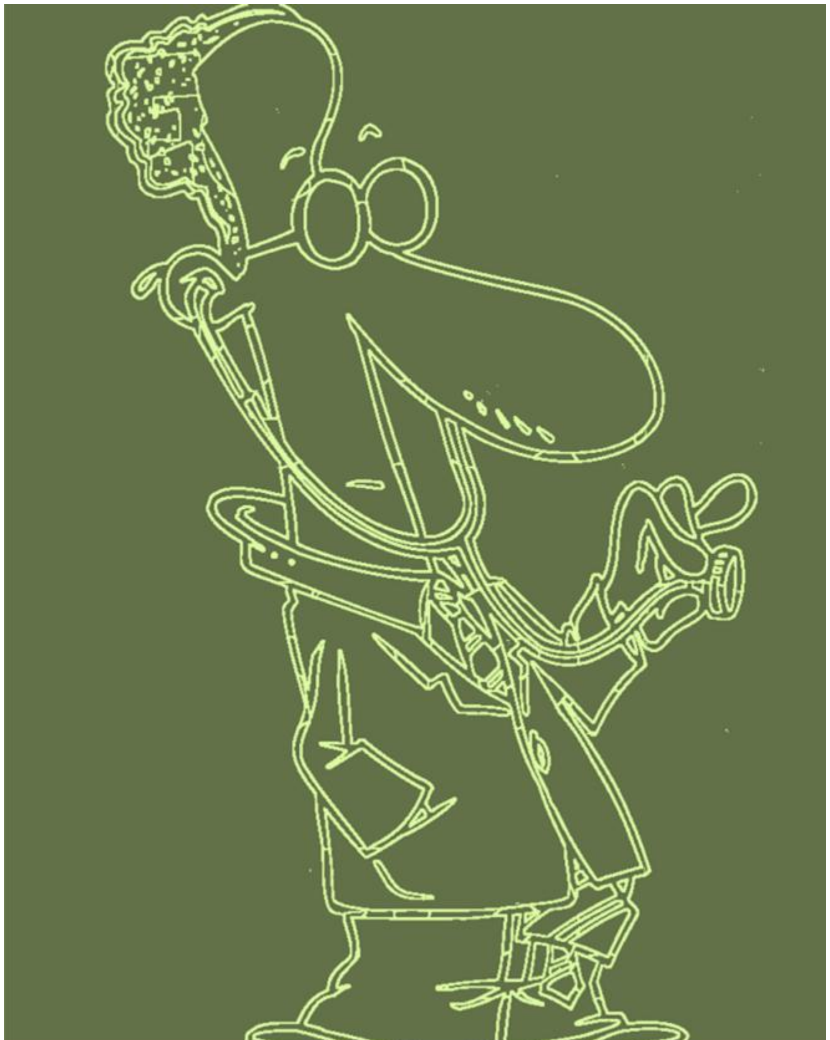
Radiation:
A Stethoscope of a Nuclear Physicists



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Saha Institute of Nuclear Physics.

Idea about radiation: Solar radiation

Surface temperature of the sun T=5,800K

Radius of the sun R=6.995×10^{8}m

Stefan's constant σ=5.670×10^{-8}Wm^{-2}K^{-4}

Thermal energy per second (Power) radiated by the sun is

$$P=4\pi R^2\sigma T^4=3.95\times10^{26}\text{W}$$

It is known that the cause of solar radiation is basically a nuclear process.

Cavendish Laboratory

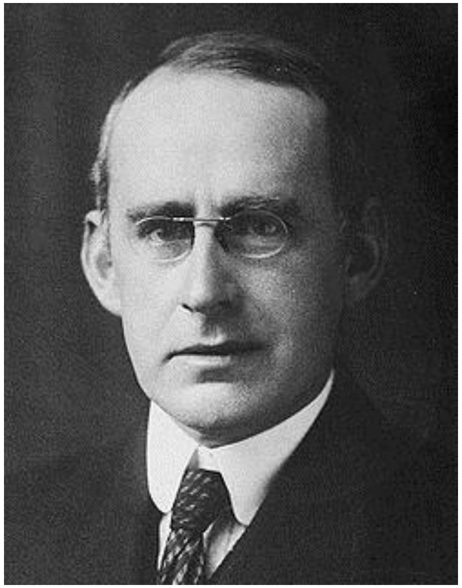
How it was predicted

F.W. Aston

In 1920 Aston discovered that the mass of the helium atom is slightly less than four times the mass of the hydrogen atom.

Beginning of Nuclear astrophysics

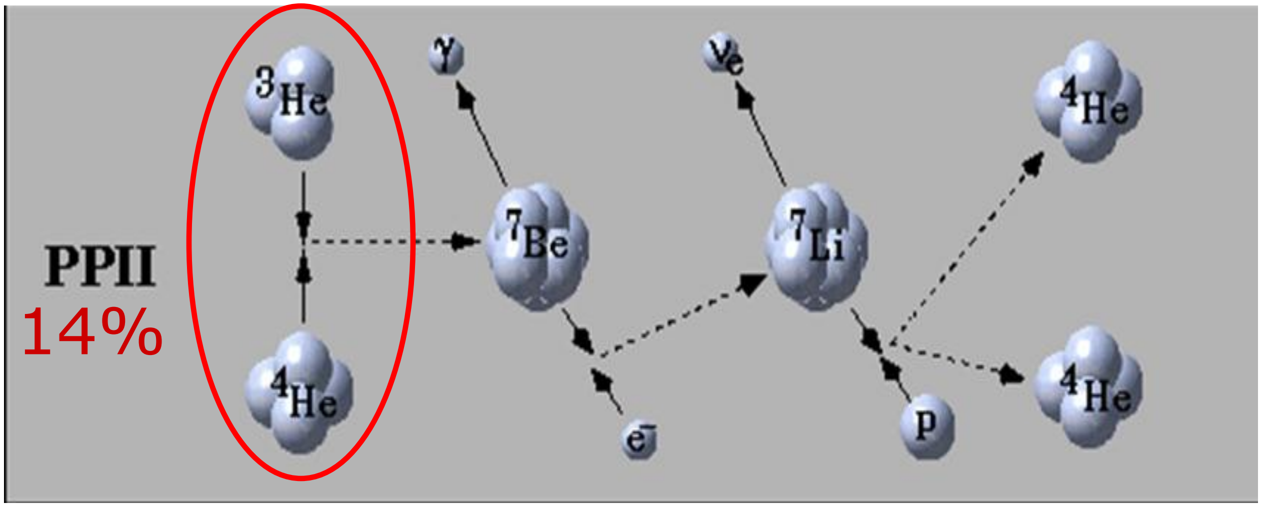
Immediately afterward, Eddington suggested in his 1920 presidential address to the British Association for the Advancement of Science that Aston's discovery would explain the energy generation of the Sun via the conversion of hydrogen to helium.



What is possible in Cavendish laboratory may not be too difficult in the sun.

Reaction among nuclear species were the source of energy in stars

Atkinson (1936) proposed the fusion of two hydrogen nuclei to deuterium as a source of stellar energy generation. A detailed treatment of this reaction was provided by Bethe in 1938 showed that the p + p reaction gives indeed an energy generation of the correct order of magnitude for the Sun.



$^3He(\alpha,\gamma)^7Be$

PHYSICAL REVIEW C 87, 065804 (2013)

Astrophysical *S* factor of $^{3}He(\alpha,\gamma)^{7}Be$

$$S(E) = E \cdot \sigma(E) \cdot \exp(2\pi\eta)$$

$$2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{0.5}$$

Big bang nucleosynthesis is initiated by *p* + *n* fusion one second after the big bang. It defines the abundances of the primordial isotopes, mostly hydrogen and helium, that later provide the seed for the nucleosynthesis in the first generation of stars. Big bang nucleosynthesis (BBN) calculations agree very well with abundance observations in old stars apart from the abundance of ^{7}Li, which the models overproduce by a factor of 3.The rate of this reaction is known well enough that it is unlikely that it would solve this so called *lithium problem*.

BBN calculation versus observations

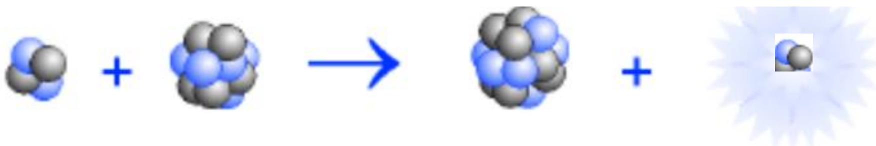
	BBN calculations		Observations	
	Cyburt et al. 2008	*Coc & Vangioni 2010*		
^{4}He	0.2486±0.0002	0.2476±0.0004	0.245-0.262	$\times 10^0$
D/H	2.49±0.17	2.68±0.15	2.84±0.26	$\times 10^{-5}$
^{3}He/H	1.00±0.07	1.05±0.04	(0.9-1.3)	$\times 10^{-5}$
^{7}Li/H	**$5.24^{+0.71}_{-0.62}$**	**5.14±0.50**	**1.58±0.31**	**$\times 10^{-10}$**

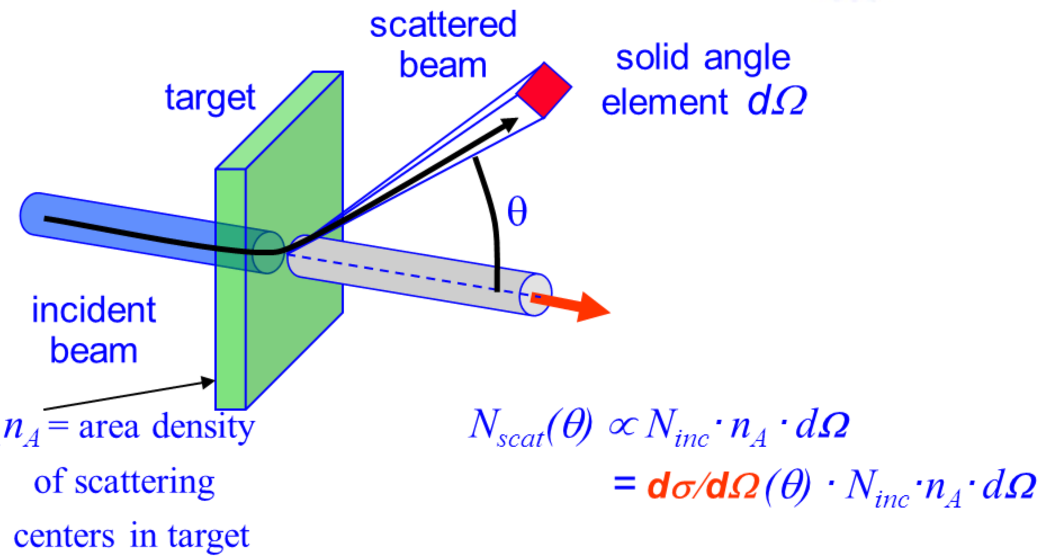
✦ Nuclear solution to the Li problem ?

How to calculate these abundance

Cross section of the particular nuclear reaction

Differential cross sections **dσ/dΩ** are used to express the probability of interactions between elementary particles.



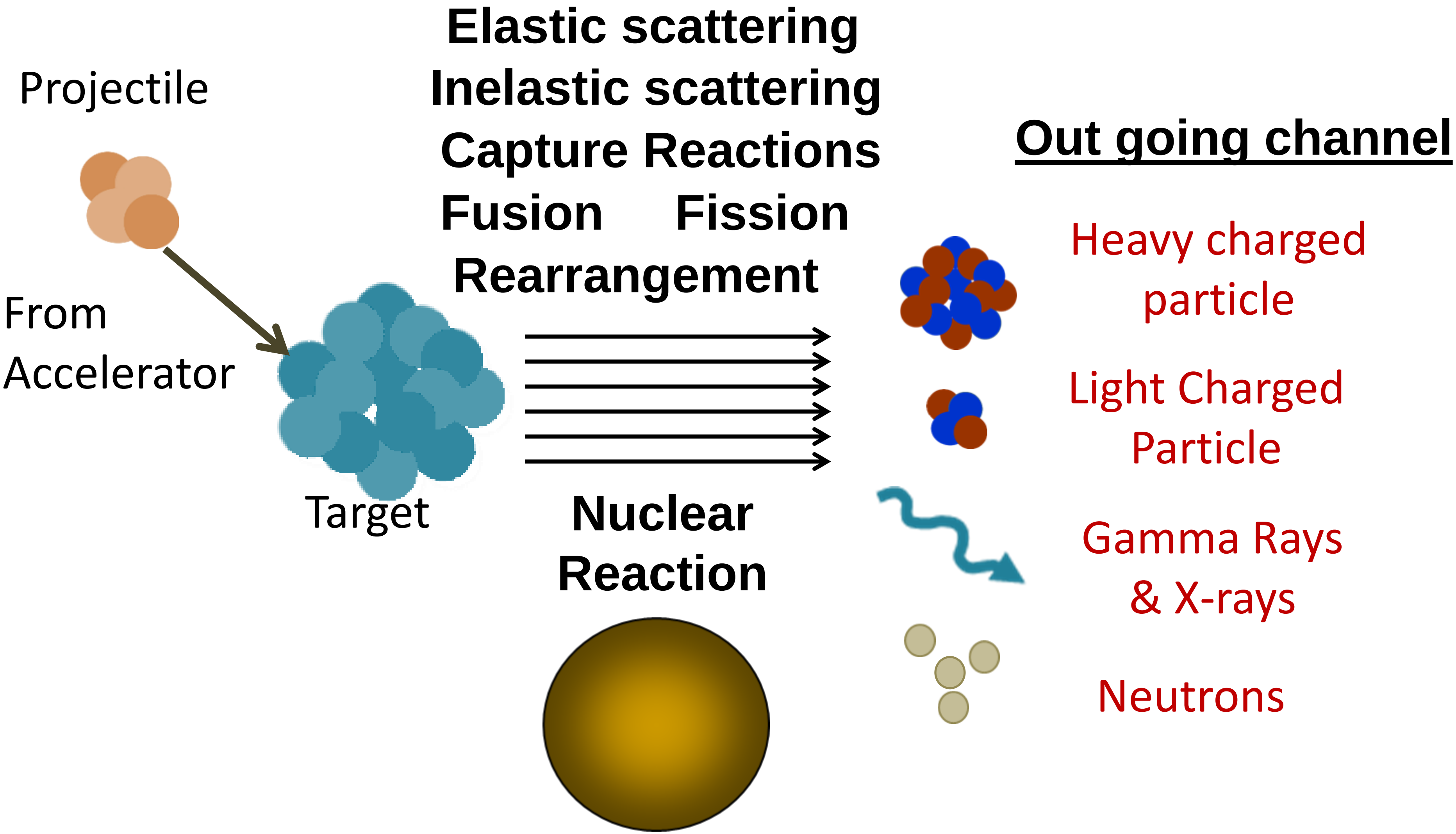


Cross sections depend on the nuclide, the reaction, and energy.

$$rate = \sigma N I$$

N is the number of target nuclei per unit area;
I is the beam intensity

For cross section measurements we have to characterize the properties of the outgoing radiation



These emitted particles carry the information about the nuclear processes involved

How to determined the cross section Catch hold of the emitted radiation

- When radiation interacts with matter, result is the production of energetic electrons. (Neutrons lead to secondary processes that involve charged species)
- Want to collect these electrons to determine the occurrence of radiation striking the detector, the energy of the radiation, and the time of arrival of the radiation.

Basic Radiation Detector Systems

What do you want to know about the radiation?
Energy?
Position (where did it come from)?
How many / how much?
Time of arrival of the radiation?

Important properties of radiation detectors
(depends on application)
Energy resolution
Time resolution
Spatial resolution
Sensitivity
Counting Speed

Detector characteristics

- Sensitivity of the detector
- Energy Resolution of the detector
- Time resolution of the detector
- Detector efficiency

Summary of detector types

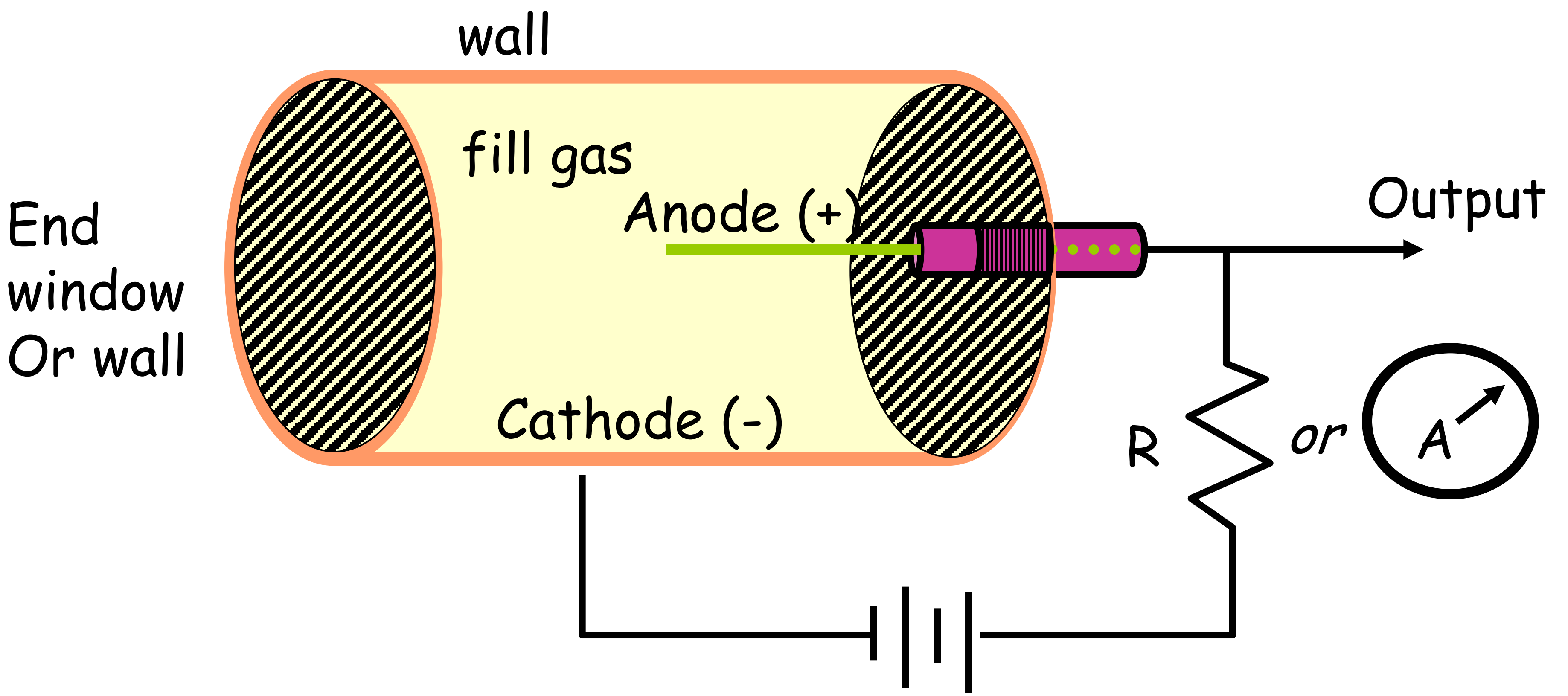
- Gas Ionization
- Scintillators
- Ionization in a Solid (Semiconductor detectors)

Gas Detectors

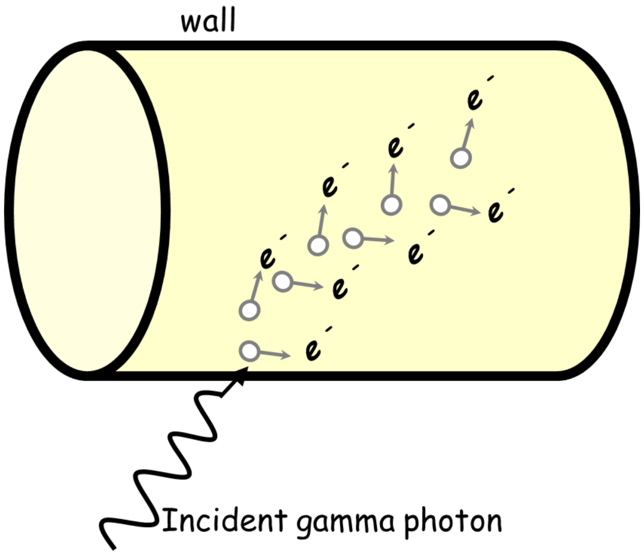
Gas-Filled Detectors - Components

- Variable voltage source
- Gas-filled counting chamber
- Two electrodes well insulated from each other
- Electron-ion pairs
  - produced by radiation in fill gas
  - move under influence of electric field
  - Due to the movement of these electron ion pairs
  - Induced charge in the electrodes
  - Time dependent voltage: pulse formation
  - Pulse amplitude is a measure of the energy of the incident radiation
  - Time of occurrence of the pulse

