Scintillation detectors

- *incoming radiation (charged particle, γ-rays) creates excited states in atoms or molecules.*
- *excited states decay via emission of photons, typically in visible range.*
- *photons are detected and converted into electrical signals*

requirements at scintillation material:

- *high light output*
- *linear conversion: particle energy – number of photons*
- *transparent medium, no self absorption*
- *short life time of excited states -> timing properties*
- *optical quality, light collection at large dimensions*
- *refraction index (close to glass)*

Scintillation detectors

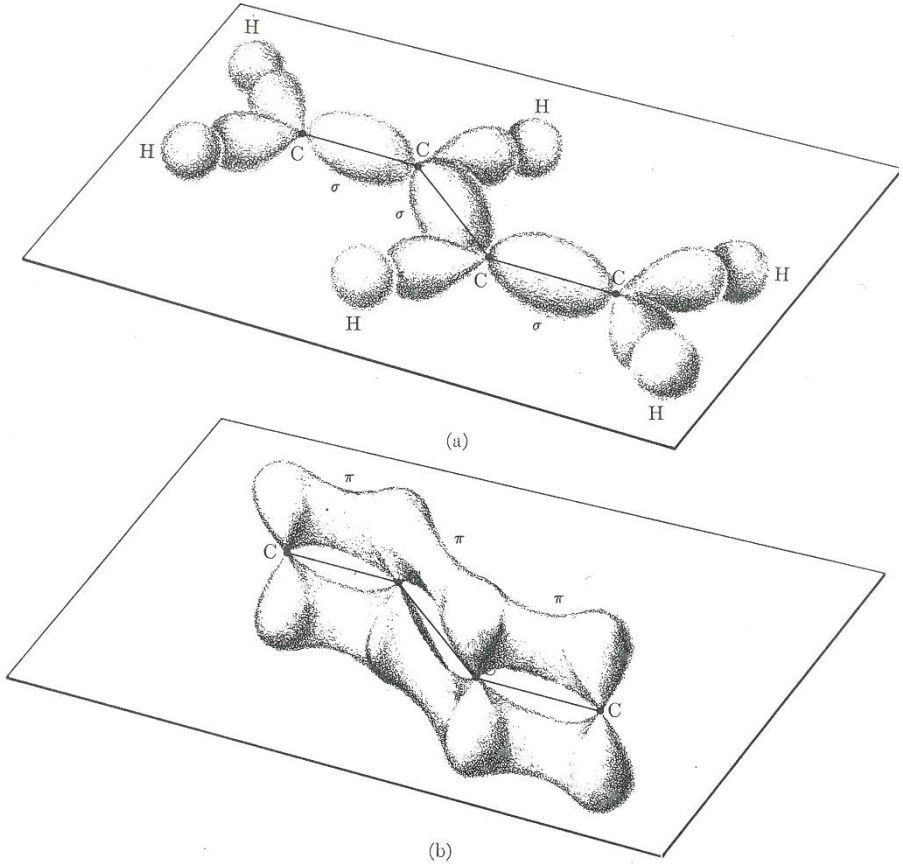


Abb. 5-24. Elektronenverteilung in Butadien. (a) Lokalisierte σ-Bindungen; (b) unlokalisierte π-Bindungen.

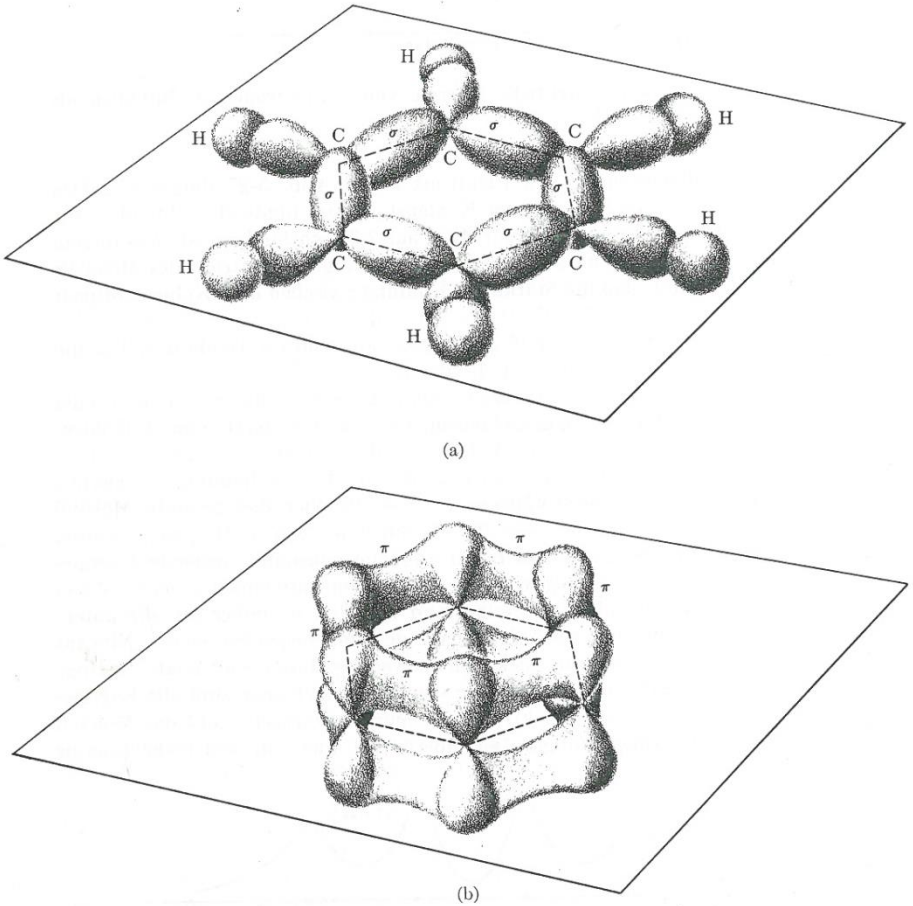


Abb. 5-28. Molekülorbitale für Benzol. (a) Lokalisierte σ-Bindungen; (b) unlokalisierte π-Bindungen.

Scintillation detectors

Organic scintillator:

- *Energy levels of individual molecules, no interactions with neighbour. Material can be solid (powder), fluid, gaseous.*

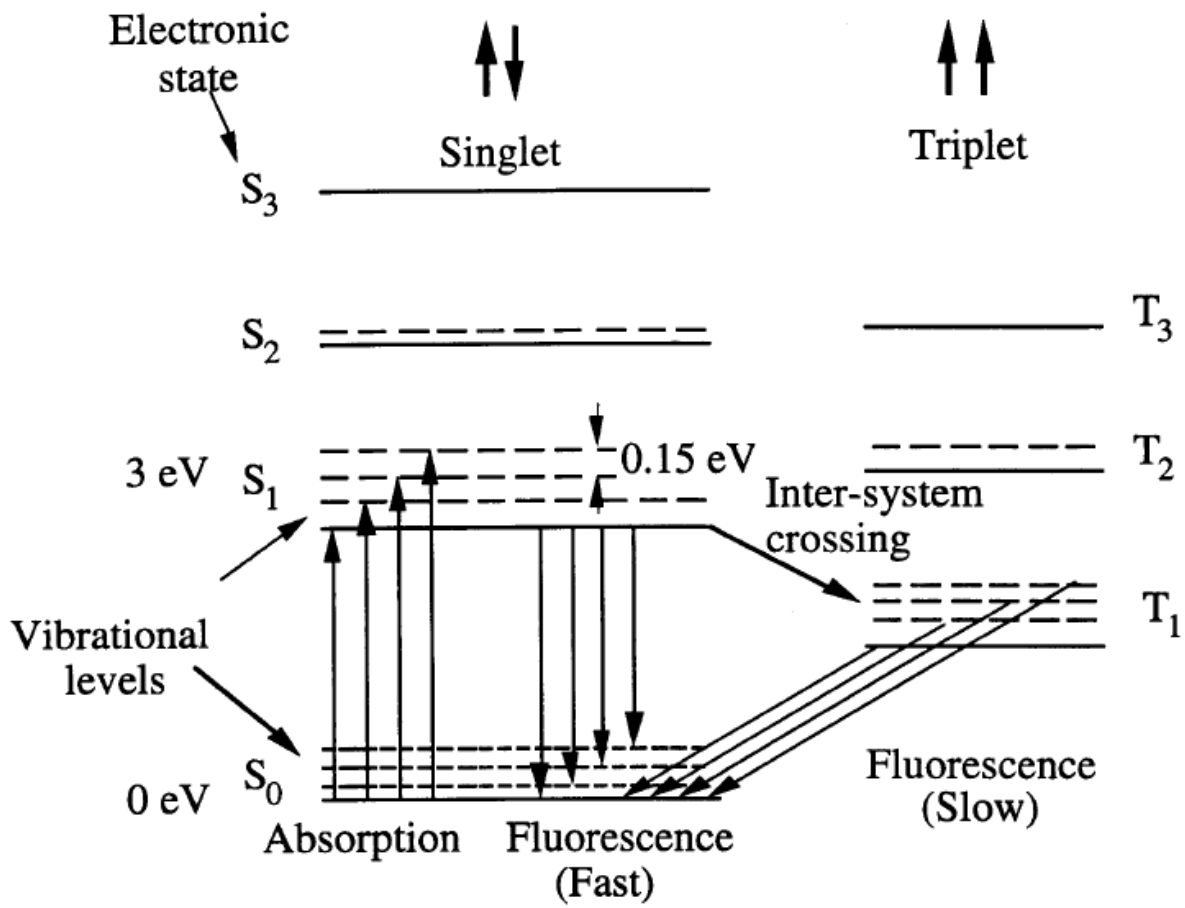
room temperatur electrons in g.s.

- radiation populates states in S_1 band

- radiation less decay in S_1 band head

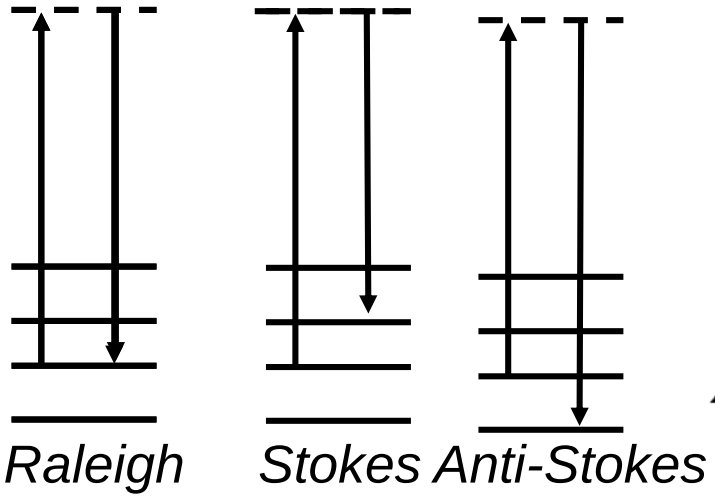
- decay in S_0 band light emission

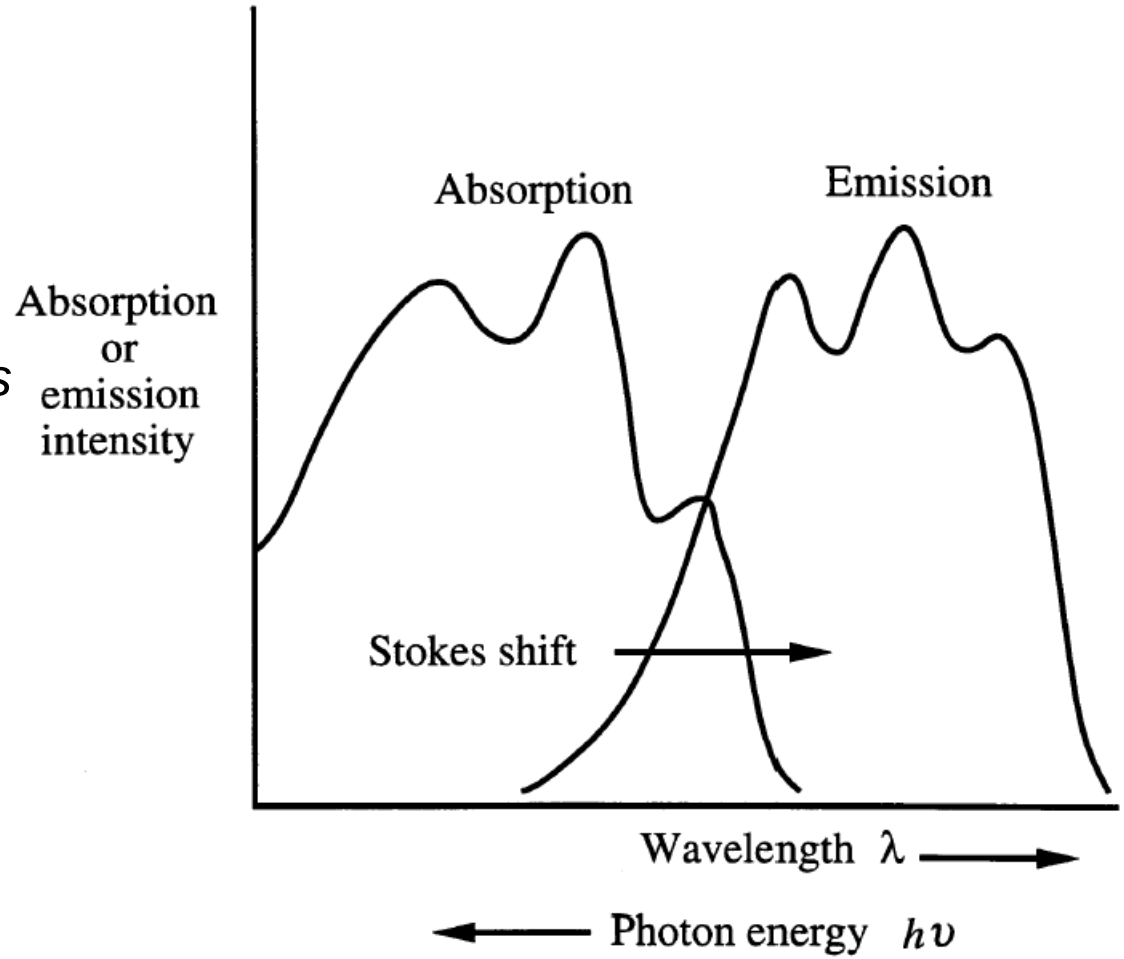
- decays in triplet state slow decays



Scintillation detectors

important: emitted light should not be re-absorbed!



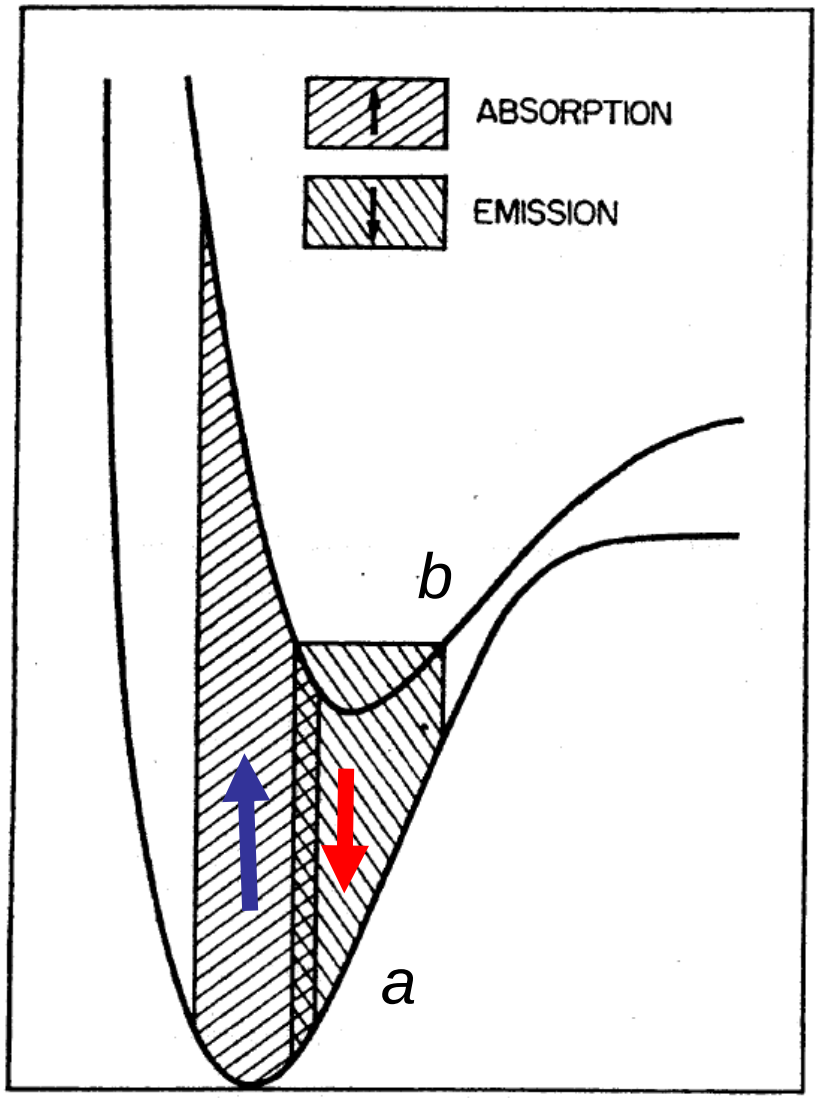


Scintillation detectors

Loss process:
width of absorption- and emission spectrum depends on level density in minimum a and minimum b. Both minima must be sufficiently separated.

