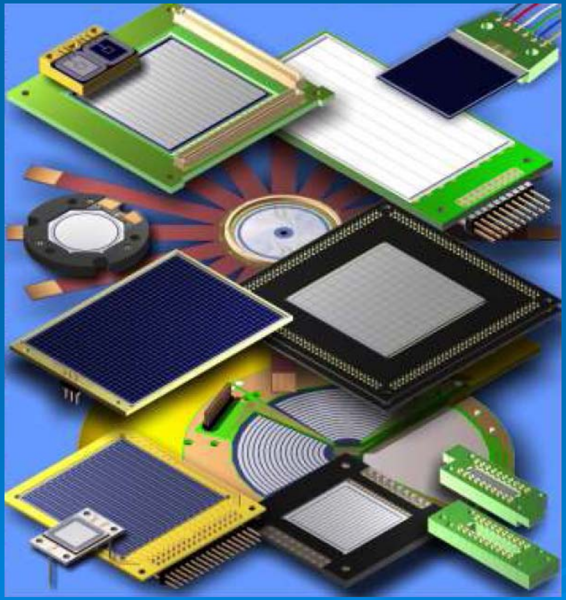
RNC Lecture, (2008) Oct. 8

Semiconductor Detectors

Shunji Nishimura



Silicon Detector

Germanium Detector

Outline of this Lecture

- Introduction
  - Detectors General Requirements
  - Why use semiconductor detectors?

- Basic Principles
  - P-type, N-type
  - Depletion layer
  - Type of detectors

- Performance
  - Energy Measurement
  - Position Measurement
  - Timing Measurement

- Electronics

- Operation : How to use?

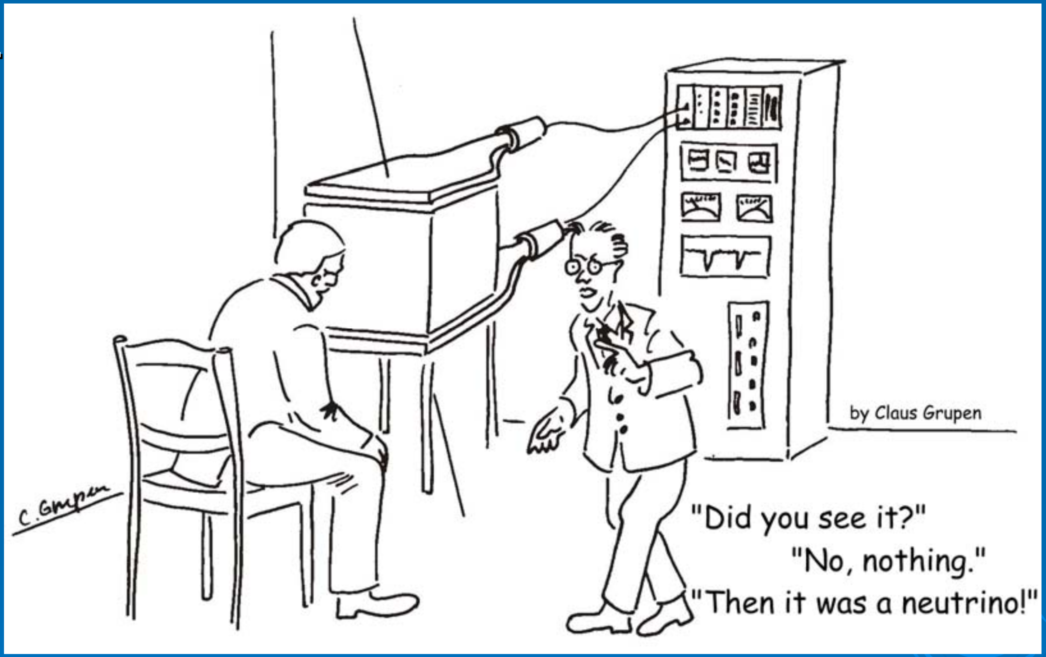
Detectors General Requirements

[Particle Identification]

Hadrons
- proton, neutron, d, t, 3He, …
- pion, kaon, …

Photon
- Gamma-ray (γ)

Lepton
- Electron (β), Muon (μ), Tau(τ)
- Neutrino (ν)



We want to detect the particle positively.
- what kind of particles?!
- momentum, direction, time, etc..