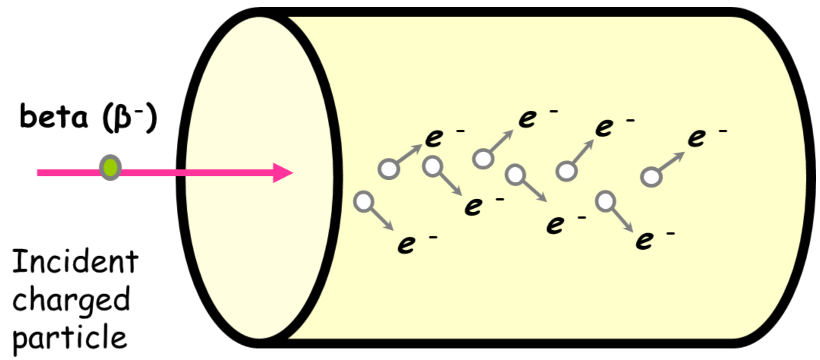
Gas- Filled Detectors



Indirect Ionization Process



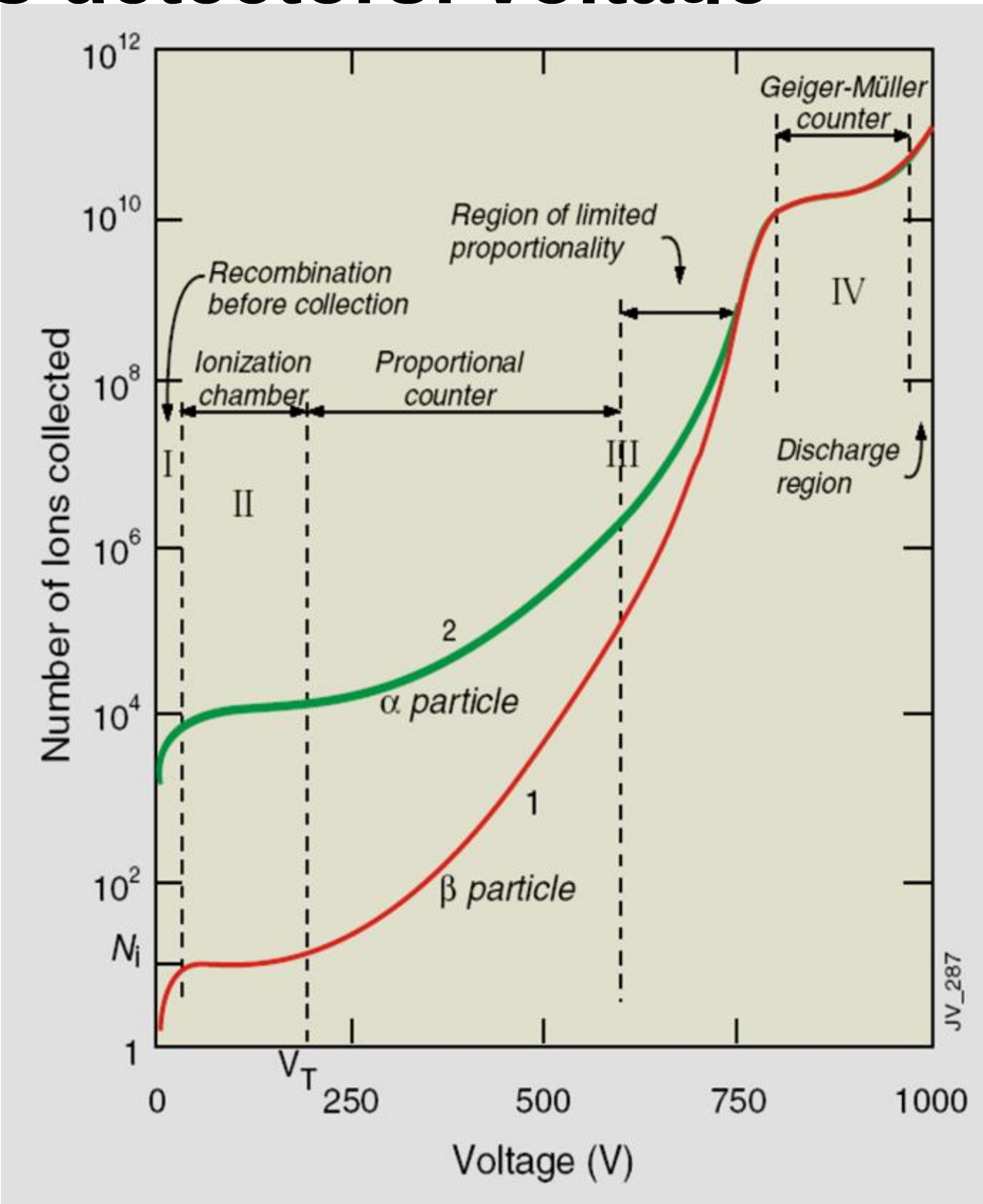
Direct Ionization Process



- Gas filled detectors operate in either
  - current mode
    - Output is an average value resulting from detection of many values
  - pulse mode
    - One pulse per particle

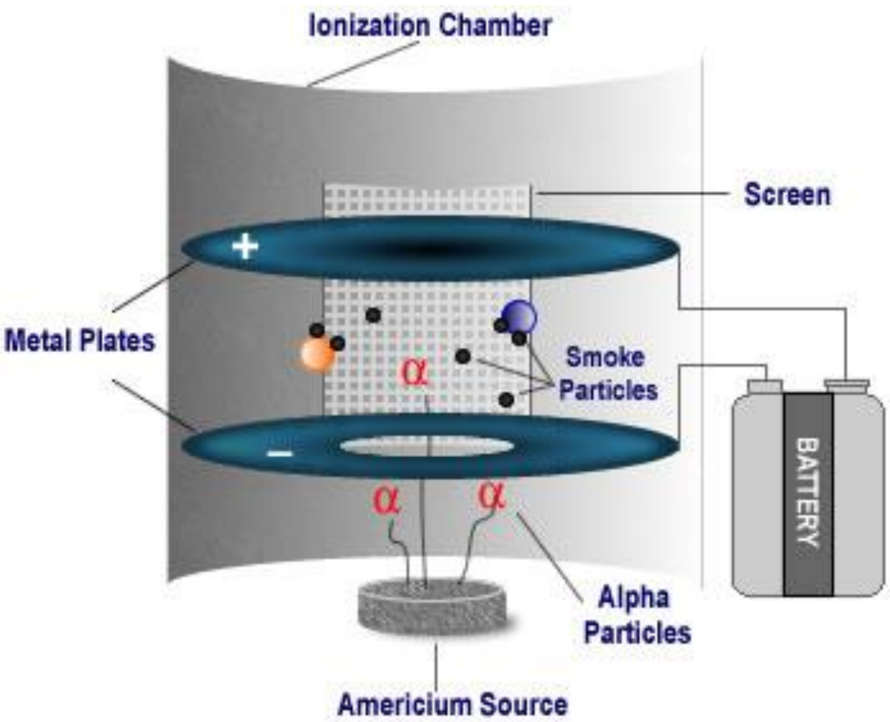
Operating gas detectors: voltage

- Tunable parameter: field strength
- Qualitatively different behavior vs. field



Operating Regions of Gas-Filled Detectors

Smoke Detector



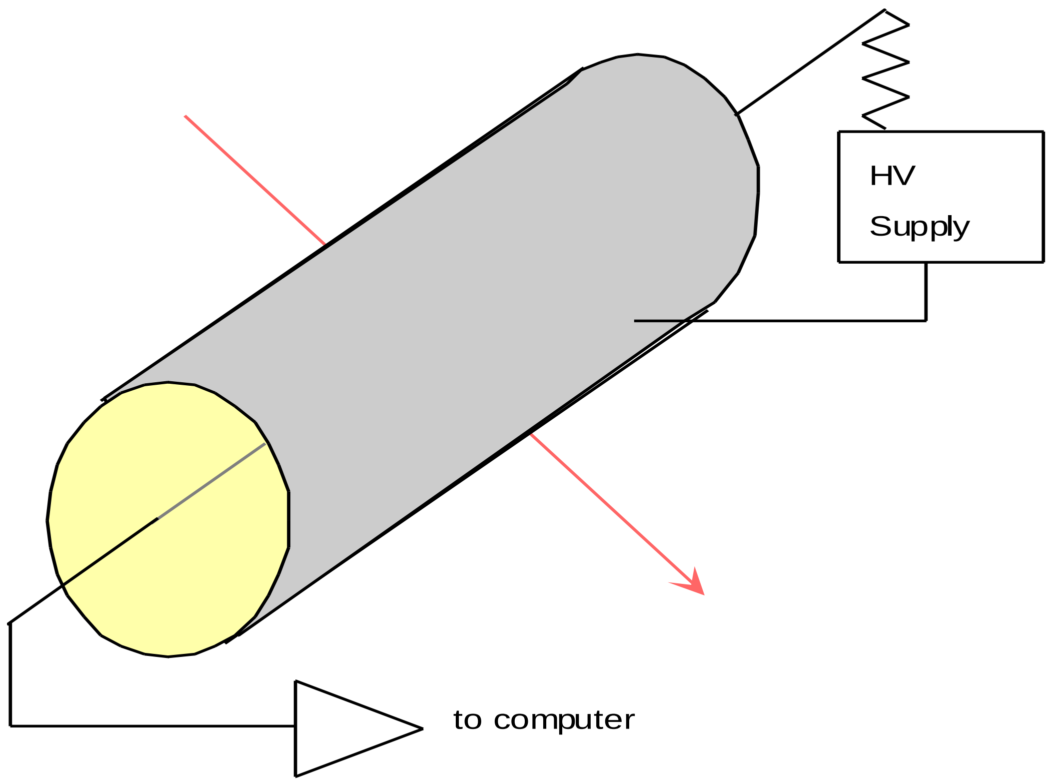
^{241}Am: Half life:432 years
α-emitter.

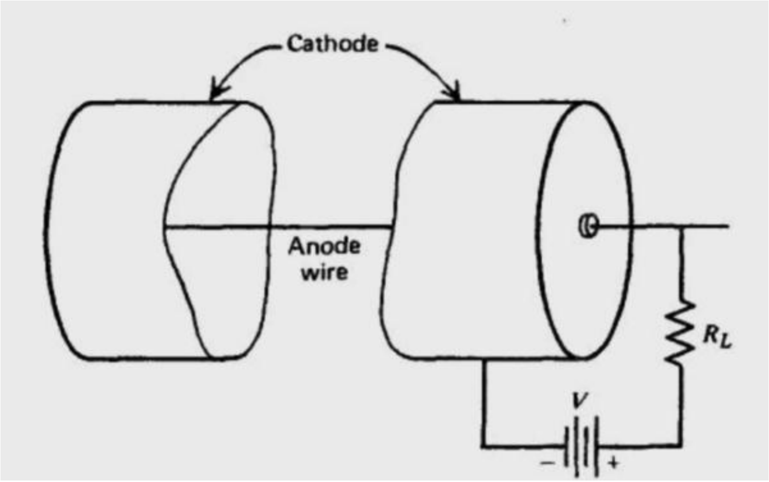
The radioactive isotope americium-241 in the smoke detector emits ionizing radiation in the form of alpha particles into an ionization chamber(which is open to the air). The air molecules in the chamber become ionized and these ions allow the passage of a small electric current between charged electrodes placed in the chamber. If any smoke particles pass into the chamber the ions will attach to the particles and so will be less able to carry the current. An electronic circuit detects the current drop, and sounds the alarm.

Proportional Counters

- Operates at higher voltage than ionization chamber
- Initial electrons produced by ionization
  - are accelerated with enough speed to cause additional ionizations
  - cause additional free electrons
  - produces more electrons than initial event
- Process is termed: gas amplification

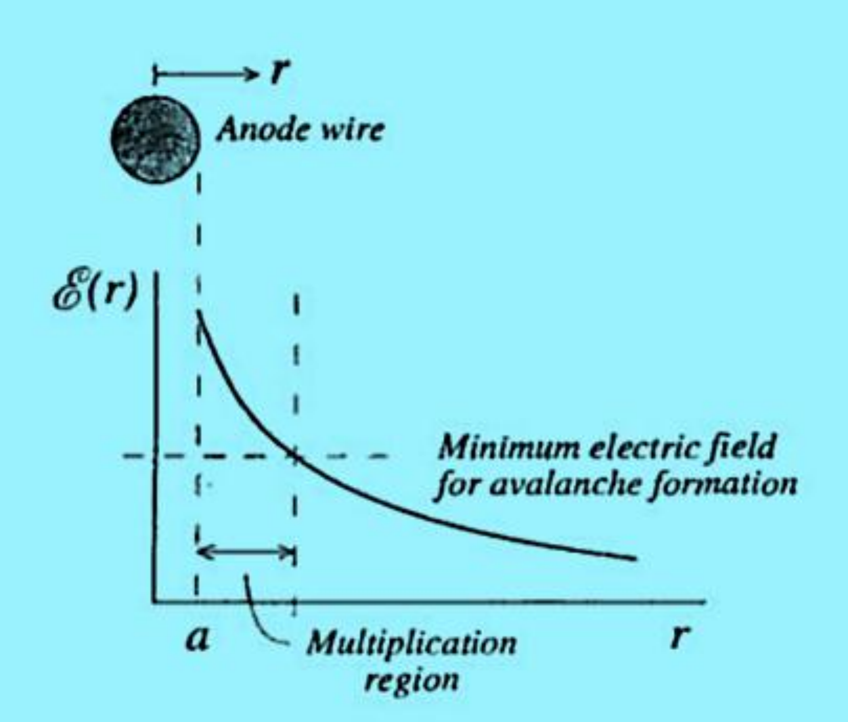
A Single-wire Proportional Chamber





Basic elements of a proportional counter. The outer cathode must also provide a vacuum - tight enclosure for the fill gas. The output pulse is developed across the load resistance R_L

Pulse shape is independent of the position of interaction.



$$\mathscr{E}(r) = \frac{V}{r \ln(b/a)}$$

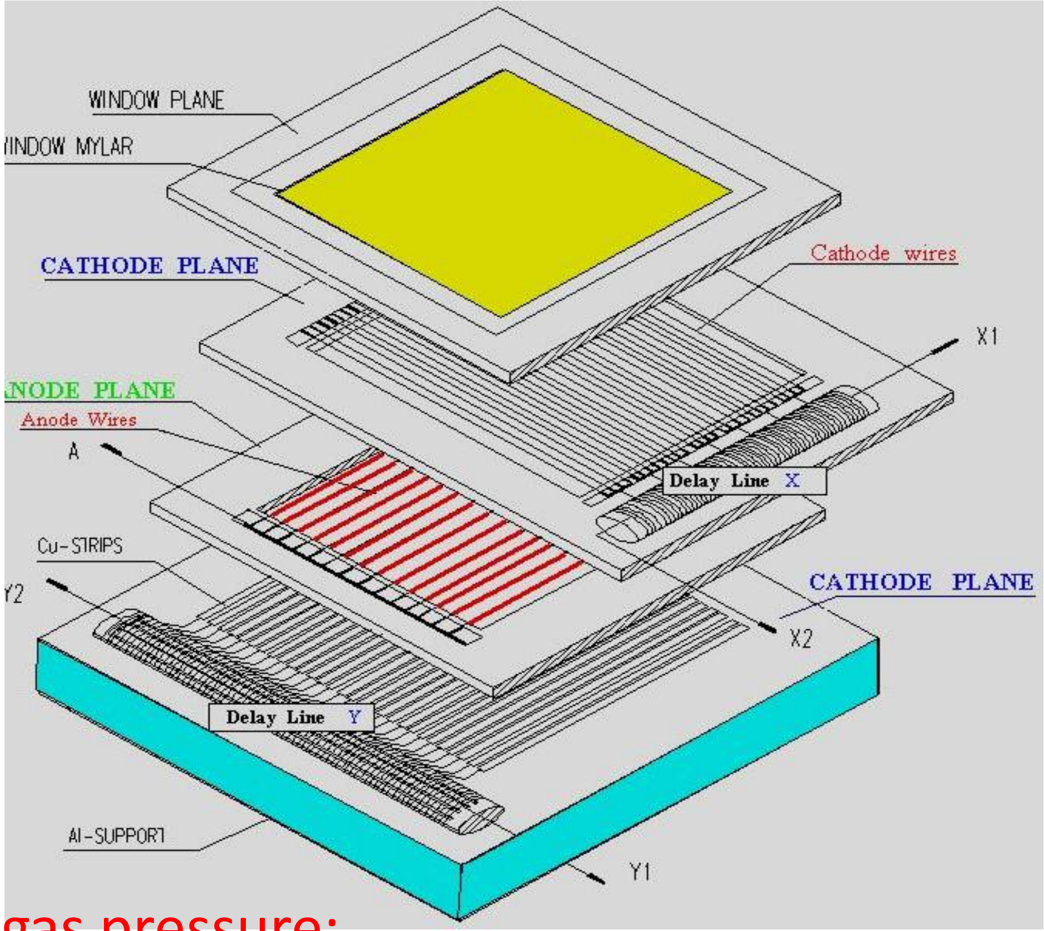
The rapid decrease in the electric field with distance from the anode wire limits the multiplication region to a small volume.

Multi wire proportional counter

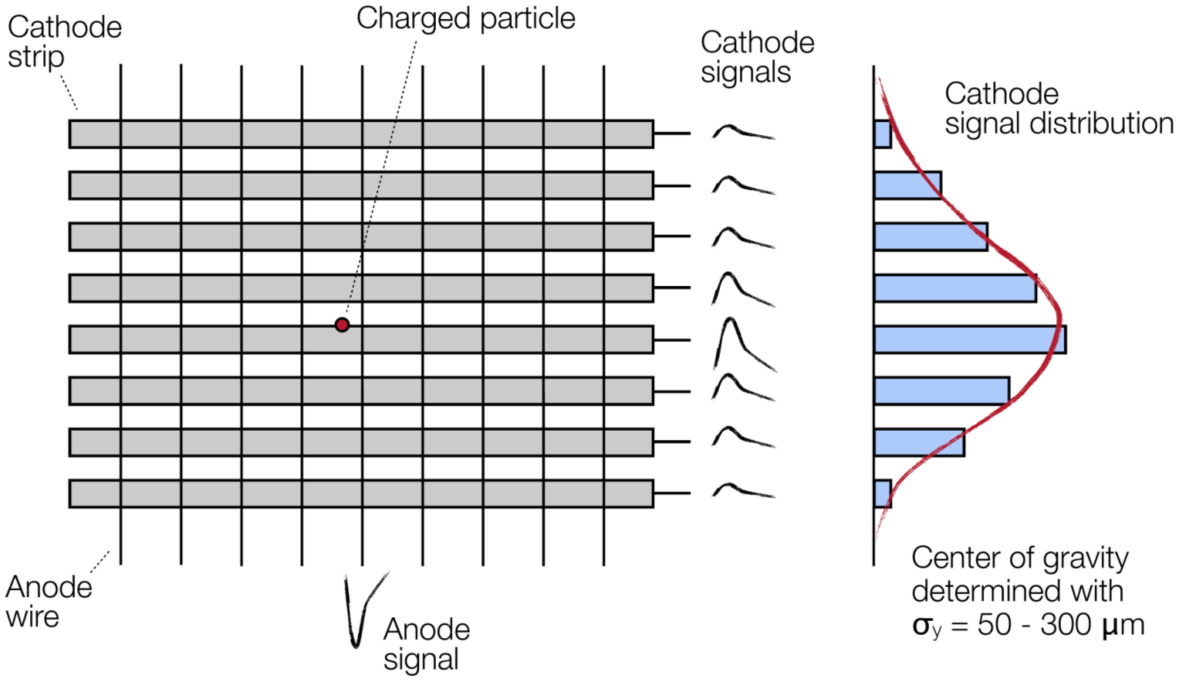
position localization of the ionizing particles.