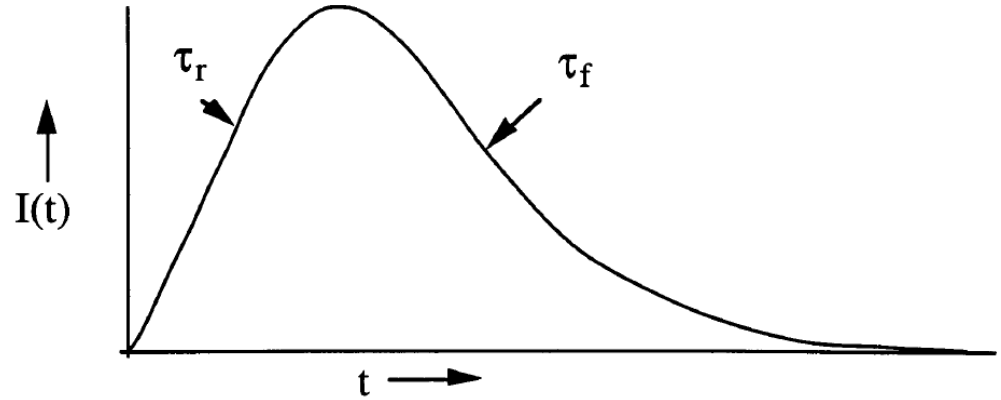
With growing temperature the regions increase and cause more overlap.

⇒reduced light output with increasing temperature



Scintillation detectors

Timing properties
- radiationless decays: 0.2 – 0.4 ns
- fluorescenc S_1 -> S_0 : 1 – 3 ns



$$\text{rise time}: \; I(t) \propto 1 - e^{-t/\tau_{n.r.}}$$

$$\text{decay time}: \; I(t) \propto e^{-t/\tau_f}$$

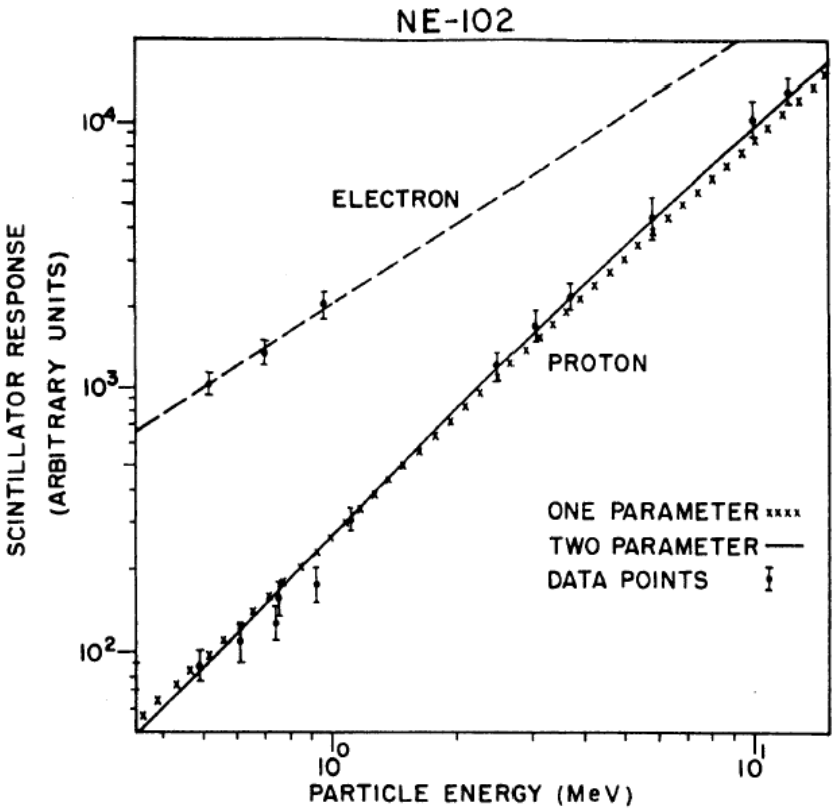
$$\text{puls shape}: \; I(t) = I_0 (e^{-t/\tau_f} - e^{-t/\tau_{n.r.}})$$

Material	State	λ_{max} [nm]	τ_f [ns]	ρ [g/cm^3]	photons/MeV
Anthracene	crystal	447	30	1.25	$1.6 \cdot 10^4$
Pilot U	plastic	391	1.4	1.03	$1.0 \cdot 10^4$
NE104	plastic	406	1.8	1.03	$1.0 \cdot 10^4$
NE102	liquid	425	2.6	1.51	$1.2 \cdot 10^4$

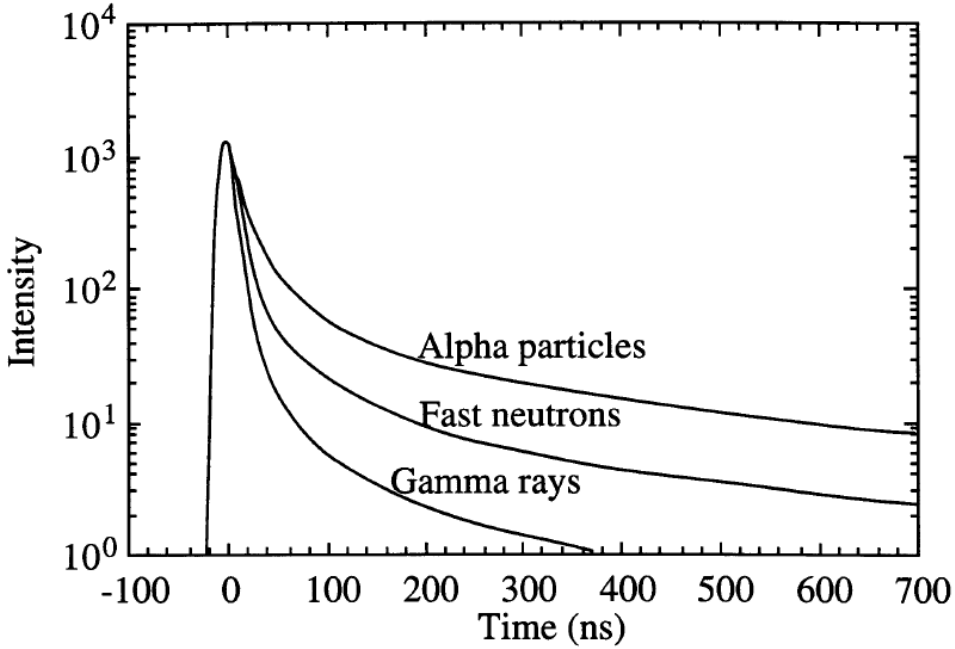
Scintillation detectors

Light yield and decay time depend on ionisation density.

Light yield



Decay time



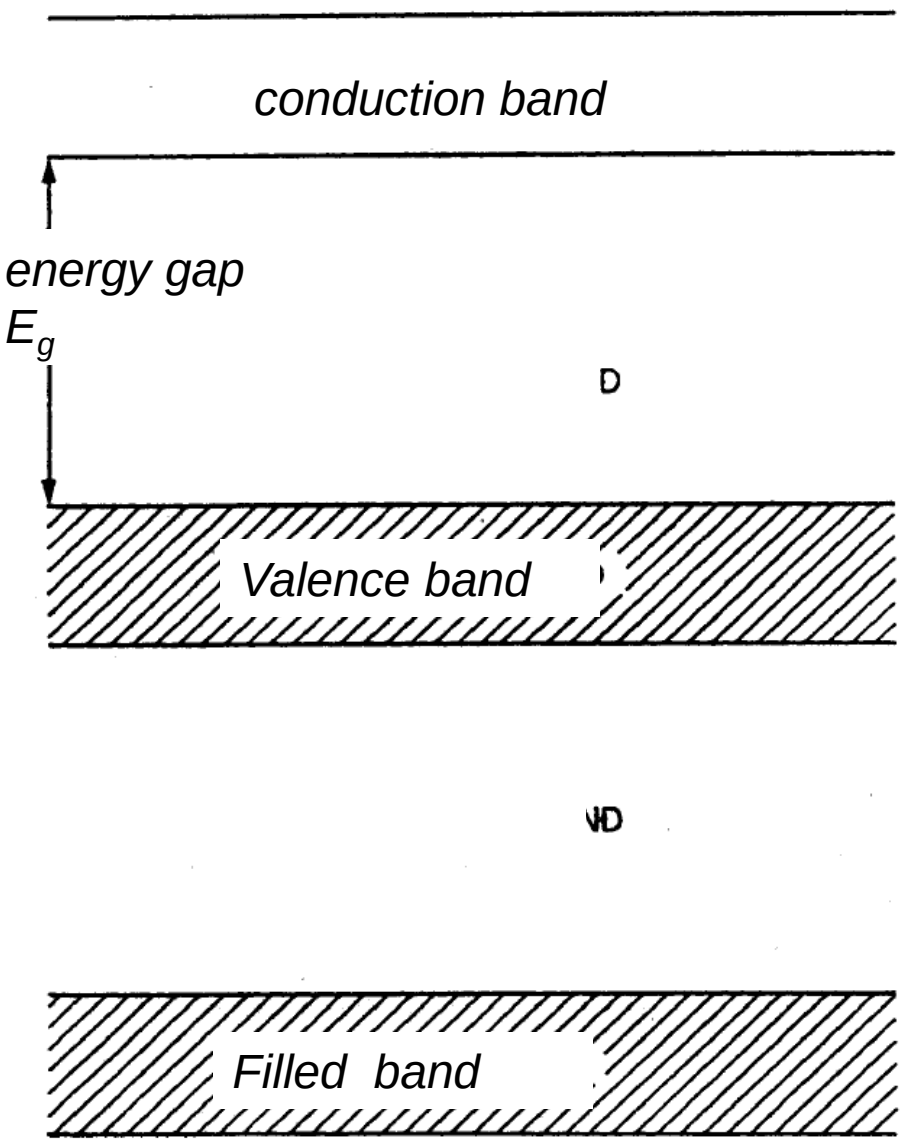
-> effect is used for particle identification!

Scintillation detectors

Anorganic scintillator
- higher Z
- higher density
- higher stopping power
- highest light output

Isolator:
energy gap >> kT , no electrons in conduction band. Radiation excites electrons from valence band into conduction band and creates electron-hole-pairs.

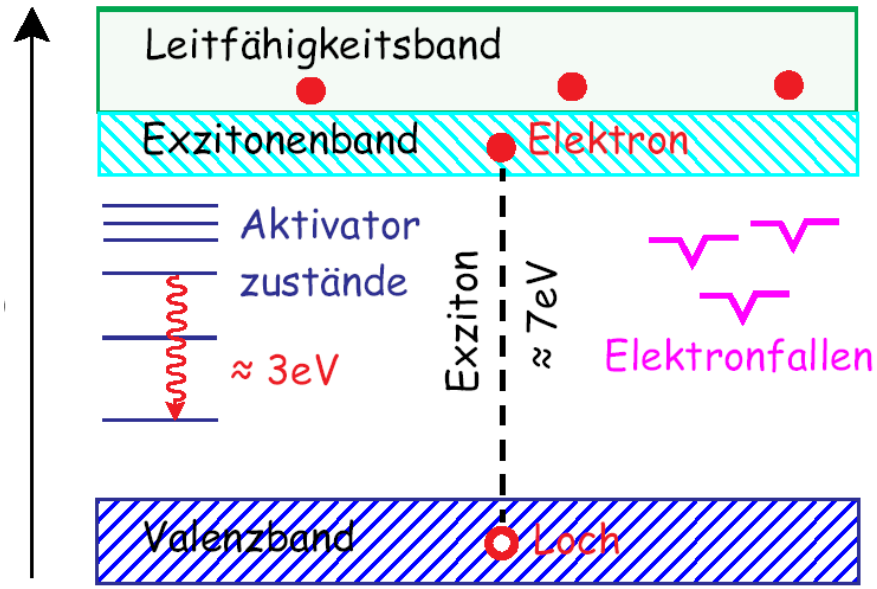
electrons in conduction band and holes in valence band move freely through crystal.



Scintillation detectors

Example: sodium iodid NaJ

- isolator with band gap 7eV
- scintillates in pure state at low temperature
- replace 0.1% of Na atoms by thallium
- moves energy in visible range
- higher light yield
- reduced self absorption
- excitons are created
- excitons move through crystal until absorption by Tl center



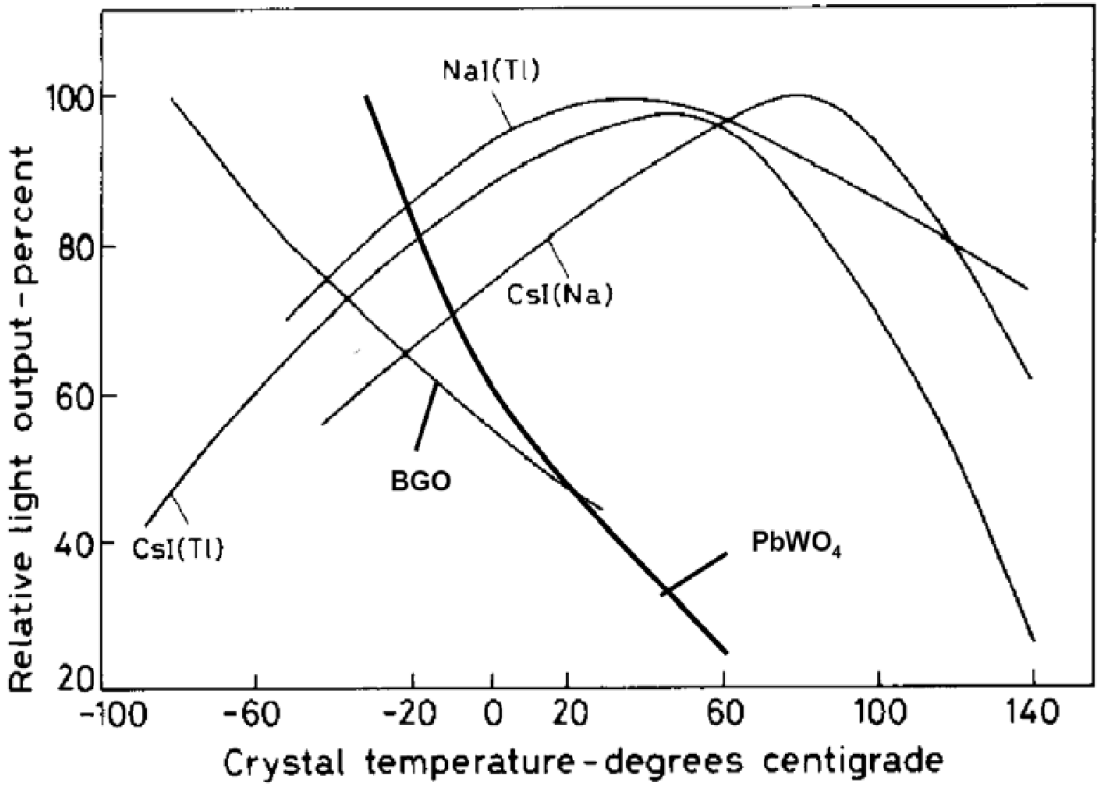
- emission of luminiscence photons (3 eV~400 nm)
- material is transparent in this wave length range

Scintillation detectors

Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)	crystal	540	800	4.51	60,000
CsI (pure)	crystal	315	16	4.51	2,300
CsF	crystal	390	2	4.64	2,500
BaF_2 (slow)	crystal	310	630	4.9	10,000
BaF_2 (fast)	crystal	220	0.8	4.9	1,800
Gd_2SiO_5(Ce)	crystal	440	60	6.71	10,000
$CdWO_4$	crystal	530	15000	7.9	7,000
$CaWO_4$	crystal	430	6000	6.1	6,000
CeF_3	crystal	340	27	6.16	4,400
$PbWO_4$	crystal	460	2, 10, 38	8.2	500

Scintillation detectors

temperature dependence of light yield



Scintillators require:

