$	$1.773 \times 10^{7}$	8.91%
<b>Final statistics:</b> Identified A within $\gamma$ -time cut	$1.609 imes10^7$	8.09%
Identified A with more than one $\gamma$ -ray per event	$7.265 \times 10^{6}$	3.65%
Identified A with more than three $\gamma$ -rays per	$7.27{ imes}10^5$	0.37%
event		
Identified $A$ with recoil particle coincidence	$1.437{\times}10^6$	0.72%
Identified $A$ with recoil particle coincidence and	$4.87 \times 10^{5}$	0.24%
number of $\gamma$ rays $n_{\gamma} > 1$		
Th channel: Identified Ba isotopes within $\gamma$ -ray	$5.1  imes 10^4$	0.03%
time cut, recoil particle coincidence and $n_{\gamma} > 0$		

## 4.9 Doppler correction

PRISMA data are used to perform an event-by-event Doppler correction of the  $\gamma$  rays detected by AGATA as these are emitted by fast moving reaction fragments. The Doppler effect causes an energy shift of  $\gamma$  rays emitted from a moving particle in the laboratory frame of reference. That Doppler shift depends on the particle's velocity  $\beta$  and the  $\gamma$ - ray's angle of emission with respect to the velocity vector of the particle. The relationship between the real  $\gamma$ -ray transition energy  $E_{\gamma,0}$  in the center-of-mass frame and the detected energy  $E_{\gamma}$  is:

$$E_{\gamma} = E_{\gamma,0} \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta} \tag{4.21}$$

The angle  $\theta$  is formed by the velocity vector **v** of the beam- or target-like fragment and the first interaction point within the HPGe array. It is determined from the polar coordinates at the MCP entrance detector. The ejectile velocity is reconstructed by the determination of the ion path  $L(\theta, \phi)$  along the mass spectrometer described in section 4.3 and the time difference between the entrance MCP and the focal plane MWPPAC, standing for the ion's time of flight. The resulting velocity vector is then given by the line between the target position and the interaction point on the MCP and a magnitude proportional to  $\beta$  determined in the path reconstruction algorithm.



Figure 40: Angle set used for the Doppler correction of  $\gamma$  rays.

As the well measured beam-like fragments are not in the main focus of interest in this experiment, one also wants to extract quantities for a Doppler correction of target-like particles via kinematic coincidence. For this purpose velocities, scattering angles and energies are calculated event-by-event within the relativistic formalism with a binary partner kinematics calculator in the **PrismaManager**. Those formulas are derived in the following. The equations for momentum conservation are

$$p_B = p_E \cos \theta + p_R \cos \phi \qquad (4.22)$$
$$0 = p_E \sin \theta - p_R \sin \phi$$

B stands again for beam, T for target, E for ejectile and R for recoil. Energy conservation

yields to

$$E_B + m_T c^2 + Q_{gg} = E_E + E_R + E_x \equiv E_{tot}$$
 (4.23)

where  $E^2 = p^2 m^2 + m^2 c^4$  and  $E = K + mc^2$ . The  $Q_{gg}$  value is defined as  $(m_R + m_E - m_B - m_T)c^2$ , while  $E_x$  is the intrinsic excitation of the two reaction products. K is the kinetic energy. By squaring and adding the equations in 4.22, one gets:

$$(p_B - p_E \cos \theta)^2 = p_B^2 + p_E^2 \cos^2 \theta - 2p_B p_E \cos \theta = p_R^2 \cos^2 \phi \qquad (4.24)$$
$$p_E^2 \sin^2 \theta = p_R^2 \sin^2 \phi$$
$$\rightarrow \qquad p_B^2 c^2 + p_E^2 c^2 - 2p_B p_E c^2 \cos \theta = p_R^2 c^2$$

Substituting  $E_R^2 = (E_{\text{tot}} - E_E)^2$  into the last equation and using  $E_E^2 = p_E^2 c^2 + m_E^2 c^4$  leads to:

$$p_B^2 c^2 + p_E^2 c^2 - 2p_B p_E c^2 \cos \theta = (E_{\text{tot}} - E_E)^2 = E_{\text{tot}}^2 + E_E^2 - 2E_{\text{tot}} E_E - m_R c^4$$
$$2p_B p_E c^2 \cos \theta = -E_{\text{tot}}^2 + 2E_{\text{tot}} E_E + (m_R - m_E) c^4 + p_B^2 c^2 \qquad (4.25)$$

After squaring both sides of the last line in equation 4.25, one has:

$$4p_B^2 p_E^2 c^4 \cos^2 \theta = \left(-E_{\text{tot}}^2 + 2E_{\text{tot}} E_E + (m_R - m_E) c^4 + p_B^2 c^2\right)^2 \tag{4.26}$$

With an expansion of the right side of the last equation and grouping the various terms in terms of powers of  $E_E$ , one gets the following quadratic equation:

$$E_{E}^{2} \left( 4p_{B}c^{2}\cos^{2}\theta - 4E_{tot}^{2} \right) + E_{E} \left( 4E_{tot}^{3} - 4p_{B}c^{2}E_{tot} + 4m_{E}^{2}c^{4}E_{tot} - 4m_{E}c^{4}E_{tot} \right)$$

$$+ \left( 2p_{B}^{2}c^{2}E_{tot}^{2} - 2m_{E}c^{4}E_{tot}^{2} + 2m_{E}^{2}c^{4}p_{B}^{2}c^{2} + 2m_{R}^{2}c^{4}E_{tot}^{2} - 2m_{R}c^{4}p_{B}^{2}c^{2} \right)$$

$$+ 2m_{R}^{2}c^{4}m_{E}^{2}c^{4} - E_{tot}^{4} - p_{E}^{4}c^{4} - m_{E}^{4}c^{8} - m_{R}^{4}c^{8} - 4m_{E}^{2}c^{4}p_{E}^{2}c^{2}\cos^{2}\theta \right) = 0$$

$$(4.27)$$

This equation of the form  $aE_E^2 + bE_E + c = 0$  can be trivially solved using:

$$E_E = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$
(4.28)

The interesting quantities can be calculated easily:

$$E_R = E_{\text{tot}} - E_E \qquad p_R = \sqrt{E_3^2 - m_R^2 c^4} \qquad (4.29)$$
  
$$\phi = \arcsin\left(\frac{p_E}{p_R}\right) \sin\theta \qquad \beta_R = \frac{p_R c}{E_R}$$

The relative velocity distributions of both beam- and target-like nuclei are presented in figure 41. The ejectile velocity ranges from  $\approx 6.5\%$  to  $\approx 10\%$  of the speed of light.



 $\beta$  distribution of beam- and target-like nuclei

Figure 41: Relative velocity distributions of beam- and target-like particles. The recoil velocity is calculated using the measured kinematic observables of the beam-like particles.

These quantities allow the reconstruction of the trajectory of the recoiling ions. Thus, it is possible to perform an event-by-event Doppler correction of the  $\gamma$  rays detected by the AGATA array in coincidence with the signals from PRISMA. The precision of the Doppler correction is superior to comparable experimental setups, because AGATA is able to determine the position of the first interaction of the  $\gamma$ -ray by pulse shape analysis and tracking algorithms very precisely.
# 5 Analysis for Beam-Like Nuclei

The following chapter will describe and discuss the  $\gamma$ -ray spectra obtained for the individual multi-nucleon transfer channels. Each channel section contains a  $\gamma$ -ray singles spectrum and a list of detected transitions. Furthermore, all observed transitions are summarized in level schemes in which the sequences of transitions and the level assignments are taken from literature data.

#### 5.1 Analysis Procedure

The low statistics in the  $\gamma$ - $\gamma$  correlation matrices do not qualify to determine the specific positions of the transitions in the level scheme. An analysis of spin and parity is not possible with the given setup. In all following tables, the uncertainties next to the measured energies were obtained from the fit program hdtv. These generally small uncertainties illustrate how well the applied fit routine describes the peak. Further systematic uncertainties arise from the Doppler correction and are in the range of 0.5 keV. [19]

The multiplicity denotes the number of different  $\gamma$  rays that are contained in each event and that were determined by the  $\gamma$ -ray tracking algorithm. Multiplicity distributions for all analyzed events and for events in the Te and Ba channels are depicted in figure 5.42(a). The multiplicity drops rapidly for  $n_{\gamma} > 2$ , the maximum value observed is  $n_{\gamma} = 10$ . A spectrum of all single AGATA events is called *singles spectrum*. These spectra do not contain any information on the position of the transitions and their corresponding levels in the level scheme. Simultaneously emitted  $\gamma$  rays, i.e.  $\gamma$  rays originating from the deexcitation of a complete  $\gamma$ -ray cascade (or from random coincidences), can be analyzed with so-called  $\gamma$ -rays in each event. The  $\gamma$ -ray energies  $E_{\gamma}$  of all possible permutations  $\{ij\}, i \neq j$  are filled into a two-dimensional matrix. Gates can be placed at a region around a certain peak energy with the analysis software tv. Coincidence spectra are created by projecting the  $\gamma$ - $\gamma$  matrix onto one of its axes. Additional background cuts may be placed in the same way. The final spectra are weighted by the width of the background cut or the number of counts in the cut before they are subtracted from the original cut. Figure 5.42(b) shows an example  $\gamma$ -ray coincidence spectrum, Doppler corrected for the recoil <sup>238</sup>U. In the low-energy region around the dashed line dramatically less events are visible. Apparently, the  $\gamma$ -ray tracking malfunctions for energies lower than 200 keV, imposing huge challenges for the whole  $\gamma$ - $\gamma$  analysis.



Figure 42:  $\gamma$ -ray multiplicities in AGATA for all analyzed events and for events in the Te and Ba channels. Note the logarithmic scale. The maximum observed multiplicity is  $n_{\gamma} = 10$ . (b)  $\gamma$ - $\gamma$  coincidence spectrum, Doppler corrected for the recoil <sup>238</sup>U. The dashed line marks the region, where the  $\gamma$ -ray tracking seems to fail.

# 5.2 Two-Proton pickup channel: Barium

There are seventeen barium mass channels selected with the PRISMA spectrometer, ranging from <sup>130</sup>Ba to <sup>146</sup>Ba. Characteristic peaks and  $\gamma$ -ray signatures in the singles  $\gamma$ -ray spectra only appear for A > 134. <sup>130-134</sup>Ba spectra only contain transitions of the corresponding +4n channels. This anomaly arises in various A > 134 channels as well.  $\gamma$ -ray peaks of high intensity emerge in +4n channels, but never in  $\gamma$ -ray spectra of -4n channels. As described in figure 31 in section 4.5, there is in fact no leakage of events into directly neighboring mass channels. The individual separation of the reaction channels is very clean. The +4n repetition anomaly is therefore an effect of the magnetic separation itself, not a nonconformance regarding the gating procedure in the PRISMA analysis. Figure 43 shows the prompt time signal plotted against the ejectile Doppler corrected  $\gamma$ -ray energy. Except peaks in the X-ray region and two structures at ~ 650 and ~ 900 keV originating from false Doppler corrected background peaks, all barium  $\gamma$ -ray transition candidates were recorded within the prompt peak.



# 5.2.1 +2p-3n channel: $^{135}$ Ba

Via the two-proton pickup and three-neutron stripping channel

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{135}$ Ba +  $^{239-xn}$ Th + xn

the even-odd stable nucleus <sup>135</sup>Ba is identified in PRISMA. <sup>135</sup>Ba is a N = 79 isotope and therefore has three neutron holes with respect to the closed neutron shell at N = 82. It has six valence protons outside the closed shell Z = 50. The channel comprises  $1.007 \times 10^5$ events and is the seventh largest contribution to the Ba channel. Moreover, it is the last neutron-stripping channel showing  $\gamma$  rays that could be identified with transitions of the corresponding isotope. Indeed, isotopes ranging from <sup>130</sup>Ba up to <sup>134</sup>Ba were identified and selected in PRISMA as well, but here only  $\gamma$ -rays of the corresponding +4n channels are visible in the singles spectra. The singles spectrum of <sup>135</sup>Ba is shown in figure 44, the analyzed  $\gamma$ -ray transition lines are listed in table 9.



Figure 44:  $^{135}$ Ba  $\gamma$ -ray singles spectrum with a cut on the prompt time coincidence between AGATA and PRISMA.

The peak at 148.6 keV and the broad peak structure at ~ 1307 keV are <sup>139</sup>Ba contaminants from the +4n channel. All other observed transitions are consistent with existing literature data [1, 72]. The most recent studies on excited states in <sup>135</sup>Ba at high spins were issued by Che *et al.* in 2006 [73] and Kumar *et al.* in 2010 [74]. Both groups employed the <sup>130</sup>Te(<sup>9</sup>Be,4n)<sup>135</sup>Ba reaction at 45 MeV and 42.5 MeV beam energy, respectively.

	Experiment		Ι	literature		
$E_{\gamma}  [\text{keV}]$	m FWHM[keV]	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma} [\text{keV}]$	Ref.
128.80(16)	1.65(29)	129.5(14)	3211.8	$(23/2^+)$	128.0	[1]
148.57(13)	1.88(25)	199(29)	$^{139}\text{Ba}$	contaminat	tion	[1]
167.47(27)	2.57(55)	171(33)	*	*	*	
204.28(16)	2.66(45)	374(58)	3415.7(6)	$(25/2^+)$	204.0	[1]
246.96(51)	4.1(11)	170(42)	*	*	*	
343.25(19)	1.62(53)	284(40)	3758.3(7)	$(27/2^+)$	342.6	[1]
391.76(60)	3.20(67)	336(76)	2393.5(5)	$(21/2^{-})$	390.6	[1]
423.55(28)	3.51(66)	236(46)	4180.9	$(29/2^+)$	422.6	[1]
496.75(59)	$\approx 3$	149(67)	4254.1	$(31/2^+)$	495.8	[1]
683.11(13)	3.82(34)	596(60)	950.5(3)	$(15/2^{-})$	682.3	[1]
738.02(27)	3.13(54)	169(28)	2739.6	$(23/2^{-})$	737.0	[1]
1051.98(19)	4.96(36)	479(38)	2002.6(5)	$(19/2^{-})$	1052.1	[1]
$\sim 1307$			$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			[1]

**Table 8:** <sup>135</sup>Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a  $\star$  were not observed yet in the literature.

Two moderately weak peaks at 167.5 and 247.0 keV cannot be associated to known transitions. The highest excitation energy identified in this reaction channel is the  $(31/2^+)$  state at 4255 keV. The  $\gamma$ - $\gamma$  analysis is difficult due to the low statistics in the corresponding cuts for most of the applied cuts. Only three cuts in the  $\gamma$ - $\gamma$  matrix can be evaluated, they are depicted in figure 45. A gate on 423 keV shows coincidence peaks at 204, 390, 423, 682 and 1052 keV. The last four peaks are consistent with the literature level scheme [1, 73]. A gate on the previously unknown 167 keV transition gives peaks at 279 and 390 keV. Both  $\gamma$ - $\gamma$  gates confirm the decay chain fed by the  $(29/2^+)$  state at 4182 keV (compare level scheme in figure 46). Neither the 818 keV nor the 1082 keV transition connecting the  $(23/2^+)$  3212 keV state with the  $(19/2^-)$  2003 keV state are found in the singles spectrum. Nevertheless, a gate on  $E_{\gamma} = (818 \pm 2)$  keV in the  $\gamma$ - $\gamma$  spectrum gives a clear peak at 1050  $\pm$  2 keV with a FWHM of 4 keV and a volume of 11 counts. Moreover, a coincidence with the feeding 423 keV transition is visible. The unknown 247 keV transition appears as well. Peaks at 161, 382 and 571 keV might be of random nature, this  $\gamma$ - $\gamma$  gate has to be treated with caution.



Figure 45: <sup>135</sup>Ba coincidence spectra for three meaningful gates in the  $\gamma$ - $\gamma$  matrix. Compare indicated levels with those in table 8.



Figure 46: <sup>135</sup>Ba level scheme. Data taken from [1].

#### 5.2.2 +2p-2n channel: $^{136}$ Ba

The <sup>136</sup>Ba channel comprises  $1.968 \times 10^5$  events and is the third largest contribution to the Ba chain. It is produced by a two-proton pickup and two-neutron stripping reaction.

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow$   $^{136}$ Ba +  $^{238-xn}$ Th +  $xn$ 

<sup>136</sup>Ba is a N = 80 isotope, it has six valence protons outside the closed shell Z = 50 and two-neutron holes with respect to the closed shell N = 82.