Detectors Requirements

- **Energy measurement**
  - Energy loss (dE)
  - Total energy (E)
  - Pulse shape
- **Position measurement**
  - (X, Y, Z) → Tracking
  - Bρ → Momentum (p)
- **Timing measurement**
  - Timing (velocity β)
  - High counting rate (dN/dt)
- **Count measurement**
  - Sensitivity to particle (ε)
  - Insensitive to background (S/N)
  - Radiation hardness

There are many types of detectors.

- Scintillation detector (Suda-san)
- Gas detector
- ⇨ - Semiconductor detector

→ Is there a perfect detector ?!

What is the advantage of semiconductor detector?

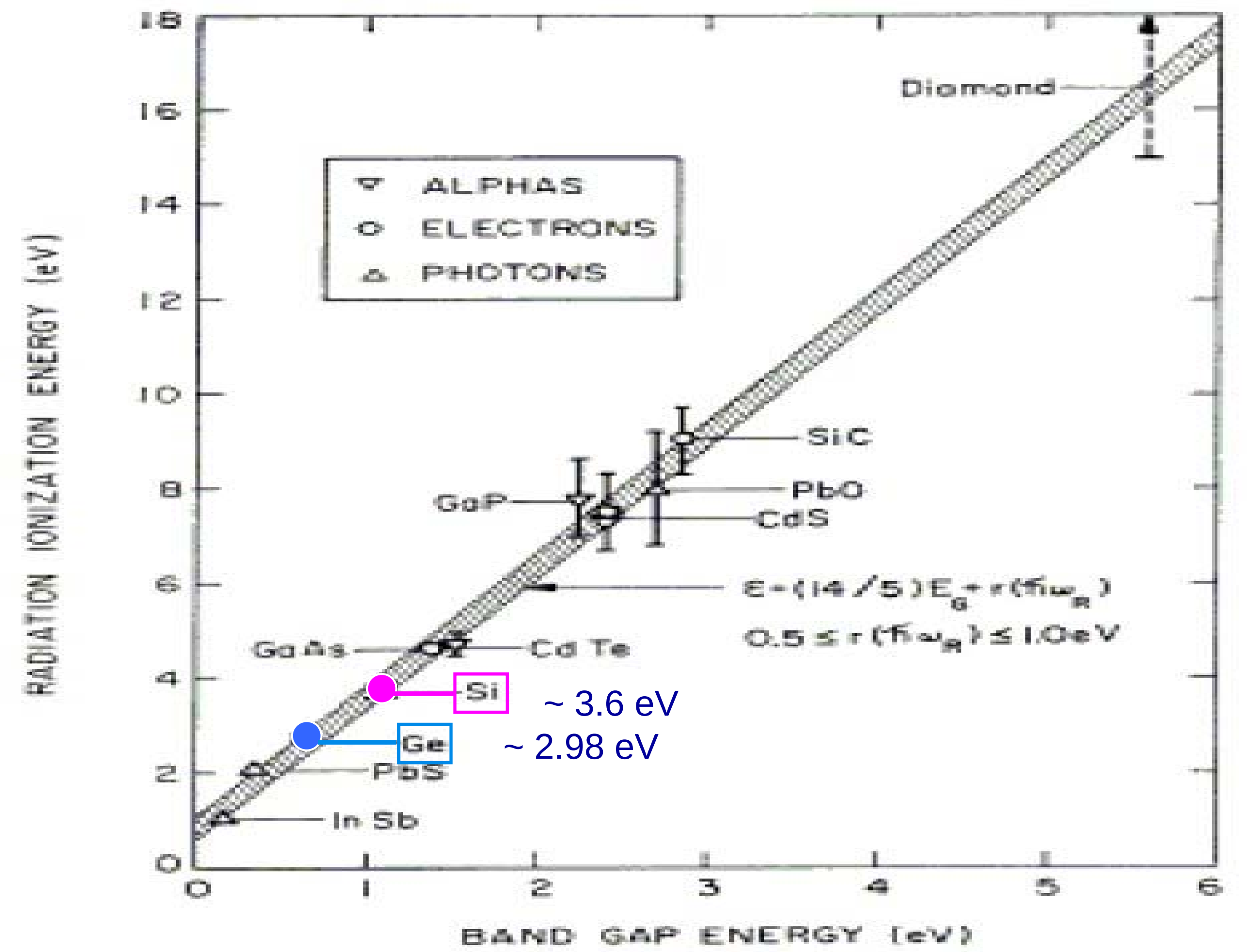
Why Semiconductor?