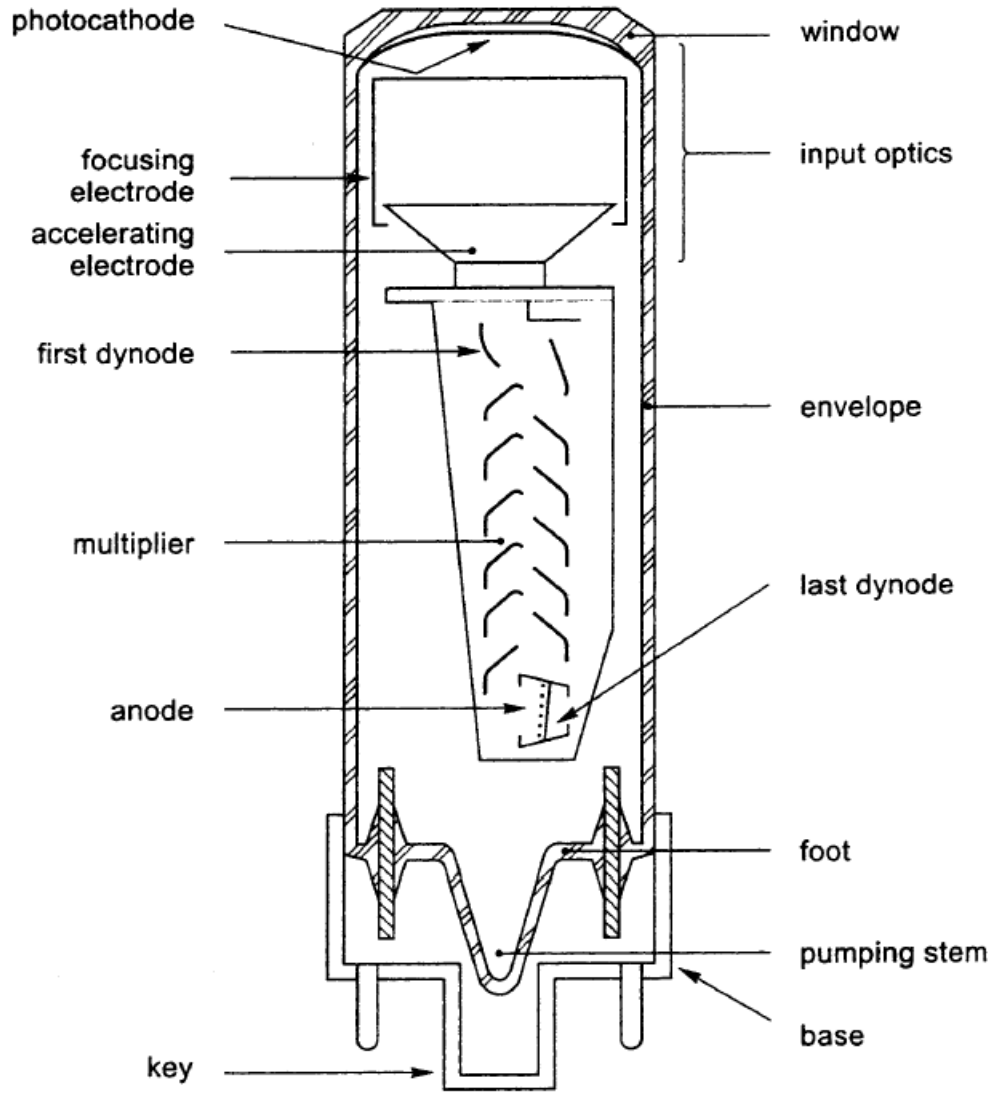
- careful calibration and inspection
- temperature stabilisation

Scintillation detectors

Photo multiplier:
conversion of scintillation light
=> electron signal
quantum efficiency Q.E.

$$\text{Q.E.} = \frac{\#\,\text{emitted photo electrons}}{\#\,\text{incoming photons}}$$

photo cathode	Q.E.	λ_{max}
AgOCs	0.4%	800 nm
BiAgOCs	7%	420 nm
CS_3SbO	21%	390 nm
Na_2KSbCs	22%	380 nm
K_2CsSb	27%	380 nm
Na_2KSb	21%	360nm
KCsRbSb	24%	440 nm
RbCsSb	25%	450 nm
CeTe	18%	200 nm
CsI	15%	135 nm

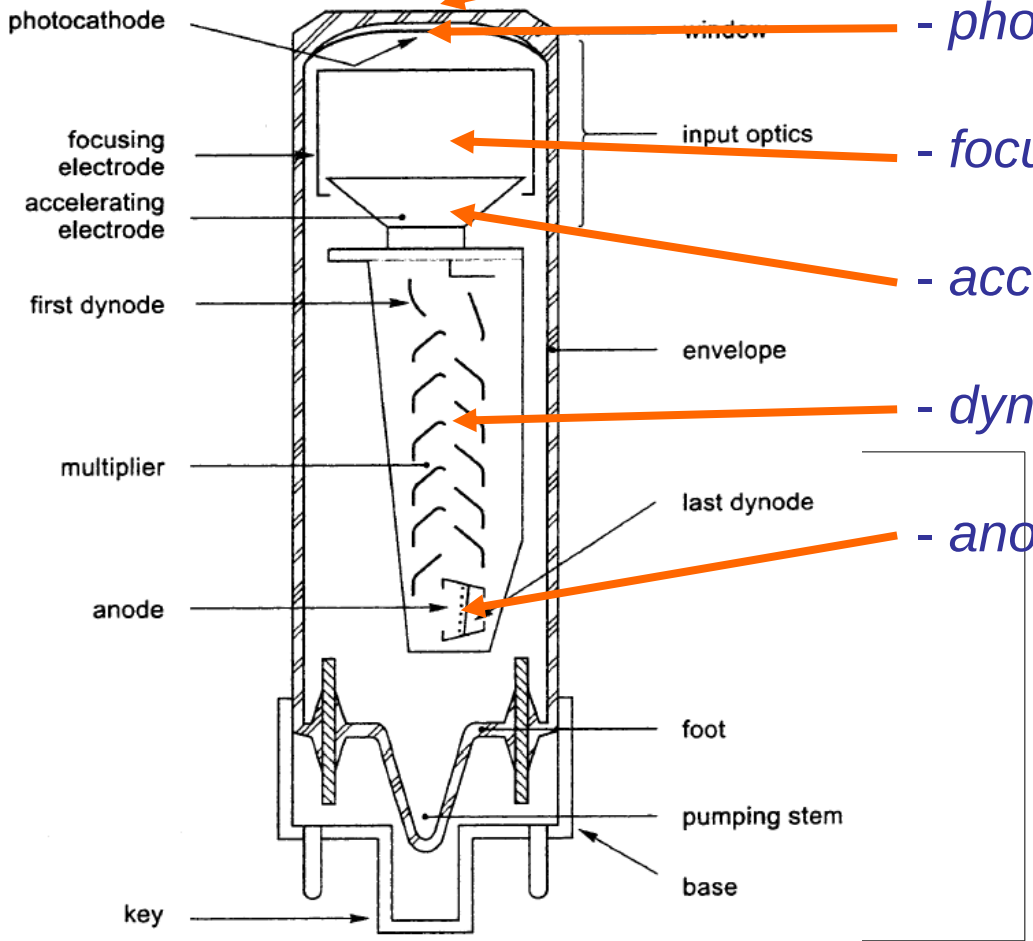


Scintillation detectors

photo multiplier tube

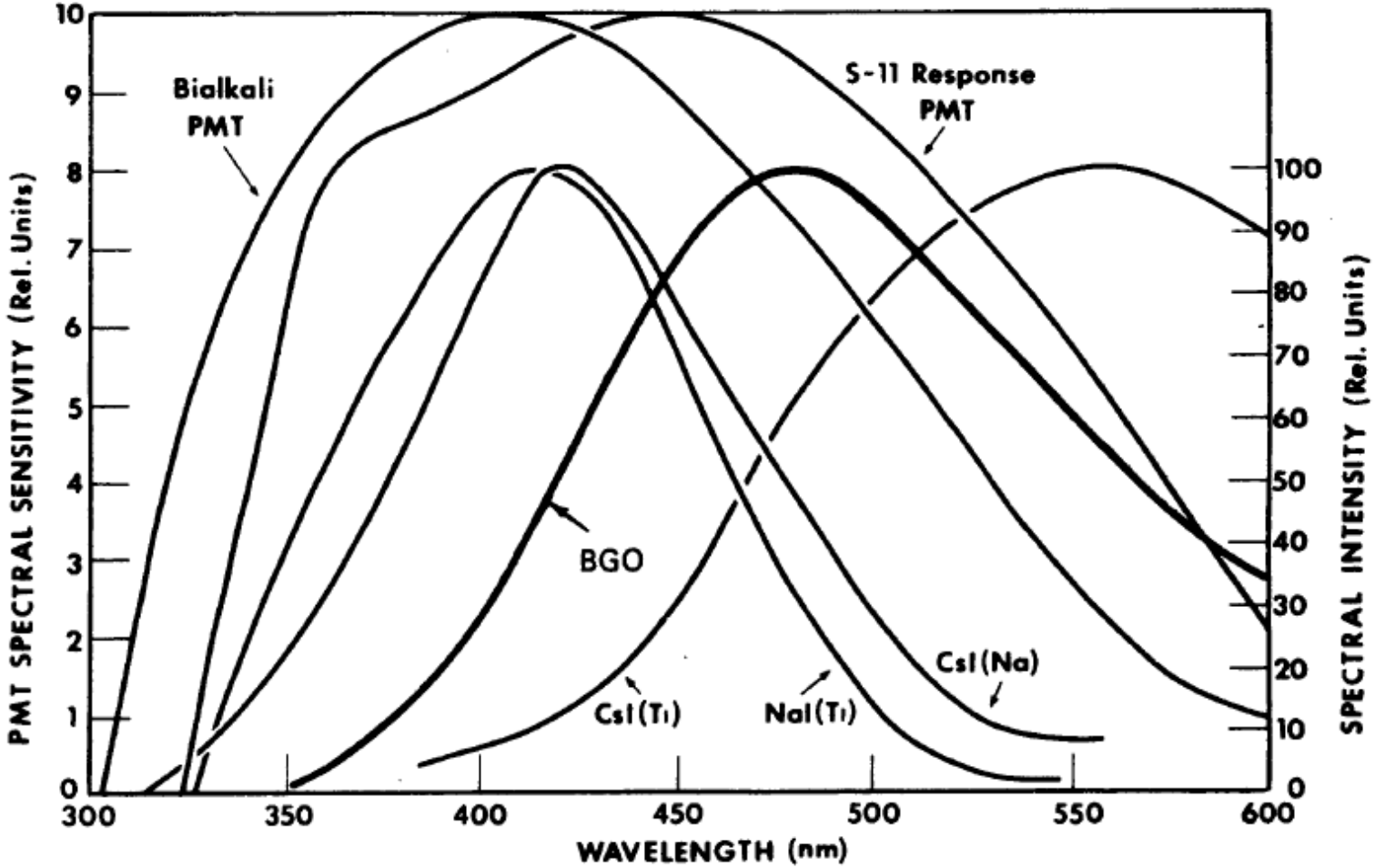
conversion scintillation light
-> electrical signal

- match to detector
- *photo cathode*
- *focusing electrode*
- *accelerating field*
- *dynode structure*
- *anode*



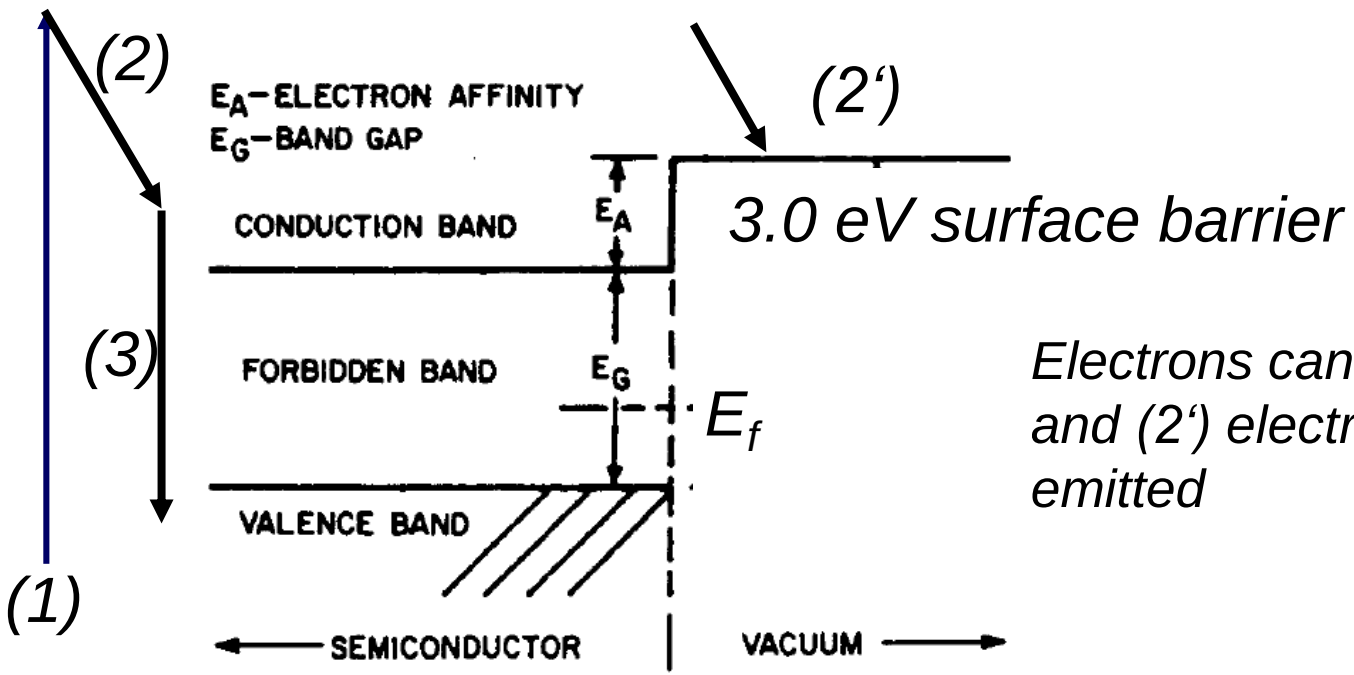
Scintillation detectors

Spectral distribution of different scintillator materials and spectral sensitivity of photo cathodes



Scintillation detectors

Photo cathode: *- low work function for electrons*
- thin layers of semiconductor, antimony alkali compounds
- (1) excitation from incoming photon
- (2) deexcitation via lattice, phonons (~1ps)
- (3) recombination



Electrons can move to surface and (2') electrons above E_A are emitted

Scintillation detectors

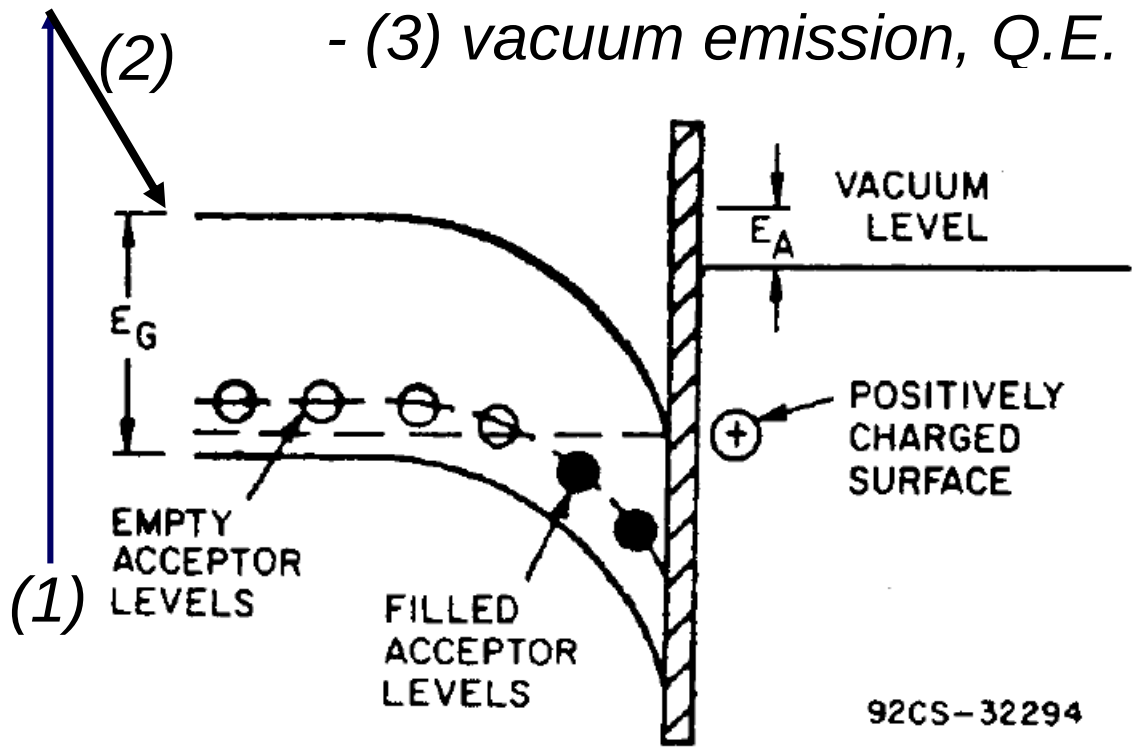
Photo cathode: - thin surface of electro positive material (Cs) onto doped semiconductor (GaP + acceptor)

-> negative electron affinity material

- (1) photon excitation

- (2) deexcitation via phonons (~1ps)