Figure 47: <sup>136</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

The singles spectrum of <sup>136</sup>Ba gated on the prompt peak between AGATA and PRISMA is shown in figure 47, the analyzed  $\gamma$ -ray transitions are listed in table 9. Except of three peaks, all observed transitions are consistent with existing data. Three peaks at 530, 602 and 807 keV are <sup>140</sup>Ba contaminants from the +4n channel. Moderately weak lines at 262.4 and 1399.2 keV and a weak line at 1380.0 keV cannot be associated to known transitions. The highest excitation energy identified in this reaction channel is 5393 keV. The  $\gamma$ - $\gamma$  data do not show significant peaks due to the low statistics in the corresponding cuts.

	and/or spin assig					
	Experiment		Lit	eratu	re	
$E_{\gamma} [\mathrm{keV}]$	FWHM [keV]	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}  [\text{keV}]$	Ref.
130.72(12)	1.60(21)	201(29)	?	?	130	[75]
144.41(16)	1.57(34)	141(31)	(3850)	?	144	[75]
262.41 (38)	1.47(57)	221(41)	*	*	*	
267.78(20)	1.55(37)	115(26)	?	?	268	[75]
328.56(18)	1.98(42)	195(39)	(5393)	?	328	[75]
349.284(73)	2.95(18)	3706.0	1043(65)	?	349.2(2)	[75, 76]
509.46(12)	3.48(30)	620(58)	4214.9	?	508.9(1)	[75, 76]
529.61(28)	3.84(57)	280(40)	$^{140}$ Ba co	[1]		
602.06(51)	6.7(12)	337(51)	$^{140}$ Ba co	ontami	ination	[1]
807.46(84)	3.0(14)	158(51)	$^{140}$ Ba co	ontami	ination	[1]
817.50(43)	3.0(14)	125(41)	818.6(2)	$2^{+}$	818.6(2)	[75]
848.47(30)	4.07(74)	241(57)	(5065)	?	849	[75]
963.20(53)	3.1(12)	87(27)	2994	$8^{+}$	963.6(2)	[75]
1046.84(30)	2.34(85)	84(26)	1867	$4^{+}$	1048.1(1)	[76]
1213.55(39)	3.85(76)	131(25)	(5065)	?	1215	[75]
1379.95(48)	5.5(10)	158(29)	*	*	*	
1399.19(58)	5.5(10)	365(38)	*	*	*	

**Table 9:** <sup>136</sup>Ba singles  $\gamma$ -ray spectrum evaluation. Transition energies marked with a  $\star$  were not observed yet in the literature. A ? stands for transitions without a level and/or spin assignment.

No transitions between states below the 3357 keV (10<sup>+</sup>) state are found in the spectrum. The (10<sup>+</sup>) state is a  $(\nu h_{11/2})^{-2}$  isomer which was simultaneously found by Gan *et al.* [76] employing a 450 MeV <sup>82</sup>Se beam on a <sup>139</sup>La target and by Valiente-Dobón *et al.* [75] using a multi-nucleon transfer reaction between a <sup>198</sup>Pt target and an 850 MeV <sup>136</sup>Xe beam in 2003. The isomer's half-life was found to be 91 ± 2 ns [75]. Isomeric (10<sup>+</sup>) states have been found in all even-A N = 80 isotones from <sup>132</sup>Sn up to <sup>148</sup>Er [72]. The largest peaks in the spectrum are located at 349.3 and 509.5 keV, respectively. They are located on top of the 3357 keV isomer state. Peaks at 131, 144, 238, 849, 1164 and 1215 keV are consistent with those found by Valiente-Dobón *et al.* [75]. A level scheme with spin and energy assignments, taken from [75, 76], is depicted in figure 48.



Figure 48: <sup>136</sup>Ba level scheme above the  $(10^+)$  isomer. Data taken from [1, 75, 76].

#### 5.2.3 +2p-1n channel: $^{137}$ Ba

In the two-proton pickup and one-neutron pickup channel, the even-odd stable nucleus <sup>137</sup>Ba is identified in PRISMA:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{137}$ Ba +  $^{237-xn}$ Th + xn

<sup>137</sup>Ba is a N = 81 isotope with one neutron hole with respect to the closed neutron shell at N = 82. The nucleus has six valence protons outside the closed shell Z = 50. The channel contains  $2.455 \times 10^5$  events and is the second largest contribution to the Ba channel. The singles spectrum of <sup>137</sup>Ba is shown in figure 49, the analyzed  $\gamma$ -ray transition lines are listed in table 10.



Figure 49: <sup>137</sup>Ba  $\gamma$ -ray singles spectrum. The only known transition is at an energy of 274.863(57) keV.

Level schemes of <sup>137</sup>Ba were mainly obtained in studies of <sup>137</sup>Cs  $\beta^-$ -decay as well as <sup>137</sup>Cs electron capture decays. Further studies employed (d,p), (n, $\gamma$ ), (p,d), (n, $n'\gamma$ ) and Coulomb excitation reactions [1]. The only study populating high-spin excited states in <sup>137</sup>Ba was

performed by Kerek *et al.* [77] at the Research Institute for Physics Stockholm in 1972. A <sup>136</sup>Xe enriched gaseous target was irradiated with  $\alpha$  particles to populate both <sup>137</sup>Ba and <sup>138</sup>Ba.  $\gamma$ -ray spectra were taken for 20, 23, 26 and 29 MeV  $\alpha$ -bombarding energies. Excited states were observed up to  $\approx 3$  MeV excitation energy, among them a newly introduced  $t_{1/2} = 0.59 \pm 10$  µs isomeric state at 2349.1 keV with possible spin assignments (<sup>15</sup>/<sub>2</sub>, <sup>17</sup>/<sub>2</sub>, <sup>19</sup>/<sub>2</sub>). This state was found to decay via a 120.2 keV  $\hookrightarrow$  1567.3 keV  $\gamma$ -ray cascade, finally populating the 2.55 min isomeric state (11/2<sup>-</sup>) at 661.6 keV. A 274.7  $\pm$  0.3 keV  $\gamma$ -ray decay connects another higher lying 2623.8 keV (19/2) state with the 2349.1 (17/2<sup>-</sup>) isomer state. The half-life of this transition was observed to be smaller than 30 ns.

	Experiment		Li	iterature		
$E_{\gamma}$ [keV]	FWHM [keV]	Volume	$E_{\text{Level}} [\text{keV}]$	$J^{\pi}$	$E_{\gamma}$ [keV]	Ref.
116.74(35)	2.26(100)	108(40)	*	*	*	
178.57(20)	2.84(32)	567(56)	*	*	*	
222.24(12)	2.56(32)	484(55)	*	*	*	
274.863(57)	2.47(10)	1155(51)	2623.8(6)	(19/2)	274.7(3)	[1]
279.702(81)	2.47(10)	627(42)	*	*	*	
281.03(99)	3.02(23)	132.6(14)	*	*	*	
289.08(14)	3.02(23)	574.7(14)	*	*	*	
295.59(17)	3.02(23)	450.5(14)	*	*	*	
485.41(40)	2.23(40)	201(48)	*	*	*	
487.58(23)	2.23(40)	332(62)	*	*	*	
623.21(49)	3.29(89)	292(66)	*	*	*	
629.78(68)	3.29(89)	82(31)	*	*	*	
678.55(29)	4.84(44)	366.6(14)	*	*	*	
698.54(31)	4.84(44)	335.7(14)	*	*	*	
889.92(20)	3.37(38)	310.3(14)	*	*	*	
1178.57(38)	4.33(32)	213.4(14)	*	*	*	
1183.97(20)	4.33(32)	449.4(14)	*	*	*	
1192.65(56)	4.33(32)	234.6(14)	*	*	*	
1195.91(25)	4.33(32)	352.4(14)	*	*	*	
1217.08(28)	3.46(74)	187(48)	*	*	*	

Table 10:  $^{137}$ Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a $\star$  were not observed yet.

The only known peak from a prompt  $\gamma$ -ray decay in the analyzed singles spectrum is the above mentioned 274.7 keV transition. A level scheme presenting all levels and transitions below the 2349 keV state found by Kerek *et al.* is depicted in figure 50. Altogether, 19 candidates for new transitions were found in the singles spectrum. A  $\gamma$ - $\gamma$  analysis with

and without background subtraction does not give conclusive results. The level schemes of the ±2n isotones <sup>135</sup>Te and <sup>139</sup>Ce were investigated in detail [78, 79]. Since these nuclei are neutron-rich, nuclear structure properties should be governed by neutron shell excitations. Both the sequence of decays and the energy gaps between levels in the observed negative parity ground-state band of <sup>139</sup>Ce are very similar to the only fragmentary level scheme of <sup>137</sup>Ba. In <sup>139</sup>Ce, a long-living 70 ns 19/2<sup>-</sup> isomer is located at 2631.7 keV which deexcites via a 271 keV  $\leftrightarrow$  1607 keV  $\leftrightarrow$  754 keV  $\gamma$ -ray cascade to the 3/2<sup>+</sup> ground state. The equivalent cascade of  $\gamma$ -ray transitions in <sup>137</sup>Ba is 120 keV  $\leftrightarrow$  1568 keV  $\leftrightarrow$  662 keV. <sup>135</sup>Te shows a different transition sequence of 50 keV, 325 keV and 1180 keV from the (19/2<sup>-</sup>) level to the 7/2<sup>-</sup> ground state. In <sup>139</sup>Ce, a 187 keV 21/2<sup>-</sup>  $\rightarrow$  19/2<sup>-</sup> transition corresponds to the 274 keV transition in <sup>137</sup>Ba. As mentioned above, the 2349 keV state populated by the 274 keV transition was assigned by Kerek *et al.* to be either of spin 15/2, 17/2 or 19/2. The 2624 keV level on top could therefore be of spin 21/2<sup>-</sup>, if the level assignment in the +2n nucleus <sup>139</sup>Ce is correct.



Figure 50: <sup>137</sup>Ba level scheme for the  $\gamma$  rays seen in the singles spectrum of <sup>137</sup>Ba. Data taken from [77] and [1].

#### 5.2.4 +2p+0n channel: $^{138}$ Ba

The <sup>138</sup>Ba channel comprises  $2.501 \times 10^5$  events and is the strongest Ba channel. <sup>138</sup>Ba is produced in a two-proton pickup reaction:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{138}$ Ba +  $^{236-xn}$ Th +  $xn$ 

<sup>138</sup>Ba is a semi-magic N = 82 isotope, it has six valence protons outside the closed proton shell Z = 50. The singles spectrum of <sup>138</sup>Ba gated on the prompt peak between AGATA and PRISMA is depicted in figure 51, the analyzed  $\gamma$ -ray transition lines are listed in table 11.



Figure 51: <sup>138</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

High-spin states in <sup>138</sup>Ba above the 8<sup>+</sup> yrast band state were first observed in 1973 by Kerek *et al.* [77] employing a <sup>136</sup>Xe( $\alpha, xn$ ) reaction. The corresponding level scheme was revised by Astier *et al.* [80]. Here, N = 82 isotones were studied with <sup>12</sup>C + <sup>238</sup>U and <sup>18</sup>O + <sup>208</sup>Pb fusion-fission reactions. Thirteen transitions up to a maximum excitation energy of 6209.7 keV can be found in the spectrum. This high excitation energy is remarkable and cannot be seen in the other analyzed Ba channels, nor in the Xe channels which were

	Experiment		L	iterature		
$E_{\gamma}$ [keV]	FWHM [keV]	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}$ [keV]	Ref.
112.713(86)	1.55(15)	290(27)	2201.4	$6^{+}$	112.1(5)	[80]
174.42(23)	3.23(55)	3.23(55)	*	*	*	
183.73(65)	3.1(11)	316(106)	5923.7	$12^{+}$	183.7(5)	[80]
186.28(61)	3.1(11)	225(80)	*	*	*	
235.83(20)	1.70(29)	201(35)	*	*	*	
238.81(18)	1.70(29)	150(33)	*	*	*	
285.48(18)	2.55(28)	353.8(14)	6209.0	$(13^{+})$	258.5(3)	[80]
288.16(17)	2.55(28)	378.8(14)	3908.6	$10^{+}$	288.2(3)	[80]
302.22(52)	4.71(34)	275(45)	*	*	*	
306.86(41)	4.71(34)	377(43)	*	*	*	
341.40(46)	3.48(67)	198(44)	*	*	*	
351.81(32)	3.48(67)	249(45)	*	*	*	
396.76(30)	2.37(54)	156(41)	*	*	*	
438.332(89)	3.42(13)	980.0(14)	3620.3	$10^{+}$	438.3(3)	[80]
447.72(10)	3.42(13)	932.5(14)	3631.1	$9^{-}$	449.1(3)	[80]
482.68(57)	1.5(13)	197(72)	5184.2	$13^{-}$	481.8(3)	[80]
705.62(21)	3.82(52)	414(60)	5392.2	$13^{-}$	705.2(3)	[80]
727.17(13)	3.96(40)	892(83)	3908.6	$10^{+}$	726.7(3)	[80]
778.91(12)	3.54(33)	1016(80)	4687.0	$12^{+}$	778.4(3)	[80]
805.37(25)	1.73(41)	95(23)	6196.4	$15^{-}$	804.2(3)	[80]
939.65(45)	1.8(12)	50(28)	*	*	*	
980.07(30)	6.46(76)	566(93)	3182.0	$8^{+}$	980.3(3)	[80]
1072.55(43)	2.39(93)	218(67)	4702.4	$11^{-}$	1071.3(3)	[80]
1092.96(13)	4.68(32)	1400(57)	3182.0	$8^{+}$	1092.7(3)	[80]
1156.78(69)	3.5(11)	144(47)	*	*	*	
1166.51(30)	3.5(11)	200(38)	*	*	*	

**Table 11:**  $^{138}$ Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a $\star$  were not observed yet in the literature.

analyzed in [19]. Here maximum excitations of around 4.8 to 5.0 MeV were observed.

In parts, the  $\gamma$ - $\gamma$  data show significant peaks. Nevertheless, the low statistics hamper a thorough  $\gamma$ - $\gamma$  analysis. Meaningful coincidence spectra can be obtained for six  $\gamma$ -ray transitions. These cut spectra are shown in figure 53. A cut on the largest peak at 1091 keV with and without background subtraction does not yield a clean  $\gamma$ - $\gamma$ -ray spectrum. Cuts on 233 keV, 438 keV and 395 keV give large peaks at 1093 keV. The 438 keV transition lies in fact on top of the one at 1093 keV [80]. The 233 keV and 395 keV transitions were not observed in recent studies. They cannot feed yrast states below the long-living 0.8 µs 6<sup>+</sup> state



Figure 52:  $^{138}\mathrm{Ba}$  level scheme up to the observed 6209 keV state. Data taken from [1, 80].

since none of these transitions are found in the spectrum. Subsequently, it is a reasonable assumption that these states lie above the 3182 keV level, they can not be parallel to the 980 keV transition. Other peak structures in the 233 keV coincidence spectrum could be explained by false binning effects.



Figure 53: <sup>138</sup>Ba coincidence spectra for six cuts on the  $\gamma$ - $\gamma$  matrix. All cuts marked with a  $\star$  are new transitions not observed in recent studies. Compare indicated levels with those in table 11.

The cut spectrum of the 940 keV transition contains significant peaks at 286, 726 and 1093 keV. The corresponding level may be positioned above the 3909 keV  $10^+$  level. Since the 286 keV transition belongs to the highest observed level at 6209 keV and decays via an isolated sequence of  $13^+ \rightarrow 12^+ \rightarrow 11^+$ , the 940 keV transition may connect that highenergy states with the medium-spin yrast level structure. Furthermore, the 286 keV and 779 keV peaks are coincident with the 705 keV peak. Both peaks are visible in the corresponding cut spectrum of 704 keV. This coincidence confirms the literature level sequence [80]. Here, the 5392 keV 13<sup>-</sup> state decaying by a 705 keV  $\gamma$ -ray is succeeded by the 778 keV vrast  $12^+ \rightarrow 10^+$  state transition. In return, a cut on 286 keV yields a distinct peak at 779 keV. If the literature level assignment in the high-energy region is correct, the energy difference between the 285 keV  $\gamma$ -ray fed 12<sup>+</sup> state and the yrast 12<sup>+</sup> state decaying with the 778 keV  $\gamma$ -ray would be 1237 keV. This amount of energy cannot be reconstructed by a sum of observed unknown transitions. 173, 238, 447 and 1093 keV peaks are visible in the cut on 306 keV. All transition energies except the 1093 keV  $12^+ \rightarrow 10^+$  transition are unknown. A cut on 395 keV gives  $\gamma$ - $\gamma$  coincidence peaks at 286, 448 and 1090 keV. An additionally appearing peak at 569 keV does not correspond to a peak in the singles spectrum.