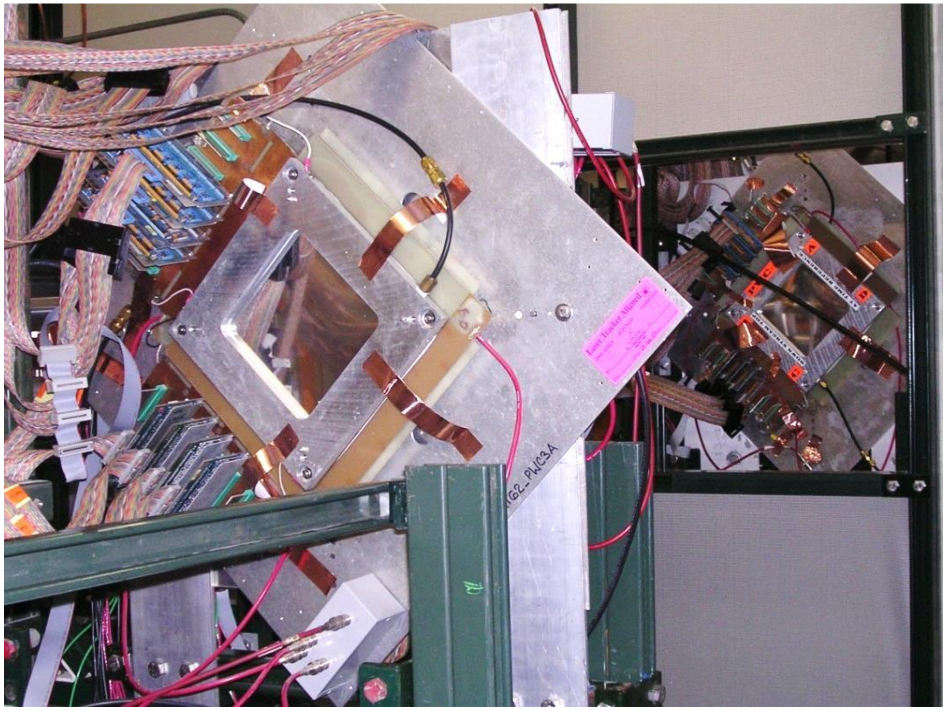
Array of thin wires: placed between two conductive planes serving as cathodes, so that the thin wires acts like an individual proportional counter.

The electrons of the primary ionization drift towards the wire which is closest and get multiplied in its vicinity. Thus sensing the anode wire which carries the negative signal determines one coordinate of the incident radiation.

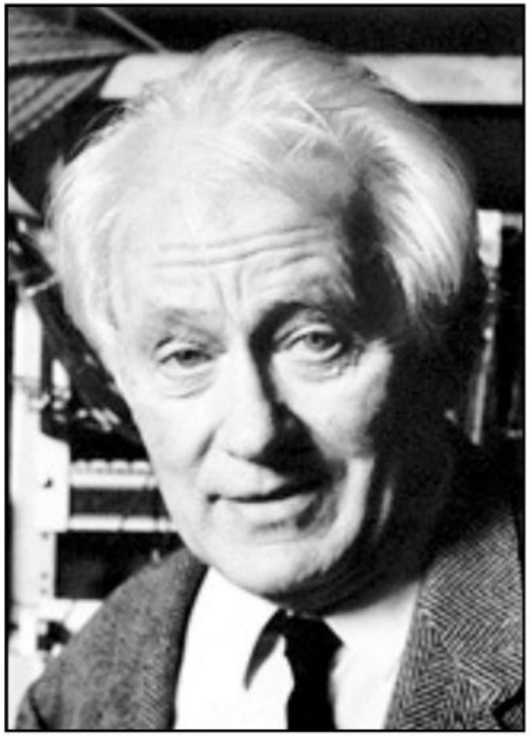


MWPC are operated at very low gas pressure: transparent to low mass charged particle.





G.Charpak
Nobel Prize 1992



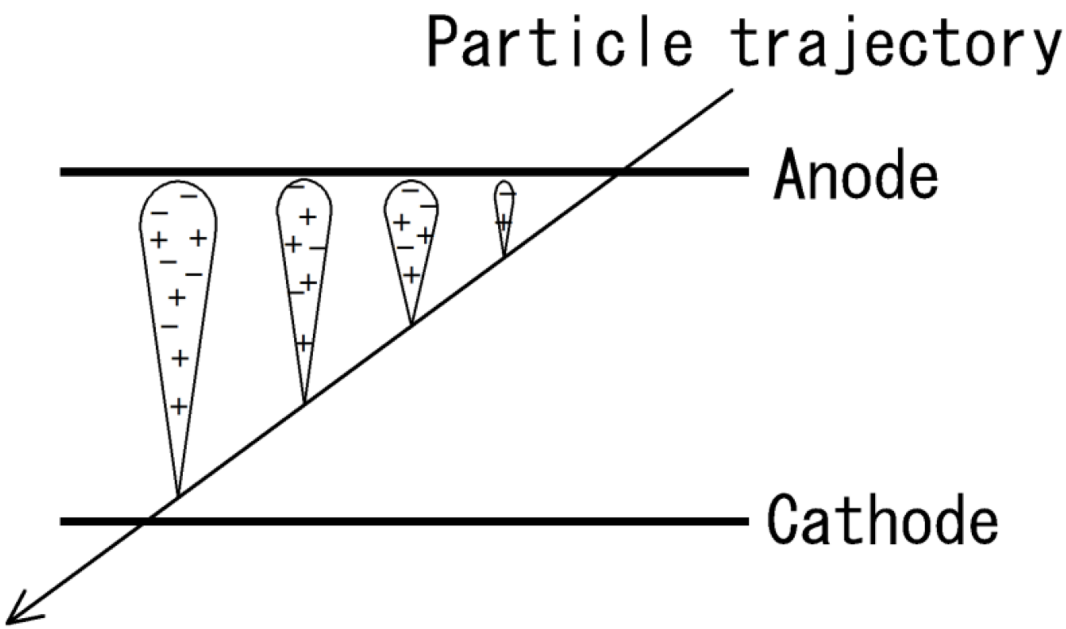
What is a PPAC?

(Parallel Plate Avalanche Counter)

- Two flat, conducting plates with a little gas in between
- Simple, low cost device
- Can be radiation hard
- Unaffected by heat, light
- No electronics or photodetectors attached

Timing information is more important than energy resolution

Detection of heavy charged particle



A homogeneous electric field is produced between the plates, which under the condition of relative low gas pressure, can reach a value of as high as $4x10^6$ V/m

A charged particle that traverses the gas between the plates leaves a trail of ions and electrons that are multiplied by usual gas multiplication process.

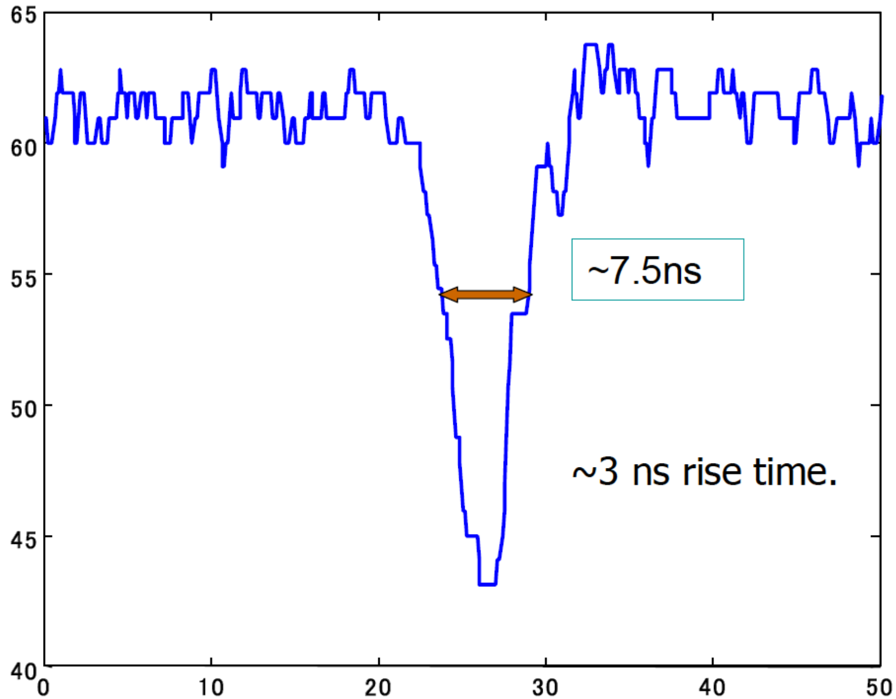
Maximum gain ~ 10^4 is possible.

Timing response of a PPAC

■PPAC output

Fast rise time due to higher reduced electric field,

Low energy loss & constant pulse height



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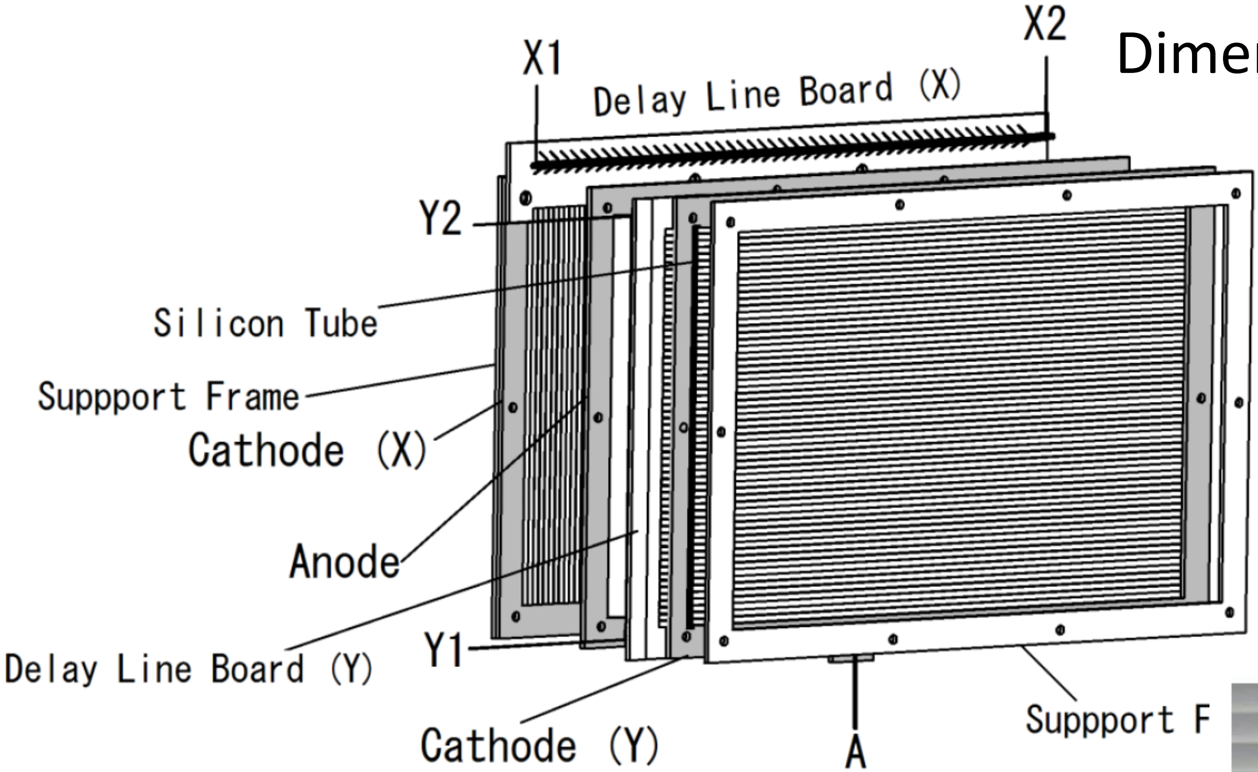
Rise time~ 3nsec.

Dimension: 240mm x 150mm

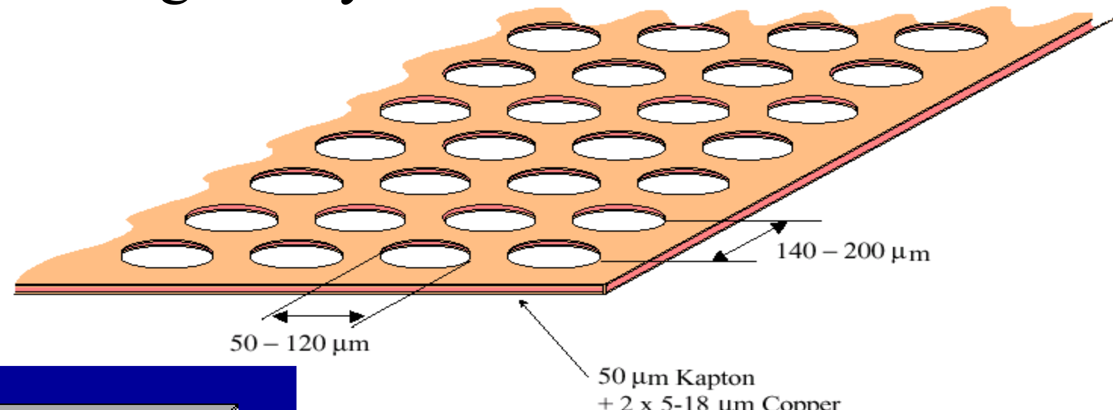


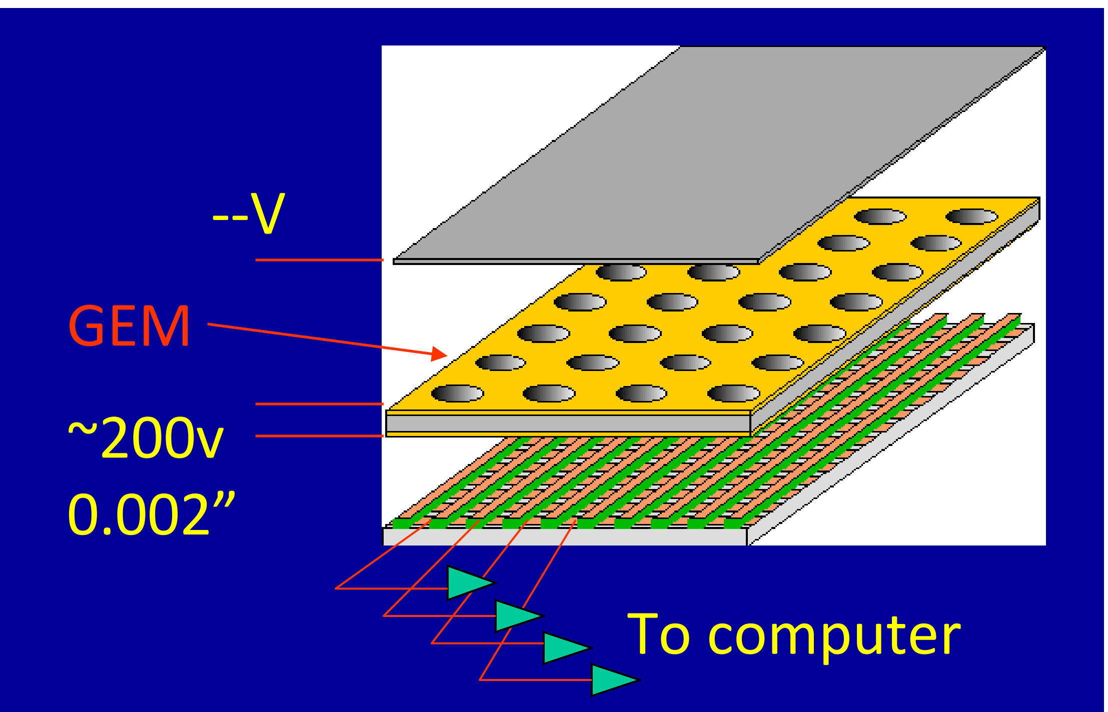
Schematic view of a double sided PPAC

Gas Electron Multiplier (GEM)

- Gas *Ionization* and *Avalanche Multiplication*
  - … a different way to get an intense electric field,
  - … without dealing with fragile tiny wires.

Consist of insulating foils with conductive surfaces with regular pattern of small-diameter etched holes





Modest voltage difference leads to field **E** ~ V / h ~ (200V / 5*10^{-3}cm) = 40kV/cm in holes, providing amplification

Several GEMs in series can provide amplification of ~10^4

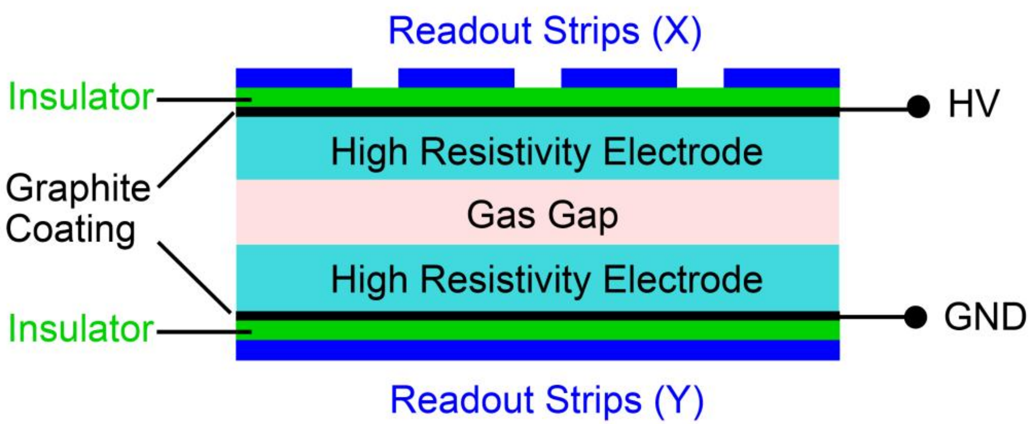
Large area gas detectors

- Need to cater large areas (e.g. 100’s of m^2)
- cost constraints; need cheap and reliable technology
- Still desire good (sub-mm) position resolution
- Calls for simple detectors operating in limited streamer mode to produce large signals, since electronics needs to be cheap too

RPC – resistive plate chambers

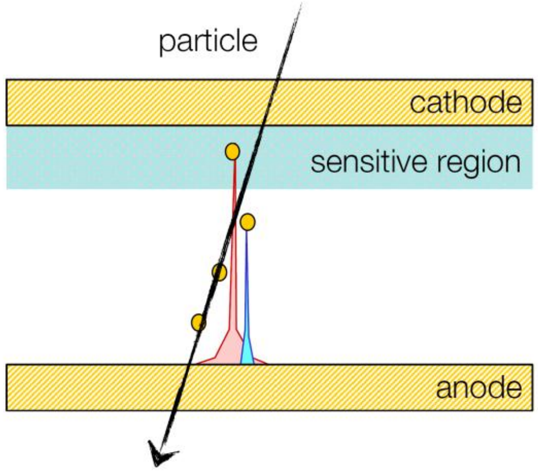
- Consist of few mm gap between highly resistive and flat planes of glass or ceramic with a high potential (~10kV) across them

Electrons of ionization clusters start to produce an avalanche immediately



Schematic image of typical RPC geometry

Only avalanches traversing full gas gap produce detectable signal: Limited signal region close to cathode



Schematic view of avalanche process

Gap size matters!
[the smaller the better]

Scintillator

Scintillation detectors

The disadvantage of gas filled counters is their low efficiency. This can be overcome by going to detectors with higher densities (solids, liquids).

However to be a workable solid detector we need:

1) material must support high E (to collect the e^- and ions)
2) little or no current must flow in the absence of radiation
3) e^- must be easily removed by radiation and must be able to travel

(1) & (2): Insulator → SEMICONDUCTORS ← (3): conductor

Bulk material in large size was long unavailable. → Scintillation counters (1950)

As a charged particle traverses a medium it excites the atoms (or molecules) in the medium. In certain materials called scintillators a small fraction of the energy released when the atoms or molecules de-excite goes into light.