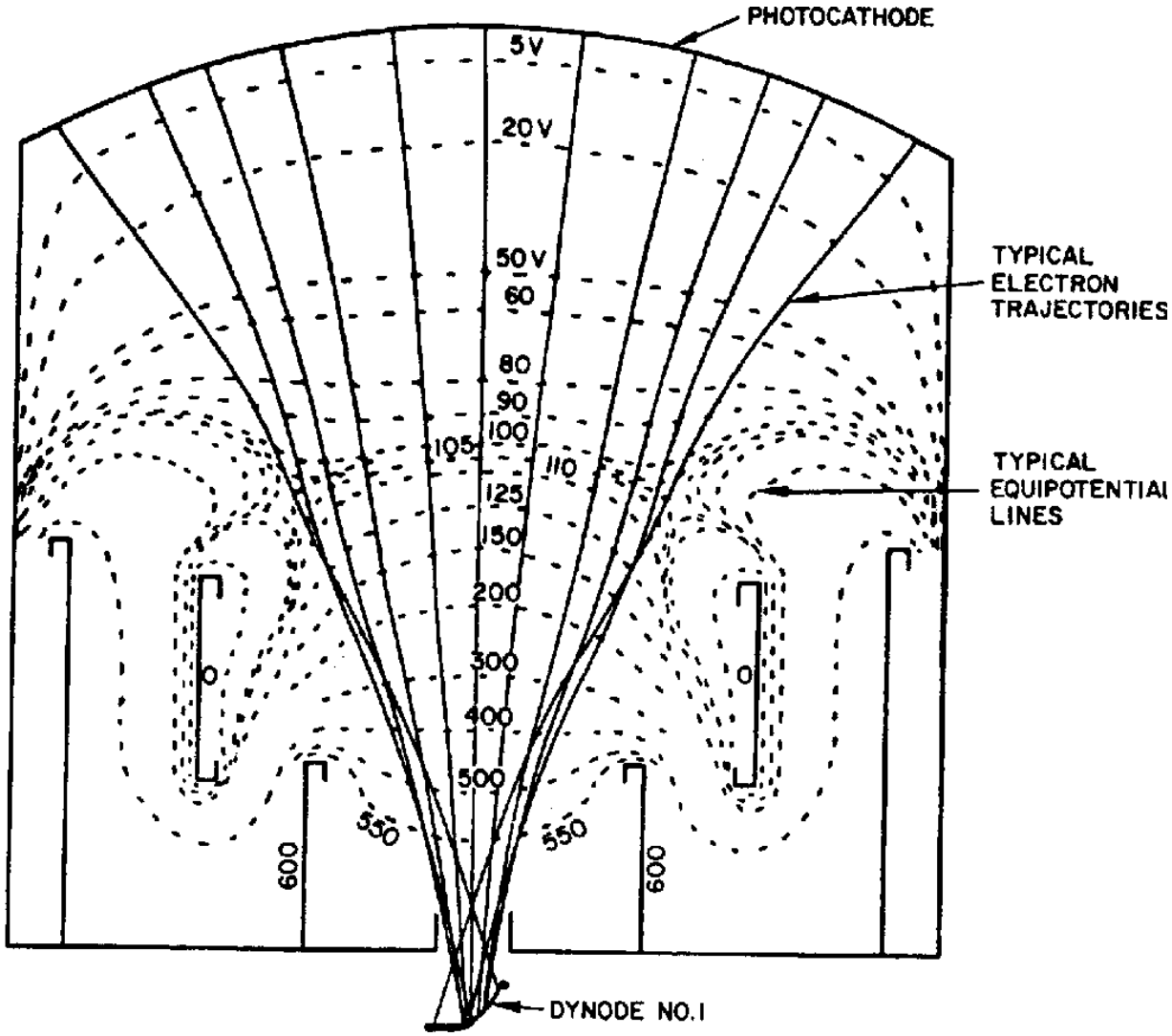
- (3) vacuum emission, Q.E. ~ 80% !!!



- used also for dynode material

Scintillation detectors

Equipotential line and electron trajectory in photo multiplier

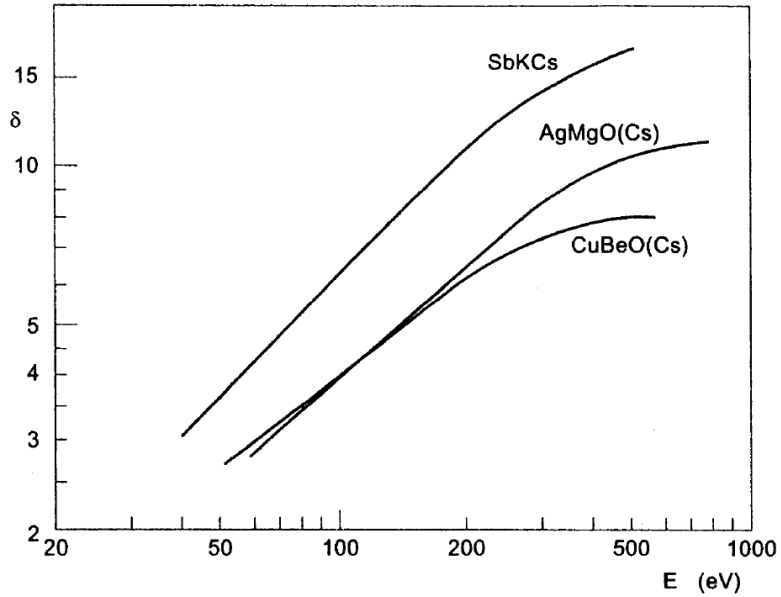


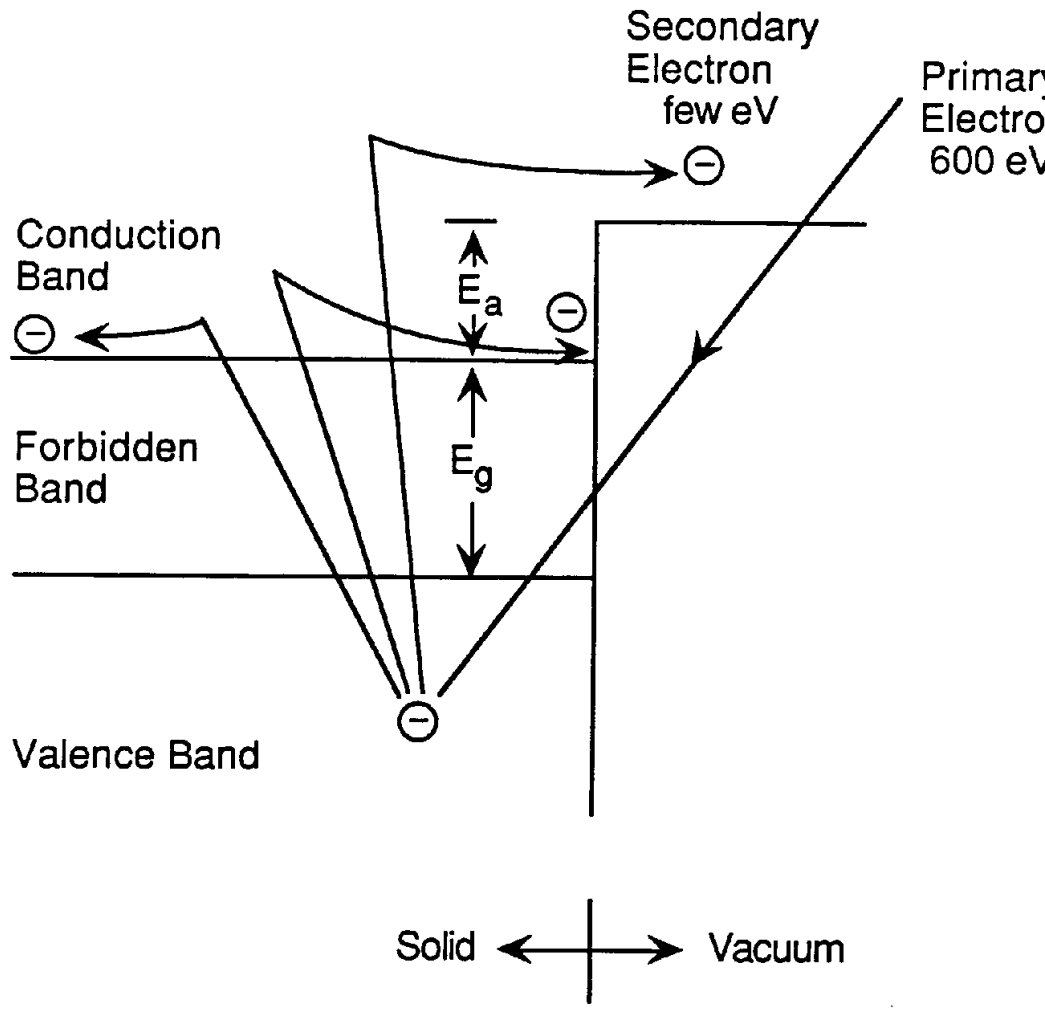
Scintillation detectors

-Secondary multiplication *by dynodes*

- similar process like at photo cathode, incoming particle is electron

-typical materials: BeO(Cs), Cs_3Sb, MgO





Scintillation detectors

Magnetic fields *affect amplification of Photo Multiplier Tube, Properties depend on orientation of B-field.*
-> protection, shielding with μ-metall

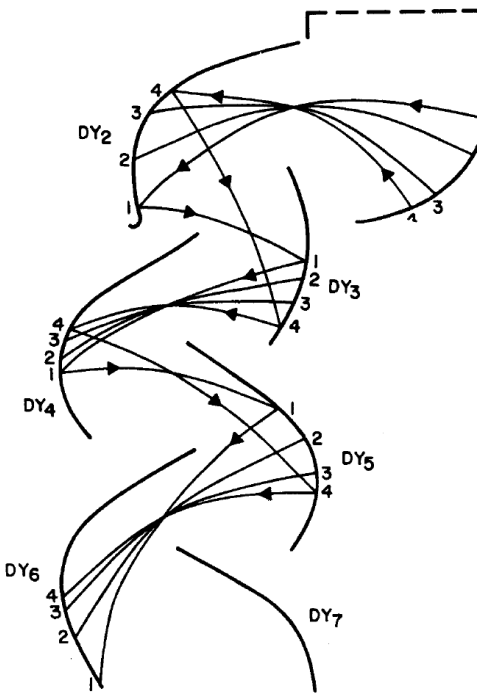
Timing properties *depend on dynode configuration.*

- *typical time from photo cathode to anode ~30 ns*

- *typical rise time ~1.5 –2.0 ns*

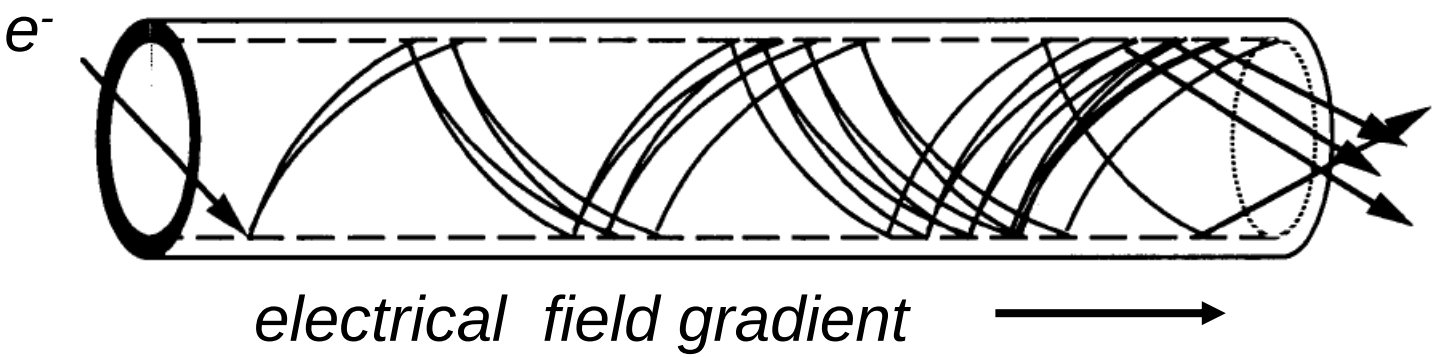
- *two coincident PMTs with ~1500 photo electrons allow a timing resolution of ~200 - 250 ps.*

- *Special dynode structure to minimize broadening.*

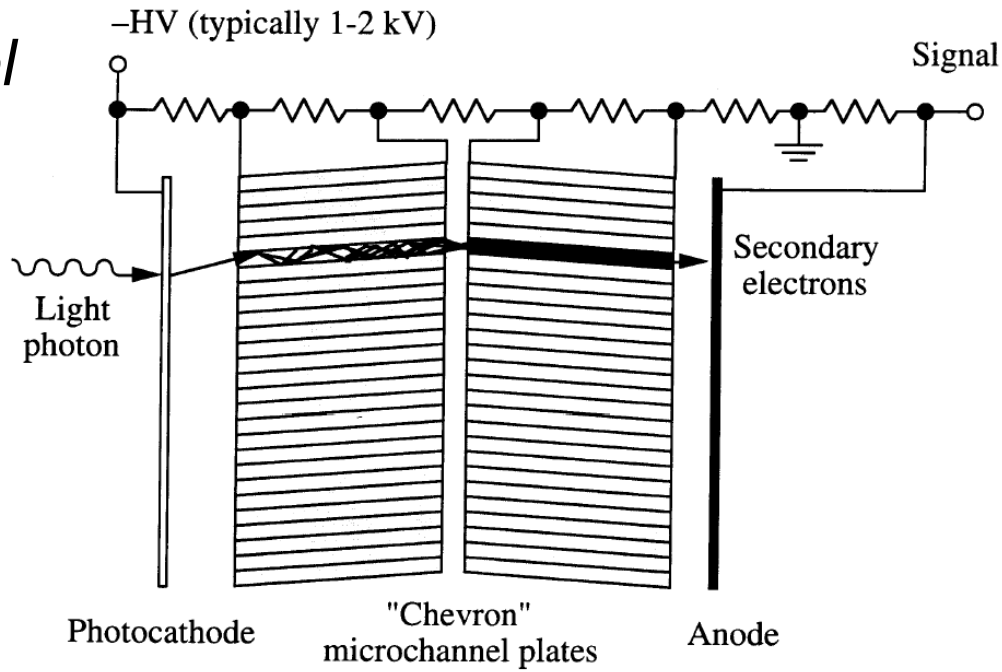


Scintillation detectors

Continuos multiplier structure: *Micro channel plates*



Two staged micro channel plate detector



⇒ *position sensitive detection of photons*

Scintillation detectors

Signal yield is determined by*:*

- Light collection (isotropic emission of light) in crystal affected by reflection and total reflection at surfaces

$\Rightarrow$ *reflecting material around crystal*

$\Rightarrow$ *no difference in diffraction index*

(matter between crystal and entrance window of PMT)

- High transmission through entrance glass window of PMT

- High photon absorption in photo cathode material

$\Rightarrow$ *adapt the wave length* λ *:*

- high transmission of photo electrons through cathode

- electron focus at first dynode

Scintillation detectors

Signal development

example:

1. *E absorption in scintillator* — *511 keV in NaJ*

2. *Population of excited states*
   time constant

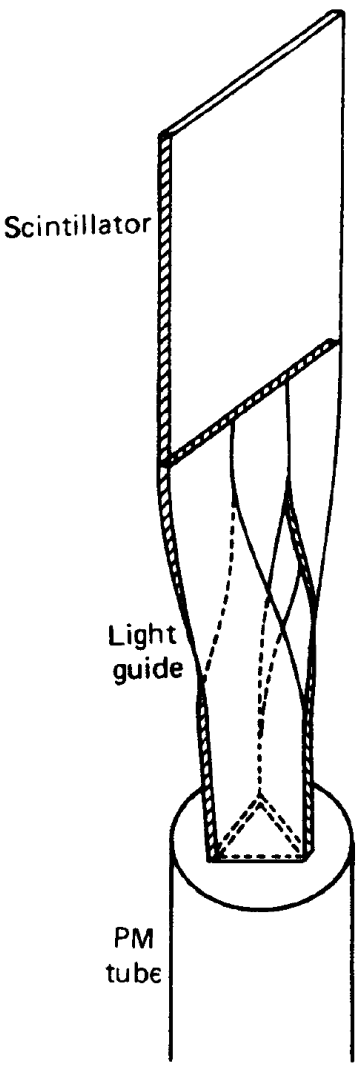
3. *Decay of states -> photons*
   time constant, absorption, reflection in crystal — *25000 photons @ crystal*

4. *Absorption in photo cathode -> Photo electrons*
   transmission in glas, absorption in cathode, quantum efficiency — *15000 photons @*

5. *Multiplication of photo electrons* — *3000 electrons @ first dynode*; *3×10^9 electrons @ anode (~2mA)*

determines error!