#### 5.2.5 +2p+1n channel: $^{139}$ Ba

The even-odd nucleus  $^{139}$ Ba is produced by a three-nucleon pickup (+2p+1n) reaction.

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{139}$ Ba +  $^{235-xn}$ Th +  $xn$ 

<sup>139</sup>Ba is unstable and decays with a half life of 83.06 min via  $\beta^-$  decay to <sup>139</sup>La. The reaction channel comprises  $1.926 \times 10^5$  events and is the fourth strongest Ba channel. <sup>139</sup>Ba is a N = 83 nucleus with one neutron outside the magic neutron number N = 82. The  $\gamma$ -ray singles spectrum with a cut on the prompt coincidence between AGATA and PRISMA is presented in figure 54, the fitted peaks and their corresponding literature values are listed in table 12. The yrast levels are observed up to the 3089 keV level, as well as two sequences of states with unknown parity decaying to the  $(19/2^-)$  2092 keV state. The maximum excitation is the 4957 keV level [1].



Figure 54: <sup>139</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

<sup>139</sup>Ba has been extensively studied by employing <sup>138</sup>Ba(d, p)<sup>139</sup>Ba and <sup>139</sup>Ba(n,  $\gamma$ )<sup>139</sup>Ba reactions and elastic proton scattering from <sup>139</sup>La [1]. Lee *et al.* [81] reported  $\beta$  and subsequent  $\gamma$ -ray decays of <sup>139</sup>Cs using an online isotope-separator system and Ge(Li) detectors at the Ames Laboratory in 1980. The group observed 59 states. Prade *et al.* populated <sup>139</sup>Ba via the <sup>139</sup>Ba<sup>gas</sup>( $\alpha, n$ ) reaction channel at the Zentralinstitut für Kernforschung Rossendorf in 1987 and extended the existing level scheme with four new transitions. Among them, the level at 1977 keV was found to be isomeric [82]. In 2001, Luo *et al.* [79] analyzed <sup>252</sup>Cf spontaneous-fission  $\gamma$ -ray data from GAMMASPHERE. The group concurred with the Rossendorf work concerning the ground-state cascade up to the 19/2<sup>-</sup> level and established ten new transitions on top of that level with level energies up to 5 MeV.

	parity assignment	nts.				
	Experiment			Literature	)	
$E_{\gamma} [\mathrm{keV}]$	${ m FWHM}[{ m keV}]$	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}  [\text{keV}]$	Ref.
115.151(57)	1.93(14)	590(38)	2091.7(6)	$(17/2^{-})$	115.137(6)	[79]
148.351(39)	1.931(93)	1171(53)	1977.2(5)	$(15/2^{-})$	148.443(5)	[79]
339.48(34)	2.81(36)	399(42)	4956.66	$(31/2^{-})$	340.378(24)	[79]
388.17(50)	1.8(12)	248(57)	2479.37	?	387.653(5)	[79]
467.69(20)	2.81(51)	267(45)	*	*	*	
519.87(10)	3.01(21)	1510(57)	1828.14	$(15/2^{-})$	520.258(9)	[79]
725.87(17)	2.78(40)	348(88)	4616.28	$(29/2^{-})$	725.334(27)	[79]
768.31(29)	2.83(71)	390(71)	3890.95	$(25/2^{-})$	768.177(30)	[79]
882.56(34)	4.69(96)	262(64)	*	*	*	
898.72(30)	2.00(47)	79(22)	*	*	*	
902.23(33)	2.00(47)	76(22)	3381.93	?	902.564(34)	[79]
910.75(35)	1.2(25)	62(28)	*	*	*	
996.76(39)	5.25(96)	255(53)	3088.58	?	996.860(46)	[79]
1030.94(17)	4.69(44)	890(98)	3122.77	$(21/2^{-})$	1031.049(5.9)	[79]
1307.25(16)	5.43(37)	1441(145)	1307.877(17)	$11/2^{-1}$	1308.20(5)	[79]

**Table 12:** <sup>139</sup>Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a  $\star$  were not observed yet in the literature. A ? marks unidentified spin and parity assignments.

The  $\gamma$ - $\gamma$  analysis is feasible for eight coincidence gates; relevant coincidence spectra are shown in figure 55. A gate on 115 keV reveals coincidence peaks at 520, 768, 1031 and 1308 keV. A gate on 148 keV gives peaks at 520, 726 and 1031 keV. Moreover, there is a small peak at 904 keV with no peak counterpart in the singles spectrum. The two gated peaks correspond to successive transitions  $(19/2^-) \rightarrow (17/2^-) \rightarrow (15/2^-)$ , followed by the 520 keV  $(15/2^-) \rightarrow (11/2^-)$  transition. The 1031, 768 and 726 keV transitions were placed on top of the  $(19/2^{-})$  level [79]. Neither the 115 keV nor the 148 keV line is visible in each other's coincidence spectrum for the simple reason that the coincidence matrices lack statistics in the energy region below  $E_{\gamma} \approx 200$  keV due to the small efficiency of the tracking algorithm for low energies. An intuitive visualization of this effect is depicted and discussed in section 5.1. The entire  $\gamma$ - $\gamma$  analysis is very challenging and shows preliminary results.



Figure 55: <sup>139</sup>Ba coincidence spectra for seven meaningful cuts on the  $\gamma$ - $\gamma$  matrix. Compare indicated levels with those in table 12.

The 339 keV transition depopulates the 4957 keV level which is the highest analyzed excited state in the present analysis. The corresponding  $\gamma$ - $\gamma$  cut spectrum shows peaks at 520 and 1308 keV. Transitions of the directly populated levels beneath 4616 keV are not observed. The 768 keV gated coincidence spectrum contains peaks at 114, 148, 520, 1031 keV and a peak structure 904 keV. The 768 keV cut spectrum contains one distinct peak at 114 keV.

Both spectra do not have clean background conditions. A gate on the 1031 keV transition, which populates the  $(19/2^-)$  level at 2092 keV, gives coincident peaks at 148, 520 and 1031 keV itself. The most comprehensive  $\gamma$ - $\gamma$ -gated spectrum is created with a gate on 520 keV. Here the following 1308 keV transition as well as the feeding 148, 997 and 726 keV transitions are visible. On the other hand, a distinct peak at 253 keV emerges in the spectrum, although no peak of that energy appears in the singles spectrum.

Thus, we can conclude that the study of  $\gamma$ - $\gamma$  coincidences in the present analysis is very challenging and does not provide conclusive coincidences nor complete clarification of the order of  $\gamma$ -ray transitions. Nevertheless, consistent results are obtained by transitions which can be confirmed with the knowledge of literature level schemes. The bottom-left spectrum in figure 55 shows the coincidence spectrum of the previously unknown 468 keV transition; here a peak structure at 148 keV is visible. The other unknown peaks at 882.6, 898.7 and 910.6 keV do not allow a  $\gamma$ - $\gamma$  analysis.





Figure 56: <sup>139</sup>Ba singles spectrum with a cut on deep-inelastic TKEL values smaller than -200 a.u. It has to be noted, that it is not possible to discriminate whether the ejectile or the recoil particle is highly excited due to the unknown energy split between the two reaction partners. A previously hidden peak at 188 keV becomes apparent. This peak is marked with a  $\star$ .

Figure 56 shows the <sup>139</sup>Ba singles spectrum with an additional cut on TKEL values smaller than Q = -200 a.u. The corresponding TKEL spectrum is depicted as well. Under these

cut conditions, preferably deep inelastic excitations should become visible. It has to be noted that it is not possible to discriminate whether the ejectile or the recoil particle are highly excited, since the energy is shared between the two reaction partners. The resulting spectrum contains the strongest known peaks at 114, 148 and 520 keV, although reduced. A considerable large peak, compared to the suppressed peaks discussed above, appears at an energy of 188 keV. This transition belongs presumably to a high-energy level in <sup>139</sup>Ba. Neutron evaporation can be excluded as the ejectiles were positively identified with PRISMA.



Figure 57: <sup>139</sup>Ba level scheme for the  $\gamma$  rays seen in the singles spectrum of <sup>139</sup>Ba. Based on data taken from [79] and [1].

### 5.2.6 +2p+2n channel: $^{140}$ Ba

The unstable even-even nucleus <sup>140</sup>Ba is produced by the four-nucleon pickup reaction:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow$   $^{140}$ Ba +  $^{234-xn}$ Th + xn

<sup>140</sup>Ba is a N = 84 isotope with two neutrons outside the N = 82 magic shell. The singles spectrum of <sup>140</sup>Ba gated on the prompt peak between AGATA and PRISMA is shown in figure 58, the analyzed  $\gamma$ -ray transitions are listed in table 13. The channel comprises  $1.160 \times 10^5$  events and is the sixth strongest Ba channel. The <sup>140</sup>Ba ground state decays via  $\beta^-$  decay with a half-life of 12.75 d to <sup>140</sup>La.



Figure 58: <sup>140</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

Both  $\beta^-$  decay studies using <sup>140</sup>Cs and particle transfer experiments with high-resolving magnetic spectrometers employing (t,p) and (<sup>14</sup>C,<sup>12</sup>C) reactions were performed in previous studies of <sup>140</sup>Ba [1]. Zhu *et al.* [83] deduced level schemes of prompt  $\gamma$  rays from excited fission fragments after spontaneous fission of <sup>252</sup>Cf. Medium-spin states have been

extensively discussed by Urban *et al.* [84] in 1996. The A = 140-148 even-even Ba nuclei were produced as fission fragments in the spontaneous fission of <sup>248</sup>Cm and measured with the EUROGAM2 Compton-suppressed large Ge detector array at Strasbourg. Another study of high-spin states in <sup>140</sup>Ba nuclei was performed by Venkova *et al.* [85] in 2007. The group managed to populate the nucleus with <sup>12</sup>C + <sup>238</sup>U and <sup>18</sup>O + <sup>208</sup>Pb fusion-fission reactions at 90 MeV and 85 MeV bombarding energy at the Legnaro XTU accelerator. The emitted  $\gamma$  radiation was detected using the EUROBALL III and IV arrays. Several new high-spin levels above 4 MeV were observed. The level scheme could be extended by six new levels. Mukhopadhyay *et al.* [86] carried out a spectroscopic study of fission fragment nuclei produced in the <sup>235</sup>U( $n_{\rm th}$ , f) reaction.

	Experiment		L	iterature		
$E_{\gamma} [\mathrm{keV}]$	FWHM [keV]	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}$ [keV]	Ref.
328.46(35)	1.40(32)	92.0(14)	4858(1)	$(14^{-})$	328.4(1)	[85]
472.95(30)	2.51(65)	161(35)	3769.5(6)	$(11^{-})$	472.8(5)	[1]
491.13(33)	1.94(75)	129(30)	2152.1(4)	$(5^{-})$	491.9(5)	[1]
529.28(68)	4.18(16)	2206(61)	1130.60(6)	$4^{+}$	528.25(5)	[1]
Ļ			1660.3(3)	$6^{+}$	529.7(3)	[1]
568.98(48)	2.43(35)	130(31)	5426(1)	$(16^{-})$	568.2(1)	[85]
571.58(28)	2.43(35)	253(35)	2722.9(4)	$(7^{-})$	570.9(4)	[1]
574.21(26)	2.43(35)	166(30)	3296.8(5)	$(9^{-})$	573.9(4)	[1]
602.70(10)	4.20(23)	1133(65)	602.37(3)	2 +	602.35(3)	[1]
670.70(37)	2.55(96)	196(70)	*	*	*	
748.51(23)	3.23(51)	182(27)	*	*	*	
760.48(42)	4.1(14)	161(41)	4531.2(8)	$(13^{-})$	761.7(5)	[1]
808.37(17)	3.59(39)	734(66)	2468.3(4)	$(8^+)$	808.0(4)	[1]
828.60(23)	3.74(46)	242(29)	3296.8(5)	$(9^{-})$	3296.8(5)	[1]
915.26(22)	2.22(31)	214.0(14)	3383.8(6)	$(10^{+})$	915.4(4)	[1]
1020.91(34)	2.86(65)	80(14)	2152.1 4	$(5^{-})$	1021.5(5)	[1]
1142.90(39)	2.96(85)	79(30)	2800(1)	$(8^+)$	1140.2	[85]

**Table 13:** <sup>140</sup>Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a  $\star$  were not observed yet in the literature.

The  $\gamma$ -ray spectrum obtained in this work reproduces the transitions found by Urban *et al.* as well as Venkova *et al.* The highest observed excitation energy is 5426 keV and the highest spin is 16<sup>-</sup>. Two previously unknown transitions at 670.7 and 748.5 are visible in the spectrum. A  $\gamma$ - $\gamma$  analysis reveals meaningful results for six energy cuts, including the unknown peak at 748 keV. The  $\gamma$ -ray coincidence spectrum of 473 keV contains peaks at 529 and 603 keV. The 473 keV peak corresponds to the decay of a 3770 keV state via a

 $(11^-) \rightarrow (9^-)$  transition. The associated sequence decays into the 6<sup>+</sup> and 4<sup>+</sup> yrast state, respectively. Transitions between the 3296 and 1660 keV level can not be resolved from the background due to the low statistics. A cut on the peak at 529 keV reveals its double peak structure. Besides peaks at 603 keV and 808 keV, a large peak of 28 counts becomes visible at 528 keV. This cut spectrum verifies the yrast transitions from the 2468 keV (8<sup>+</sup>) level to the 0<sup>+</sup> ground state with successive 808, 530, 528 and 602 keV transitions. Contributions from other states are not visible.



Figure 59: <sup>140</sup>Ba coincidence spectra for seven meaningful cuts on the  $\gamma$ - $\gamma$  matrix. Compare indicated levels with those in table 13.

The cut on the first excited  $2^+$  state at 603 keV gives two peaks at 529 and 808 keV. Assuming the 529 keV peak to be a double peak, this coincidence spectrum also confirms the first four yrast excitations. A further peak structure at 218 keV can not be verified by the literature level scheme. There is no peak contribution in the singles spectrum. As expected after the last two coincidence spectra, a gate on the 808 keV  $(8^+) \rightarrow 6^+$  yrast transition yields peaks at 529 and 603 keV. Unexpectedly the 808 keV peak, which was within the gate window, appears as well. Only a small peak at 529 keV is visible in the cut spectrum of the  $(10^+) \rightarrow (8^+)$  yrast transition. In the cut spectrum of the unknown 748 keV peak the corresponding peak reappears. This peculiar  $\gamma$ - $\gamma$  coincidence indicates that the peak might originate from a false Doppler correction. The  $\gamma$ - $\gamma$  matrices can be excluded as a source of error since the yrast  $\gamma$ -ray cascades could be positively verified.



Figure 60: <sup>140</sup>Ba level scheme for the  $\gamma$ -rays seen in the singles spectrum of <sup>140</sup>Ba based on data taken from [85].

# 5.2.7 +2p+3n channel: $^{141}$ Ba

The +2p+3n transfer channel

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow$   $^{141}$ Ba +  $^{233-xn}$ Th + xn

is selected by gating on the even-odd nucleus <sup>141</sup>Ba identified in PRISMA. There is a total of  $5.27 \times 10^4$  events available in the channel. <sup>141</sup>Ba is a N = 85 isotope and has three neutrons outside the closed neutron shell N = 82. The nucleus is  $\beta^-$  unstable and decays with a half-life of 18.3 min to <sup>141</sup>La. The Doppler corrected singles spectrum with an applied prompt time cut between AGATA and PRISMA is shown in figure 61. Observed lines and their corresponding literature values are given in table 14. All identified transitions are summarized in the level scheme in figure 62.