- **Low ionization energy**
  - **good signal**
- **Long mean free path**
  - **good charge collection efficiency**
- **High mobility**
  - **fast charge collection**
- **Si ... Lower Z = 14**
  - **low multiple scattering**
  - **Little cooling**
- **Ge .. Higher Z = 32**
  - **higher stopping power**
  - **Cooling is required.**

Characteristics

Detector	Ionization energy I (eV)	Energy resolution @ 5MeV $2.35/\sqrt{(5\times10^6/I)}$
Scintillation	100 ~ 500	1.1 ~ 2.4 %
Gas	30	0.6 %
Semiconductor	3	0.2%

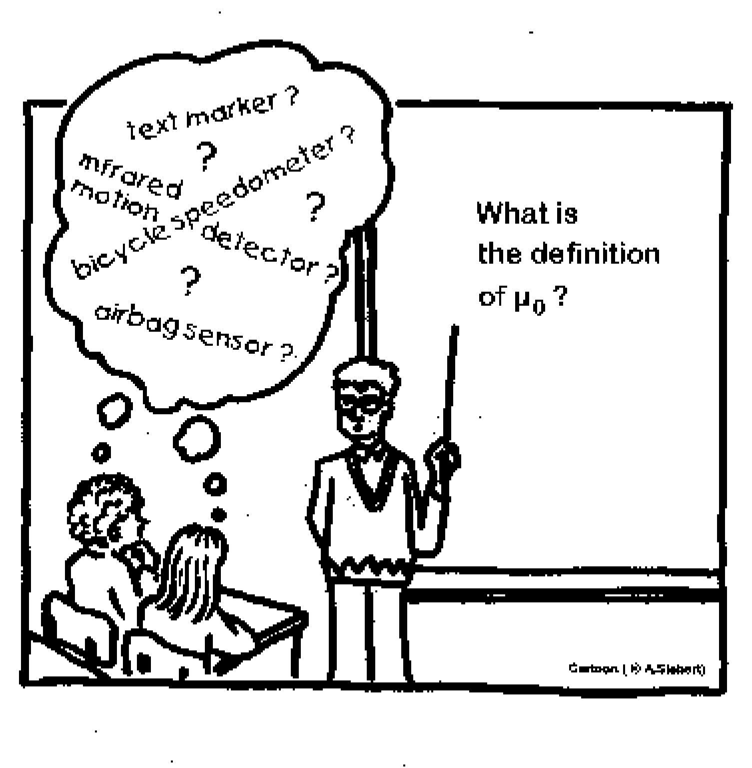
Energy required for creation of an electron-hole pair



Silicon:
The basic ingredients are ridiculously cheap

C.A.Klein, J. Applied Physics 38 (1968) 2029.

Basic Principles

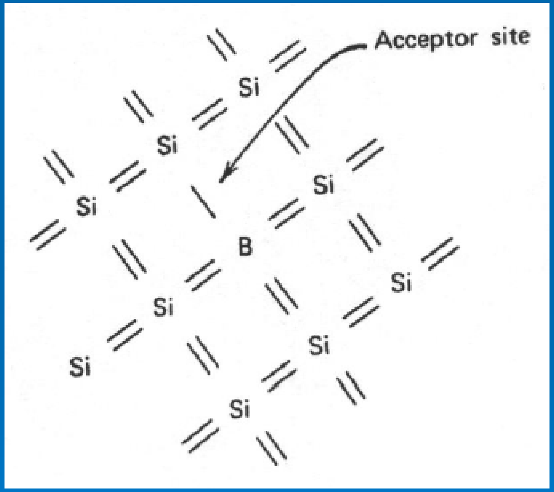


Cartoon (© A.Siebert)

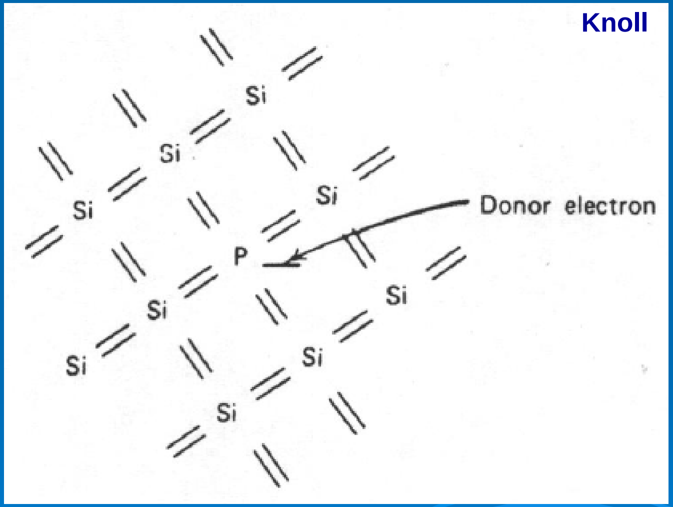
Basic Principles

[To dope the silicon with impurities]

