Classification of nuclear reactions around Coulomb barrier

- Peripheral collisions
- Grazing collisions
- Distant collisions

- Elastic scattering
direct reactions

- Incomplete fusion and
depth inelastic collisions

- Elastic (Rutherford) scattering
  Coulomb excitations
Nuclear reactions

- Coulomb excitation
- Multi-nucleon transfer reaction
- Compound nucleus reaction
Multi-nucleon Transfer

1. Beam
2. Target
3. Multinucleon transfer
4. Evaporation of nucleons
Magnet spectrometer PRISMA

- large solid angle (80 msr)
- large momentum acceptance (+/-10%)
- high mass resolution (1/300)
- high energy resolution (1/1000)

National laboratory Legnaro, Italy (LNL)
Micro Channel Plate (MCP)
- Electron multiplier high gain \(10^6 - 10^8\)
- 10^7 micro channels
- diameter 10 \(\mu\)m

MCP performance
- position resolution \((\leq 1 \text{ mm})\)
- timing \((\leq 400 \text{ ps})\)
- Large area \((80 \times 100 \text{ mm}^2)\)

- 3 grids
- Thin carbon foil \((20 \mu\text{g/cm}^2)\) at -2300 V
\[ \vec{F} = q \vec{v} \times \vec{B} \]

\[ F = qvB = m \frac{v^2}{\rho} \]
PRISMA - MWPPAC
Multi Wire Parallel Plate Avalanche Counter

- Active area 1 m x 13 cm
- Structure with 3 electrodes:
  - centrale cathode (3300 gold coated tungsten wire, 20 μm, 300 μm distance, 500 – 600 V)
  - X-plane (10 sections with 100 wires, 1mm pitch)
  - Y-plane (130 wires, 1 m length, 1 mm pitch)
- Counting gas C₄H₁₀ (Butan) at ~ 7mbar
PRISMA - MWPPAC
Multi Wire Parallel Plate Avalanche Counter

- Gas ionisation
- Electrons and ions are collected at anode and cathode
- High field strength close to wire
- Avalanche effect cause high signal amplitude
- Position resolution (1 mm X, 2 mm Y)
- Timing resolution (300 ps)
PRISMA – ionization chamber (IC)

Ionisation chamber in pulse mode

\[ V_r = \frac{n_o e}{dC} (v^+ + v^-) t \]
PRISMA – IC

Ionisation chamber in pulse mode Frisch grid
PRISMA – IC

- 10 x 4 sections / anode and cathode (10x25 cm²)
- Frisch grid (1000 wire, 100 µm diameter, 1 mm pitch, 1 m length)
- Counting gas CH₄ / CF₄ at 20-100 mbar
- Energy resolution of individual sections
- Particles are completely stopped
- Gas pressure is adapted to different energies and charges of beam like particle
PRISMA – IC

Aligned IC energy spectra

Segment ID

Energy [channels]
PRISMA - observables

1. Time of flight (ToF) – MCP and MWPPAC
2. Trajectory – MCP, MWPPAC and IC
3. Energy and energy loss – IC
Elemental identification – E / ΔE

\[ -\frac{dE}{dx} = 2\pi N_a r_e^2 \frac{Z_a}{A_a} \frac{Z^2}{\beta^2} \left[ \ln \left( \frac{2 m_e^2 v^2 W_{\text{max}}}{I^2} \right) - 2 \beta^2 - \delta - 2 \frac{C}{Z} \right] \]
A over Q – mass charge ratio

\[ A/q = B \times \rho \frac{t}{l} \]

- \( A \) – mass number
- \( q \) – charge state
- \( B \) – magnetic field strength
- \( \rho \) – bending radius
- \( t \) – time of flight
- \( l \) – flight distance
Charge state – charge of single ions

\[ \frac{E}{\rho \beta} \sim q \]

- \( E \) – Energy
- \( q \) – electr. charge state
- \( \rho \) – bending radius
- \( \beta \) – \( v/c \) velocity
Mass after multiplication

\[ \frac{A}{q} \times q = A \]
Final result

- mass and chemical element of reaction products
- angular distribution of reaction products
- velocity of reaction products
AGATA

- Advanced Gamma Tracking Array

- 8 Triple cryostats / 24 capsules

- Full digital electronics

- Online PSA and Tracking

- High resolution position sensitive γ ray spectroscopy

- High count rate capabilities
Gamma Ray Spectra

- Doppler correction needed ($\beta \sim 9\%$)
- Ejectile velocity given by PRISMA
- Recoil velocity calculated
- Gamma direction by AGATA
Final result comparison with reaction theory

- $^{56}\text{Ba}$: $+2p$
- $^{55}\text{Cs}$: $+1p$
- $^{52}\text{Te}$: $-2p$
- $^{53}\text{I}$: $-1p$
- $^{54}\text{Xe}$: $0p$

Response corrected mass yields: 
Original mass yields: 
GRAZING calculation 940 MeV:
Spectrum of $^{134}$Xe
Spectrum of $^{240}\text{U}$
Results

Reaction studies

- reaction mechanism of MNT
- cross sections and comparison with theory

Spectroscopy of heavy reaction product

- Rotational bands and octupole vibration in $^{240}$U

Light and heavy transfer products in $^{136}$Xe + $^{238}$U multinucleon transfer reactions

Spectroscopy of $^{240}$U after multinucleon transfer reactions
B. Birkenbach et al. PRC 92, 044319 (2015)
Results

Spectroscopy of light reaction product

- Nuclear structure on top of the $10^+$ and $7^-$ isomers in $^{134}\text{Xe}$

- High-spin states in $^{137}\text{Ba}$ and $^{135}\text{Xe}$
  - p-n correlations near the $N = 82$ shell closure

- High-spin states and a new spin-trap isomer in $^{133}\text{Xe}$
  - High-spin spectroscopy of $^{132}\text{Xe}$

- Isomers and high-spin structures in the $N=81$ isotones $^{135}\text{Xe}$ and $^{137}\text{Ba}$

- High-spin structure of $^{134}\text{Xe}$
  A. Vogt et al. *PRC* 93, 054325 (2016)

- High-spin structures in $^{132}\text{Xe}$ and $^{133}\text{Xe}$ and evidence for isomers along the $N=79$ isotones
Results

Spectroscopy of light reaction product

- Backbending in $^{131}$Xe in the favoured neg.-parity band
- Description within the shell-model

- High-spin states and new $23/2^+$ spin-trap isomers in $^{133}$Xe and $^{135}$Ba

- High-spin states in $^{136}$Ba and $^{137}$Ba
- p-n correlations near the $N = 82$ shell closure