Figure 61: <sup>141</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

The nucleus <sup>141</sup>Ba has been previously studied via the  $\beta^-$  decay of <sup>141</sup>Cs (among others: Yamamoto 1982 [87]). Zhu *et al.* [88] studied high-spin states using  $\gamma$ -ray coincidence

studies after spontaneous fission of <sup>252</sup>Cf at the GAMMASPHERE setup at Lawrence Berkeley National Laboratory in 1997. Four bands and an alternating parity band were reported. The group proposes a 246.5 keV transition from the 3175.4 keV (25/2<sup>+</sup>) level to the (23/2<sup>-</sup>) state at 2928.8 keV in the ground state band. The (23/2<sup>-</sup>) level should decay via two successive 814 and 813 keV transitions which are unresolvable in the  $\gamma$ -ray singles spectrum. Urban *et al.* [89] investigated the near-yrast structure of neutron rich N = 85 isotopes. Excited states in <sup>141</sup>Ba were populated after the spontaneous fission of <sup>248</sup>Cm employing the EUROGAM2 multiple anti-Compton spectrometer array. Among other corrections the parity of the band on top of the 1187 keV state was stated to be negative. In 2002, the group around Luo [90] proposed an extended level scheme from <sup>252</sup>Cf spontaneous fission data taken with GAMMASPHERE. Mukhopadhyay *et al.* [86] from the Bhabha Atomic Research Centre, Mumbai studied various fission products employing the <sup>235</sup>U( $n_{\rm th}$ , f) reaction. Yrast and near-yrast level structures in several isotopes including <sup>140-146</sup>Ba have been deduced. No data from transfer reactions are available yet.

	× were not obser	veu yet in tik	interature.			
	Experiment			Literature		
$E_{\gamma} [\mathrm{keV}]$	FWHM [keV]	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}  [\text{keV}]$	Ref.
189.20(22)	1.50(66)	50.5(14)	*	*	*	
245.82(35)	2.02(97)	66(21)	3175.4	$(25/2^+)$	246.5	[1]
416.27(17)	2.79(42)	199(24)	1719.6	$(17/2^{-})$	417.58(4)	[90]
589.48(19)	2.23(27)	291(34)	643.81	$(11/2^{-})$	588.59(2)	[90]
602.53(34)	3.38(49)	194(40)	*	*	*	
609.86(28)	3.38(49)	134(21)	2328.9	$(21/2^{-})$	609.28(11)	[90]
628.94(26)	3.71~(63)	176(25)	*	*	*	
733.93(25)	1.83(67)	49(14)	*	*	*	
812.19(51)	5.2(11)	117(30)	2114.8	$(19/2^{-})$	812.94(5)	[90]
846.39(41)	4.93(76)	141.4(14)	3175.4	$(25/2^{-})$	845.97(9)	[1]
886.03(61)	5.7(16)	91(33)	*	*	*	

**Table 14:** <sup>141</sup>Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a $\star$  were not observed yet in the literature.

The <sup>141</sup>Ba singles spectra of the present analysis contain all ground state band lines up to the 2115 keV (19/2<sup>-</sup>) level established by all four groups. The 55 keV (7/2<sup>-</sup>)  $\rightarrow$  (5/2<sup>-</sup>) ground state transition is not visible due to the low-energy cut-off. Moreover, three lines at 734 keV, 846, keV and 610 keV situated above the 1187 keV level in the positive parity (denoted by Zhu *et al.*) band respectively negative parity band introduced by the more recent studies of Urban *et al.* and Luo *et al.* are observed. The 734 keV transition was only



**Figure 62:** <sup>141</sup>Ba level scheme for the  $\gamma$  rays seen in the singles spectrum based on data taken from Zhu *et al.* [88] (denoted with an filled circle  $\bullet$ ), Luo *et al.* [90] (denoted with a half-filled circle  $\bullet$ ), Urban *et al.* [89] (denoted with an unfilled  $\bigcirc$ ) and Mukhopadhyay *et al.* [86] (denoted with a crossed circle  $\oslash$ ). The red marked 247 keV observed by Zhu *et al.* is observed with 66(21) counts within this analysis, but was not seen in the three recent publications. The double peak structure of the 813 and 814 keV peaks can not be examined with the existing  $\gamma$ - $\gamma$  coincidence data.

reported by Luo *et al.* According to Zhu *et al.* and Luo *et al.*, the 1720 keV state should decay with nearly equal intensities via a 532 keV transition into the  $(13/2^-)$  band state and via a 418 keV transition to the 1302 keV  $(15/2^-)$  level in the negative parity ground state band. In the present study only a line at 416.27(17), but no peak structure at 523 keV, nor one of the successive 577 and 562 keV transitions can be found in the spectrum. The missing lines are plotted grey in the level scheme in figure 62. According to Zhu *et al.*, the 3175 keV state should decay via a 246.5 keV  $\gamma$  ray to a proposed 2929 keV  $(23/2^-)$  level. Urban *et al.*, Luo *et al.* and Mukhopadhyay *et al.* do not assign a 2929 keV state, but a 2950 keV level. In the level schemes created by Urban *et al.* and Luo *et al.*, this state is fed by a 215 keV  $\gamma$  ray. No peak at this energy is observed in this study. The position of contradictory or inconsistent transitions is marked red. The missing 835 keV transition feeding the 2115 keV level is shaded grey at the right hand side of the level scheme.

Five previously unknown transitions are observed. The 886.0 keV line has a quite large peak with a width of 5.7(16) keV. It might be caused by a doublet or a by a false Doppler correction and would then be meaningless for the <sup>141</sup>Ba level structure. Two peaks at 629.0 and 602.9 keV contain large numbers of counts with respect to the other observed peaks. Moreover, both peaks feature a reasonable peak width. Two low-statistic peaks at 189.2 and 733.9 keV have a clear peak form with respect to the background which remain even in a 2 keV binned spectrum. It is not possible to make a clear statement about the position of the transition candidates in the level scheme. A  $\gamma$ - $\gamma$  analysis is not conclusive due to the low statistics in the reaction channel. No clear peaks can be seen on top of the background in the corresponding  $\gamma$ - $\gamma$  coincidence spectra. Especially the double peak structure of the 813 and 814 keV lines can not be placed in the level scheme. The inconsistencies regarding the  $(23/2^-)$  state cannot be resolved.

# 5.2.8 +2p+4n channel: $^{142}$ Ba

The even-even nucleus  $^{142}$ Ba is produced by the following reaction:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow$   $^{142}$ Ba +  $^{232-xn}$ Th + xn

<sup>142</sup>Ba is a N = 86 isotope and has four neutrons outside the closed neutron shell at N = 82. The channel comprises  $3.26 \times 10^4$  events. <sup>142</sup>Ba is  $\beta^-$  unstable and decays with a half-life of 10.7 min to <sup>142</sup>La. The Doppler corrected singles spectrum of <sup>142</sup>Ba with an applied prompt time cut between AGATA and PRISMA is depicted in figure 63. The observed lines and the corresponding literature values are listed in table 15. A partial level scheme based on literature data is shown in figure 64.



Figure 63: <sup>142</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

Excited states in the <sup>142</sup>Ba ground-state band have been observed in  $\beta$ -decay studies of <sup>142</sup>Cs [91] and in fission products of <sup>252</sup>Cf [92]. In 1995, Zhu *et al.* [93] managed to extend the level scheme to spin 10 in the yrast band. Two negative-parity bands were measured.

They form, together with the ground-state band, an alternating-parity band. The group measured prompt  $\gamma$  rays from spontaneous fission of <sup>252</sup>Cf and <sup>242</sup>Pu sources with an array of 20 Compton-suppressed Ge-detectors at the Holifield Heavy Ion Research Facility at Oak Ridge National Laboratory. A further study was conducted by Urban *et al.* in 1997 employing the EUROGAM2  $\gamma$ -ray detector array at Strasbourg [84]. Prompt  $\gamma$  rays from <sup>248</sup>Cm fission products were measured to confirm the Zhu *et al.* measurement and to reveal further high-spin states which were not in reach within the earlier analysis. No data from transfer reactions are available to this date.

	× were not observ	veu yeu in ui				
	Experiment			Literature	2	
$E_{\gamma} [\mathrm{keV}]$	$\mathrm{FWHM}\left[\mathrm{keV} ight]$	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}  [\text{keV}]$	Ref.
359.57(20)	2.94(43)	156(22)	359.596(14)	$2^{+}$	359.598(14)	[1]
367.87(39)	2.88(57)	145(43)	*	*	*	
443.34(30)	2.28(46)	47(13)	*	*	*	
450.77(25)	2.28(46)	57(14)	*	*	*	
475.15(17)	3.10(37)	183(21)	834.81(9)	$4^{+}$	475.17(9)	[1]
620.57(42)	2.35(35)	63(15)	*	*	*	
631.61(25)	2.35(35)	121(22)	1465.98(24)	$6^{+}$	631.1(3)	[1]
640.81(32)	2.35(35)	108(24)	3153.2	$(11^{-})$	640.3(5)	[93]
$\hookrightarrow$			3794.0	$(13^{-})$	640.8(2)	[93]
642.76(27)	2.35(35)	64(14)	*	*	*	
693.17(26)	2.07(49)	53(13)	2159.4(4)	8 +	693.4(3)	[1]
883.40(52)	4.8(15)	80(18)	*	*	*	

**Table 15:** <sup>142</sup>Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a  $\star$  were not observed yet in the literature.

The highest excitation in a connected band is the 2159.0 keV 8<sup>+</sup> yrast level. Successive decays along the yrast lines to the ground state can be observed. Furthermore, a quite strong peak at  $\approx 640.8(3)$  keV is visible in the spectrum, corresponding to two energetically higher lying  $(13^-) \rightarrow (11^-)$  respective  $(11^-) \rightarrow (9^-)$  transitions in the negative-parity band. Zhu *et al.* specify the transition energies to be 640.8(2) and 640.3(5) keV [93]. It can not be concluded that the  $(13^-)$  state is populated in the present experiment since both lines can neither be resolved nor clearly identified in a  $\gamma$ - $\gamma$  spectrum with gates on the feeding or following transitions. There is no connection between the bands nor further transitions of the 9<sup>-</sup> state visible in the singles spectrum. Neither the 560.9 keV  $(9^-) \rightarrow (7^-)$  nor the 487.0 keV line, proposed by Urban *et al.* [84], can be identified in the spectrum. The 487.0 keV line should have an equal strength as the 693.4 keV 8<sup>+</sup>  $\rightarrow$  6<sup>+</sup>

yrast line. Five previously unknown transitions are observed as well. It is not possible to determine their position in the current level scheme as a  $\gamma$ - $\gamma$  analysis is not applicable due to the low statistics in the reaction channel. The highest peak-like structures in various  $\gamma$ - $\gamma$  coincidence spectra do not exceed four counts, comparable to a high background of two to three counts.





Figure 64: <sup>142</sup>Ba level scheme for the  $\gamma$  rays seen in the singles spectrum based on literature data taken from [1, 84, 93].

#### 5.2.9 +2p+5n channel: $^{143}$ Ba

 $^{143}$ Ba is produced via a +2p+5n transfer reaction:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{143}$ Ba +  $^{231-xn}$ Th + xn

<sup>143</sup>Ba is a N = 87 isotope and therefore has five neutron valence states with respect to the closed neutron shell at N = 82. The channel comprises  $1.767 \times 10^4$  events. <sup>143</sup>Ba is unstable and decays with a half-life of 14.5 s via  $\beta^-$  decay to <sup>143</sup>La. The fitted peaks and the corresponding literature data are summarized in table 16. A level scheme based on literature data is depicted in figure 66. The singles spectrum of <sup>143</sup>Ba is shown in figure 65, the analyzed  $\gamma$ -ray transition lines are listed in table 16.



Figure 65: <sup>143</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

The level scheme of <sup>143</sup>Ba is well known. The last study was done by Zhu *et al.* [94] investigating high spin states in neutron-rich odd-Z <sup>143,145</sup>Ba nuclei from the study of prompt  $\gamma$  rays in the spontaneous fission of <sup>252</sup>Cf. Only one known transition was found

	Da / Tay t	mgles speetium	evaluation.			
Experiment		L	Literature			
FWHM [keV] 1.70(73)	$\begin{array}{c c} Volume \\ 65(16) \end{array}$	$\frac{E_{\text{Level}} [\text{keV}]}{460.7}$	$J^{\pi}$ 13/2 <sup>-</sup>	$\begin{array}{c} E_{\gamma}  [\text{keV}] \\ 343.7 \end{array}$	Ref. [94]	

Table 16: <sup>143</sup>Ba  $\gamma$ -ray singles spectrum evaluation.

at 343.2 keV in the spectrum. The highest observable excited level is therefore the  $(13/2^-)$  state at 460 keV decaying in the 117 keV  $9/2^-$  state. A  $\gamma$ - $\gamma$  analysis is not applicable due to the low statistics in the reaction channel. Several candidates for peaks appear in the spectrum, all of them do not have a Gaussian peak structure and were not evaluated.



Figure 66: <sup>143</sup>Ba level scheme for the  $\gamma$  rays seen in the singles spectrum of <sup>143</sup>Ba based on data taken from [1, 94].

# 5.2.10 +2p+6n channel: $^{144}\mathrm{Ba}$

The +2p+6n transfer channel

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow$   $^{144}$ Ba +  $^{230-xn}$ Th + xn

is selected by gating on the even-even nucleus <sup>144</sup>Ba identified in PRISMA. The channel comprises  $1.28 \times 10^4$  events. <sup>144</sup>Ba is  $\beta^-$  unstable and decays with a half-life of 11.5 s to <sup>144</sup>La. The fitted peaks and the corresponding literature data are summarized in table 17. A level scheme based on literature data is depicted in figure 68.



Figure 67: <sup>144</sup>Ba  $\gamma$ -ray singles spectrum.

The latest study on <sup>144</sup>Ba isotopes was conducted by Urban *et al.* [84] in 1997. Even-even barium nuclei with A = 140 - 148 were produced in the spontaneous fission of <sup>248</sup>Cm and studied using the EUROGAM2 array. Four connected lines in the yrast band up to the 8<sup>+</sup> state could be found in this study. The maximum excitation energy is 1470 keV. A further peak at 167.8 keV is observed in the spectrum. This transition may correspond to a 168.8 keV non-yrast side-band cross transition from a 2158.9  $(7^+)$  state to a 1991.0 keV  $(6^-)$  state [84]. Neither feeding nor successive transitions are visible in the spectrum.

	not evaluated.					
Experiment			Lit	terature	:	
$E_{\gamma}  [\text{keV}]$	${ m FWHM}[ m keV]$	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma} [\mathrm{keV}]$	Ref.
167.81(33)	1.80(50)	24.2(89)	2158.9	$7^{+}$	167.8(2)	[84]
199.39(17)	1.42(32)	41.0(96)	199.326	$2^{+}$	199.326	[1]
331.12(18)	2.03(46)	61(11)	530.19	$4^{+}$	330.88	[1]
396.40(24)	1.27(40)	28(10)	*	*	*	
431.16(30)	3.39(60)	74(15)	961.53	$6^{+}$	431.3	[1]
508.71(27)	2.25(55)	43(11)	1470.0	$8^{+}$	509.3	[1]
542.2(19)	1.1(67)	30.0(90)	*	*	*	

**Table 17:** <sup>144</sup>Ba  $\gamma$ -ray singles spectrum evaluation. Transition energies marked with a  $\star$  were not observed yet in the literature. The peak candidates at 220 and 255 keV (compare figure 67) do not have a Gaussian peak structure and were not evaluated.

Two candidates for new transitions were found at 396.4 and 542.2 keV. A  $\gamma$ - $\gamma$  analysis is not applicable due to the low statistics in the reaction channel. Peak-like structures at 220 and 255 keV do not have a Gaussian shape and were not evaluated.



Figure 68: <sup>144</sup>Ba level scheme for the  $\gamma$  rays seen in the singles spectrum of <sup>140</sup>Ba. Data taken from [84] and [1].
## 5.2.11 +2p+7n channel: $^{145}$ Ba

The +2p+7n transfer channel corresponds to the reaction

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{145}$ Ba +  $^{229-xn}$ Th +  $xn$ 

The even-odd nucleus <sup>145</sup>Ba is identified in PRISMA. There is a total of  $9.1 \times 10^3$  events available in the channel. <sup>145</sup>Ba is a N = 89 isotope and has seven neutrons outside the closed neutron shell N = 82. The nucleus is  $\beta^-$  unstable and decays with a half-life of 4.3 s to <sup>145</sup>La. The Doppler corrected singles spectrum with an applied prompt time cut between AGATA and PRISMA is shown in figure 69. The  $\gamma$ -ray spectrum of <sup>145</sup>Ba does not contain distinct peaks. Potential transition candidates vanish in the background. An analysis of the channel is therefore not possible.