Scintillation detectors



Light guide

Photo multiplier are often coupled by light guide to scintillator.

basic principal: total reflection at surface of light guide

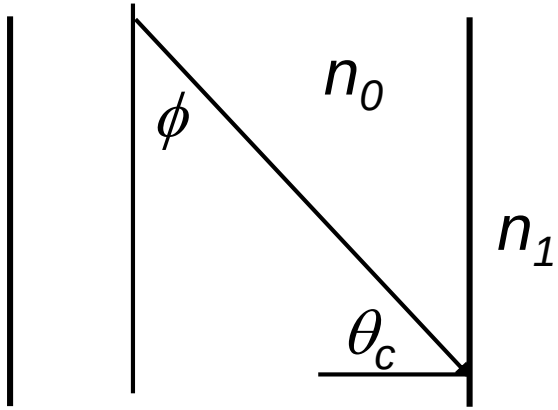
efficiency of light guide is limited by

- *angle of total reflection*

$$F = \frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_0^{\phi_c} 2\pi \sin\phi \, d\phi =$$

$$\frac{1}{2}\left(1-\cos\phi_c\right) = \frac{1}{2}\left(1-\sin\theta_c\right) =$$

$$\frac{1}{2}\left(1-\frac{n_1}{n_0}\right)$$

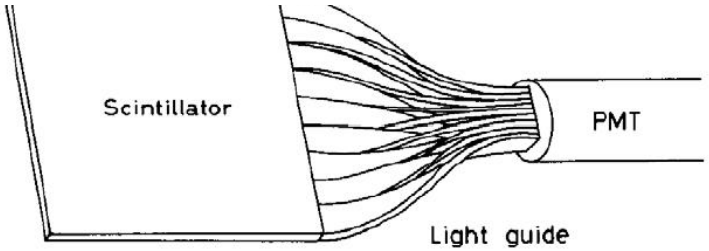


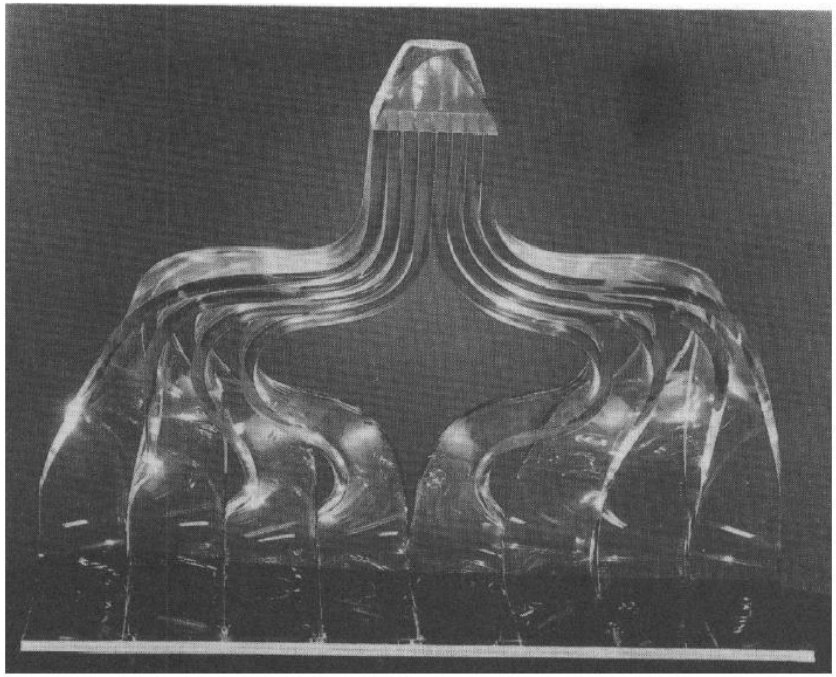
air n_1 ~1 and n_0 ~1.5

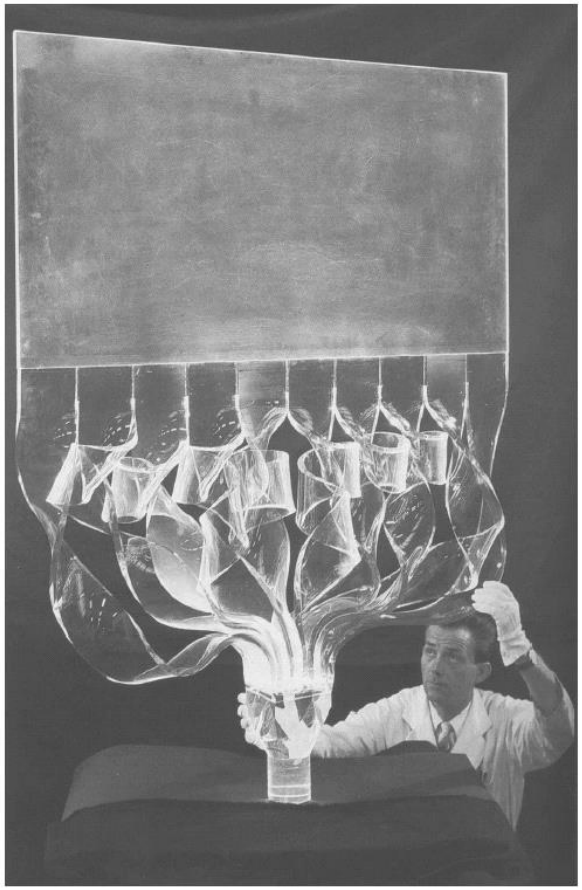
=> F=0.167

Scintillation detectors

Improved timing resolution is achieved when the light path is constant for all light guides.