ENERGY IN $\rightarrow$ LIGHT OUT

There are different types of materials that scintillate:

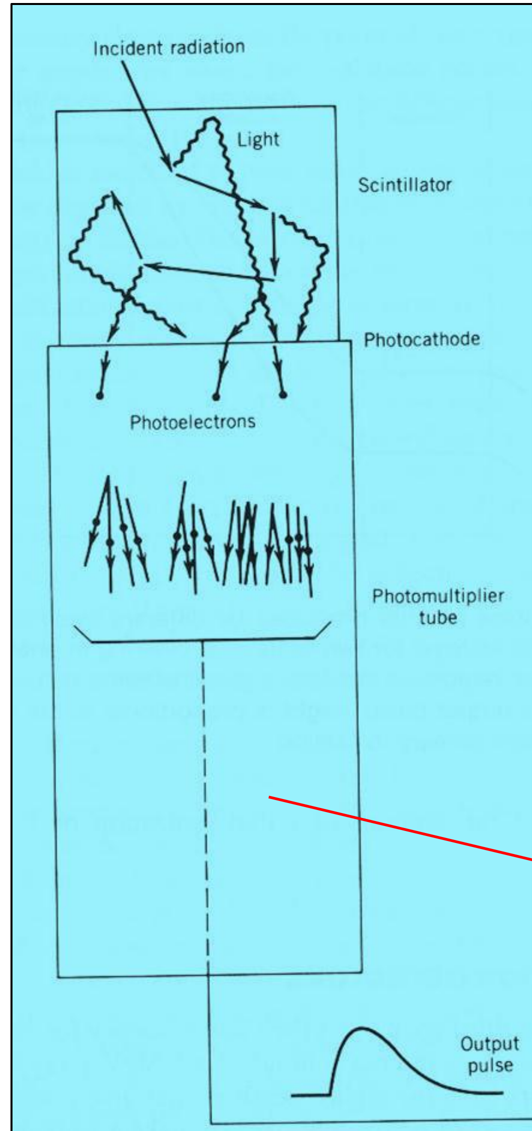
- ♦ non-organic crystals (NaI, CsI, BGO)
- ♦ organic crystals (Anthracene)
- ♦ Organic plastics (see table on next page)
- ♦ Organic liquids (toluene, xylene)

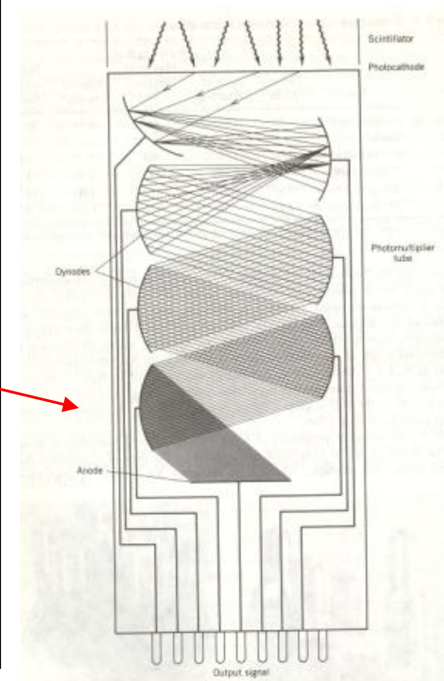
Principle of scintillation detectors

1) Incident radiation interact with material
2) Atoms are raised to excited states
3) Excited states emit visible light: fluorescence
4) Light strikes photosensitive a surface
5) Release of a photoelectron

↓

multiplication

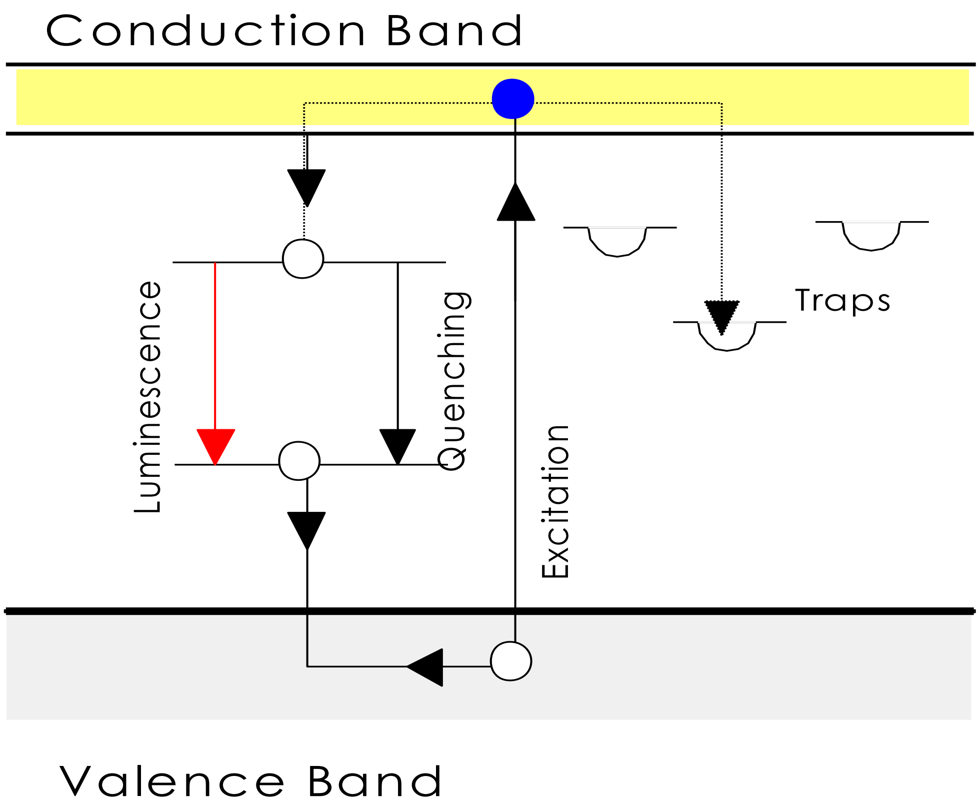




Impurities: added to inorganic scintillators: Activator

Creates special sites in the lattice:
Normal energy band structure is modified

Energy states are created within the forbidden gap through which the electrons can de excite back to the valance band



♦ Lower energy transitions can give rise to visible photons

♦ Serves as a basis of scintillator process

♦ de excitation sites are called Luminescence centers

Energy bands in impurity activated crystal

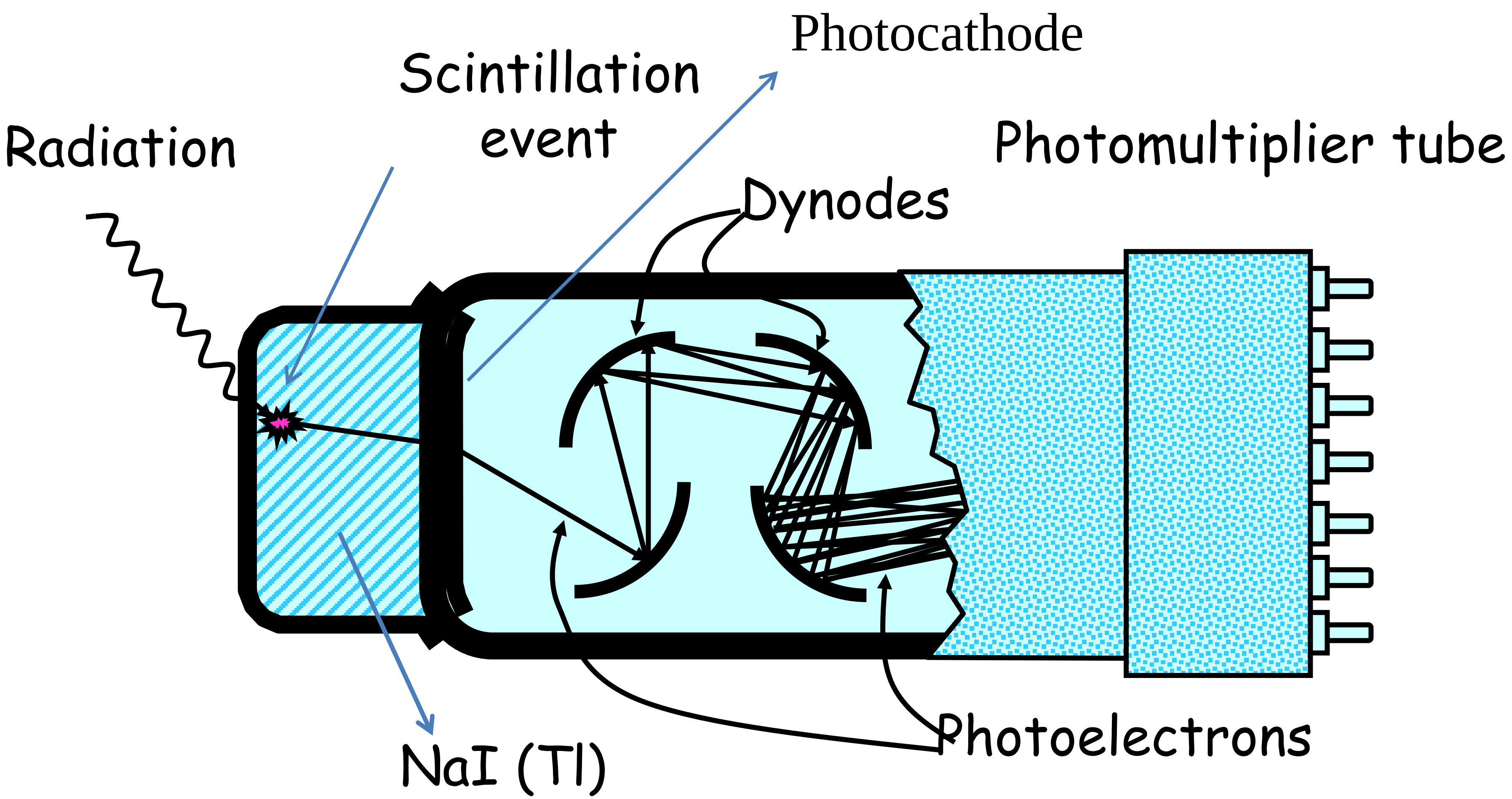
Inorganic (Crystal) Scintillators

- Most are crystals of alkali metals (iodides)
  - NaI(Tl)
  - CsI(Tl)
  - CaI(Na)
  - LiI(Eu)
  - CaF_2(Eu)
  - BGO
  - BaF_2

Detecting Scintillator Output
PhotoCathode & Photomultiplier Tubes

- Radiation interaction in scintillator produces light (may be in visible range)
- Quantification of output requires light amplification and detection device(s)
- This is accomplished with the:
  - Photocathode
  - Photomultiplier tube
- Both components are
  - placed together as one unit
  - optically coupled to the scintillator

Cutaway diagram of scintillation detector & Photomultiplier Tube

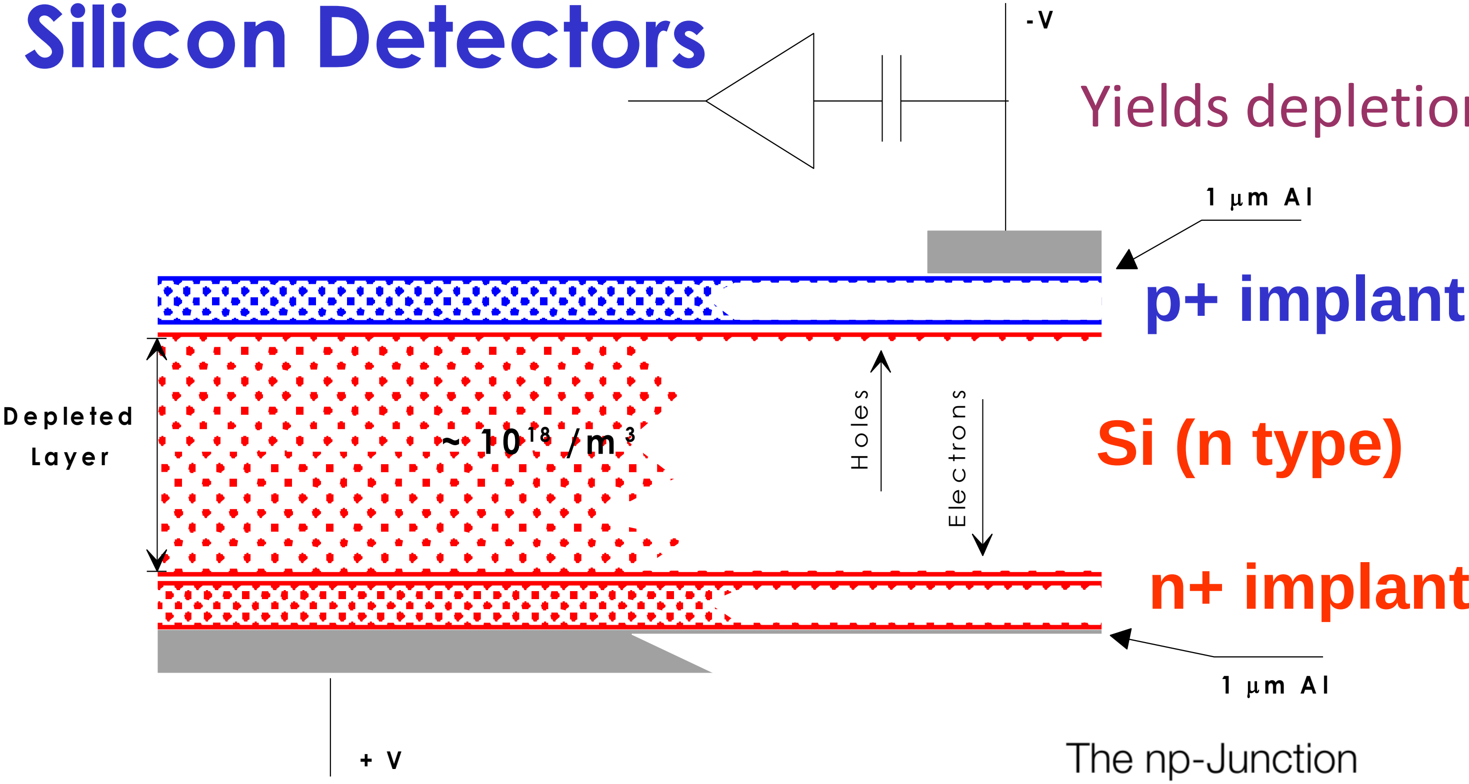


Gain ~ 10^6 - 10^7

Semiconductor Detectors

Silicon Detectors

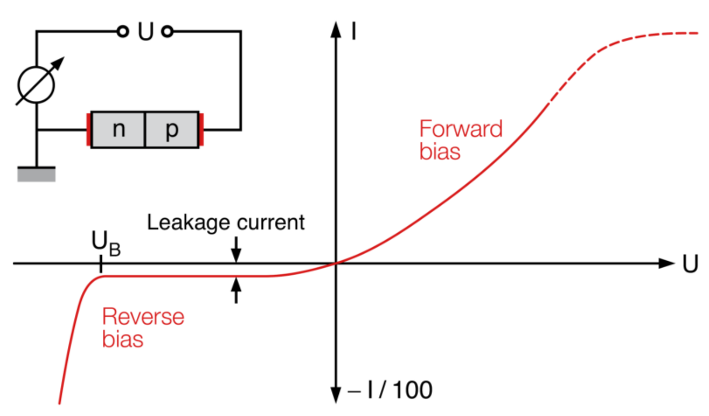
Yields depletion depth ~ 5 mm



The np-Junction

Surface Barrier Detectors

Characteristic I(V) curve of a diode



Advantage:

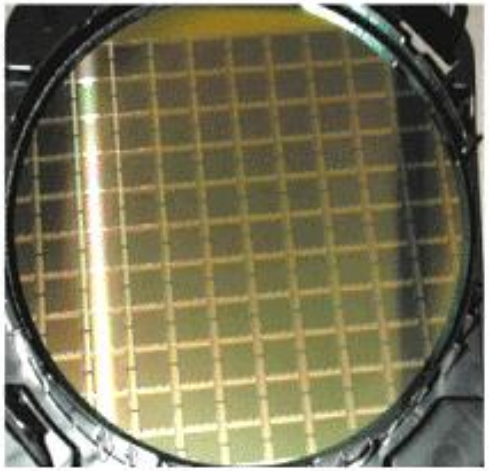
Thin entrance window

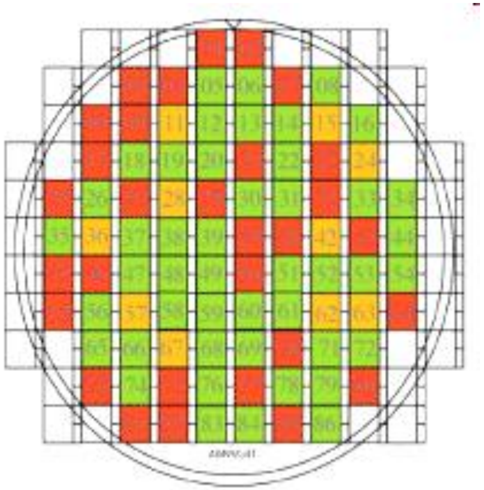
Full depletion allows dE/dX measurement

Increasing bias voltage beyond full depletion gives rise to faster signal rise

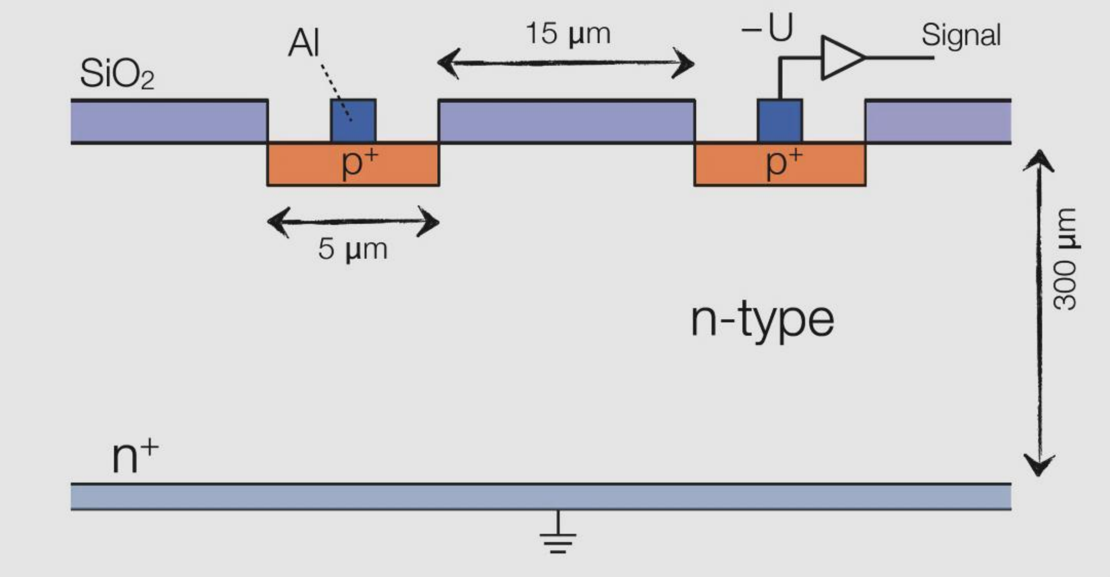
Types of Silicon detectors

- Single-sided strips (readout on p-side)
- Double-sided strips (requires n-side readout as well)
- Pixels