Figure 69: <sup>145</sup>Ba  $\gamma$ -ray singles spectrum with a cut on the prompt peak between AGATA and PRISMA.

#### 5.2.12 +2p+8n channel: <sup>146</sup>Ba

<sup>146</sup>Ba is the most  $\beta^-$ -unstable, exotic Ba isotope accessible at the fringes of the Ba mass distribution of the experiment. It has already a short half-life of only 2.2s and is produced by a ten-nucleon-pickup reaction. The <sup>136</sup>Xe beam picks up two protons and eight neutrons from the Uranium target:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow ^{146}$ Ba +  $^{228-xn}$ Th +  $xn$ 

The  $\gamma$ -ray spectrum is shown in figure 70, the analyzed  $\gamma$ -ray transition lines are listed in table 18. A  $\gamma$ - $\gamma$  analysis is not possible due to the low yield of only 3770 counts in the spectrum. The yrast band up to 6<sup>+</sup> is observed. This corresponds to a maximum excitation up to the 958.17 keV [1] level. The  $\gamma$ -ray spectrum is shown in figure 70, the analyzed  $\gamma$ -ray transition lines are listed in table 18. A level scheme is depicted in figure 71.



Figure 70: <sup>146</sup>Ba  $\gamma$ -ray singles spectrum. This reaction channel is the most exotic one in the present analysis.

	Experiment	Literature						
$E_{\gamma}  [\text{keV}]$	${ m FWHM}[ m keV]$	Volume	$E_{\rm Level}  [\rm keV]$	$J^{\pi}$	$E_{\gamma}  [\text{keV}]$	Ref.		
180.31(20)	2.04(48)	34.7(74)	181.02(5)	$2^{+}$	181.05(5)	[1]		
331.81(25)	2.28(66)	30.0(70)	513.50(7)	$4^{+}$	332.38(5)	[1]		
444.84(41)	2.89(82)	2.89(82)	958.17(11)	$6^{+}$	444.7(1)	[1]		

Table 18: <sup>146</sup>Ba  $\gamma$ -ray singles spectrum evaluation.

$6^{+}$	-	958			
		444.7			
$4^{+}$		514			
		332.4			
$2^{+}$	<u> </u>	181		-	
$J^{\pi}$ $0^+$		181.1	$E_{lavel}$ [keV]		$^{146}_{56}Ba$

Figure 71: <sup>146</sup>Ba level scheme up to the observed  $6^+$  yrast state. Data taken from [1].

## 6 Analysis for Target-Like Actinide Nuclei

### 6.1 Detection of target-like particles

The population of surviving target-like actinide nuclei can be verified employing several methods; the study of X-rays, the study of characteristic  $\gamma$  rays, and the study of DANTE hits at the grazing angle. Characteristic X-rays in the  $\gamma$ -ray spectrum are a clear signature for the presence of the nuclei of interest in the corresponding Z channel. The X-ray emission from the atomic shells depends mainly on the nuclear charge and the velocity of the reaction products, not on nuclear structure properties. Figure 72 shows the low-energy parts of  $\gamma$ -ray spectra which are now Doppler corrected for the even-Z channels Z = 92 uranium, Z = 90 thorium and Z = 94 plutonium recoil nuclei. The strongest lines in the spectra belong to the KL<sub>1-3</sub> and KM<sub>1-5</sub> lines of lead which was used in shielding materials and as a beam dump. The Pb K edge is located at 88.0 keV [95].

Strong X-ray signatures are visible in the quasi-elastic uranium channel. The KL<sub>1-3</sub> transitions at 93.8, 94.7 and 98.4 keV,  $KM_{1-5}$  transitions around 111 keV, and KN transitions around 114.5 keV are identified. Three peaks at 90.1(2), 93.3(1) and 105.3(2) keV are visible in the Th spectrum. They correspond to overlapping  $KL_{1-3}$  and  $KM_{1-5}$  X-ray transitions. The relative intensity of the Th X-rays is substantially smaller than the ones in the U spectrum. Therefore, the amount of surviving excited Th isotopes reduced with respect to the U channel, causing a sophisticated analysis of Th  $\gamma$ -ray spectra.

A more in-depth view on the population of excited target-like nuclei can be obtained in the study of the particle coincidence TAC time between PRISMA and the recoil tagging DANTE MCPs in the scattering chamber. Figure 73 shows the integrated amount of counts of the left TAC1 peak (discussed in detail in section 4.8) color coded in a Segré chart which are attributed to ejectiles identified by PRISMA. The color code axis is cut off at  $5 \times 10^4$ counts for a better visibility of the weak proton transfer channels. The TAC1 integral for Z = 56 isotopes, i.e. Th fragments in kinematic coincidence, are, although weak, clearly visible in the two-dimensional chart.



Figure 72: X-ray signatures in U, Th and Pu  $\gamma$ -ray spectra. The Th and U spectra reveal the corresponding X-ray lines of KL, KM and KN transitions. Overlapping peaks were fitted with multi-Gaussians. In the Pu spectrum no corresponding X-ray peaks are observable. Hence, highly excited Pu isotopes do not survive in the 1 GeV <sup>136</sup>Xe + <sup>238</sup>U multi-nucleon transfer reaction. The induced fission cross section has to be significantly higher. X-ray data taken from [95].

TAC1 integral from 3200 to 3545 ns



Figure 73: Two-dimensional representation of the Segré chart showing the integral of the left TAC1 peak (compare chapter 4.8) color coded. The color axis is cut off at  $5 \times 10^4$  events for better visibility. The TAC1 signal is a measure of surviving actinide fragments which were tagged by the DANTE MCPs. The absence of events in the Pu channel, i.e. the TAC1 integral for positively identified Te isotopes in PRISMA, is striking. The Th channel corresponding to the Z = 56 ejectile channel is weak compared to the U channel. <sup>136</sup>Xe holds  $4.90 \times 10^5$  TAC1 events, the complete Ba chain contains  $9.8 \times 10^4$ TAC1 events.



 $\gamma$ -ray spectrum of <sup>132</sup>Te, Doppler corrected for Pu nuclei

**Figure 74:**  $\gamma$ -ray spectra of Te, Doppler corrected for recoil nuclei. Instead of plutonium  $\gamma$  rays, only  $\gamma$ -ray transitions from the quasi-elastic channel <sup>238</sup>U are visible.

The Np channel exhibits a similar remarkable behavior. The ejectile channel corresponding to  $^{236}$ Np has a much lower abundance than the surrounding Np isotopes. It has to be noted that the one-proton transfer channels are contaminated with falsely identified Xe fragments. A detailed investigation of this issue would go beyond the scope of this thesis. It is striking that almost no Pu fragments leaving the target were recorded with the DANTE detectors. There are only  $\approx 5.0 \times 10^4$  Te events in the left PRISMA-DANTE TAC peak. Figure 74

shows two  $\gamma$ -ray spectra of Te under TAC cut with a recoil Doppler correction. A <sup>132</sup>Te spectrum with a cut on Q > -120 a.u. is shown in the upper part, while the lower part shows a sum spectrum of all Te channels. No plutonium  $\gamma$ -rays, but weak  $\gamma$ -ray transitions from the quasi-elastic channel <sup>238</sup>U are visible. The fission cross section after multi-nucleon transfer is much higher than the production cross section for surviving excited Pu isotopes.

## 6.2 Two-Proton pickup channel: Thorium isotopes

The TAC1 signals provide a measure for the Th population. Only  $9.88 \times 10^4$  events from thorium isotopes are observed after a cut on the prompt time coincidence between AGATA and PRISMA. To extract collective properties of neutron-rich actinides from the recoil Doppler corrected  $\gamma$ -ray spectrum, more refined analysis cuts have to be applied. Figure 75 shows the cut procedure as an example for the recoil  $\gamma$ -ray spectrum caused by the <sup>138</sup>Ba ejectile channel. The initial ejectile-gated  $\gamma$ -ray spectrum, Doppler corrected with the calculated recoil fragment kinematics and with an additional gate on the prompt time coincidence between PRISMA and AGATA, is quite flat and reveals only characteristic Pb and Th X-ray peaks in the low-energy region < 110 keV. A further cut on the particle coincidence TAC between PRISMA and DANTE gives first peak structures, probably belonging to a rotational band cascade. Finally, a cut on small total kinetic energy losses (TKEL), i.e. low excitation energies in the binary fragments, gives distinct peaks in the spectrum.

As depicted in figure 73, the largest recoil channel corresponds to the <sup>138</sup>Ba ejectile channel with  $2.03 \times 10^4$  observed events. For the reaction it follows:

$$^{136}$$
Xe +  $^{238}$ U  $\rightarrow$   $^{138}$ Ba +  $^{236-xn}$ Th +  $xn$ 

Assuming no neutron evaporation, one might expect <sup>236</sup>Th  $\gamma$ -ray transitions in the spectrum. The extent of neutron evaporation is not measured and has to be investigated very carefully. For this reason, various recoil Doppler corrected spectra of <sup>138</sup>Ba were examined under different TKEL cuts. A compilation of spectra with cuts on Q > -350 and Q > -70 a.u. is depicted in figure 76. The corresponding TKEL distribution is shown in the lower part of figure 75. The relevant KL and KM Th X-ray peaks are visible in all spectra. The presence of X-ray peaks provides an irrevocable evidence that the corresponding element was populated in the reaction channel. As a consequence, it is expected that the spectrum contains spectroscopic information on Th isotopes.



Figure 75: Analysis procedure for recoil  $\gamma$ -ray spectra: The initial recoil Doppler corrected spectrum with a gate on the prompt time coincidence between PRISMA and AGATA is quite flat and reveals only characteristic Pb and Th X-ray peaks. A further cut on the particle coincidence TAC between PRISMA and DANTE gives hints of a first peak structure belonging to a rotational band cascade. Finally, a cut on small total kinetic energy losses (TKEL), i.e. low excitation in the binary fragments, results in distinct peaks in the spectrum.

Successive transition energy differences in rotational bands are constant for a rigid rotor, i.e.  ${}^{dE_{\gamma}/dJ} = {}^{2\hbar^2/\mathscr{I}}$ . Spectra of  $\gamma$  rays representing a rotational band cascade of  $\Delta J = 2$  transitions should therefore show a set of uniformly spaced peaks with the following transition energies:

$$E_{\gamma}(J \to J - 2) = \frac{\hbar^2}{2\mathscr{I}} \left[ J(J+1) - (J-2)(J-1) \right] = \frac{\hbar^2}{2\mathscr{I}} (4J-2)$$
(6.1)

Accordingly, the study of energy differences in rotational spectra is of particular relevance.



 $\gamma$ -ray spectra of <sup>138</sup>Ba, Doppler corrected for Th fragments

Figure 76: <sup>138</sup>Ba recoil Doppler corrected spectra with all events (blue) and gates on small and medium (red) and small (green) TKEL values. Known peaks of the -2n and -4n evaporation channels <sup>234</sup>Th and <sup>232</sup>Th are marked. They are listed in table 19. Transitions marked with a ? cannot be assigned to

In the Q > -350 a.u. spectrum, in which all events are allowed to pass through, known peaks of <sup>234</sup>Th and even <sup>232</sup>Th are observed. The spectrum demonstrates that both -2n and -4n evaporation channels are clearly favored far over the production of <sup>236</sup>Th. By applying a more restrictive TKEL cut of Q > -70 a.u., the peaks of the -4n channel <sup>232</sup>Th vanish. Only the rotational band of <sup>234</sup>Th remains. A peak at 270.5(10) keV does not originate from the <sup>234</sup>Th rotational band. The expected  $10^+ \rightarrow 8^+$  ground-state band transition would be located at 277.8(2) keV. The maximum excitation of <sup>234</sup>Th in the Q < -70 a.u. spectrum is the  $16^+$  ground-state band level at 1923.4(8) keV. The -4n channel <sup>232</sup>Th is excited up to the 2262.4(9) keV  $18^+$  state. It is notable that no distinct peaks of the evenodd Th isotopes as <sup>233</sup>Th are identified in the spectrum. All observed peaks from figure 19 are summarized in table 19.



Figure 77: Top:  $^{136-138}$ Ba (recoil Doppler corrected)  $\gamma$ -ray sum spectrum. Mid:  $^{236-xn}$ Th and  $^{235-xn}$ Th. Bottom:  $^{236-xn}$ Th and  $^{237-xn}$ Th. The relative intensities of the peaks at 223 and 228 keV are a measure for different neutron evaporation channels.

For cuts on low total kinetic energy losses and therefore only low excited, "cold" binary partner systems, neutron evaporation to lighter even-even Th isotopes dominates. As depicted in the upper part of figure 77, sum spectra of <sup>138</sup>Ba, <sup>137</sup>Ba and <sup>136</sup>Ba, corresponding to <sup>236-xn</sup>Th, <sup>237-xn</sup>Th and <sup>238-xn</sup>Th, show the same <sup>234</sup>Th and <sup>232</sup>Th  $\gamma$ -ray peaks under restrictive Q > -90 a.u. cuts. Additionally, figure 77 shows two spectra of (mid part, orange) <sup>139</sup>Ba corresponding to <sup>235-xn</sup>Th and (lower part, red) <sup>237</sup>Ba corresponding to <sup>237-xn</sup>Th under Q > -90 a.u. cuts. Both spectra are zoomed in at an energy region around <sup>232</sup>Th and <sup>234</sup>Th 8<sup>+</sup>  $\rightarrow$  6<sup>+</sup> transitions and compared to the equivalent <sup>138</sup>Ba/<sup>236-xn</sup>Th (black). The 223 keV peak from <sup>232</sup>Th dominates in the <sup>235-xn</sup>Th  $\gamma$ -ray spectrum. The -1n neutron evaporation to <sup>234</sup>Th seems to be unfavored. On the contrary, the 228 keV peak of <sup>234</sup>Th prevails in the <sup>237-xn</sup>Th spectrum. The evaporation of five neutrons down to <sup>232</sup>Th becomes less likely.

**Table 19:** Evaluation of the <sup>138</sup>Ba  $\gamma$ -ray singles spectrum Doppler corrected for the target-like reaction products with no constraint regarding the total kinetic energy loss, i.e. Q > -350 a.u. Literature data taken from [1].

		•			
Experiment			Literature		Comment
$E_{\gamma}  [\text{keV}]$	Nuclide	$E_{\gamma} [\mathrm{keV}]$	$J^{\pi}$	$E_{\rm Level}  [\rm keV]$	
170.60(34)	$^{232}$ Th	171.2(1)	$6^+ \rightarrow 4^+$	333.26(8)	
173.38(20)	$^{234}$ Th	173.4(2)	$6^+ \rightarrow 4^+$	336.45(24)	
223.79(42)	$^{232}$ Th	223.6(1)	$8^+ \rightarrow 6^+$	556.9(1)	
228.17(25)	$^{234}$ Th	228.3(2)	$8^+ \rightarrow 6^+$	564.7(3)	
237.5(5)	$^{?}\mathrm{Th}$	?	?	?	even-odd Th?
261.2(5)	$^{?}\mathrm{Th}$	?	?	?	even-odd Th?
270.53(47)	$^{232}$ Th	269.8(1)	$10^+ \rightarrow 8^+$	826.8(1)	
277.8(5)	$^{234}$ Th	277.8(2)	$10^+ \rightarrow 8^+$	842.5(4)	deformed peak
310.5(5)	$^{232}$ Th	310.2(5)	$12^+ \rightarrow 10^+$	1137.1(5)	
$323.4(\sim 10)$	$^{234}$ Th	322.3(5)	$(12^+) \to 10^+$	1164.9(6)	small peak
345.89(40)	$^{232}$ Th	345.2(5)	$12^+ \rightarrow 10^+$	1482.2 6	double peak?
359.90(45)	$^{234}$ Th	361.8(5)	$(14^+) \to (12^+)$	1526.6(7)	
395.5(5)	$^{234}$ Th	396.8(5)	$(16^+) \rightarrow (14^+)$	1923.4(8)	
405.39(68)	$^{232}$ Th	403.9(5)	$18^+ \rightarrow 16^+$	2262.4(9)	

The thorium X-rays as a measure for the overall Th population vanish for cuts beyond  $Q \leq 200$  a.u. in the recoil Doppler corrected and TAC1 gated <sup>138</sup>Ba spectrum. Above this, is is proven that the Q-value or TKEL value seems to be a reasonable cut parameter for surviving actinide nuclei. A verification of the general correlation between lower Q values and the amount of neutron evaporation is indeed difficult. High-quality and well-known

ejectile spectra cannot be used as a probe for neutron evaporation in dependence of the Q-value since the mass was already accurately selected by the PRISMA mass spectrometer.