Boron doping (p-type)
holes are majority carriers

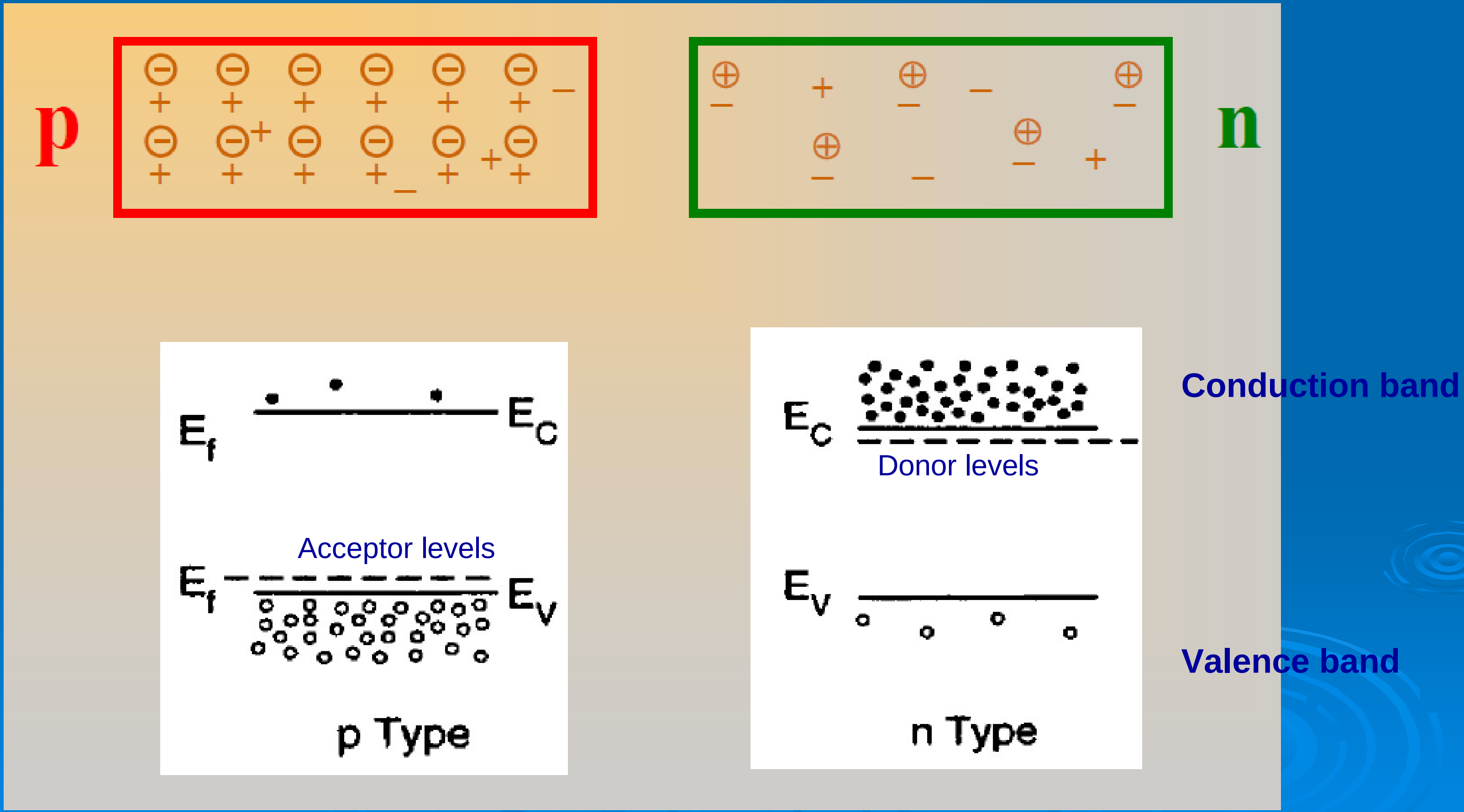


Phosphorus doping (n-type)
electrons are majority carriers



Basic Principles

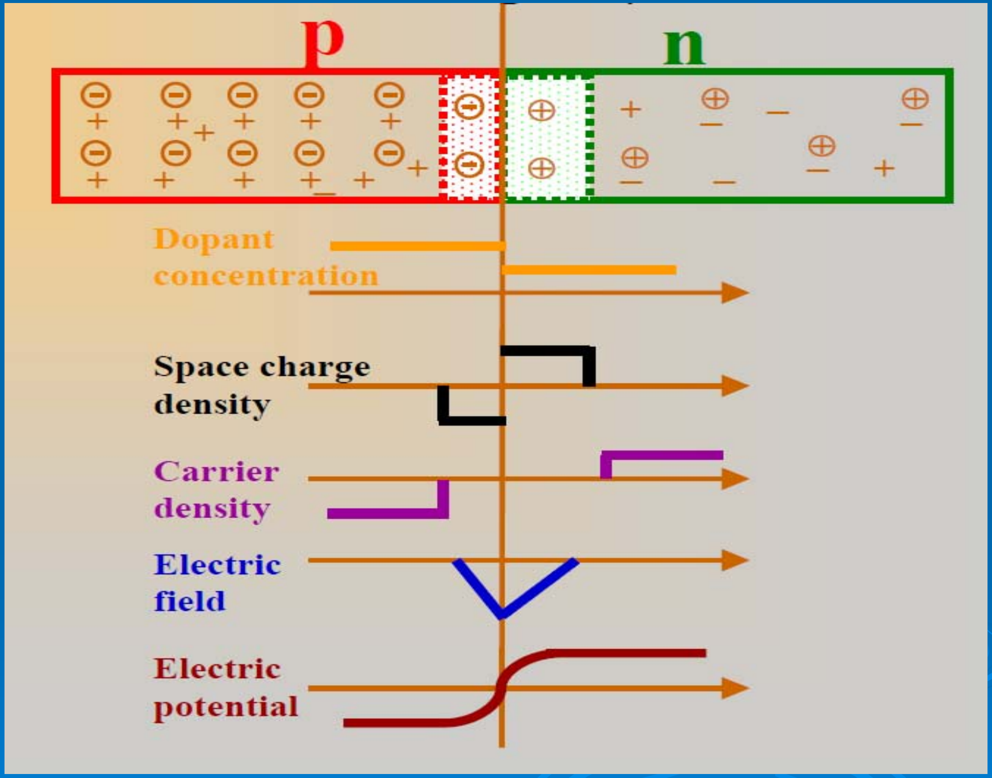
- Now we can construct a p-n junction



Basic Principles

Now for the magic part !