Schematics of Silicon Strip Detector

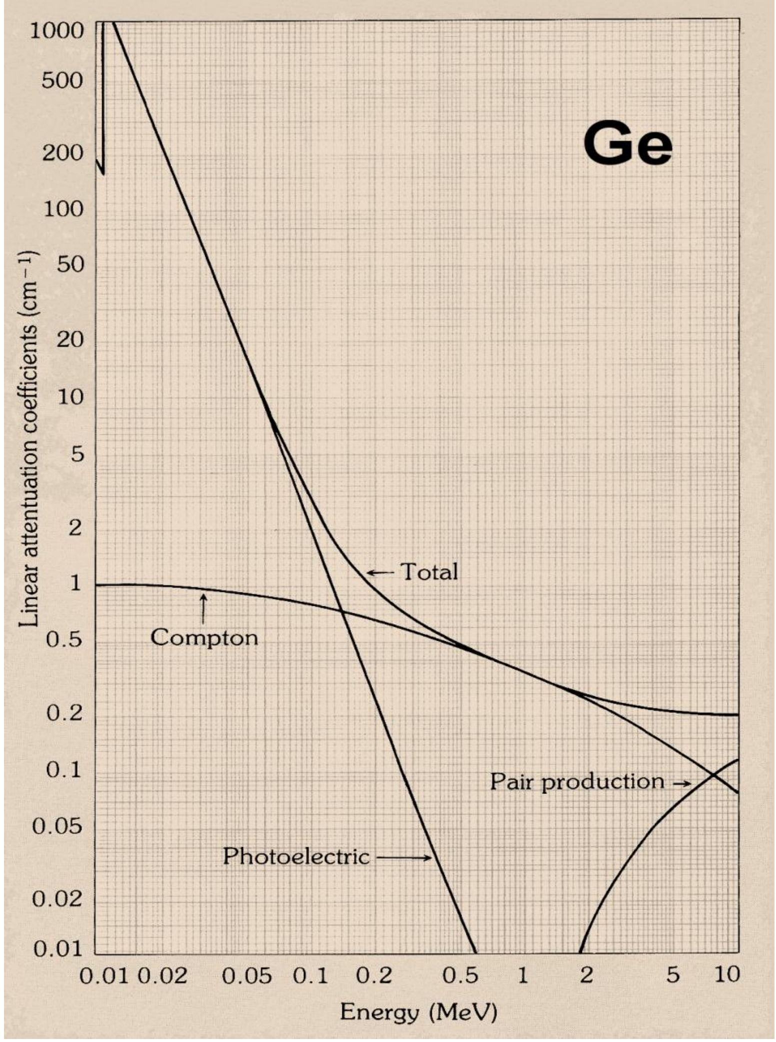


High resistive n-type silicon onto which p+ diode strips with aluminum contacts are implanted

High Resolution Photon Detectors

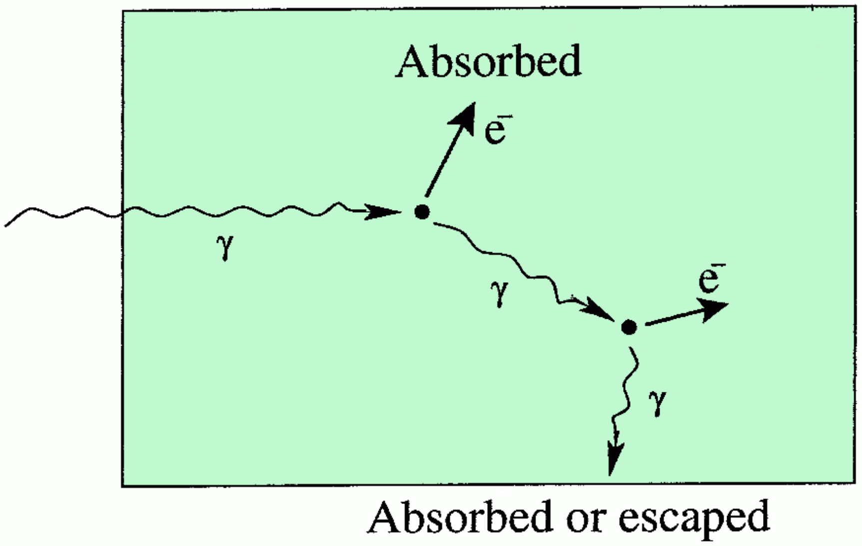
High purity Ge detectors (HPGe)

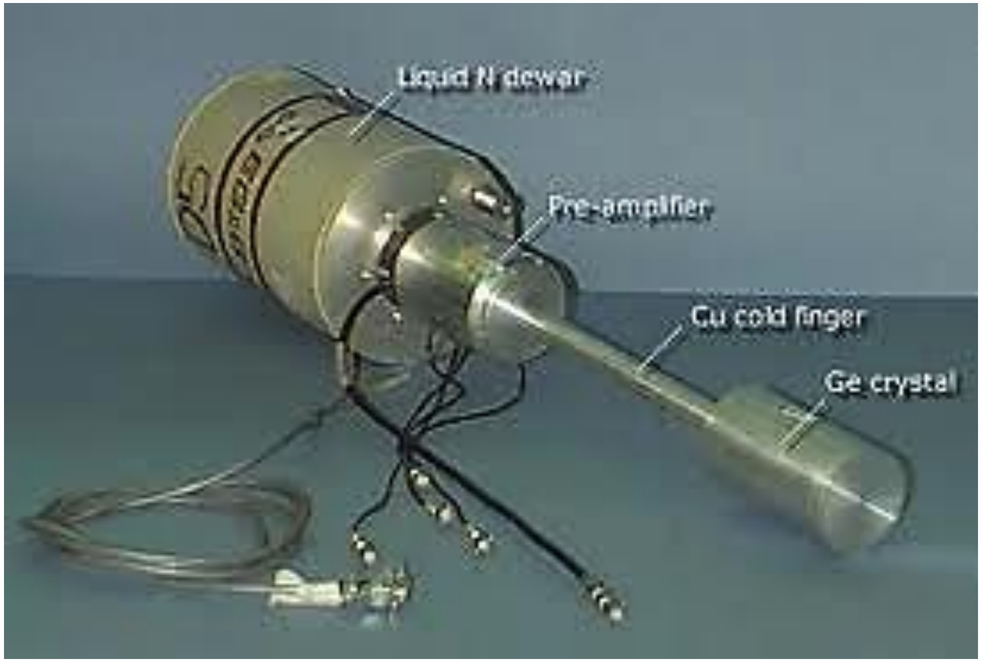
- Resolution < 2 keV at 1 MeV
- Large volume > 100 cc
- Neutron-damage resistant : can be annealed
- Can be warmed up to room temperature for storage
- High e-h mobility : short collection time ~ 100 ns

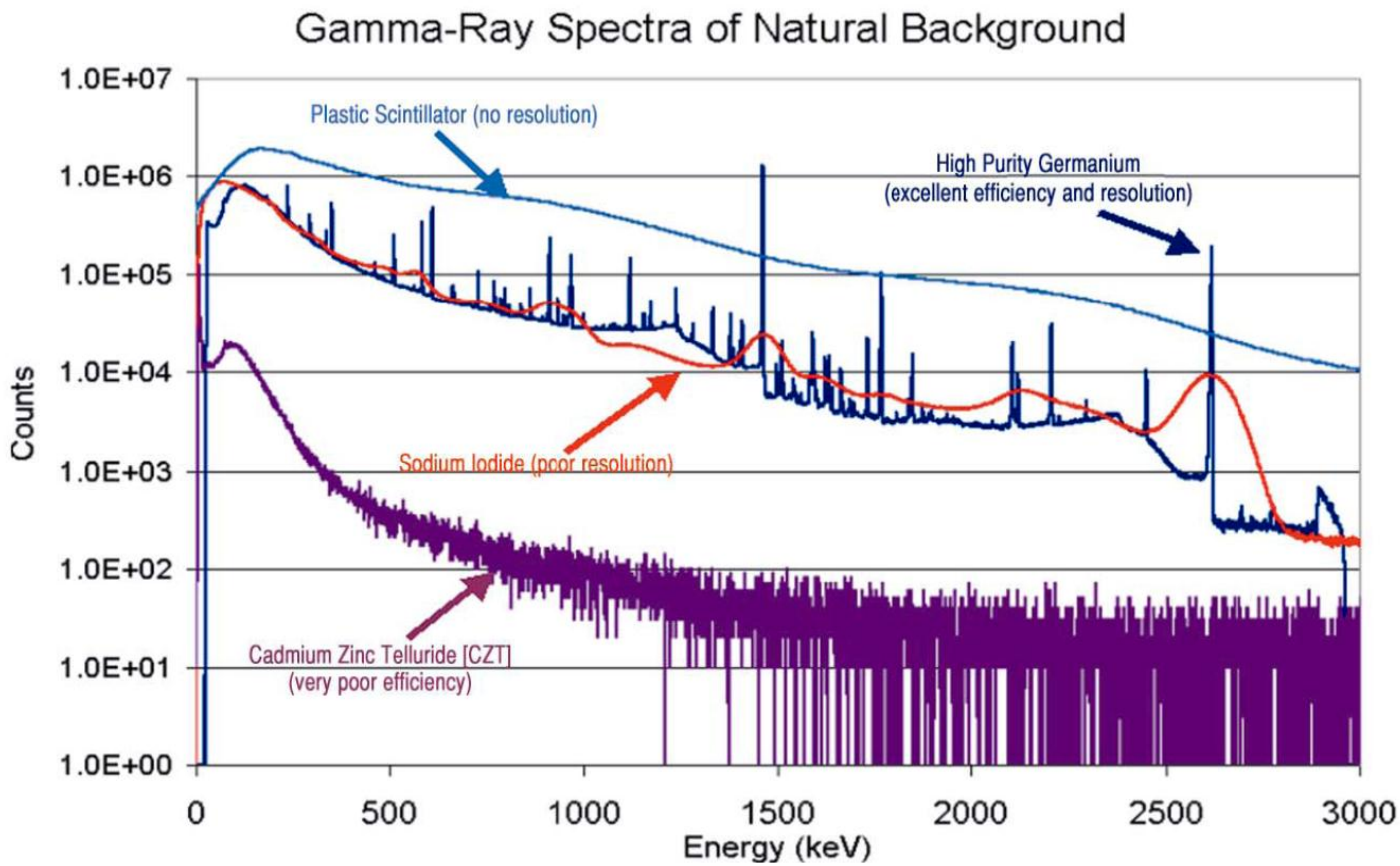


Photon interactions in Ge

- Only ~ 3% of the interactions photo-electric
- Part of photon energy absorbed in Ge after each scattering
- Total number of interactions in the crystal depends on crystal volume
- Larger fraction of E_γ deposited with bigger detectors

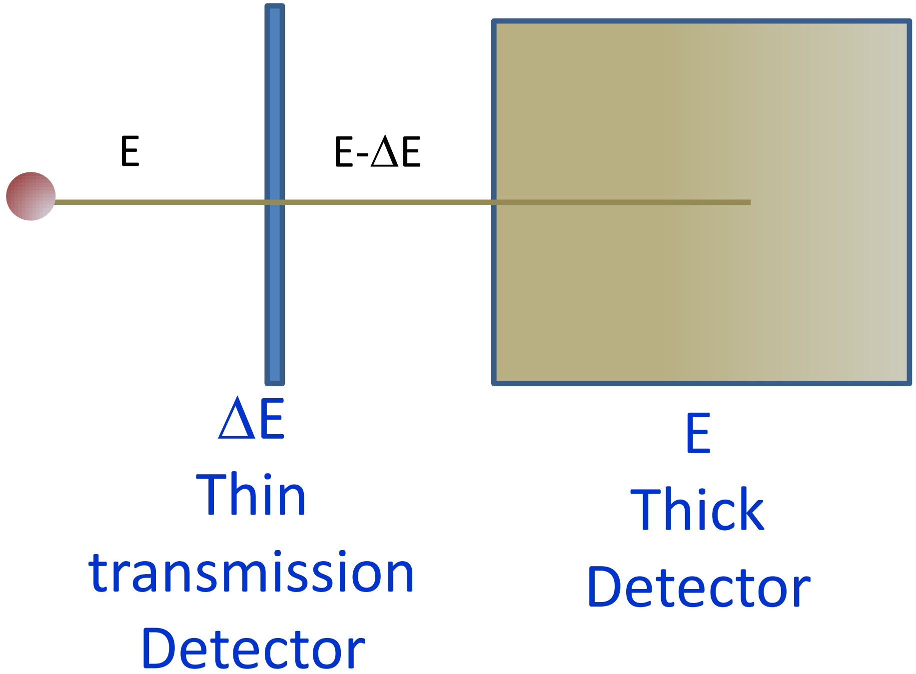






Gamma-Ray Spectra of Natural Background
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
Counts
0
500
1000
1500
2000
2500
3000
Energy (keV)
Plastic Scintillator (no resolution)
High Purity Germanium
(excellent efficiency and resolution)
Sodium Iodide (poor resolution)
Cadmium Zinc Telluride [CZT]
(very poor efficiency)

Composite Detectors



$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB$$

$$B \equiv Z\left[\ln\frac{2m_0v^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

Particle identification

- Energy Loss
  - Heavy Charged Particles lose energy primarily through ionization and atomic excitation as they pass through matter.
    - Described by the **Bethe-Bloch** formula:

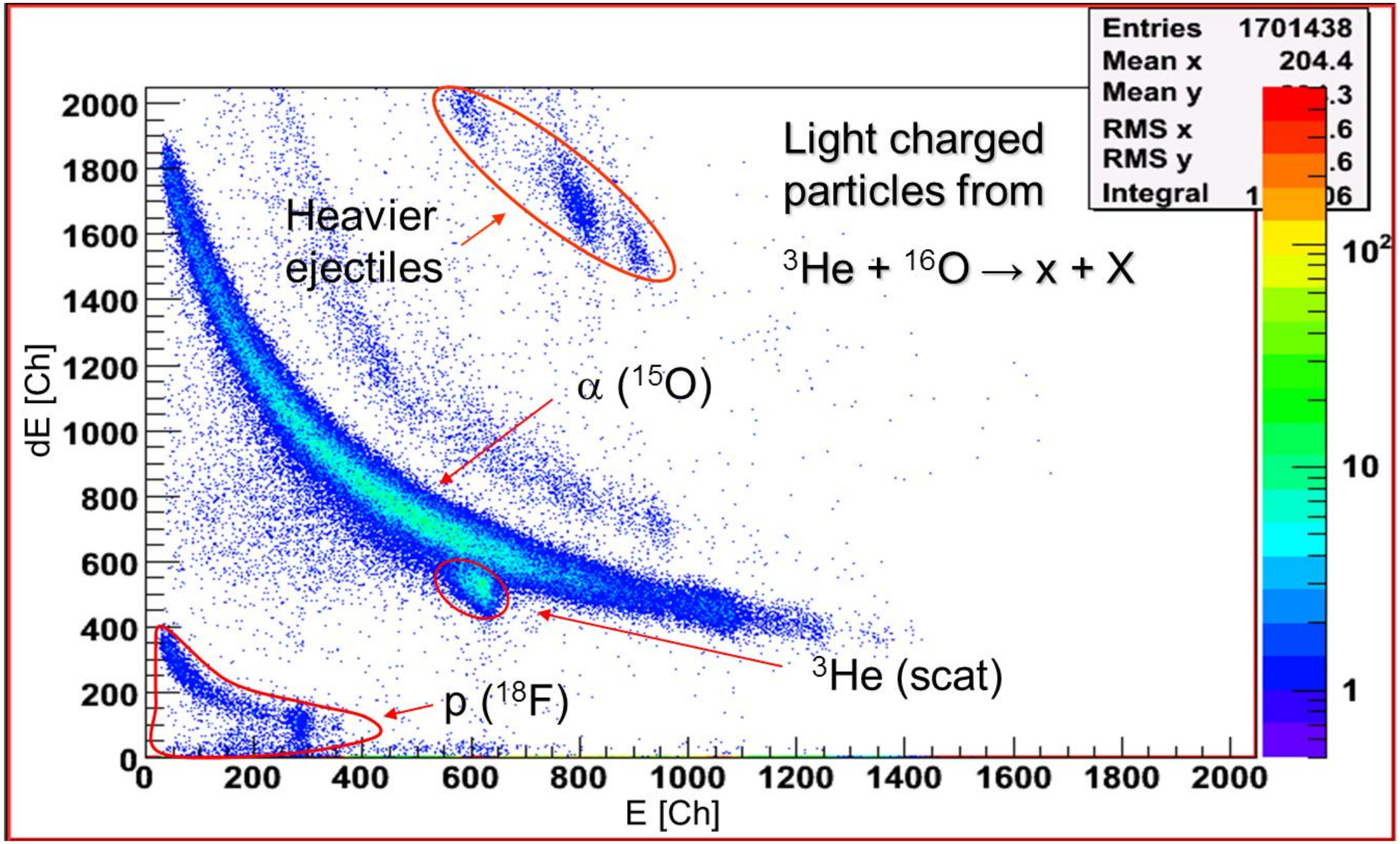
V and ze: velocity and charge of the incident particle

N and Z: Number density and atomic number of the absorber

B: slowly varying function of incident energy

$\Delta E.(E-\Delta E) \sim E.\Delta E = E.\,(dE/dx)\,dx \propto mz^2$

By accepting only those events that occur in coincidence between the two detectors, a simultaneous measurement of ΔE and E is carried out for each incident particle.



Time-of-Flight Method

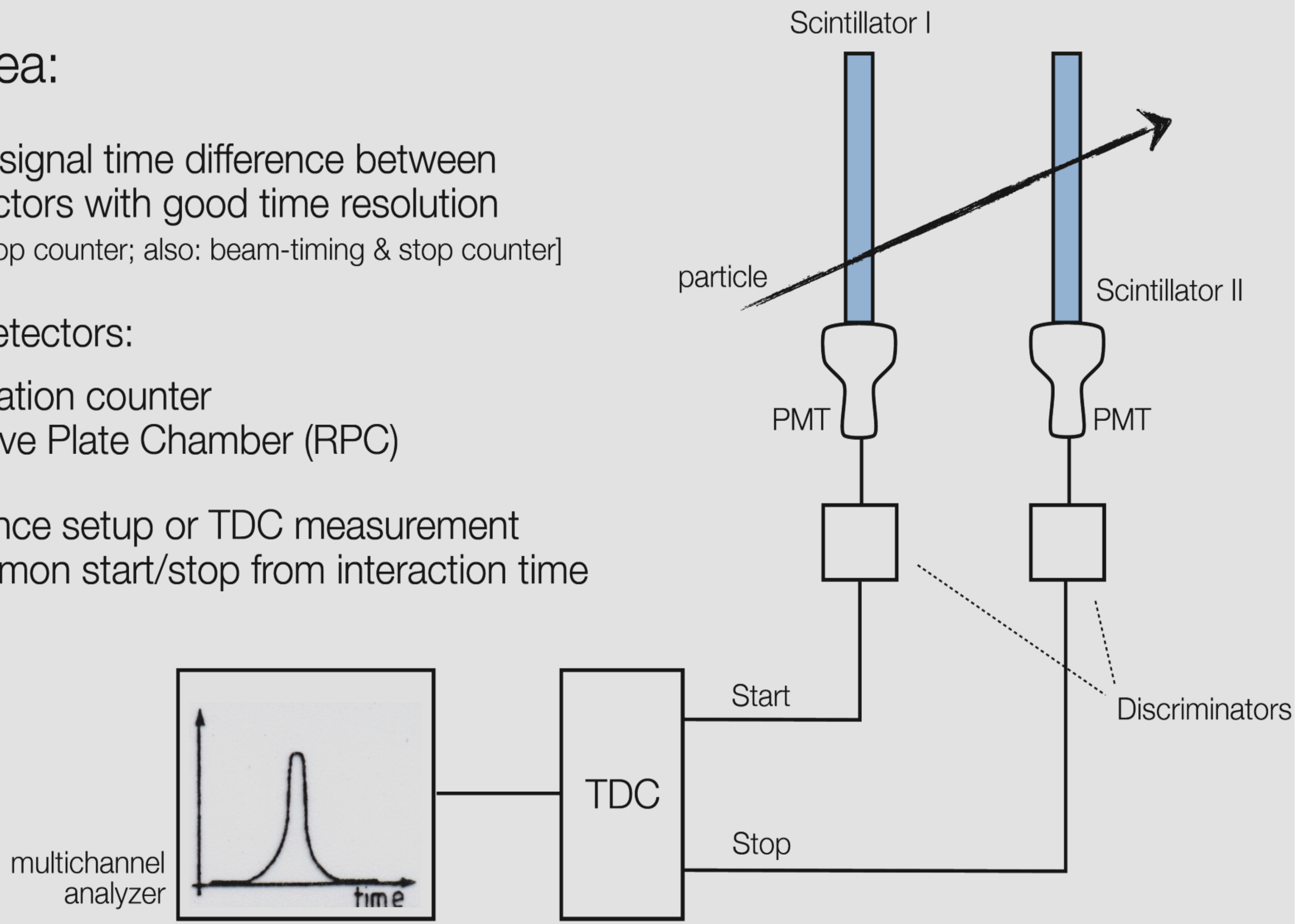
Basic idea:

Measure signal time difference between two detectors with good time resolution
[start and stop counter; also: beam-timing & stop counter]

Typical detectors:

Scintillation counter
Resistive Plate Chamber (RPC)

Coincidence setup or TDC measurement with common start/stop from interaction time



TRIUMF Annular Chamber for Tracking and Identification of Charged particles (TACTIC)

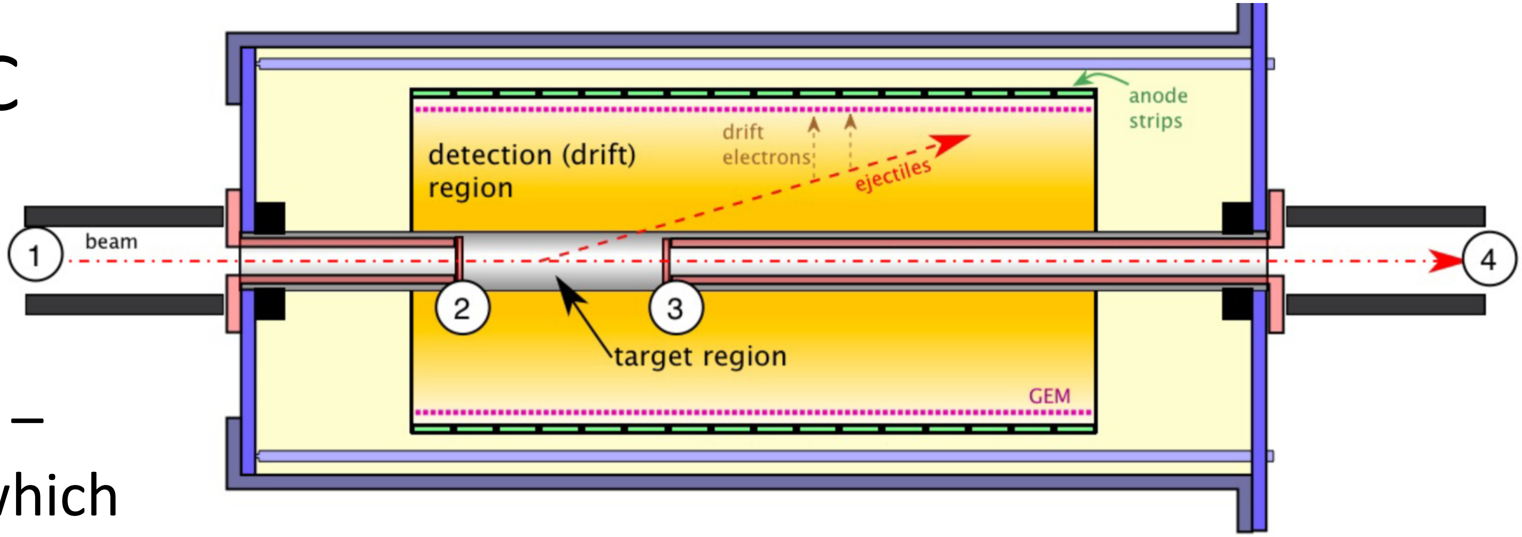
MOTIVATION: study the $^{8}Li(\alpha,n)^{11}B$ reaction

Recent *(rapid neutron capture)* r-process network calculations of core collapse supernovae have included light nuclei and shown that for particular models, two nuclear reaction chains

$\alpha(\alpha n,\gamma)^{9}Be(n,\gamma)^{10}Be(\alpha,\gamma)^{14}C$ and
$\alpha(t,\gamma)^{7}Li(n,\gamma)^{8}\mathbf{Li(\alpha,n)^{11}B}$

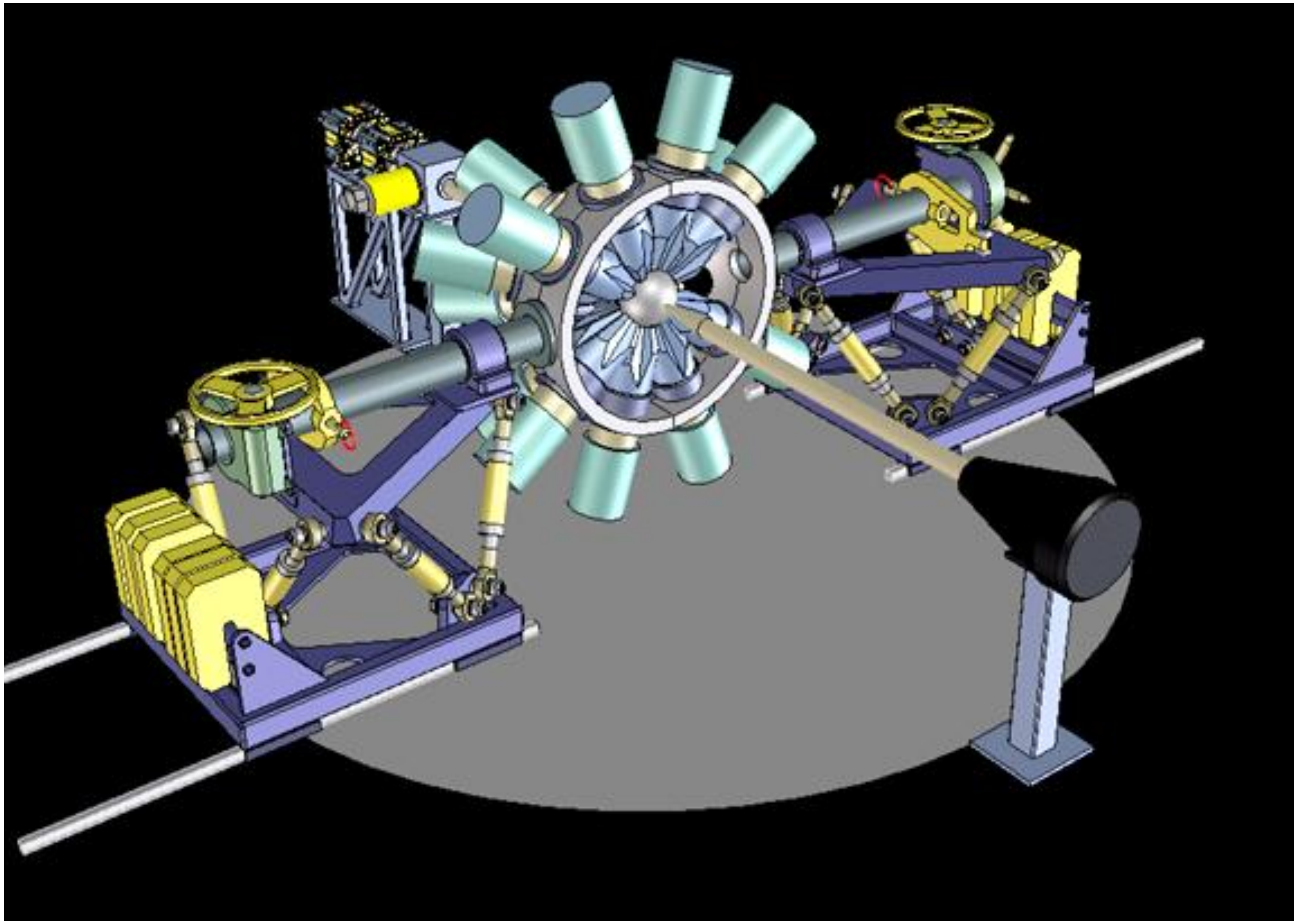
can significantly affect the final abundances of certain heavy nuclei

TACTIC



"active" target –
a detector in which
the target nucleus (in this case 4He) is a component of the detection gas.

When a scattering event occurs the ejectiles pass out of the central cylindrical cathode enter the drift region of the detector. Ejectiles ionize the drift gas ⟶ lose energy. The drift field of the detector is radial, thus the gas ionization is drifted radially from the cathode to the segmented anode. Due to the low energy of the ejectiles, a gas electron multiplier (GEM) is utilized to provide proportional amplification of the small signals. When drift electrons pass through the holes, avalanching occurs but proportionality is maintained.



Array of Detectors is required

- To increase the efficiency.
- To record all the radiation emitted in 4π solid angle.
- To establish relation between various types of radiation from a nuclear reaction

INDRA, a 4Pi charged product detection array at GANIL

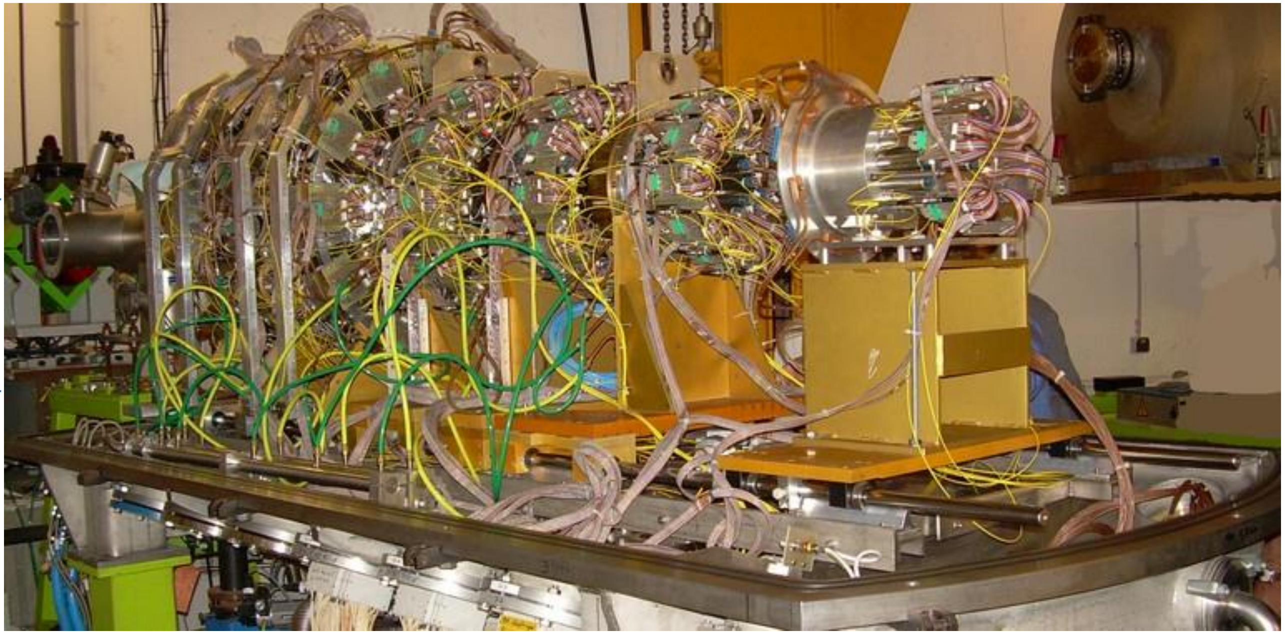
Identification of Nuclei and Detection with Increased Resolutions

Identification de Noyaux et Détection avec Résolutions Accrues

covering 90% of total solid angle

1. plastic scintillators
2. Ionization chamber
3. Silicon detectors
4. cesium iodide (CsI) scintillator
5. telescope comprising a 80-µm thin silicon detector, followed by a 2-mm Si(Li) detector

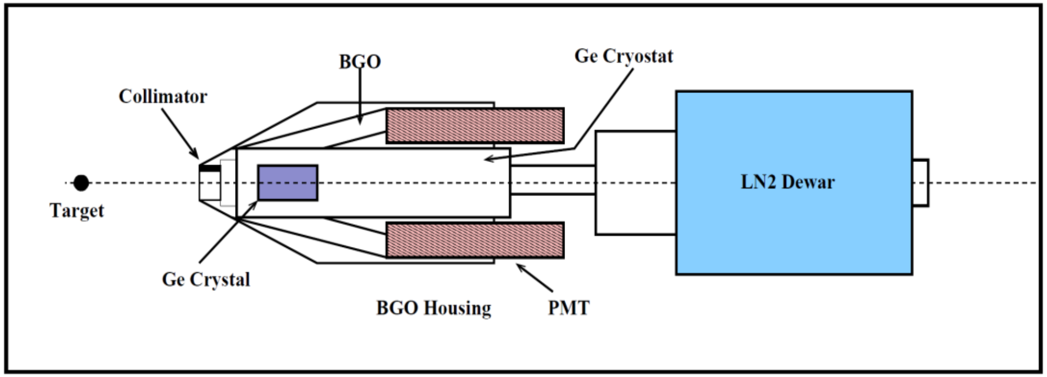
Designed for the study of the decay properties of hot nuclei, formed during heavy ion collisions with energies ranging between 30 and 100 MeV/nucleon.



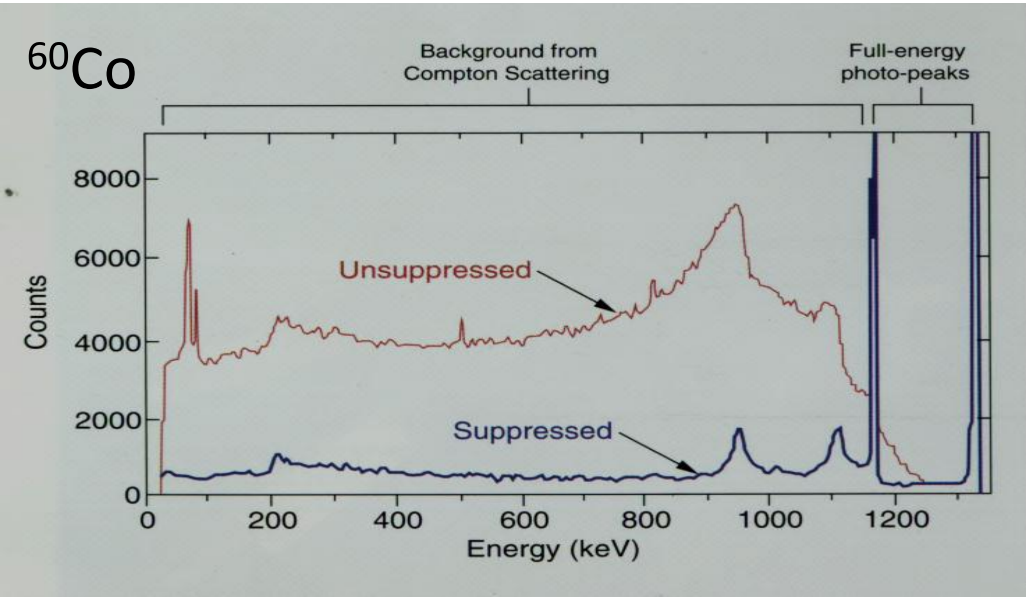
INDRA has a total of 628 detectors

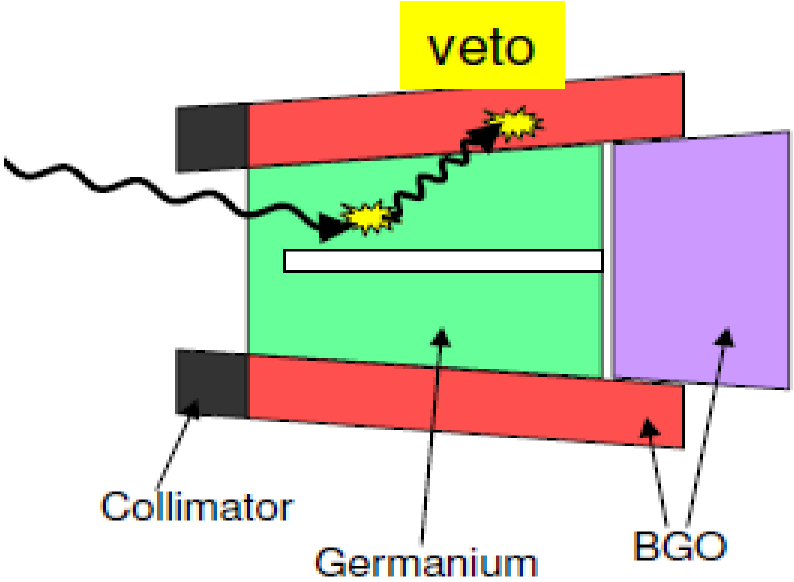
Anti-Compton shields : Why?

Totally absorbed γ = good event
Scattered γ = background



Signal from Ge + signal from BGO=>rejected event

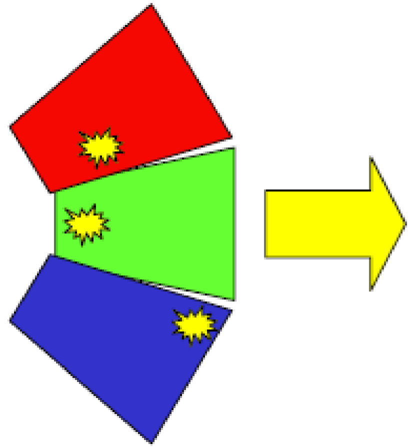




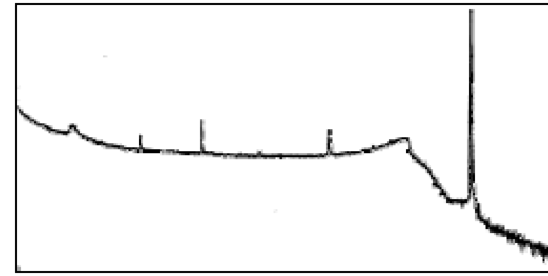
Interaction:

Photo absorption (low energy)
Compton Scattering (intermediate energy)
Pair creation (high energy)