In the analysis of the quasi-elastic channel of this experiment, B. Birkenbach [19] compared the closely spaced background-subtracted peak intensities of the one neutron transfer nuclei <sup>239</sup>U at 250 keV with the intensity of the <sup>238</sup>U line at 258 keV by dividing both peak areas. The relative area is rising for higher Q values, implying less neutrons are released from <sup>239</sup>U. Another convincing result was obtained by comparing the intensity of the 596 keV radiation emerging from the <sup>74</sup>Ge(n,n' $\gamma$ )<sup>74</sup>Ge scattering in the Ge detector material with the intensity of the throughout present 511 keV e<sup>-</sup>e<sup>+</sup> annihilation radiation. For higher TKEL values the relative intensity of the <sup>74</sup>Ge line rises, indicating more neutrons to be evaporated in the target.

While different cuts on the Q-value suppress certain neutron evaporation channels, the Q-value alone does not seem to be a sufficient cut parameter to restrict the data on nuclei without any neutron evaporation. Evaporation of two and more neutrons is a persistent effect along the Th chain. As a result, alternative cut parameters come into focus. Figure 78 shows plots of TAC 1 versus Q and TAC1 versus the calculated recoil velocity  $\beta_{\text{recoil}}$ . Two-dimensional gates are placed in both matrices selecting events within the left TAC1 peak.



Figure 78: Q versus TAC1 and  $\beta_{\text{recoil}}$  cut spectra with two-dimensional gates for more precise cuts on the left TAC peak.

The novel concept of  $\gamma$ -ray tracking allows the introduction of new and previously not possible cut procedures. The position of  $\gamma$ -ray hits in the detector array is not constrained any more by the detector segments. Instead, all interaction positions are well-known with a resolution of only a few mm within the crystals [15]. Figure 79 shows the length  $|\vec{L}_{\gamma}|$  of the vector pointing from the target defined as origin to the first interaction point  $(X_{\gamma,0}, Y_{\gamma,0}, Z_{\gamma,0})$  of the  $\gamma$  ray in AGATA. By gating on small to medium lengths  $|\vec{L}_{\gamma}| <$  280 mm one takes advantage of the high photo effect efficiency in the first segments of the front face of the detector array for low-energetic  $\gamma$  rays.



Figure 79: Length of the first-hit vector  $|\vec{L}_{\gamma}|$  as a measure for the penetration depth in the detector material of AGATA.

Furthermore, the concept of restrictive TKEL gates is discarded in favor of cuts on the  $\beta_{\text{ejectile}}$  and  $\beta_{\text{recoil}}$  distributions (compare figure 41 in section 4.9). The selection of low excited target-like fragments which survive fission and emit only few neutrons was attempted by gating on high ejectile and low recoil velocities. Low kinetic energies of the target-like nuclei and high kinetic energies of the ejectiles is expected to favor low excitation energies. Given the results on the massive x > 2 neutron evaporation in the recoil spectra shown above, gates on extremely exotic  $\geq^{238-xn}$ Th have to be considered now. A sketch of this concept is depicted in figure 80. While  $\leq^{237-xn}$ Th  $\gamma$ -ray spectra show  $\gamma$  rays from the -2n and -4n evaporation channels, heavier residues could in fact end up in  $^{236}$ Th.



Figure 80: Neutron evaporation systematics. Starting from  $^{236}$ Th only -2n and even -4n evaporation channels are observed under different TKEL gates.

Figure 81 shows the final spectrum with the following conditions: (i) Ba ejectiles of mass  $A \leq 136$ , (ii) two two-dimensional TAC gates introduced above, (iii) restrictions on  $\beta_{\text{ejectile}} > 9.0\%$ ,  $\beta_{\text{recoil}} < 4.9\%$ , and (iv), the maximum length of the  $\gamma$ -ray first-hit vector  $|\vec{L}_{\gamma}| < 280 \text{ mm}$ . Four peaks are located at 172(1), 224(1), 228(1) and 273(1) keV, respectively. The 228(1) keV peak may be caused by <sup>234</sup>Th which was observed in the other



<sup>236</sup>Th transition candidates in sum spectra of <sup>133-136</sup>Ba, recoil Doppler corrected

**Figure 81:** The  $\gamma$ -ray sum spectrum gated by  $^{\leq 136}$ Ba, Doppler corrected for target-like fragments, shows the  $^{236}$ Th ground-state band transition candidates from [35]. The peaks at 172, 224 and 273 have equal energy spacings.

spectra as well. The peak at 273(1) keV was previously unobserved in this analysis. In the corresponding energy region there were only peaks at 270.5(5) and 277.8(5) keV. The energy of the new peak matches well with the <sup>236</sup>Th 10<sup>+</sup>  $\rightarrow$  8<sup>+</sup> ground-state band transition candidate at 272.7(5) keV proposed by Ishii et. al. [35]. The energy spacings are 51 keV between the peaks at 172 and 224 keV and 49 keV between the 224 and 273(1) keV peaks, respectively. The 172(1) keV candidate lies next to both 171.2 and 173.4 keV 6<sup>+</sup>  $\rightarrow$  4<sup>+</sup> transitions of <sup>232</sup>Th and <sup>234</sup>Th. The 224(1) keV peak would only match the 6<sup>+</sup>  $\rightarrow$  4<sup>+</sup> line of <sup>232</sup>Th at 223.6 within its uncertainty. On the other hand no contribution of the <sup>234</sup>Th 10<sup>+</sup>  $\rightarrow$  8<sup>+</sup> transition around 277.8 keV is visible. Together with the 113(1) keV line, the three peaks at 171(1), 224(1) and 273(1) are strong candidates for the ground-state band cascade of <sup>236</sup>Th. The proposed level scheme of <sup>236</sup>Th is shown in figure 82 and compared to the study by Ishii *et al.* The obtained  $\gamma$ -ray transition candidates were examined to which extent they are consistent with the level scheme of a rotational band.



**Figure 82:** Proposed level scheme for <sup>236</sup>Th based on the  $\gamma$ -ray spectrum in figure 81. The 224(1) and 273(1) keV transitions match the values obtained by Ishii *et al.* The 169.4 keV transition can not be reproduced in the analysis. Instead, a peak at 172(1) keV is found. The 2<sup>+</sup> level energy is deduced from a fit of the moments of inertia in the following section 6.3.

#### 6.3 Comparison with Theoretical Predictions

Kinetic and dynamic moments of inertia  $\mathcal{I}^{(1)}$  and  $\mathcal{I}^{(2)}$ , which were introduced in chapter 2.3, are now calculated for <sup>236</sup>Th. The  $\gamma$ -ray transitions of the ground-state rotational band define the kinetic moment of inertia, while the dynamic moment of inertia  $\mathcal{I}^{(2)}$  parametrizes energy differences in the rotational band cascades:

$$\mathcal{I}^{(1)} = \frac{(2J-1)\hbar^2}{\Delta E_{J\to J-2}} \qquad \qquad \mathcal{I}^{(2)} = \frac{4\hbar^2}{\Delta E_{J\to J-2} - \Delta E_{J-2\to J-4}} \tag{6.2}$$

This analysis procedure is adapted from various studies of rotational properties in highmass regions. [96–99] Both quantities  $\mathcal{I}^{(1)}$  and  $\mathcal{I}^{(2)}$  can be parametrized with the Harris parametrization [21].

$$\mathcal{I}^{(1)} = \mathcal{I}_0 + \mathcal{I}_1 \omega^2 \qquad \qquad \mathcal{I}^{(2)} = \mathcal{I}_0 + 3 \mathcal{I}_1 \omega^2 \qquad (6.3)$$

The corresponding rotational frequencies  $\omega_{\rm kin}$  and  $\omega_{\rm dyn} = \langle \omega_{\rm kin} \rangle$  are given by

$$\hbar\omega_{\rm kin} = \frac{E_{J\to J-2}}{2} \qquad \hbar\omega_{\rm dyn} = \hbar\frac{\omega_{J\to J-2} + \omega_{J-2\to J-4}}{2} \tag{6.4}$$

The moments of inertia for the yrast bands are plotted as a function of rotational frequency  $\omega$  in figure 83. A fit using the Harris parametrization was feasible up to  $10^+$ .

## $\mathcal{I}^{(1)}$ and $\mathcal{I}^{(2)}$ for $^{236}\mathrm{Th}$ ground-state band candidates



Figure 83: Kinetic and dynamic moments of inertia  $\mathcal{I}^{(1)}$  and  $\mathcal{I}^{(2)}$  for the hard-toreach nucleus <sup>236</sup>Th. The lines are fits to the data points using the Harris parametrization given in equation 6.3. The dashed black data points are taken from theoretical calculations of Delaroche *et al.* [29]. The black solid line shows the simple rigid rotor model.

The two fit parameters and their statistical errors were found to be

$$\mathcal{I}_0 = (60.25 \pm 0.09) \frac{\hbar^2}{\text{MeV}} \quad \text{and} \quad \mathcal{I}_1 = (322 \pm 8) \frac{\hbar^4}{\text{MeV}^3} \quad (6.5)$$

Ishii *et al.* found  $\mathcal{I}_0 = 62.6(2) \hbar^2/\text{MeV}$  and  $\mathcal{I}_1 = 334(23) \hbar^4/\text{MeV}^3$  [35]. The results of the HFB cranking model calculation of Delaroche *et al.* [29] are plotted with black triangles. The data obtained in this analysis allows a first comparison with the HFB cranking model calculations for low energies. Future investigations are motivated by a backbending which should take place at higher frequencies in the order of  $0.2 \text{ MeV}/\hbar$ .

The  $2^+ \rightarrow 0^+$  transitions were not detected in the  $\gamma$ -ray spectrum because these low-lying states decay almost entirely by internal electron conversion. The corresponding internal conversion coefficient can be calculated using the BrIccS code [100]. For  $\Delta J = 2$  E2 transitions a large value of  $\alpha_T \approx 308$  is computed. The  $4^+ \rightarrow 2^+$  transition has a conversion factor of  $\alpha_T \approx 6.6$ . Moreover, the detectors were shielded by their housing and the scattering chamber itself. Hence, low-energy  $\gamma$  rays are heavily suppressed. However, an extrapolation to lower energies was performed in order to determine the energy of the unobservable  $2^+ \rightarrow 0^+$  transition in <sup>236</sup>Th with the Harris expansion coefficients  $\mathcal{I}_0$  and  $\mathcal{I}_1$ , using the expression [96]

$$J = \mathcal{I}_0 \,\omega + \mathcal{I}_1 \,\omega^3 + \frac{1}{2} \tag{6.6}$$

A rearranged form of the rotational frequency gives the following expression:

$$\omega_{\rm kin}^{2^+ \to 0^+} = -\frac{2^{2/3} \mathcal{I}_0}{3^{1/3} \left(27 \mathcal{I}_0^2 + \sqrt{3} \sqrt{16 \mathcal{I}_0^3 \mathcal{I}_0^3 + 243 \mathcal{I}_0^4}\right)^{1/3}} + \frac{\left(27 \mathcal{I}_0^2 + \sqrt{3} \sqrt{16 \mathcal{I}_0^3 \mathcal{I}_0^3 + 243 \mathcal{I}_0^4}\right)^{1/3}}{6^{2/3} \mathcal{I}_0}$$
(6.7)

The corresponding  $2^+ \to 0^+$  transition energy  $E_{\gamma} \equiv \Delta E$  is then calculated to be:

$$\Delta E_{2^+ \to 0^+} = 2 \hbar \omega_{\rm kin}^{2^+ \to 0^+} \simeq (49.7 \pm 3) \,\rm keV \tag{6.8}$$

The calculation of the error propagation of  $\Delta \mathcal{I}_0$  and  $\Delta \mathcal{I}_0$  in the expression above was performed with the computer-algebra software Mathematica [101]. Ishii *et al.* estimated  $E_{2^+\to 0^+}$  to be 48.4(3) keV. The  $2^+ \to 0^+$  transition at  $E_{\gamma} = 113.5(5)$  matches the quadratic fit function of the kinetic moment of inertia very well. According to the fit function, peaks of the  $12^+ \rightarrow 10^+$  and  $14^+ \rightarrow 12^+$  transitions should be located at 314(3) and 353(4) keV, respectively. Unfortunately, no peaks are found at these energies due to limited statistics.

Figure 84 shows adopted ground-state band level energies [1] of even-even  $^{220-234}$ Th isotopes up to spin 10<sup>+</sup>. Further on, the corresponding level energy candidates of  $^{236}$ Th obtained in this study are included. The lines represent level energies calculated within the *sdf* Interacting Boson Model by Nomura *et al.* [33]. The figure shows that the observed transition energies, spins and the deduced  $2^+ \rightarrow 0^+$  transition energies are similar to those from neighboring lighter nuclei.



Figure 84: Ground-state band excitation energies (dots depict experimental values taken from [1]) along the isotopic chain of Th. The colored lines represent sdf IBM calculations by Nomura *et al.* up to <sup>232</sup>Th. Transition energies and spins of <sup>236</sup>Th obtained in the present analysis are similar to those from neighboring lighter nuclei. Modified, original from K. Nomura [33].

Lifetimes could not be measured in the given experimental setup. Nevertheless,  $B(E2) \uparrow$  values can be deduced model dependent from empirical relationships which are valid for A > 56 (compare treatment by Raman *et al.* [102, 103]). The mean  $\gamma$ -ray lifetime in ps can be related to the  $B(E2) \uparrow$  value in  $e^2b^2$  in the following way:

$$\tau_{\gamma} = 40.81 \times 10^{13} E^{-5} \left( \frac{\mathrm{B}(\mathrm{E2})\uparrow}{e^{2}\mathrm{b}^{2}} \right)$$
 (6.9)

A global fit of experimental data of even-even nuclei gives  $\tau_{\gamma}$  (in ps) in dependence of the nuclear charge Z, mass A and 2<sup>+</sup> level energy E:

$$\tau_{\gamma} = 1.25 \times 10^4 \, E^{-4.0} Z^{-2} A^{0.69} \tag{6.10}$$

The dimensionless quadrupole deformation parameter  $\beta_2$  can be calculated in dependence of the B(E2)  $\uparrow$  value. With  $R_0^2 = 0.0144 A^{2/3}$  b it follows:

$$\beta_2 = \left(\frac{4\pi}{3 Z R_0^2}\right) \sqrt{\frac{\mathcal{B}(\mathcal{E}2)\uparrow}{e^2}} \tag{6.11}$$

By combining the last four equations,  $\beta_2$  can be calculated as follows:

$$\beta_2 \approx (466 \pm 41) E^{-1/2} A^{-1} = 0.280(25)$$
 (6.12)

This result is in good agreement with the theoretical value of  $\sim 0.275$  obtained in axialsymmetric reflection symmetric/asymmetric relativistic mean-field (RS/RAS-RMF) calculations by Guo *et al.* [32]. The theoretical results along the Th isotopic chain are shown in figure 85.



Figure 85: Theoretical quadrupole deformation parameters  $\beta_2$  along the Th isotopic chain. The values were obtained in axial-symmetric reflection symmetric and axial-symmetric reflection asymmetric relativistic mean-field calculations by Guo *et al.* The nucleus of interest <sup>236</sup>Th is labeled with dashed lines. Modified reprint from [32].

# 7 Discussion and Outlook

The present experiment and its results demonstrate successfully the synergies of the high efficiency  $\gamma$ -ray-tracking spectrometer AGATA in combination with the ancillary mass spectrometer PRISMA and the multichannel-plate detector DANTE. It could be shown that the AGATA/PRISMA setup is qualified to track down the most elusive  $\gamma$  rays from weakly populated reaction channels under demanding conditions caused by the high fission background emerging from the employed actinide target. The novel  $\gamma$ -ray tracking technique allows a precise Doppler correction for both beam- and particle-like fragments. Furthermore,  $\gamma$ -ray tracking provides new analysis methods such as cuts on different  $\gamma$ -ray penetration depths. By demanding particle coincidences of ejectile nuclei with surviving recoil fragments measured at the grazing angle, a rigorous fission suppression could be successfully performed. This capability enables the experimentalist to extract hard-to-reach nuclear properties in the low-statistics recoil channels.