Scintillation detectors

Applications of scintillators in nuclear and high energy physics

- *high efficiency, low resolution γ-spectroscopy*

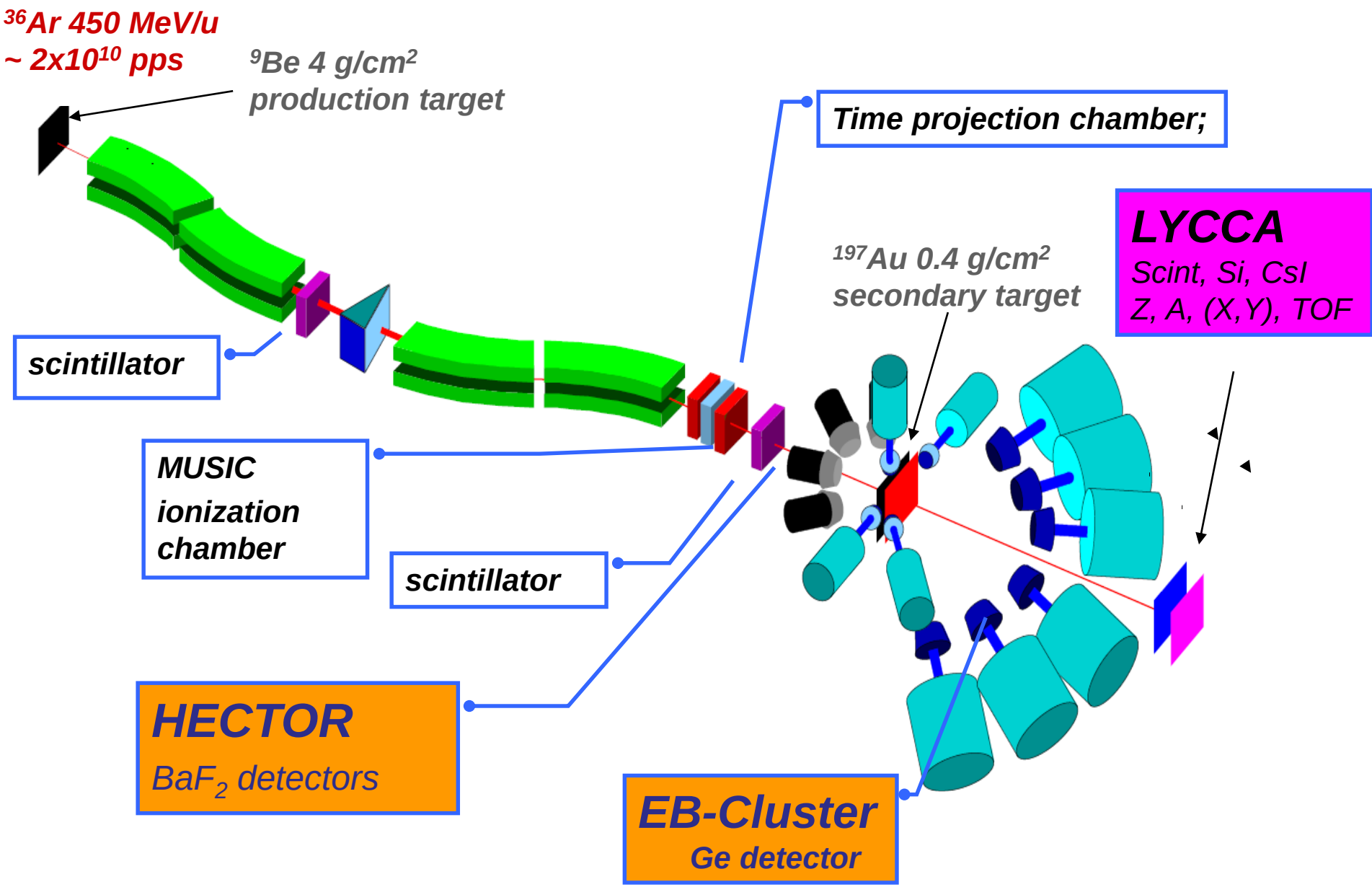
- *time of fligth TOF measurements*

- *particle calorimetry, kinetic energy*

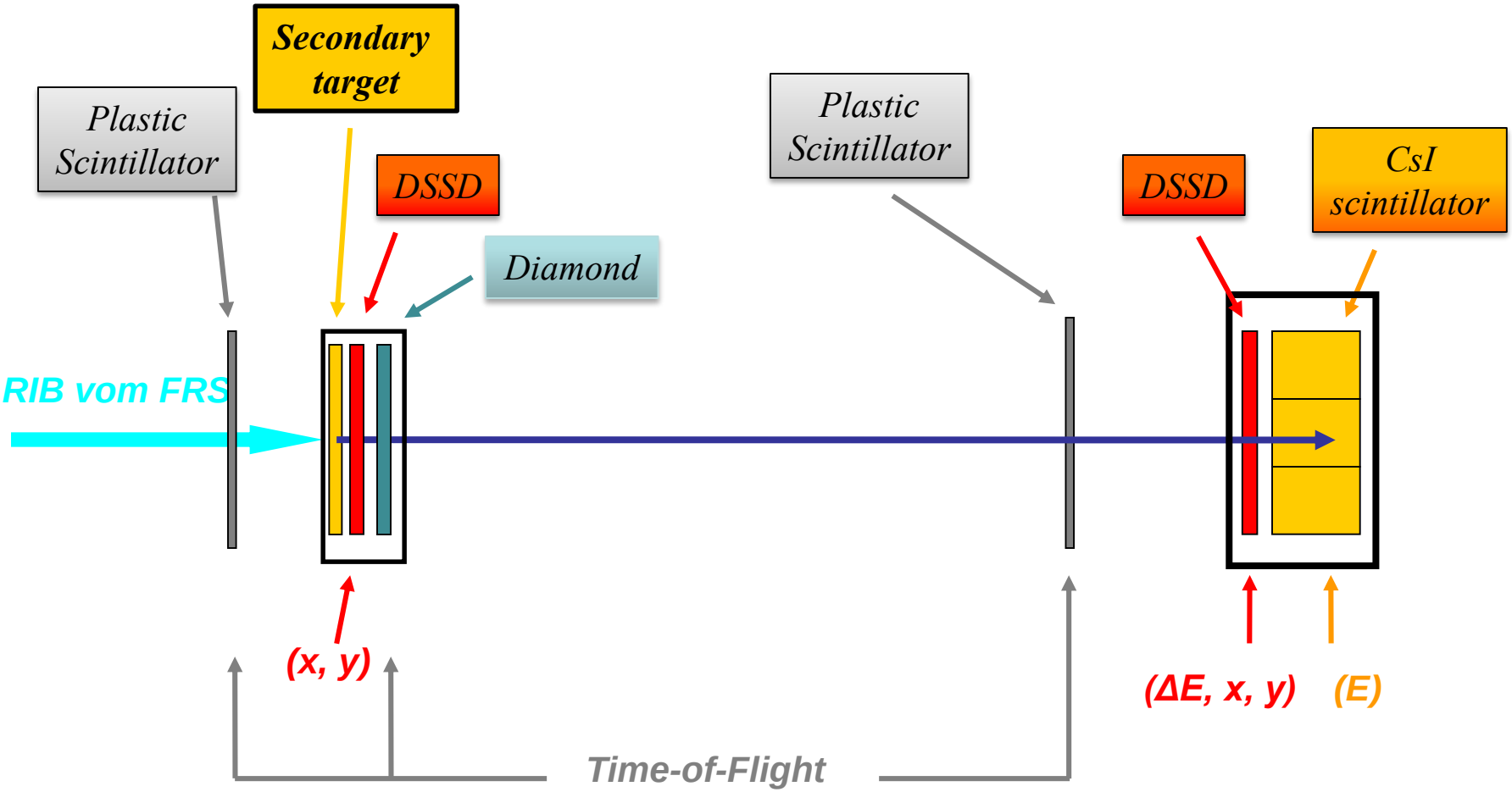
- *electromagnetic shower detector*

- *hadron spectroscopy*

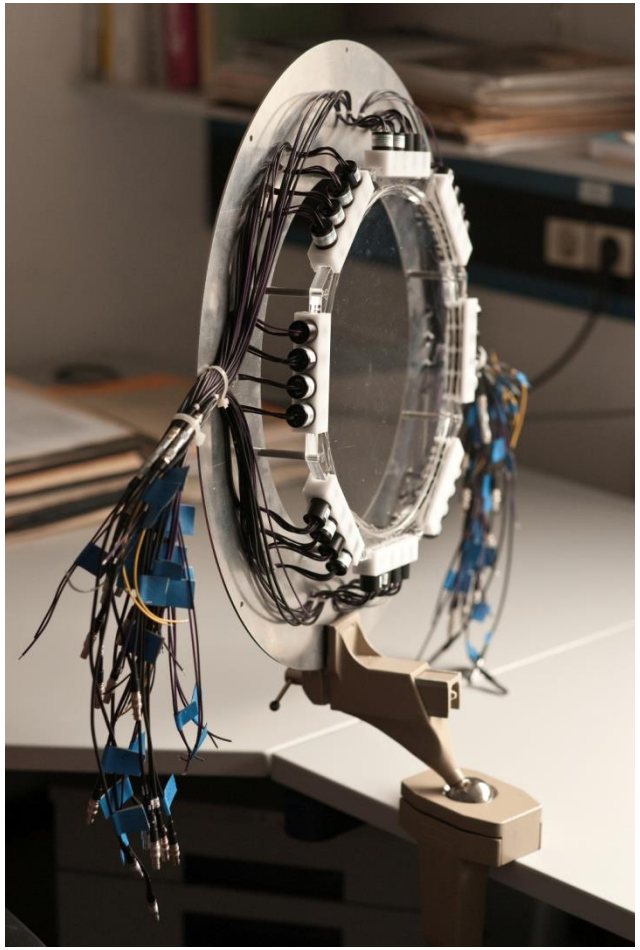
PRESPEC fast beam set-up at GSI



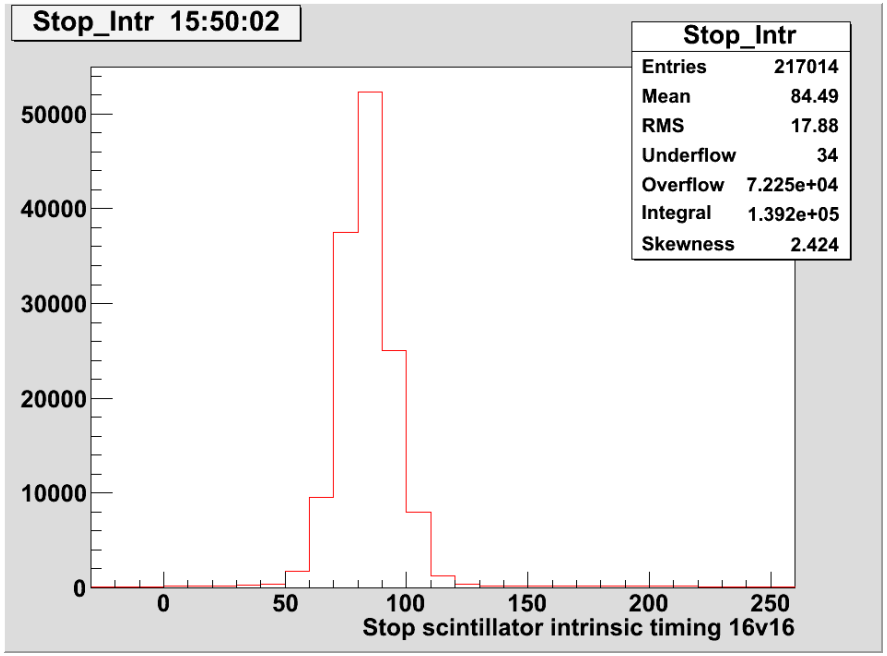
LYCCA – detection principle



TOF



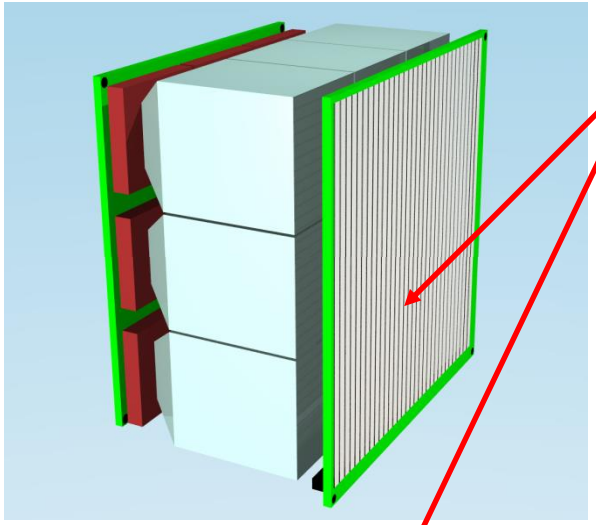
2 mm BC 420 - 32 PMT



Intrinsic timing resolution: 12,5 ps FWHM

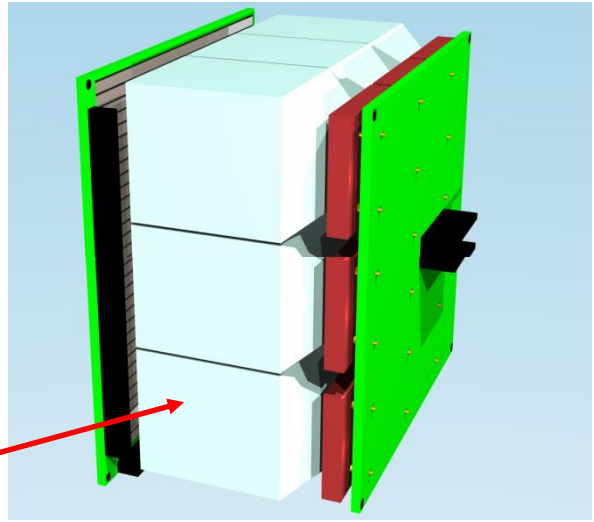
Exp. TOF resolution: 27 ps FWHM

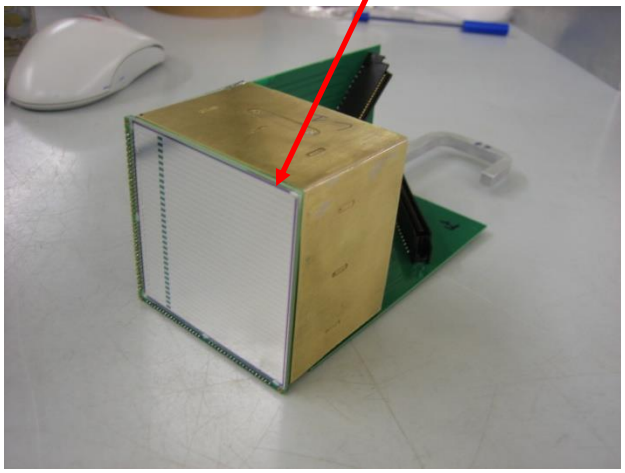
LYCCA ΔE-E-Modul

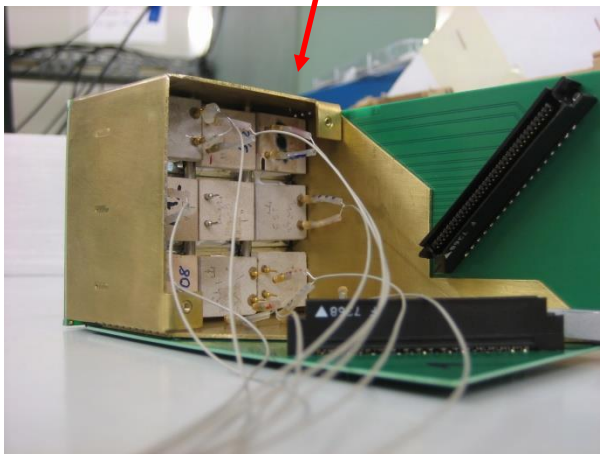


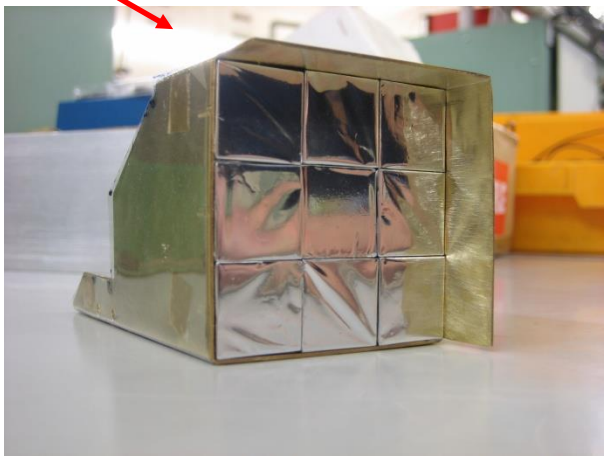
ΔE - Detector
DSSD, 58 × 58 mm²,
310 µm,
32 Strips per side

E - Detector
9 CsI-Scintillators,
19 × 19 mm²,
10 oder 33 mm
APD-readout

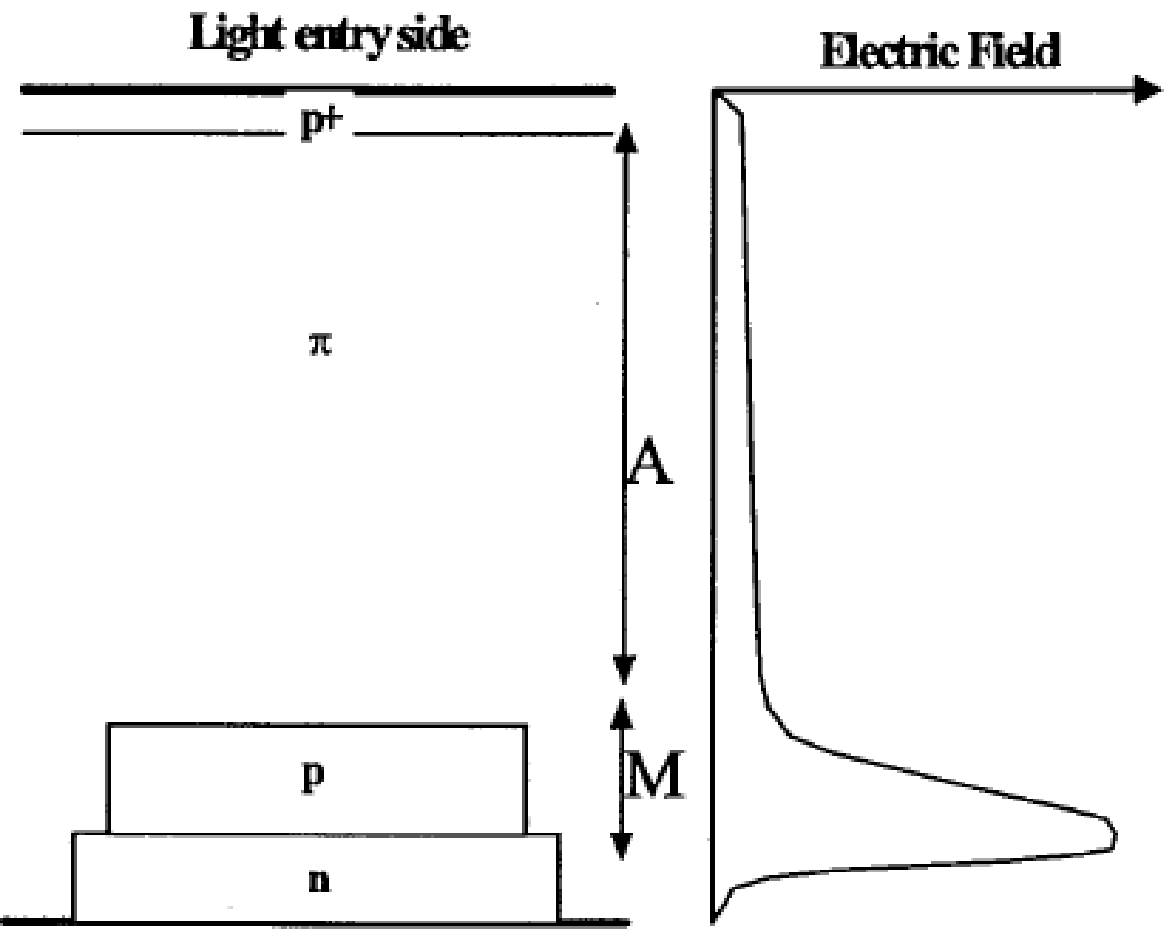








avalanche photo diode APD



p+-doped side and instrisic Si is used for light absorption, electron hole generation
A absorption and collection region

At pn junction the reverse voltage cause acceleration in high E field of electron into
M multiplication region

High electric field strength cause secondary charge carriers by ionisation and secondary amplification

Operation voltage of several 100V close to break through.

M = 100...500 multiplication factor

Scintillation crystals for calorimetry

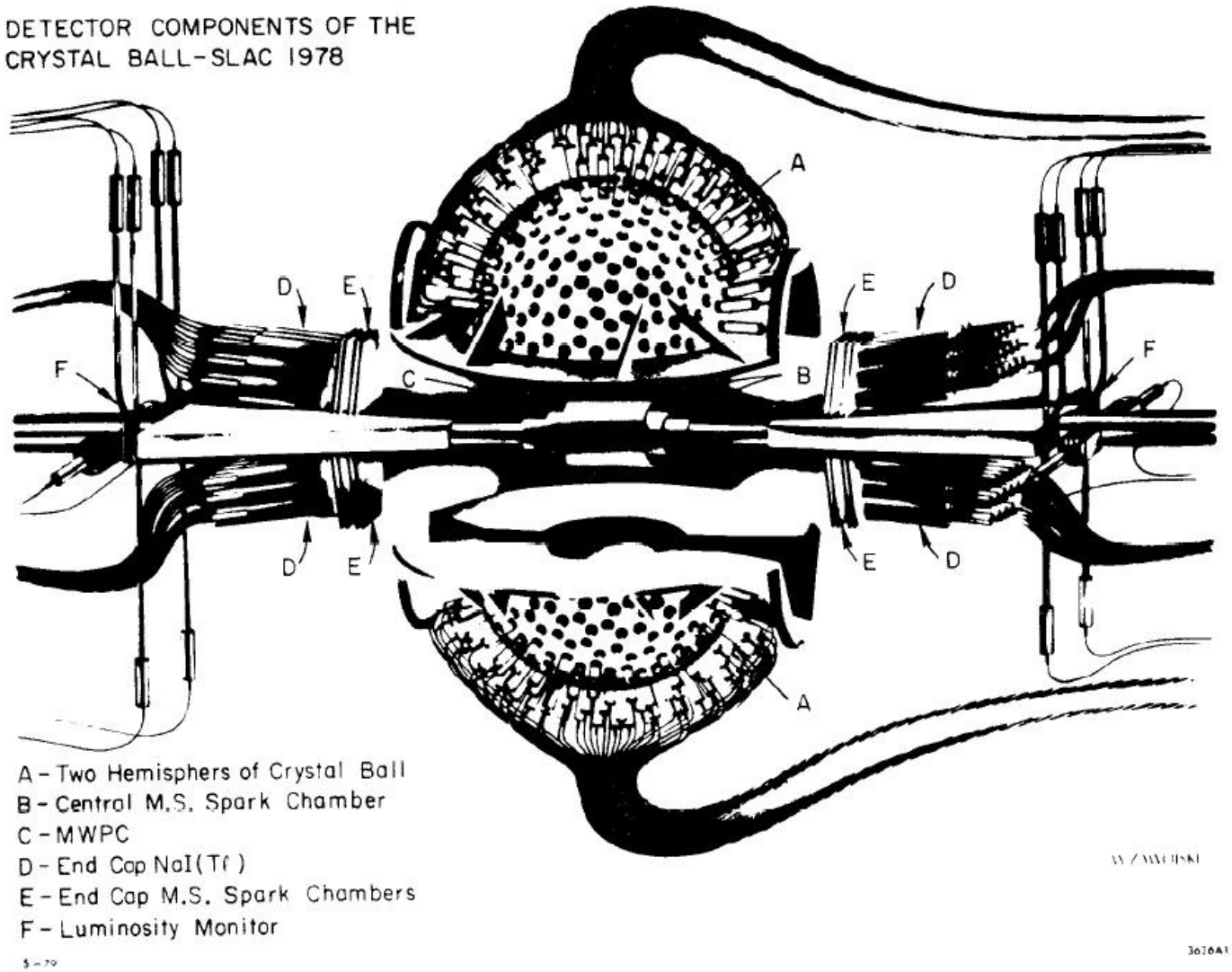
Crystal	Density g/cm^3	Refractive index	Radiation Length cm	Moliere Radius cm	λmax nm	Light yield %NaI(Tl)	Decay time ns	dLY/dT %/^{o}C	Melting point ^{o}C
NaI(Tl)	3.67	1.85	2.59	4.13	410	100	230	~0	651
CsI(Tl)	4.51	1.79	1.86	3.57	560	165	1250	0.3	621
CsI	4.51	1.95	1.86	3.57	420 310	3.6 1.1	30 6	-0.6	621
BaF_2	4.89	1.50	2.03	3.10	300 220	36 3.4	630 0.9	–2 ~0	1280
CeF_3	6.26	1.62	1.70	2.41	300	7.3	30	0.14	
BGO ($Bi_3Ge_3O_{12}$)	7.13	2.15	1.12	2.23	480	21	300	-1.6	1050
PWO ($PbWO_4$)	8.3	2.20	0.89	2.00	425 420	0.29 0.083	30 6	-1.9	1123
LSO (Lu_2SiO_5:Ce)	7.40	1.82	1.14	2.07	420	84	42	~0	2050
GSO (Gd_2SiO_5:Ce)	6.71	1.85	1.38	2.23	440	30	60	-0.1	1950

High Energy Physics Crystal Calorimeters

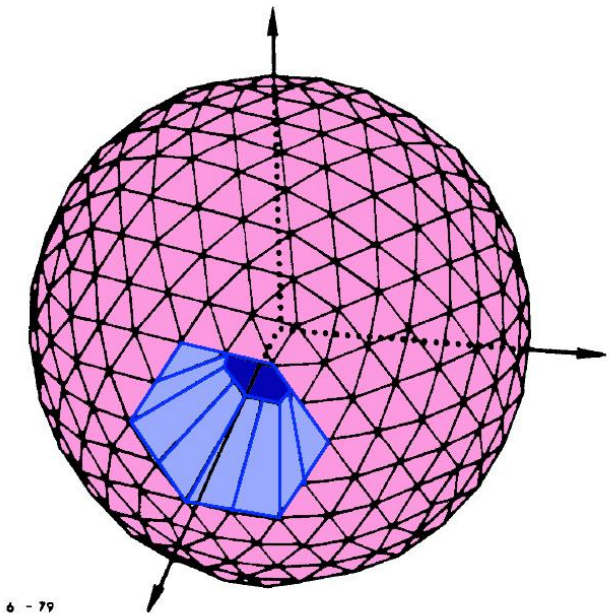
Experiment	**Crystal Ball, SPEAR, SLAC**	**SND, BINP Novosibirsk**	**L3, LEP, CERN**	**KTeV Tevatron Fermilab**	**CLEO c, CESR, Cornell**	**BABAR PEP II SLAC**	**BELLE KEK B KEK**	**CMS, LHC, CERN**
Time	75–85	90–15	80–00	96–00	80–08	94–08	94–18	95–20
Crystal	NaI(Tl)	NaI(Tl)	BGO	CsI	CsI(Tl)	CsI(Tl)	CsI(Tl)	$PbWO_4$
N crystals	672	1640	11400	3260	7800	6580	8800	76000
Inner radius (m)	0.254	0.25	0.55	-	1.0	0.9	1.25	1.29
Volume (m^3)	1	1	1.5	2	7	5.9	9.5	11
Thickness (X_0)	16	13.4	22	27	16	16-17.5	16.2	26
Photo sensor	PMT	VPT	Si PD	PMT	Si PD	Si PD	Si PD	APD, VPT
Noise (MeV)	0.05	0.2	0.8	-	0.5	0.15	0.2	30
Dynamic range	10^4	10^3	10^5	10^4	10^4	10^4	10^4	10^5

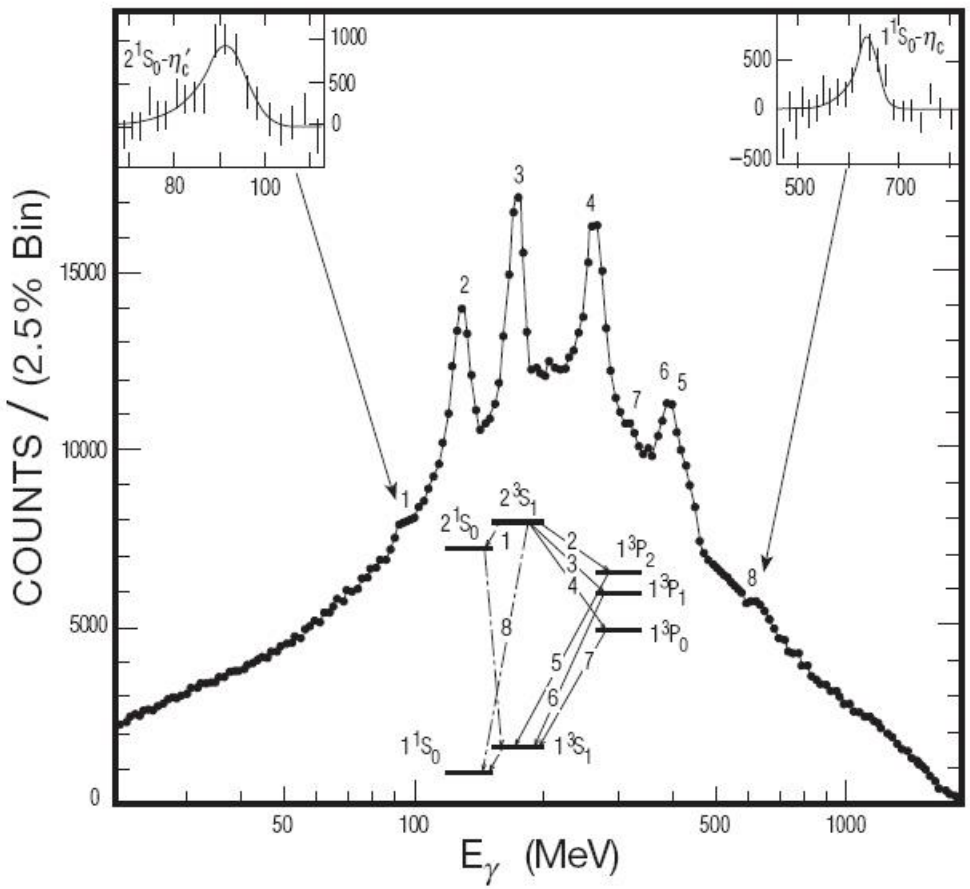
Crystal Ball Detector

first large-scale crystal calorimeter in high energy physics
NaI(Tl) calorimeter Crystal Ball detector