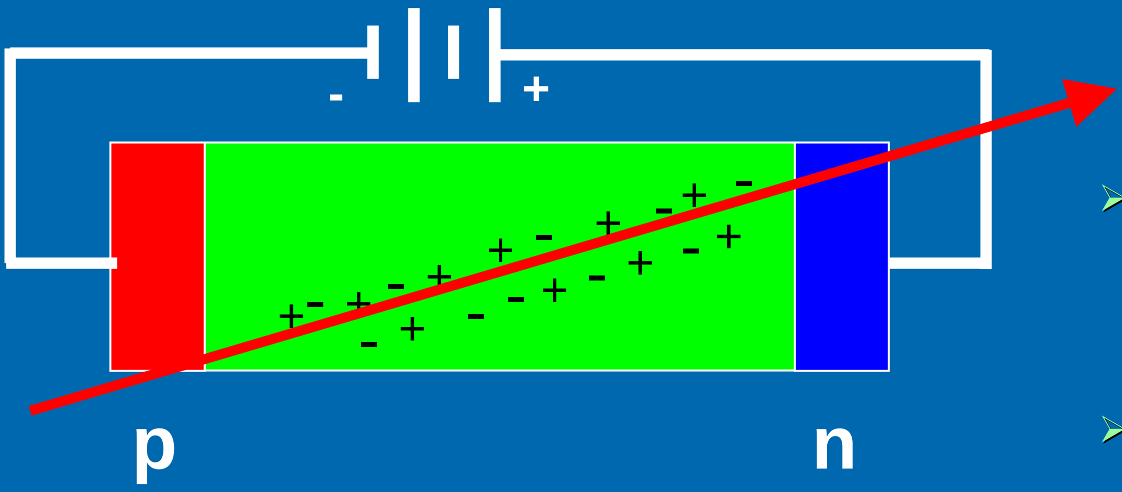
When brought together to form a junction, the majority diffuse carriers across the junction. The migration leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region. The electric field set up in the region prevents further migration of carriers.