Various existing software tools were combined and newly developed in order to extract the rare events of interest. The interplay of C++ standalone programs and C/Python macros with the CERN **root** framework ensures an efficient analysis procedure. Nevertheless, most of the analysis steps, especially for the PRISMA spectrometer, can not be automatized since two-dimensional cuts have to be set graphically in an elaborate and often time-consuming way. Instabilities during the beam time caused unforeseen difficulties concerning the long-term stability of the detectors and their consecutive analysis. As a result, the analysis had to be split up into several individual parts. Particularly, aberration corrections and the optimization of the mass resolution included sophisticated analysis steps requiring utmost care to avoid contamination from neighboring channels. Finally, clean and high quality  $\gamma$ -ray spectra were extracted for a wide range of Ba and Th nuclei. Although PRISMA works at its specified limits with a <sup>136</sup>Xe beam, the final mass resolution of  $m/\Delta m = 297.5 \pm 0.7$  in the Ba channel is remarkably good.

Neutron evaporation from excited actinide reaction products dominates the  $\gamma$ -ray spectra in the target-like two-proton-stripping thorium channel. By adding the recoil-Dopplercorrected  $\leq^{136}$ Ba  $\gamma$ -ray singles spectra and applying various restrictive cuts on the data, convincing candidates for the ground-state band transitions of  $^{236}$ Th nuclei emerge. Coincidence gating is not feasible due to the low statistics. The transition candidates match in part with the results obtained by Ishii *et al.* [35]. Energy spacings and the corresponding moments of inertia are consistent with the model predictions for rotational nuclei. Kinetic and dynamic moments of inertia  $\mathcal{I}_0 = (60.25 \pm 0.09) \hbar^2/\text{MeV}$  and  $\mathcal{I}_1 = (322 \pm 8)\hbar^4/\text{MeV}^3$ were calculated using the Harris parametrization and were, for the first time, compared to theoretical predictions. Both values agree nicely with the experimental results of Ishii *et al.* [35]. The quadrupole deformation parameter  $\beta_2 = 0.280(25)$  was obtained by employing empirical fit formulas. It matches theoretical predictions by Guo *et al.* [32]. Nevertheless, these preliminary results have to be treated with caution since an unambiguous identification of  $^{236}$ Th is not possible with the given setup.

A rich dataset on various A = 135 - 146 barium isotopes was collected in the experiment. A variety of candidates for previously unknown  $\gamma$ -ray transitions were extracted from the data. Especially the nucleus <sup>137</sup>Ba is of high interest. Only one known transition above a long-living isomeric state could be observed. A dedicated experiment on high-spin states in <sup>137</sup>Ba should be performed to clarify the level scheme above excitation energies of 2.6 MeV. More statistics is desirable for a conclusive analysis of  $\gamma$ - $\gamma$  coincidence matrices. Neither spin nor parity assignments, for which the study of angular correlations is necessary, could be made with this experimental setup.

Based on this work, the analysis will be extended in the near future to the neighboring Z channels. A complete analysis of the tellurium, iodine and caesium reaction channels has to be conducted. The corresponding even-odd and odd-odd protactinium and neptunium channels are also of high interest. These  $\gamma$ -ray spectra are more complicated due to the contamination of the neighboring quasi-elastic Xe/U channel. The conversion of mass yields into cross sections using the methods introduced in section 4.7 is in preparation.

The GANIL facility will host the European AGATA HPGe array starting from late 2014. AGATA will be coupled to the VAMOS mass spectrometer. Future experiments investigating the collective properties of neutron-rich Th isotopes employing multi-nucleon transfer reactions will require the same dedicated triggers to suppress the large fission background. As the capabilities of the DANTE MCPs inside the target chamber was not exploited, an equivalent detector like DANTE will be needed to provide a two-dimensional position information. Unfortunately, the corresponding (x, y) position spectra of this experiment were corrupted and did not provide a meaningful result like the almost identically constructed PRISMA MCP (compare figure 16). If the right angles of the recoil residues could could have been recorded event-by-event employing DANTE, a very efficient background reduction would be performed. However, this experiment shows that neutron evaporation has to be investigated very carefully since it obstructs the correct assignment of  $\gamma$ -ray transition candidates to the corresponding target-like nuclei. Ambiguities do not exist for the ejectile channels because the nuclei were accurately selected by PRISMA.

In a future experiment at a suited accelerator, neutron-rich actinides could also be investigated in inverse kinematics by shooting <sup>238</sup>U ions on a lighter target and detecting  $\gamma$  rays with a high-resolution Germanium detector array in coincidence with the binary fragments measured with a mass spectrometer like VAMOS at GANIL suited for ions in that high mass regime. In this way, the surviving thorium nuclei beyond <sup>234</sup>Th would be detected directly. Individual neutron evaporation channels, e.g. <sup>232</sup>Th and <sup>234</sup>Th, would be resolved and would not pose a problem any more, because neutron evaporation has taken place a long time before the particle enters the spectrometer.

# Appendix:

# Master Introductory Project Study of $B^0_s \to J/\psi \phi$ decays with ATLAS

As part of the second Master Thesis Introductory Project, I worked on a particle physics project at the University Bonn in the workgroup of Prof. Dr. N. Wermes under supervision of Dr. E. von Törne from April to September 2013. The results of this project are presented in a brief report as a thematically separate part in this appendix. The mass and lifetime of the  $B_s^0$  meson are determined by their  $B_s^0 \rightarrow J/\psi \phi$  decay, reconstructed in the ATLAS detector at the LHC using reduced pp collision data with successfully detected high-energy muons. The lifetime which is determined by a maximum likelihood lifetime fit, is  $1.327 \pm$ 0,017 (stat.) ps. A total number of  $9118 \pm 95$  (stat.) signal  $B_s^0$  decays are observed with a fitted  $B_s^0$  mass of  $5365.7 \pm 0.7$  (stat.) MeV. Both the extracted  $B_s^0$  meson mass and lifetime are consistent with the world average PDG values within the determined errors.

#### The ATLAS detector at the LHC

ATLAS (A Toroidal LHC Apparatus) [104] is one of four big particle detector experiments installed in its experimental cavern at the Large Hadron Collider (LHC) [105] at CERN. The LHC extends the frontiers of particle physics by providing previously unreached high energy and luminosity. Bunches of up to  $10^{11}$  protons with energies up to 14 TeV in the end configuration provide proton-proton collisions with luminosities up to  $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ .



Figure A1: Sketch of the ATLAS detector. ATLAS is constructed as a series of concentric cylinders around the proton-proton interaction point. Reprint from [104].

ATLAS is constructed as a series of concentric cylinders around the proton-proton interaction point. It consists of four major detector parts, each itself made of multiple layers: the Inner Detector, hadron and electromagnetic calorimeters, the Muon Spectrometer and two magnet systems. The Inner Detector precisely tracks impinging charged particles using silicon pixel detectors and transition-radiation trackers based on straw drift tubes to reconstruct the particle vertices. The calorimeters measure the energy of easily stoppable particles such as electrons, photons and hadrons. The Muon Spectrometer measures the highly penetrating muons. To measure momenta via the magnetic bending of charged particles, all detectors are immersed in a 2 T magnetic field provided by two magnet systems. A sketch of the detector system is depicted in figure A1.

## Production of $\mathbf{B}_s^0$ at the LHC

The production of  $B_s^0$  mesons is driven by the strong force and proceeds in two separate steps. b-quark/antiquark pairs are produced in proton-proton collisions by elementary quark or gluon processes. At the so-called hadronization stage  $b\bar{b}$ -pairs separate and then bound hadrons are created. This study focuses on the the decay  $B_s^0 \rightarrow J/\psi \phi$ , for which the weak force is responsible. This decay branch occurs via  $b \rightarrow c\bar{c}s$  transitions. The  $c\bar{c}$ and  $s\bar{s}$  pairs form the particles  $J/\psi$  and  $\phi$ , respectively.



Figure A2: Feynman diagram of a  $B_s^0$  meson decaying into a  $J/\psi$  and a  $\phi$  meson.

The ATLAS detector can observe decays involving charged particles.  $B_s^0$  mesons can therefore be detected via a vertex reconstruction of the charged secondary decay product tracks from each combination of the  $J/\psi \rightarrow \mu^-\mu^+$  and  $\phi \rightarrow K^+K^-$  in the  $B_s^0 \rightarrow$  $J/\psi(\mu^-\mu^+)\phi(K^+K^-)$  decay channels. The two muon tracks are constrained to the PDG average  $J/\psi$  mass of 3096.92 MeV [106]. These quadrupulets of tracks are from now on assumed to originate from the desired decay channel and used for the construction of a  $B_s^0$  four-vector in order to obtain its invariant mass. A reduced dataset of the full 2011-12 campaign is used.

## Muon reconstruction and $J/\Psi$ selection

The first step of the  $B_s^0$  analysis is the reconstruction of  $J/\psi$  mesons in the decay branch  $J/\psi \rightarrow \mu^-\mu^+$ . Every detected muon has an assigned muon ID. By looping over all presorted events with at least two detected and identified muons in the ATLAS muon chambers one creates a pair of muon tracks of the custom C++-class Lepton which contains the muon's

momentum, energy and flight path from the measurement of the electromagnetic shower in the detector. In this track a Lorentz vector of the root class TLorentzVector is created in cylindrical coordinates with the root function TLorentzVector::SetPtEtaPhiM using the transverse momentum component  $P_t$ , the pseudo-rapidity

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right) = \frac{1}{2}\ln\left(\frac{|\vec{p}| + p_{\parallel}}{|\vec{p}| - p_{\parallel}}\right) \tag{A.1}$$

with  $p_{\parallel}$  the momentum component in direction of the beam line, the azimuthal angle  $\phi$  of the flight path and the muon mass m = 105.7 MeV  $(c \equiv 1)$ :

$$p = \begin{pmatrix} E \\ P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} \sqrt{(\vec{P}_{xyz})^2 - m^2} \\ P_t \cos \phi \\ P_t \sin \phi \\ P_t \sin h \eta \end{pmatrix}$$
(A.2)

Cuts on low quality muons (mu.qual<3 are discarded) and low muon momenta ( $P_t < 3.0 \,\text{GeV}$ ) are applied. Identified muons are categorized in the ATLAS D3PD files with respect to the quality of the reconstruction with a set of predefined selection requirements based on the algorithms used for the reconstruction. The desired muon quality 3 requires the tracked muons to be both tight and combined. Tight muons are reconstructed with a global algorithm plus quality criteria on hits, segments and impact parameters. Besides, combined muons were fitted successfully with a combined track in the muon detector sections as well as in the inner calorimeters, so that the measured muon momentum in the muon spectrometer can be corrected for the energy loss in the calorimeters and combined with the track results from the inner detector.

In a next step, a loop on all muon IDs in one event is implemented to find all muon pairs with an opposite charge. After that, the simple particle track algorithm RecSV [107] finds the secondary vertex, i.e. the point of the  $J/\psi$  decay, by projecting both tracks, which are assumed to be linear next to the decay point, on a plane transverse to the z axis. The intersection point in the two-dimensional plane is calculated. Intersections can always be found (with the exception of parallel tracks) in a two-dimensional plane. Generally, this is not valid in the three-dimensional space. The resulting coordinates of the intersection of the secondary vertex are stored in the 3D-vector  $\overrightarrow{SV}$ . All track parameters are relative to the reconstructed primary vertex  $\overrightarrow{PV} = (0, 0, 0)$  which marks the place of the pp-collision.  $\overrightarrow{PV}$  expressed in ATLAS detector coordinates differs from zero and varies event-by-event. The used J/ $\psi$  reconstruction algorithm can be seen in the following box:

```
if(mu_Muid_n > 1) { // more than one muon in event
1
    for (int jj=0;jj<mu_Muid_n;jj++){</pre>
2
      Lepton mu1, mu2; // setting up two muon containers
3
      SetMuon(jj,mu1); // set Lorentz vector for first muon
4
      if (mu1.qual<3) continue;
5
      Track mutrk1, mutrk2; // setting up two tracks
6
7
      mutrk1.SetTrackFromLepton(mu1);
8
9
      for(int ii=jj+1;ii<mu_Muid_n;ii++){</pre>
10
        SetMuon(ii,mu2); // set Lorentz vector for second muon
11
        if (mu2.qual<3) continue; // only tight and combined muons
12
        mutrk2.SetTrackFromLepton(mu2);
13
14
        // set Secondary Vertex SV with tracks
15
        TVector3 SV;
16
        RecSV(mutrk1,mutrk2,SV);
17
18
        // muon opposite charge check
19
        if(mu1.id * mu2.id > 0) continue; // only opposite charges
20
        // momentum cut
^{21}
        if(mu1.p.Pt() < 3000. || mu2.p.Pt() < 3000. ) continue;
22
23
        // Secondary vertex reconstruction
24
        if (mutrk1.Get3DDistance(SV) > 0.15) continue;
25
        if (mutrk2.Get3DDistance(SV) > 0.15) continue;
26
27
        // Invariant mass determination
28
        TLorentzVector dimuon = (mu1.p + mu2.p);
29
        double M_jpsi = (mu1.p + mu2.p).M();
30
31
        [... Analysis ...]
32
        }
33
     }
34
35 }
```

Muon reconstruction code.

The invariant mass of the dimuon system can be calculated with the muon four-vectors by using the four-vector momentum conservation:

$$p_{\rm dimuon} = p(\mu^-) + p(\mu^+)$$
 (A.3)

The invariant mass then reads as follows:

$$m^{2} = p_{\text{dimuon}}^{2} = p_{\nu}p^{\nu} = (E_{\mu^{-}} + E_{\mu^{+}})^{2} - |\vec{p}_{\mu^{-}} + \vec{p}_{\mu^{+}}|^{2}$$
(A.4)

The resulting invariant mass spectrum is illustrated in figure A3. Several particles which decay in two opposite charged muons can be seen. Besides the desired J/ $\psi$ , also  $\rho$ ,  $\omega$ ,  $\phi$  (1020),  $\psi$ (2S),  $\Upsilon$ (1S),  $\Upsilon$ (2S),  $\Upsilon$ (3S) and Z<sup>0</sup> are reconstructed.

Invariant dimuon mass distribution



Figure A3: Invariant mass spectrum of the dimuon reconstruction.

A cut on the reconstructed invariant dimuon mass with  $m_{J/\psi}^{\text{rec}} \in [2.9, 3.3]$  GeV is set. Any dimuon with an invariant mass in this mass window is from now on considered as a  $J/\psi$ candidate. There are  $4.96 \times 10^6 J/\psi$  mesons reconstructed. That corresponds to a relative rate of 12.8% compared to other dimuon candidates in the data sample. The mean of the reconstructed  $J/\psi$  mass is  $(3087.2 \pm 0.1)$  MeV and the mass FWHM is about 124 MeV. The measured  $J/\psi$  mass is in a sufficient, but not good agreement with the PDG world average value [106] of 3096.9 MeV. The dimuon spectrum is shown in figure A3. A J/ $\psi$  mass fit is depicted in figure A4.



Figure A4:  $J/\psi$  mass fit in the invariant dimuon mass distribution.