Crystal Ball NaI(Tl) Calorimeter



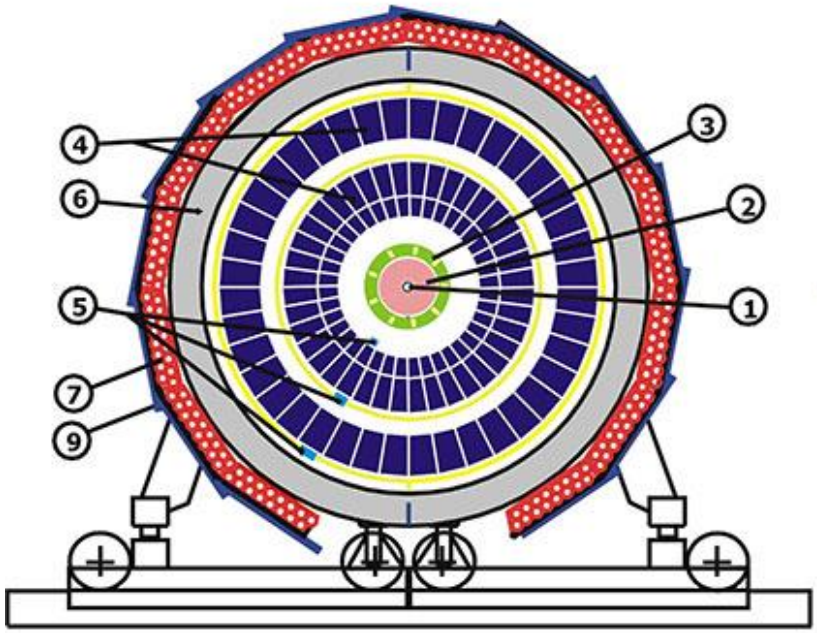


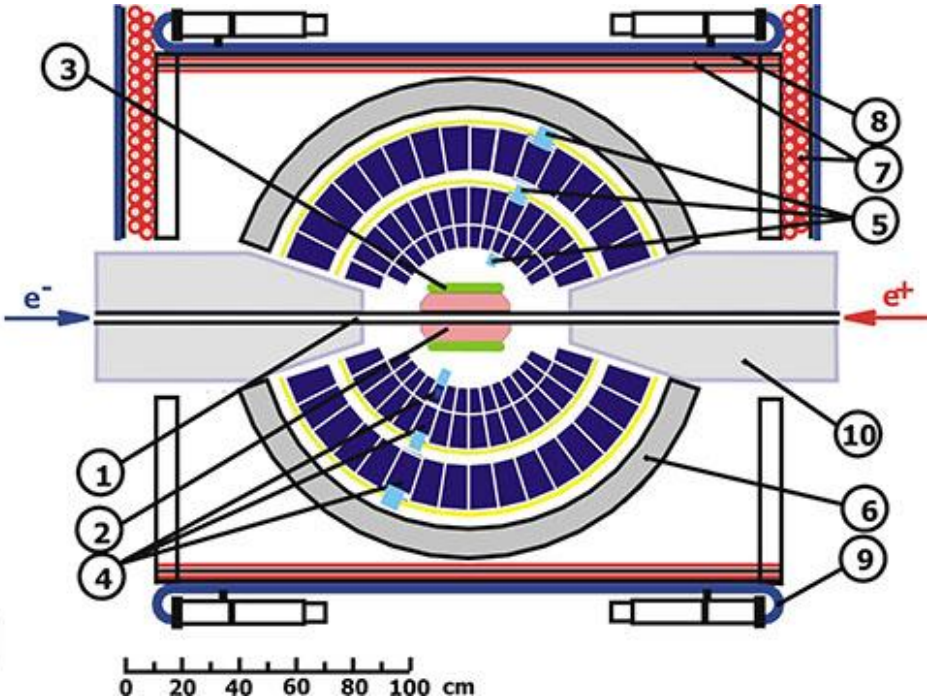
Number of crystals 672
Inner radius 25.4 cm
Outer radius 66.0 cm
Thickness 16 X_0
Solid angle coverage 93%
Photodetector PMT
Noise 0.05 MeV
Dynamic range 10^4

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt[4]{E(\mathrm{GeV})}}$$

Inclusive photon spectrum at $\psi(2S)$ resonance

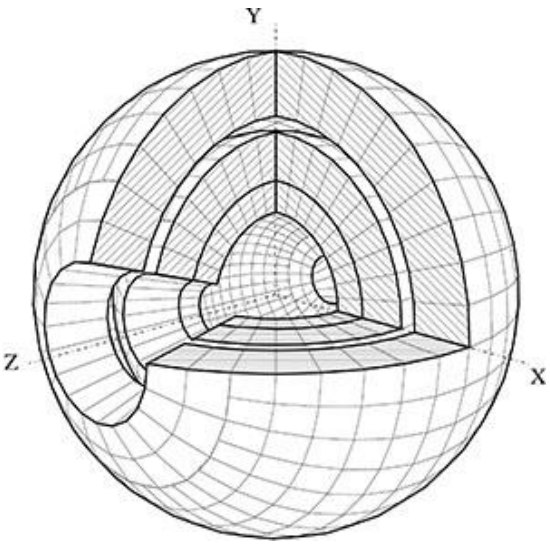
SND detector



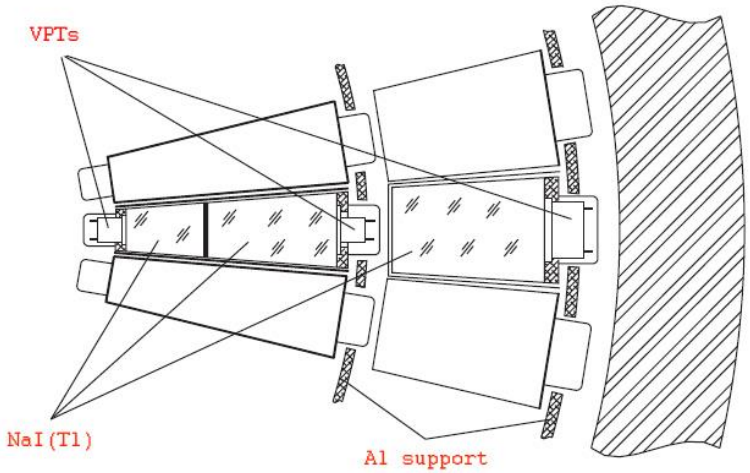


SND detector
1 – Be vacuum chamber
2 – tracking system
3 – aerogel Cherenkov counters
4 – NaI(Tl) scintillation counters
5 – vacuum phototriodes
6 – iron absorber
7,8 – muon system.

SND NaI(Tl) calorimeter



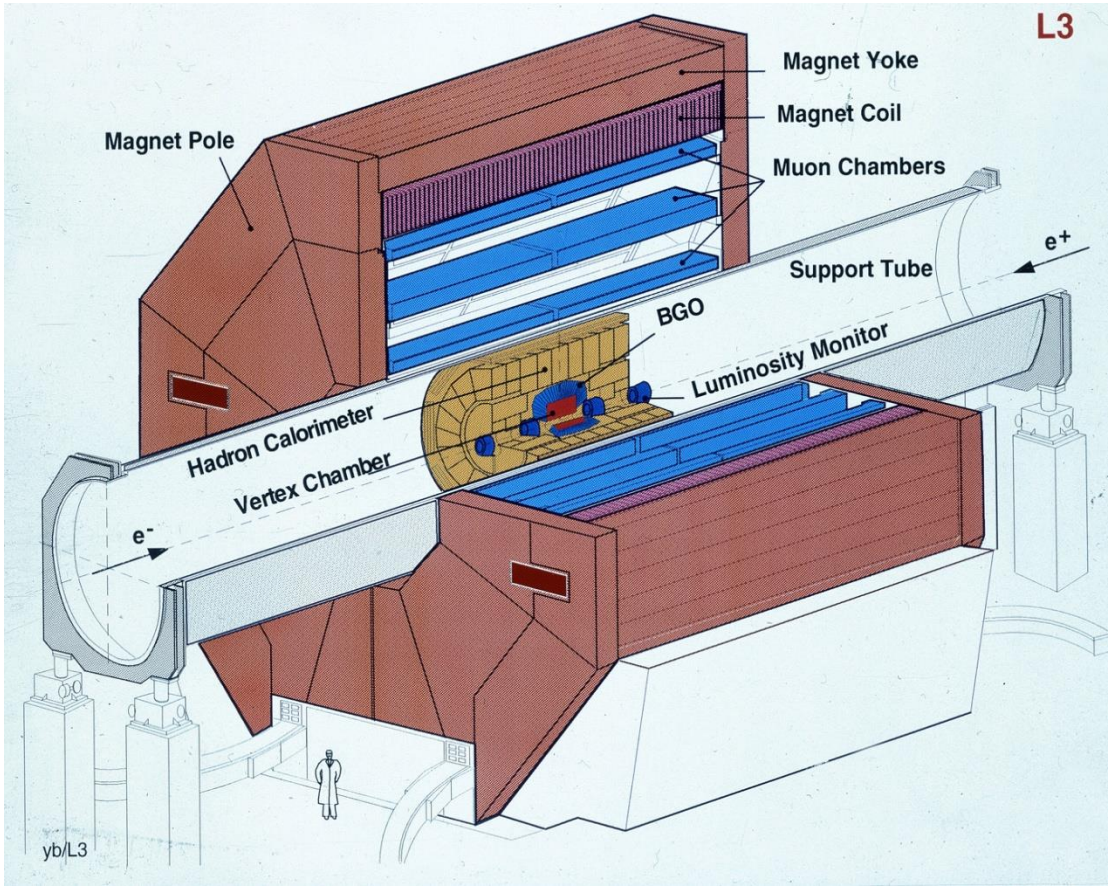
SND calorimeter geometry



SND calorimeter segment

Number of crystals - 1632, thickness – 13.5 X_0, mass – 3.5 tons
Photodetectors – vacuum phototriodes with photocathode quantum efficiency of ~15% and gain ~10.

L3 BGO calorimeter



L3 detector at LEP 1980-2000

Number of crystals:
- Barrel – 7680
- Endcaps – 2×1527

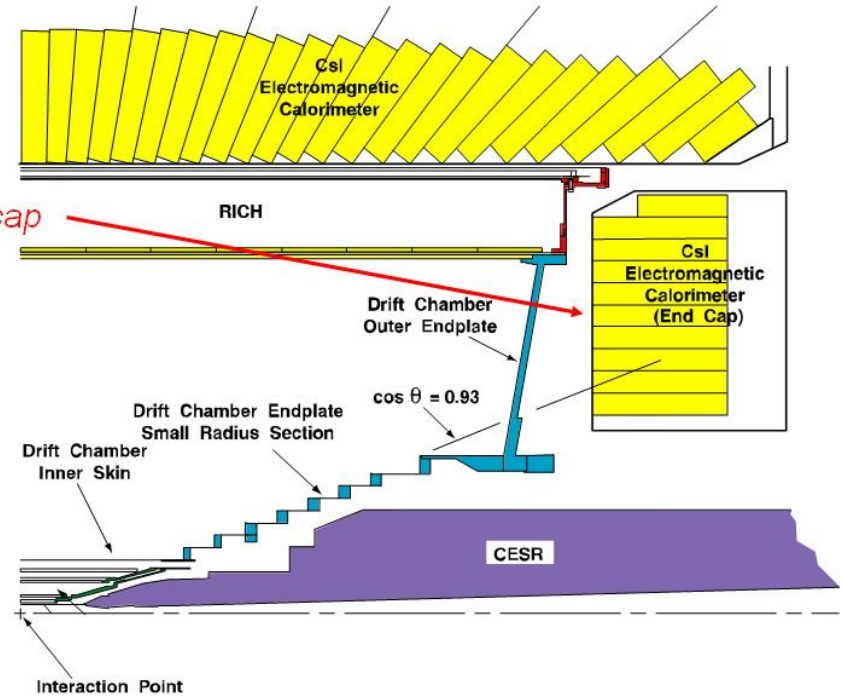
Thickness – $22X_0$

Photo detector – Si PD

CLEO-c CsI(Tl) calorimeter

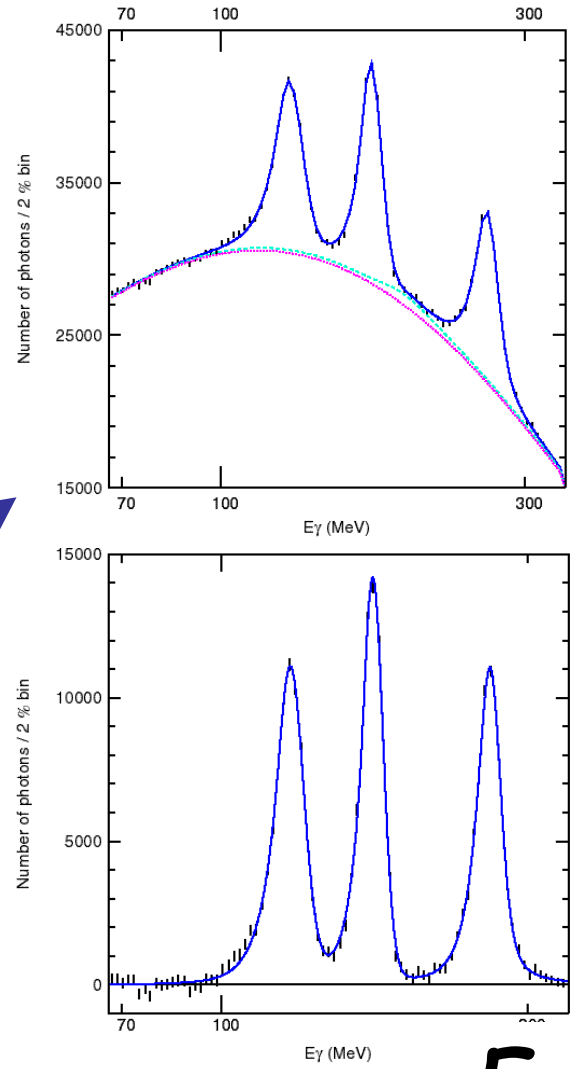
- Number of crystals 7784:
  Barrel – 6144
  Endcaps – 2×820
- Crystal size – 5x5x30 cm3
- Thickness – 16.2 X_0
- Inner radius – 1.02 m
- Barrel length – 3.26 m
- Total CsI(Tl) mass – 27000 kg
- Solid angle coverage – 95%
- Photodetector Si photodiode (4 per crystal)
- Material in front of the barrel part – 0.18X_0

- installed 1990
- *Improved endcap*
- photon det.
- electron ID
- Trigger
- Luminosity
- π^0, η
- missing E



Spectroscopy of γ-decays from $\psi(2S)$

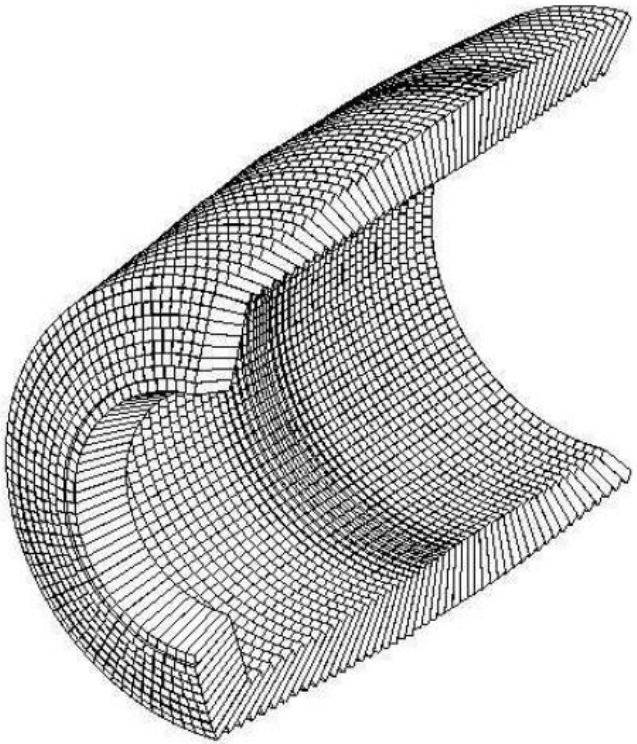
- $\pi^0 \rightarrow \gamma\gamma$
- $\eta \rightarrow \gamma\gamma$
- $\mu^+\mu^-\gamma$
- $\psi(2S) \rightarrow \gamma\chi_{cJ}$