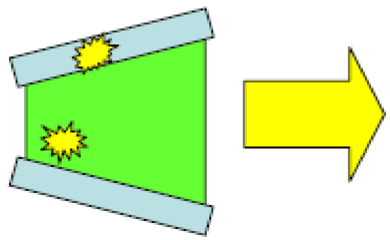
Without Compton suppression shields

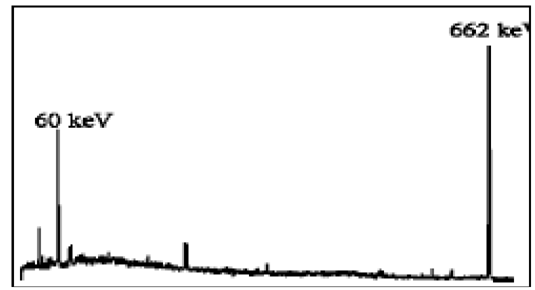


Compton continuum. => Large peak to total ratio



With BGO shielding



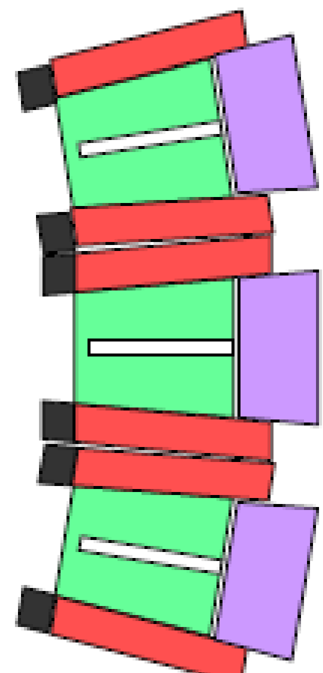


Less solid angle coverage => Big drop in efficiency

peak-to-total ratio

- unsuppressed
  P/T ~ 0.15
- suppressed
  P/T ~ 0.6

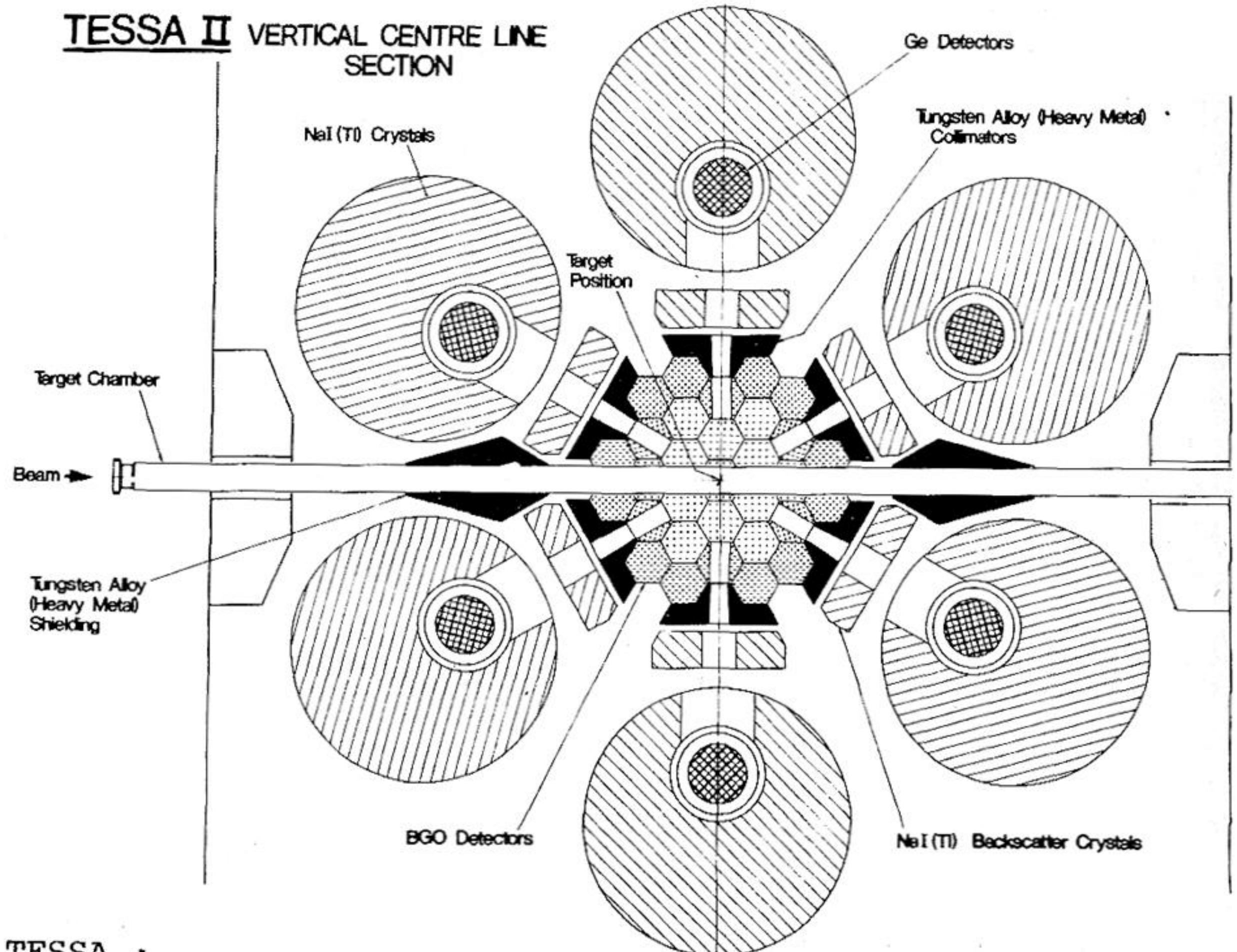
to increase efficiency:
use many detectors



Array

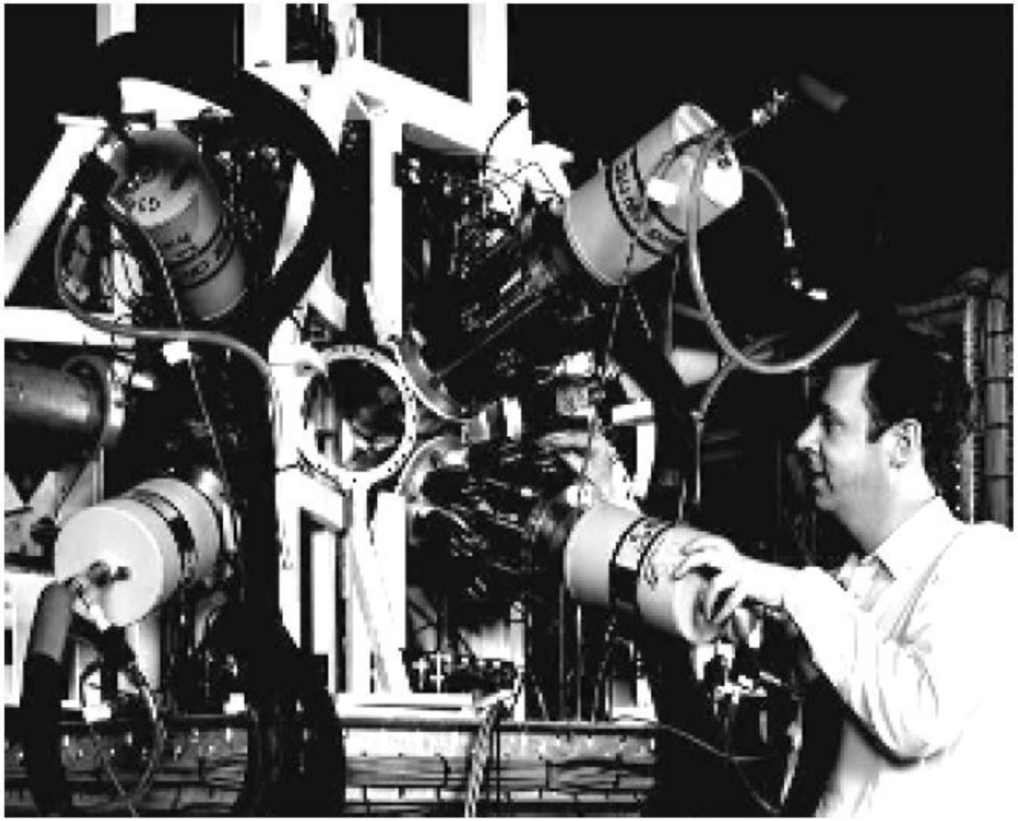
TESSA-II - First Compton Suppressed Array

- 6 Detector Array at Daresbury
- NaI Shield
- Front NaI catcher
- Ge detectors inserted from top



TESSA :

Nucl. Phys. A409(1983)343c



TESSA 2:
6 Compton suppressed
Ge detectors

TESSA3:
12 Compton suppressed
Ge detectors

The quest of high spin superdeformed band in ^{152}Dy

Composite HPGe detectors: Clover

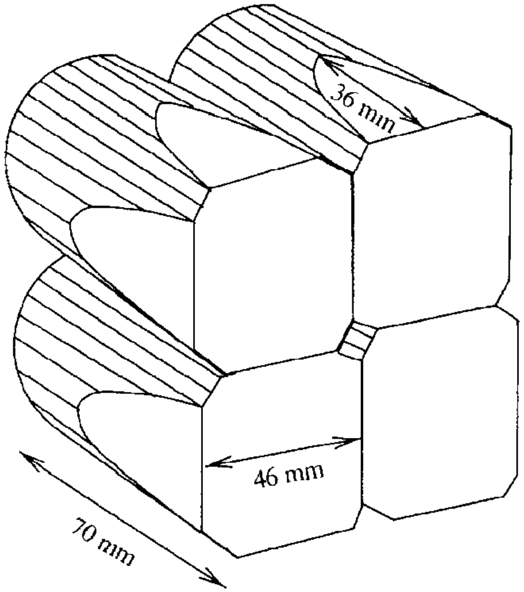
Detectors larger than 7 cm ∅ difficult to fabricate

Large charge collection time & Doppler broadening

Increased neutron damage sensitivity

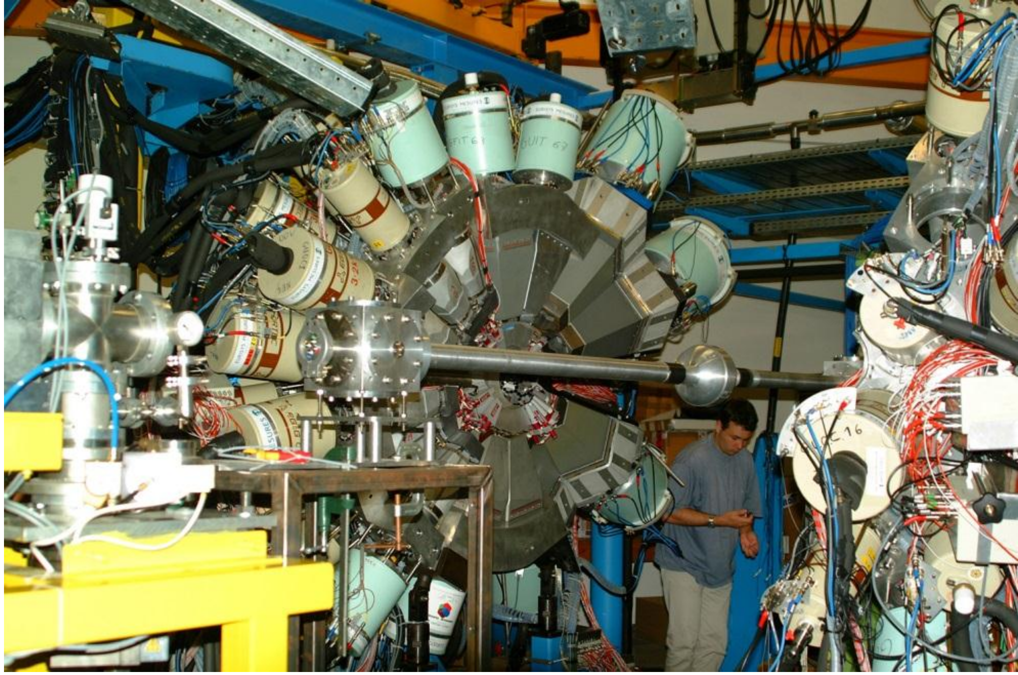
Solution

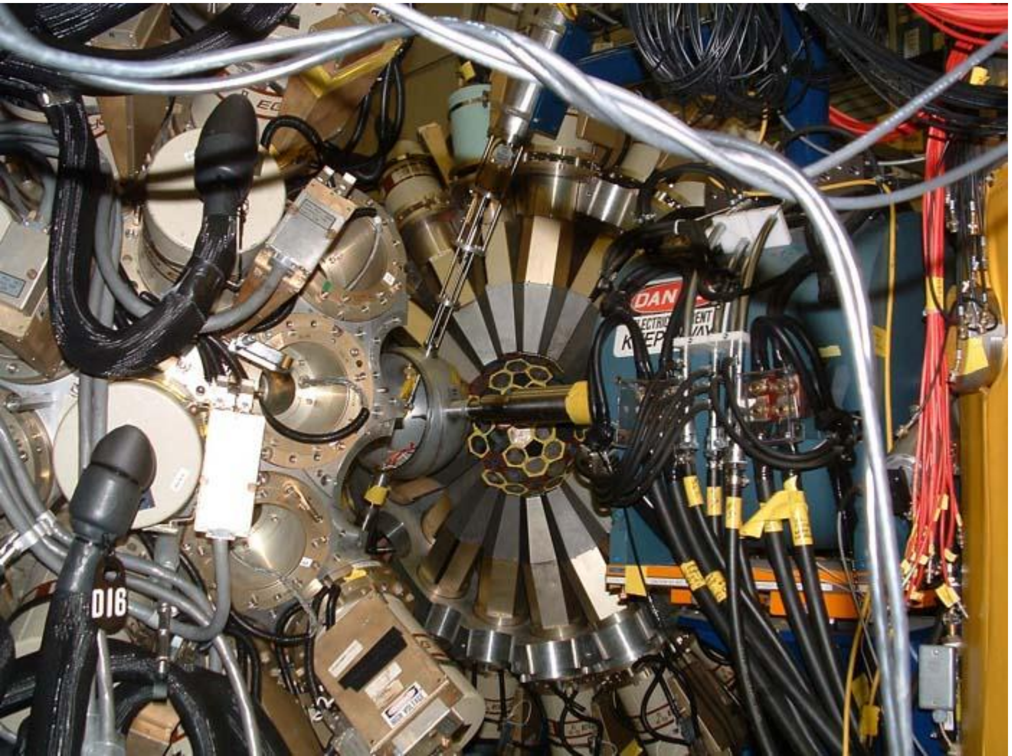
- More than one detector within common cryostat and ACS
- Less dead space due to common ACS
- Increased solid angle coverage & granularity
- Scattering from one detector to another increases photopeak efficiency



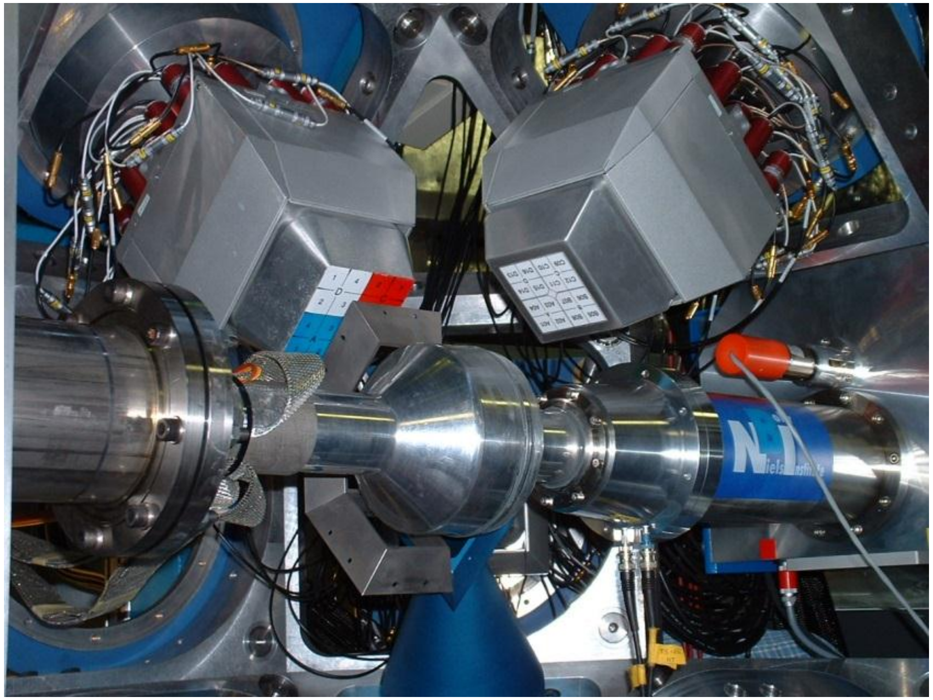
- Four 5 cm ∅ x 7 cm long crystals within the same cryostat
- High probability of a Compton-scattered event in one crystal being absorbed in another crystal
- 50% 'Addback efficiency' at 2 MeV