## Estimation of the $\mathbf{B}_s^0$ reconstruction yield

To estimate the number of reconstructed  $B_s^0$  mesons, it is necessary to examine the different decay and production branchings. Based on the number of  $J/\psi$  particles found in the dimuon mass spectrum, described by the reconstruction efficiency  $\varepsilon_{J/\psi}$ , the amount of  $J/\psi$ mesons which actually originate out of the decay of a B hadron  $Br(B \to J/\psi \to \mu^- \mu^+)$  and the production fractions of  $B_s^0$  mesons respectively b-hadronization fractions  $Br(b \to B_s^0)$ must be taken into account. Moreover, the relative branching of the decay  $B_s^0 \to J/\psi \phi$ with respect to the overall branching of  $B_s^0 \to J/\psi X$  and the branching ratio of the kaonic decay of the  $\phi$  mesons have to be considered. The following values are used:

- $\varepsilon_{J/\psi} = 0.128$  (measurement from section 7)
- $Br(B \rightarrow J/\psi \rightarrow \mu^- \mu^+) \approx 0.25$
- $Br(b \to B_s^0) = 0.104$
- $\frac{\operatorname{Br}(\operatorname{B}^0_{\mathrm{s}} \to \mathrm{J}/\psi \phi)}{\operatorname{Br}(\operatorname{B}^0_{\mathrm{s}} \to \mathrm{J}/\psi X)} \approx \frac{1.0 \times 10^{-3}}{3.6 \times 10^{-3}} = 0.274$
- $Br(\phi \rightarrow K^+K^-) = 0.49$

For the estimated number of reconstructed  $\mathbf{B}^0_{\mathrm{s}}$  mesons one obtains:

$$N_{\mathrm{B}^{0}_{\mathrm{s}}}^{\mathrm{theo.}} = \left(\varepsilon_{\mathrm{J}/\psi} \times \mathrm{Br}(\mathrm{B} \to \mathrm{J}/\psi \to \mu^{-}\mu^{+}) \times \mathrm{Br}(\mathrm{b} \to \mathrm{B}^{0}_{\mathrm{s}}) \times \frac{\mathrm{Br}(\mathrm{B}^{0}_{\mathrm{s}} \to \mathrm{J}/\psi \phi)}{\mathrm{Br}(\mathrm{B}^{0}_{\mathrm{s}} \to \mathrm{J}/\psi X)} \right) \times \mathrm{Br}(\phi \to \mathrm{K}^{+}\mathrm{K}^{-}) N_{\mu^{-}\mu^{+}} \approx \boxed{17300}$$
(A.5)

# $\mathbf{B}^0_s$ candidate reconstruction and invariant mass fit

Finally the  $B_s^0 \rightarrow J/\psi(\mu^-\mu^+) \phi(K^+K^-)$  decay is reconstructed by fitting two additional kaon tracks to the known secondary vertex point which is the intersection point of two known muon tracks originating from the the decaying  $J/\psi$  candidate. Due to the very short lifetimes of the  $J/\psi$  and the  $\phi$  meson in the order of  $7 \times 10^{-21}$  s and  $1.5 \times 10^{-22}$  s, respectively, both mesons would only travel a distance of a few fm, a flight length far from the ATLAS detector resolution. Such being the case, the secondary vertex  $\overrightarrow{SV}$  can be assumed as the common decay point of the  $B_s^0$  mother particle. A schematic of the whole reconstruction process is reproduced in figure A5.



Figure A5: Scheme of the  $B_s^0$  decay analysis: Construction of a secondary vertex SV as a common point of origin for all decay products.

Since the  $J/\psi$  natural mass peak width is very small, the dimuon tracks in the fit are constrained to the  $J/\psi$  world average mass of  $M_{PDG}(J/\psi) = 3096.916 \pm 0.011 \text{ MeV}$ :

$$m_{\rm B_s^o}^{\rm constrained} = m_{\rm B_s^o} - m_{\mu^-\mu^+} + M_{\rm PDG}(J/\psi)$$
 (A.6)

Figure A6 shows the mass of the reconstructed  $B_s^0$  mesons versus the mass of the J/ $\psi$  mesons from the dimuon reconstruction.



**Figure A6:** Mass of the reconstructed  $B_s^0$  mesons versus the mass of the  $J/\psi$  mesons from the dimuon reconstruction. Since the  $J/\psi$  natural mass peak width is very small, the  $B_s^0$  mass can be constrained to the literature  $J/\psi$  mass to avoid unwanted resolution effects in the  $B_s^0$  mass spectrum.

This constraint improves the  $B_s^0$  mass resolution and corrects the  $J/\psi$  mass shift that is shown in the  $J/\psi$  fit in figure A4. A loop over all charged hadronic jets and its tracks is carried out under kaon hypothesis within the dimuon reconstruction loop. As a consequence, the four-vectors are filled for pairs of oppositely charged tracks assuming the PDG kaon mass. Then the two-kaon track vertices are checked on whether they originate from the secondary vertex point set up by the  $J/\psi$  reconstruction loop. Due to the fact, that the invariant mass of the  $\phi$  (1020) is near the kinematic threshold of the dikaon reconstruction, the phase-space volume is very small and therefore the angle between the two particles must be very small as well. Moreover, kaons undergo multiple scattering processes in the inner detector parts, so that the error of the track fit is quite larger than the one of the muon track fit. To guarantee a sufficient  $\phi$  reconstruction, kaon tracks are allowed to have a maximum deviation with regards to the secondary vertex point  $\overrightarrow{SV}$  set by the  $J/\psi$  reconstruction. That acceptance value for the maximum distance of the tracks at the intersection point is determined to be 0.30 mm. The kaon reconstruction code scheme is presented in the following:

```
1 [... Muon reconstruction loop ...] {
2 // loop over jets
3 for (int ijt=0; ijt<jet_AntiKt4TopoEM_n; ijt++) {
</pre>
```

```
int ntrk = (*jet_AntiKt4TopoEM_trk_n)[ijt];
4
      // loop over tracks in jets
5
      for (int itr=0; itr<ntrk; itr++){</pre>
6
         // initialize tracks
7
         Track tk1, tk2;
8
         // set first track under kaon hypothesis
9
         SetTrack(itr,ijt,MKAON,tk1);
10
         for (int itr2=itr+1; itr2<ntrk; itr2++) {</pre>
11
            // set second kaon
12
            SetTrack(itr2,ijt,MKAON,tk2);
13
            // kaon charge check
14
            if(tk1.fQ * tk2.fQ > 0.0) continue;
15
16
            // kaon vertex check
            double kaonSVdist = 0.35;
17
            if (tk1.Get3DDistance(SV)>kaonSVdist) continue;
18
            if (tk2.Get3DDistance(SV)>kaonSVdist) continue;
19
            // create Lorentz vectors for checks and fillings
20
            TLorentzVector dikaon = (tk1.p + tk2.p);
21
            TLorentzVector BOs_meson = dikaon + dimuon;
22
23
            [... Filling root tree ...]
24
          }
25
        }
26
     }
27
  }
^{28}
```

Kaon reconstruction code.

The invariant mass of the  $B_s^0$  four-vector is calculated again and filled into a histogram, conditional upon the gate on the measured  $J/\psi$  peak, an estimated  $\phi$  mass window of [1005,1035] MeV, and a cut on the  $B_s^0$  flight pathlength  $l_{3D} \stackrel{!}{>} 0.2 \text{ mm}$ . The path length in the laboratory system is given by:

$$l_{3D}^{\text{lab}} = v\gamma\tau_0 = \beta\gamma \ c\tau_0 \qquad \qquad \beta\gamma = \frac{p}{m_0c} \tag{A.7}$$

If  $p_t = 30 \text{ MeV}$  is considered for a  $B_s^0$  meson, then the assumed momentum results in a boost of  $\beta \gamma \approx 6$  (PDG  $c\tau_{B_s^0} = 441 \,\mu\text{m}$ ) and therefore a flight path  $l_{3D} \approx 2.6 \,\text{mm}$ . With a cut on the first 0.2 mm flight path, mainly prompt and background decays are discarded and the signal-to-background ratio improves. The final invariant mass spectrum is depicted in figure A7. A Gaussian mass fit with a linear background subtraction is applied. A total



Figure A7: Invariant mass distribution of the  $B_s^0$  meson. A linear background subtracted Gaussian fit was applied with a costom-written root macro.

number of 9118  $\pm$  95 (stat.) signal  $B^0_s$  decays are observed in the measurement, with a fitted  $B^0_s$  mass of

$$m_{\rm B^0} = 5365.7 \pm 0.7 \,({\rm stat.}) \,{\rm MeV}$$

Initially, the  $\phi$  meson can not be seen in the K<sup>+</sup>K<sup>-</sup> reconstruction mass spectrum. Subsequent cuts on the B<sup>0</sup><sub>s</sub> mass peak deliver a clearly visible  $\phi$  peak in the dikaon spectrum, as depicted in figure A8. A linear background subtracted Gaussian fit gives a mass of  $m_{\phi} = 1020.01 \pm 0.10$  (stat.) MeV.

## $\mathbf{B}_{s}^{0}$ lifetime measurement

With t the flight time of the  $B_s^0$  particle in the laboratory system, the Lorentz factor  $\gamma$  and the eigentime of the flight in the particle rest frame  $\tau$ , one obtains the following expression for the proper decay time for each  $B_s^0$  meson candidate:

$$\tau = \frac{t}{\gamma} = \frac{l_{3D}}{\gamma v} = \frac{l_{3D}}{\gamma \beta c} = \frac{l_{3D}}{\gamma \beta c} = \frac{l_{3D}m}{P_{3D}c} = \frac{l_{2D}/\sin\theta}{c} \frac{m}{P_t/\sin\Theta} = \frac{l_{2D}m_{\rm PDG}}{cP_t}$$
(A.8)


Figure A8:  $\phi$  mass fit.

 $l_{3D}$  and  $l_{2D}$  are the two- respectively three-dimensional distances between the primary vertex at  $\overrightarrow{PV} = (0, 0, 0)$  and the secondary vertex  $\overrightarrow{SV}$ .  $\theta$  is the polar angle of the decay point respective to the z-axis of the ATLAS coordinate system in direction of the proton beam line.  $P_t$  is the transverse component of the particle momentum  $P_{3D}$  while m is the invariant mass (compare figure A9).



**Figure A9:** Construction of  $l_{2D}$  with  $l_{3D}$  and  $\theta$  in respect to the *z* coordinate.

Depending on the relative position of the secondary vertex to the primary vertex  $\overrightarrow{PV}$ , a positive or negative sign has to be assigned to the decay time  $\tau$ . If the reconstructed decay point at the secondary vertex lies behind the primary vertex,  $\tau$  becomes negative, otherwise it is positive. This convention for the flight time can be expressed with a scalar

product:

$$\langle \overrightarrow{SV} - \overrightarrow{PV}, \overrightarrow{P}_{3D} \rangle > 0$$
 (A.9)

In order to benefit from the far better determined transverse momentum, this study uses the scalar product of the two-dimensional projections:

$$\langle \vec{l}_{2D}, \vec{P}_t \rangle \begin{cases} > 0 & \text{for } \vec{l}_{2D} \text{ and } \vec{P}_t \implies \\ < 0 & \text{for } \vec{l}_{2D} \text{ and } \vec{P}_t \implies \end{cases}$$
(A.10)

 $\vec{l}_{2D}$  and  $\vec{P}_t$  can be easily constructed in 2D cylindrical coordinates using the azimuthal angle  $\varphi$  and either the vector magnitudes  $l_{2D}$  or  $P_t$ . Therefore, every flight time resulting out of a real decay carries a positive sign. One has to allow negative signs in order to quantify the detector response of the vertex reconstruction. That response is given by a Gaussian distribution around the mean value  $\tau = 0$ :

$$\mathcal{G}(t,0,\sigma) = C \, e^{-t^2/2\sigma^2} \tag{A.11}$$

The signal function S(t) consists of two components: The prompt part is formed of  $B_s^0$  particles which decay instantly after hadronization at or near to the primary vertex  $\overrightarrow{PV}$ . It can be expressed as a delta distribution at  $t = \tau = 0$ . The second component behaves exponentially  $\propto \exp(-t/\bar{\tau})$  and is caused by all  $B_s^0$  in-flight decays.  $\bar{\tau}$  is the mean  $B_s^0$  lifetime. The signal function can be written in the following form:

$$\mathcal{S}(t) = C_{\text{prompt}} \,\delta(t) + C_{\text{exp}} \,e^{-t/\bar{\tau}} \,\Theta(t) \qquad \Theta(t) = \begin{cases} 1, & \text{if } t > 0\\ 0, & \text{if } t < 0 \end{cases}$$
(A.12)

The step-function  $\Theta(t)$  assures that the exponential decay component becomes only valid for positively signed flight times. The complete fit function  $\mathcal{F}(t)$  is then the convolution of the signal function and the Gaussian detector resolution. One gets:

$$\mathcal{F}(t) = (\mathcal{S} \circ \mathcal{G})(t)$$

$$= \int_{-\infty}^{+\infty} \left( C_{\text{prompt}} \delta(s) + C_{\exp} e^{-t/\bar{\tau}} \Theta(s) \right) \cdot \exp\left(\frac{(t-s)^2}{2\sigma^2}\right) \mathrm{d}s$$

$$\dots = N_{\text{prompt}} \exp\left(\frac{-t^2}{2\sigma^2}\right) + N_{\exp} \sigma \sqrt{\frac{\pi}{2}} \exp\left(\frac{\sigma^2 - 2t\bar{\tau}}{2\bar{\tau}^2}\right) \cdot \operatorname{Erfc}\left(\frac{\sigma^2 - t\bar{\tau}}{\sqrt{2}\sigma\bar{\tau}}\right)$$
(A.13)



**Figure A10:** Fitted flight time of  $B_s^0$  mesons.

The Erfc function is the complementary error function, defined as

$$\operatorname{Erfc}(x) = 1 - \operatorname{Erf}(x) = 1 - \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^{2}} dt$$
 (A.14)

In this study, the signal function is convoluted with a double Gaussian to describe detector resolution effects. One gets with the convolution parameter  $\zeta$ :

$$\tilde{\mathcal{F}}(t) = \mathcal{F}(t)\Big|_{\sigma_1} + \zeta \cdot \mathcal{F}(t)\Big|_{\sigma_2}$$
(A.15)

The fit function has six parameters, the scale parameters  $N_{\text{exp}}$  and  $N_{\text{prompt}}$ , the detector resolution  $\sigma_{\text{exp}}$  together with  $\sigma_{\text{prompt}}$ , the convolution parameter  $\zeta$  and the mean decay time  $\bar{\tau}$ . The full calculation of the fit function  $\mathcal{F}(t)$  is carried out in [108]. The fit is implemented as a C++ macro [107] and is applied to a root histogram with cuts on the J/ $\psi$  ([2950, 3250] MeV),  $\phi$  ([1005, 1035] MeV) and B<sup>0</sup><sub>s</sub> constrained mass ([5330, 5405] MeV). The fit is shown in figure A10. The B<sup>0</sup><sub>s</sub> lifetime is then given by

$$\bar{\tau}_{\rm B_s^0} = (1.344 \pm 0.017 \text{ (stat.)}) \,\mathrm{ps}$$

#### Summary

In this study the mass and lifetime of the  $B_s^0$  meson in the decay branch  $B_s^0 \rightarrow J/\psi(\rightarrow \mu^-\mu^+) \phi(\rightarrow K^+K^-)$  were investigated. The evaluated  $B_s^0$  lifetime is  $1.344 \pm 0.017$  (stat.) ps. A total number of  $9118 \pm 95$  (stat.) signal  $B_s^0$  decays is observed in the measurement, with a fitted  $B_s^0$  mass of  $5365.7 \pm 0.7$  (stat.) MeV.

The extracted  $B_s^0$  meson mass is consistent with the world average Particle Data Group values [106] within the determined errors. The measured lifetime reproduces the value of the PDG evaluation as well as most of the PDG cited experiments which were used to create the PDG Average. A comparison is given in table 20. The evaluated masses of the decay products  $J/\psi$  and  $\phi$  are not within the errors of the PDG data. The mass of the  $J/\psi$  mass peak is shifted by 4 MeV, but this effect can be minimized by the usage of constrained mass values in the  $B_s^0$  mass determination.

The number of reconstructed  $\phi$  mesons under a  $B_s^0$  mass cut is lower than the number of reconstructed  $B_s^0$  candidates. This is expected due to the fact that the  $\phi \to K^+K^-$  decay has to be reconstructed near the kinematic threshold. Reconstruction uncertainties arise especially from the choice of maximum distances in the intersection point search with the vertex reconstruction algorithm and the choice of hard or soft mass windows. The reached  $B_s^0$  reconstruction yield  $N_{B_s^0}^{measured}/N_{B_s^0}^{predicted}$  is 53%.

	*	0
	This study	PDG Average value
$B_s^0$ Mass [MeV] $B_s^0$ Lifetime [ps]	$5365.7 \pm 0.7 (\text{stat.})$ $1.344 \pm 0,017 (\text{stat.})$	$5366.7 \pm 0.4$ 1.429 ± 0.088 PDG Evaluation 1.517 ± 0.026 PDG Average
$J/\psi$ Mass [MeV] $\phi$ Mass [MeV]	$3087.2 \pm 0.1 (\text{stat.})$ $1020.01 \pm 0.10 (\text{stat.})$	$3096.916 \pm 0.011$ PDG Average $1019.455 \pm 0.020$ PDG Average

Table 20: Comparison of measured values with PDG average masses.

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# Eidesstattliche Erklärung

Hiermit bestätige ich, dass ich meine Masterarbeit selbstständig angefertigt und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

Köln, den 5. Juni 2014