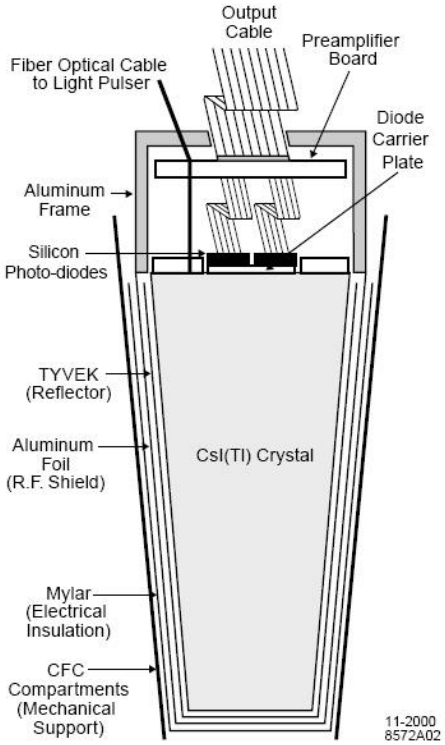


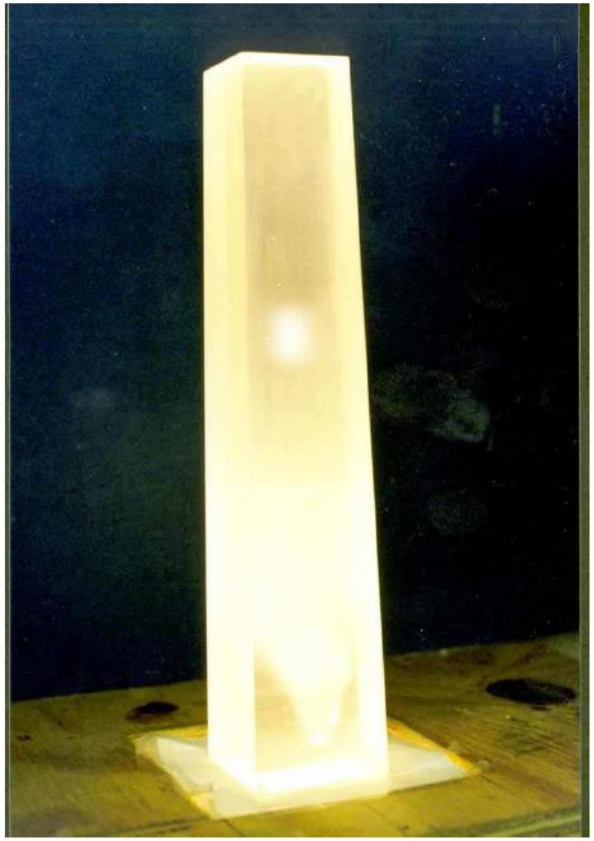
Fit huge combinatoric background & subtract

E_γ

BABAR CsI(Tl) Calorimeter

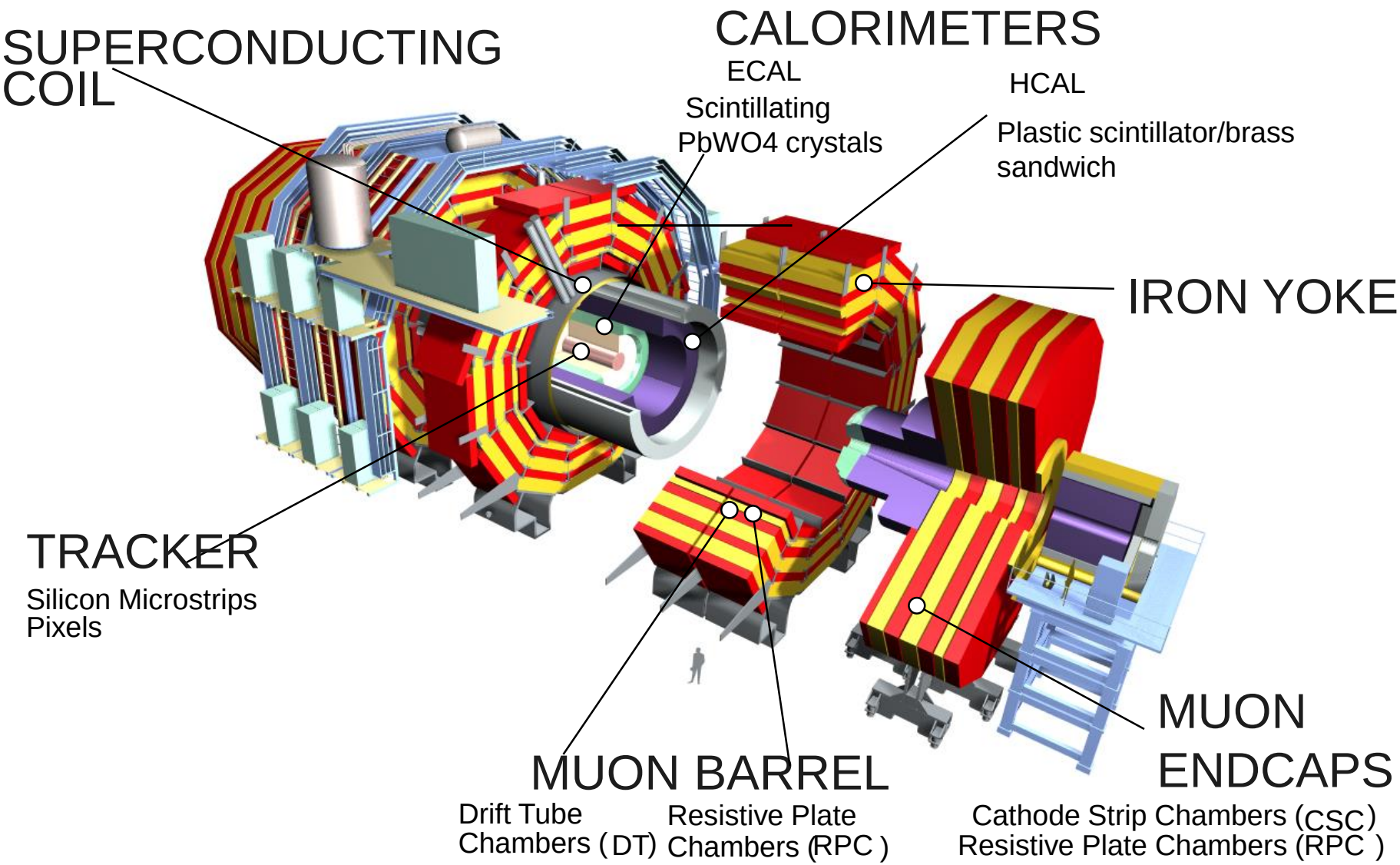




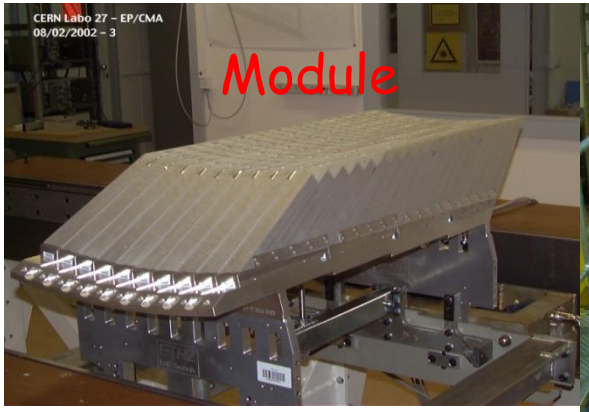


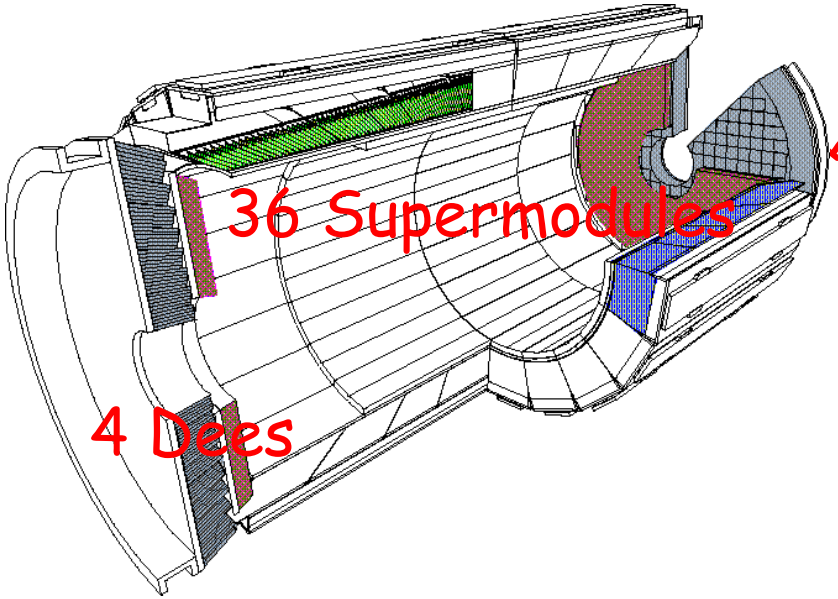
Number of crystals: 6580
Thickness: 16 -17.5 X_0
Inner radius: 0.92 m
Length: 2.9 m
Solid angle coverage: 90%

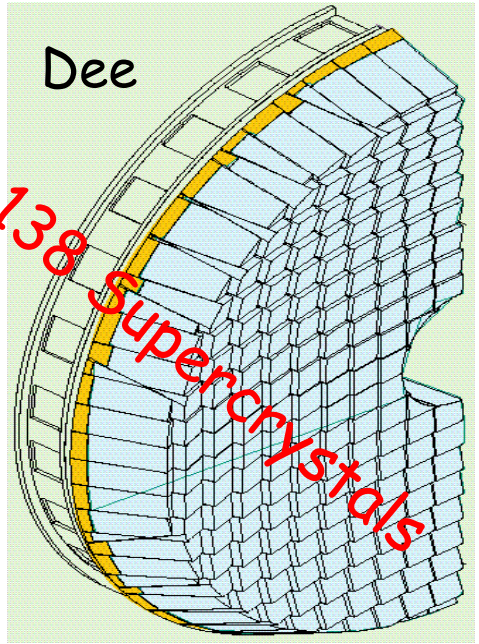
CMS at LHC Detector Overview



Construction Overview







Barrel

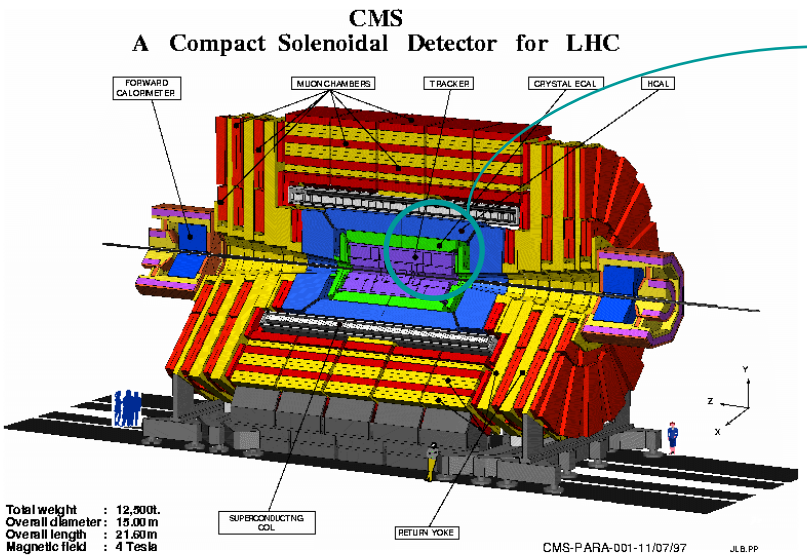
61,200 $PbWO_4$ crystals

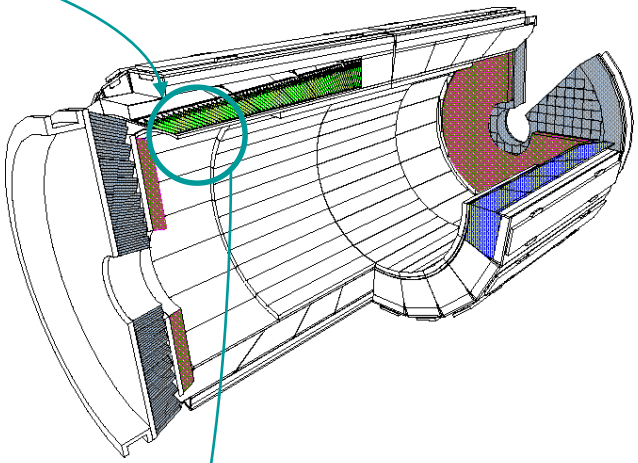
Readout with 122,400 APD's

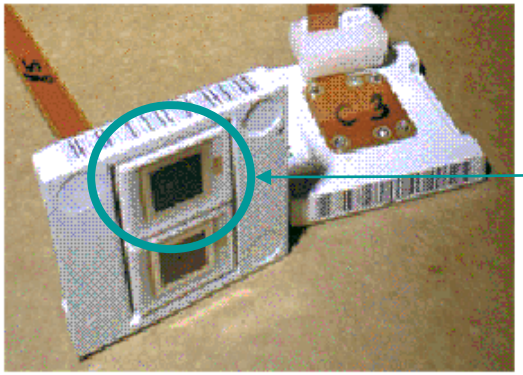
Endcap

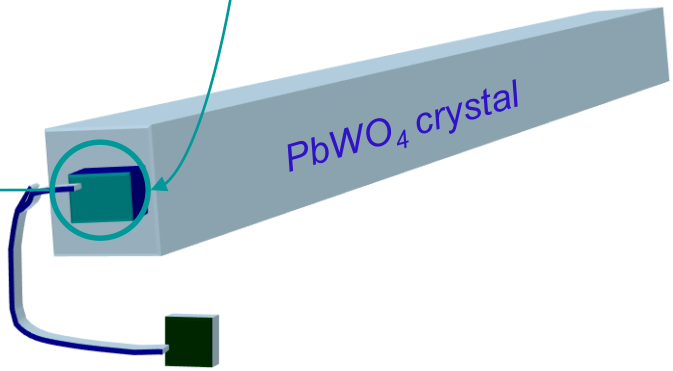
14684 crystals readout with VPT's.

CMS detector





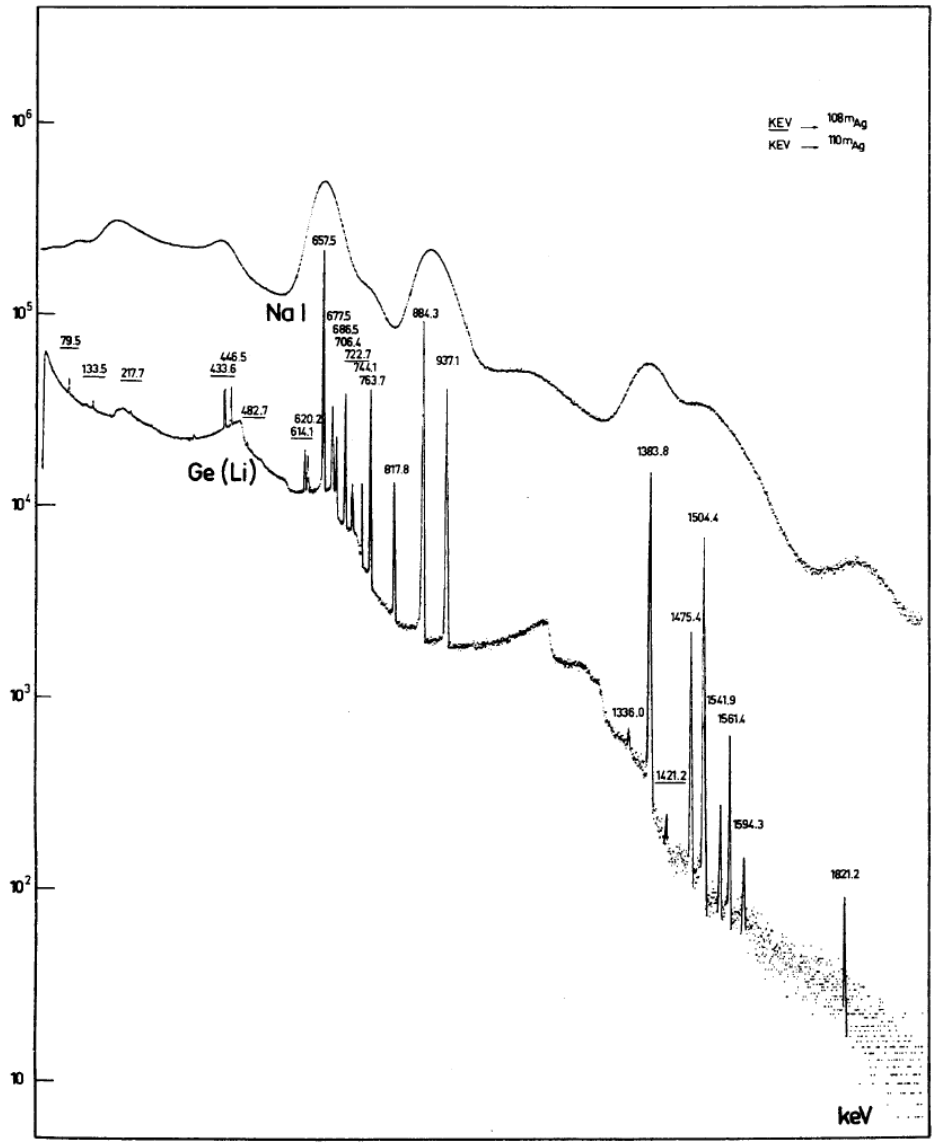




Outlook

NaI detector (scintillator)

Ge detector (semiconductor) for γ-ray spectroscopy



(J.Cl. Philippot, IEEE Trans. Nucl. Sci. NS-17/3 (1970) 446)