EUROBALL





GAMMASPHERE

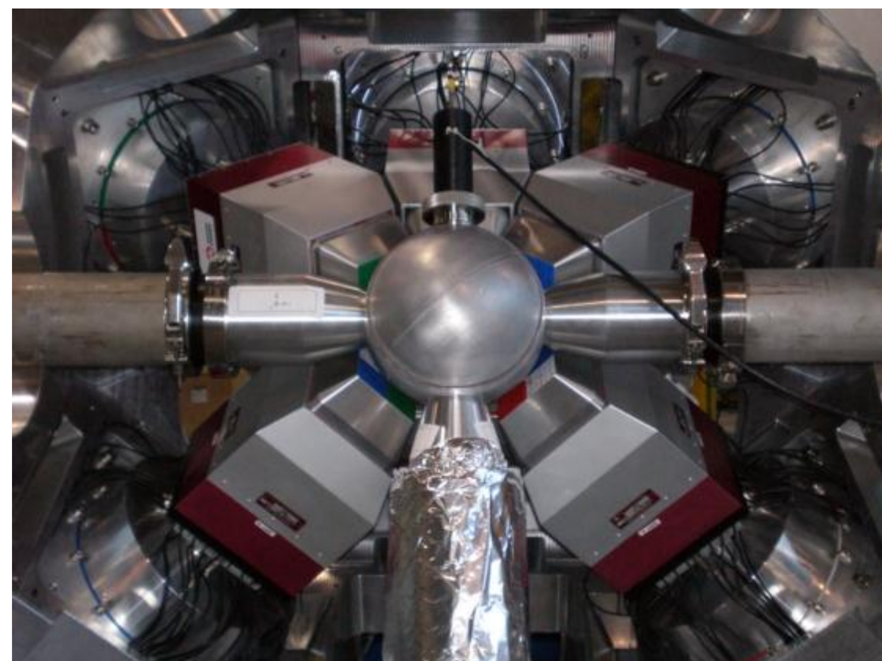


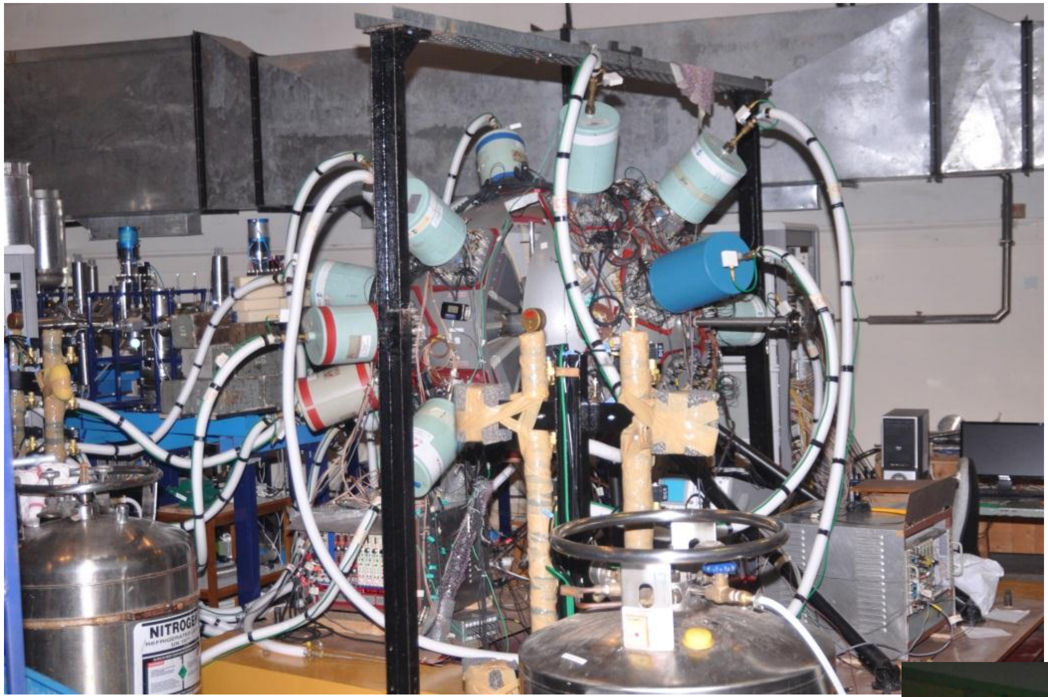
For use with

Radio Active Beam

Exogam

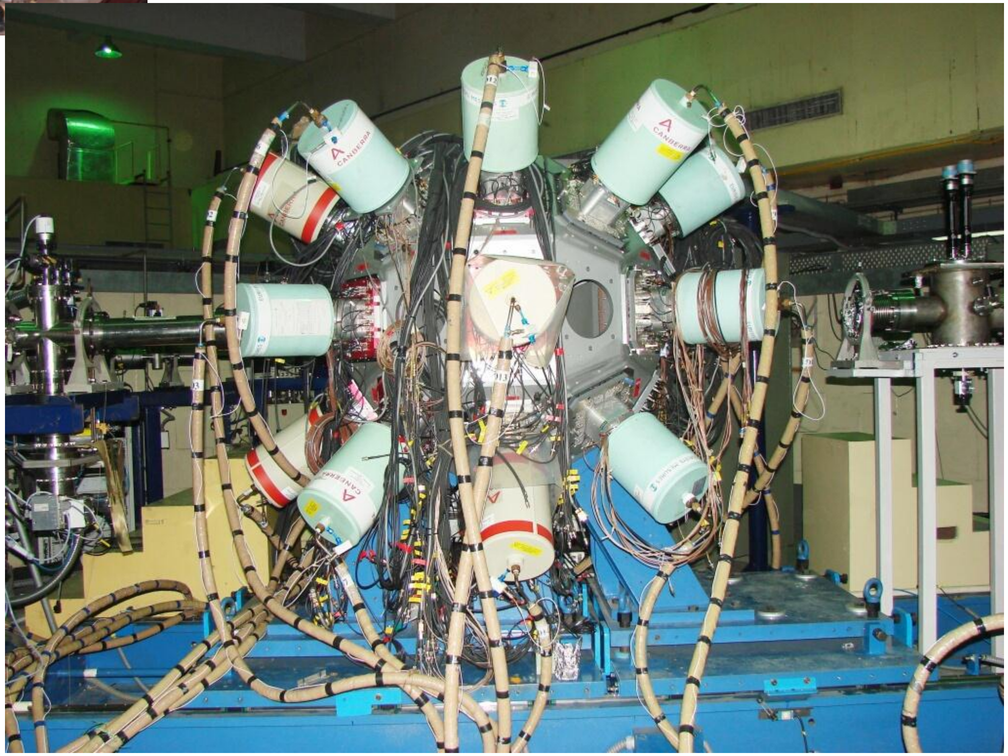
TIGRESS





24 Clover Detector Array

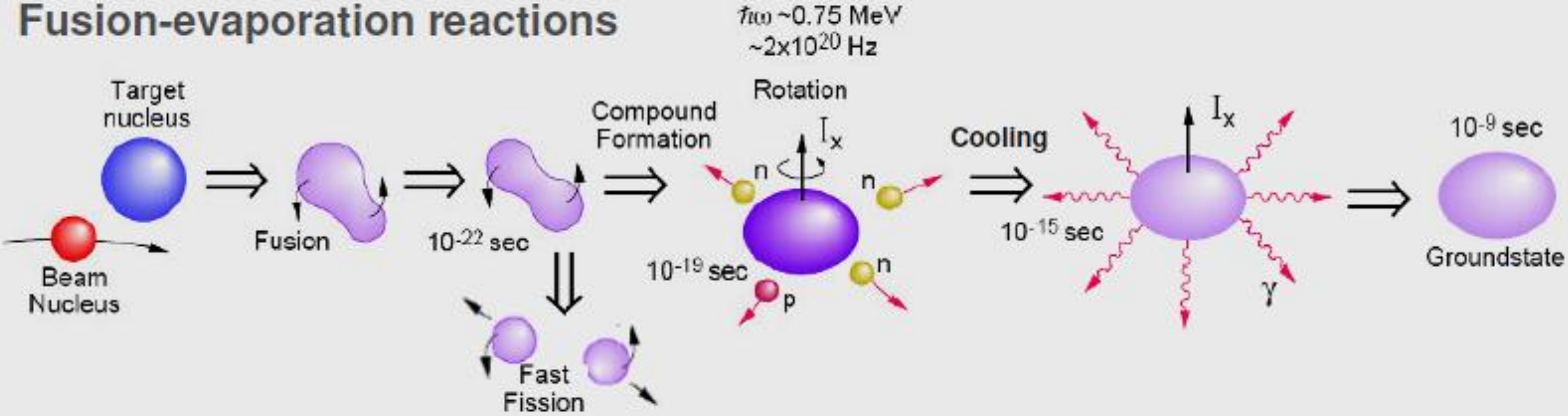
IUAC

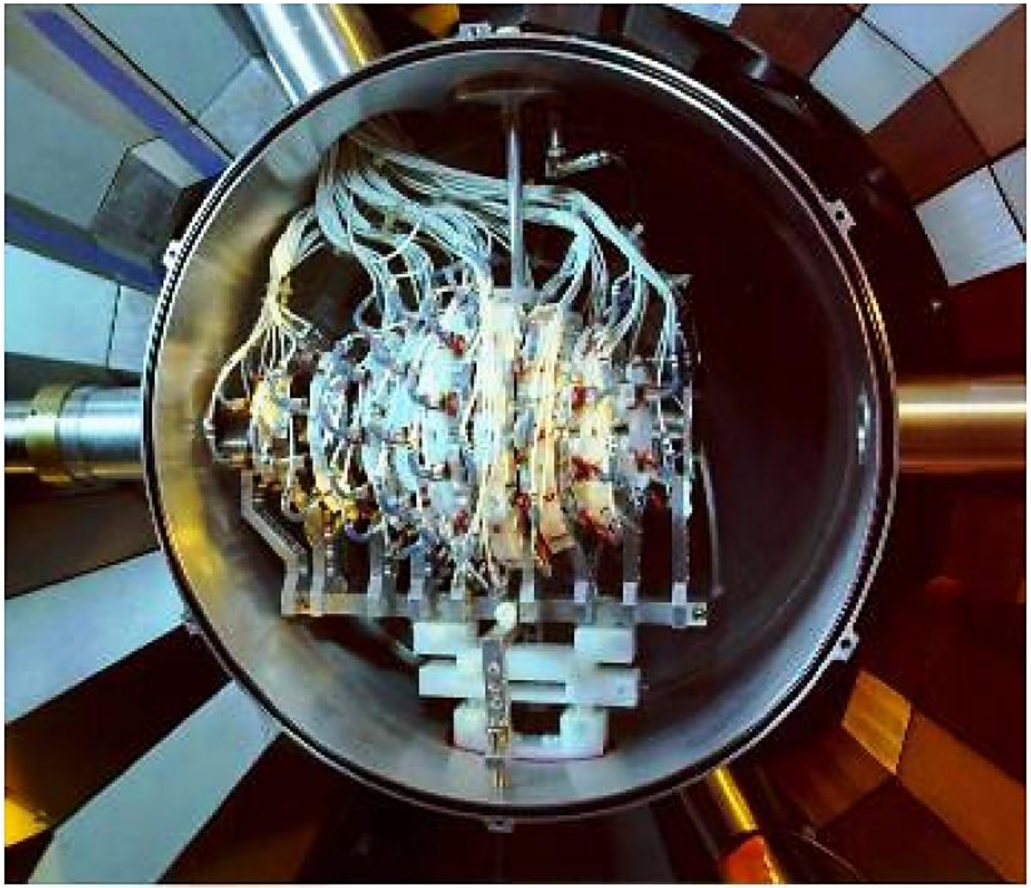


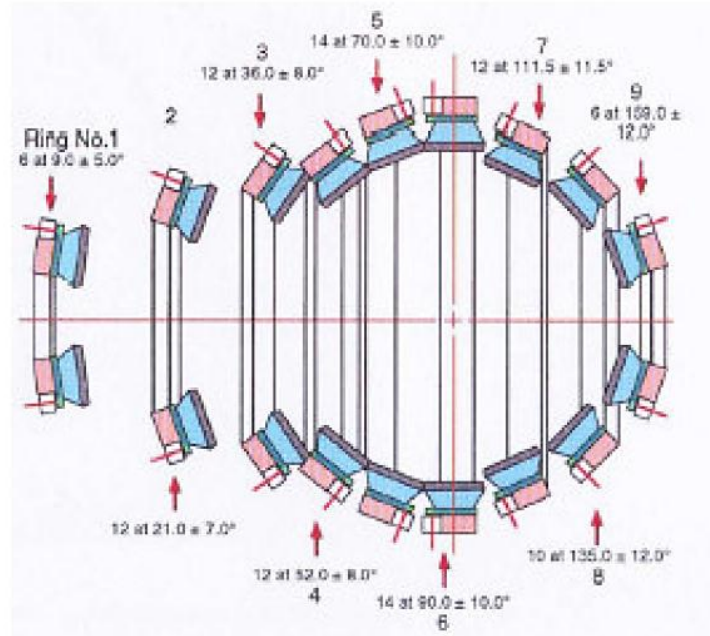
TIFR

Indian National Gamma Array (INGA)

Fusion-evaporation reactions





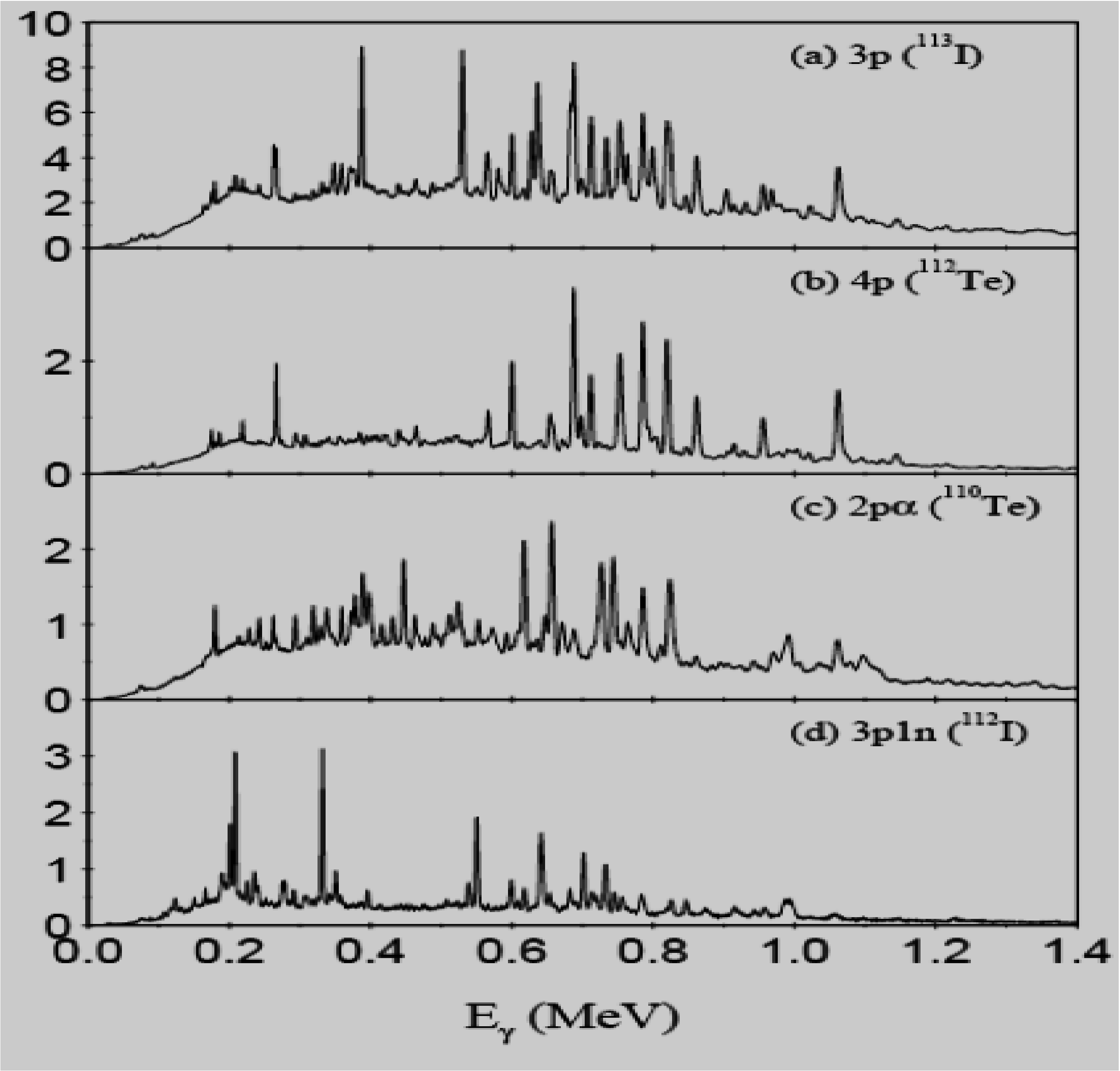


95 CsI(Tl) Scintillators
in 9 rings

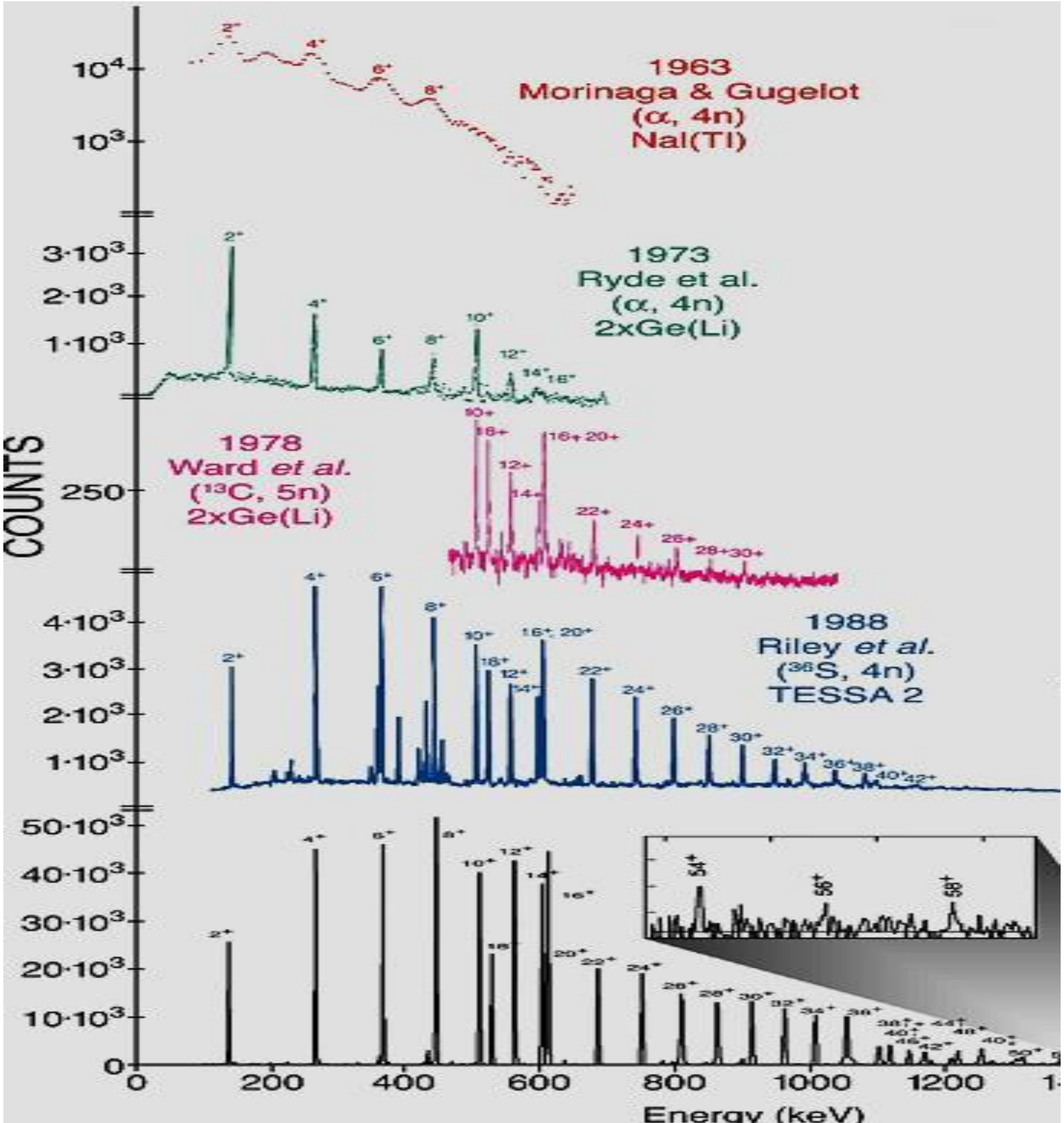
used with
Gammasphere

Microball,
Washington University St. Louis

Chanel Selection

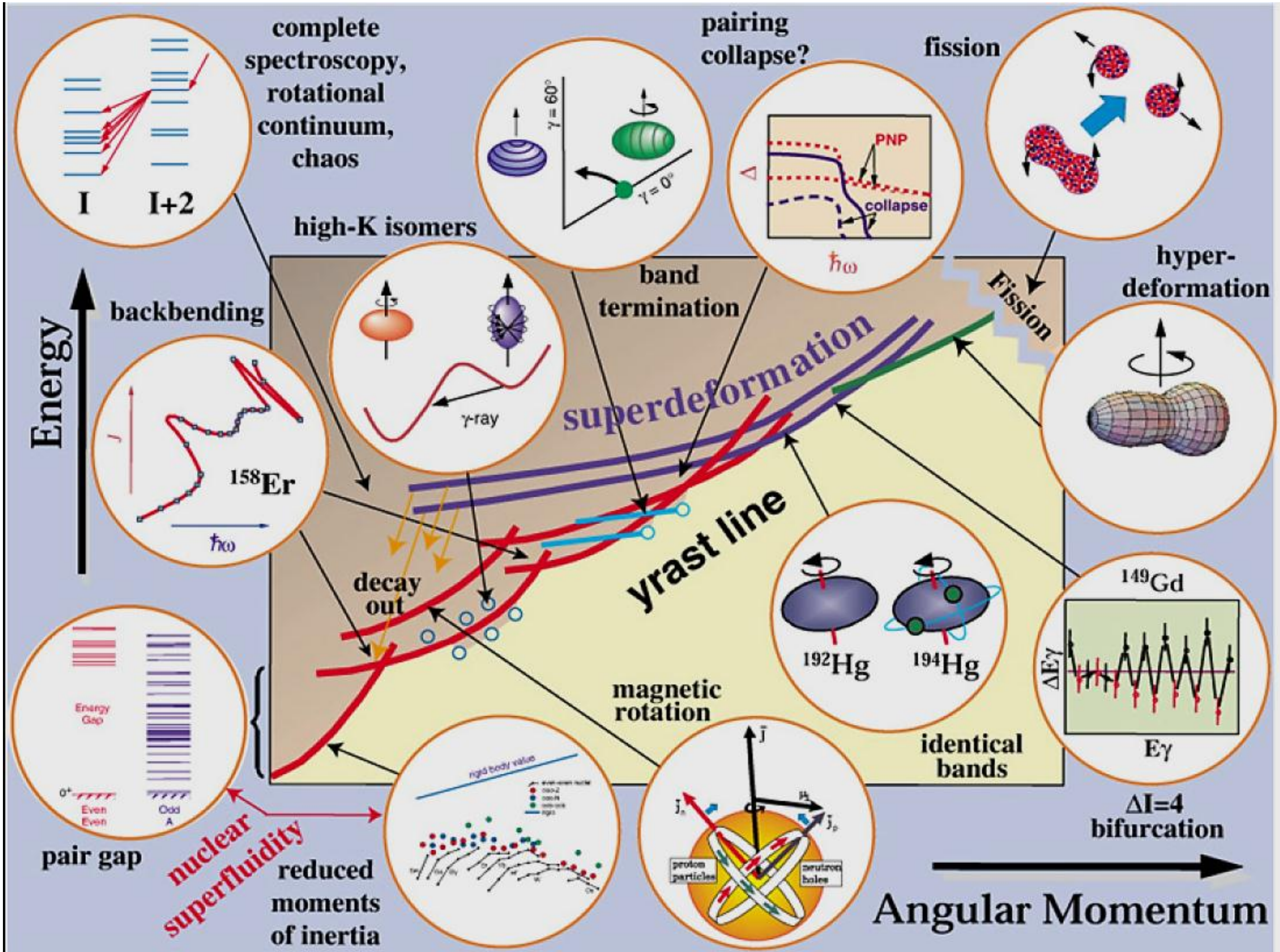


The Evolution of Gamma-Ray Spectroscopy



- Each advance in γ-ray detectors has resulted in new discoveries.
- Shells of highly-segmented Ge detectors which can track all the γ-rays event by event.

1998
Kondev et.al.
(36S,4n)
GAMMASPHERE



complete spectroscopy, rotational continuum, chaos
I
I+2
pairing collapse?
fission
high-K isomers
γ = 60°
γ = 0°
PNP
collapse
Δ
ħω
band termination
Fission
hyper-deformation
backbending
Energy
γ-ray
superdeformation
158Er
ħω
yrast line
decay out
192Hg
194Hg
149Gd
ΔEγ
Eγ
magnetic rotation
identical bands
Energy Gap
Even Even
Odd A
rigid body value
proton particles
neutron holes
ΔI=4 bifurcation
pair gap
nuclear superfluidity
reduced moments of inertia
Angular Momentum

Thank you for your attention