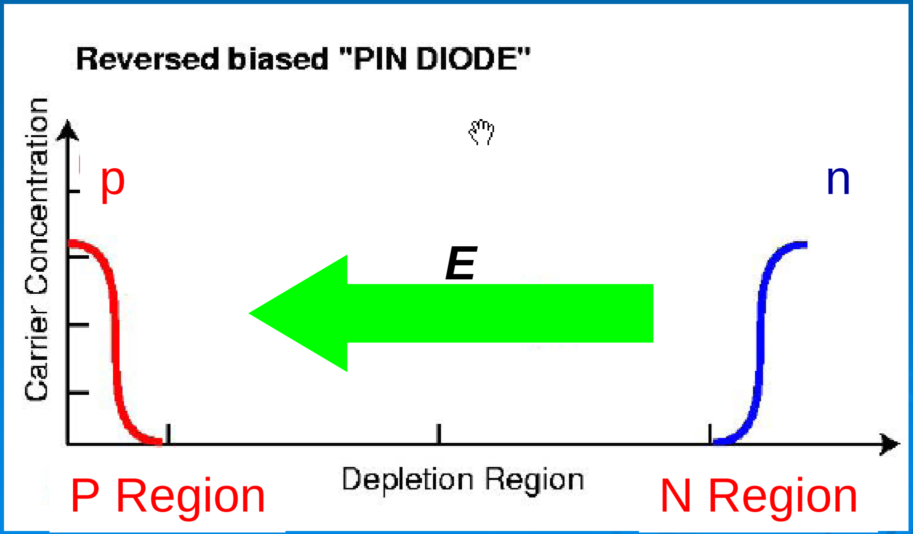


P. Collins (CERN)

Basic Principles

[Semiconductor structure]





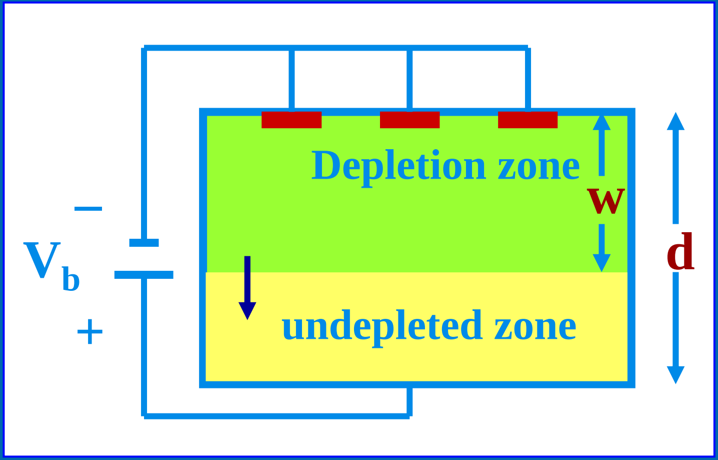
- **Use ionization signal left behind by charged particle passage.**
- **Ionization produces electron(e)-ion(h) pairs, use electric field to drift the e and h to the oppositely charged electrodes.**
- **Si needs 3.6eV to produce one e-h pair.**

Depletion zone

- Depletion zone

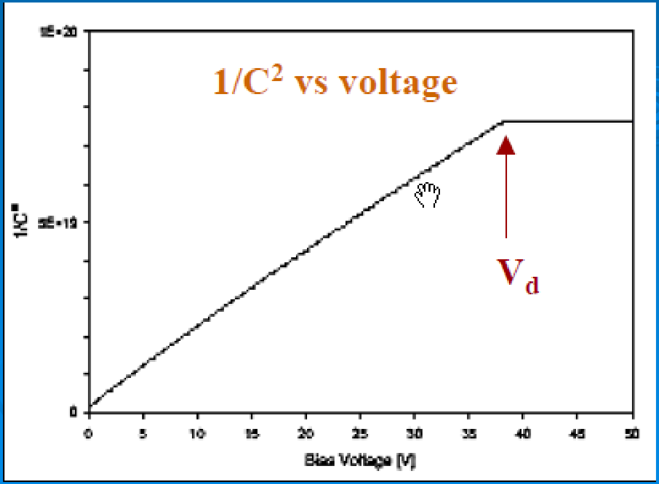
$$w = \sqrt{2\varepsilon\rho\mu V_b}$$

where $\rho = 1/q\mu N$ for doped materiel and
N is the doping concentration
(q is always the charge of the electron)



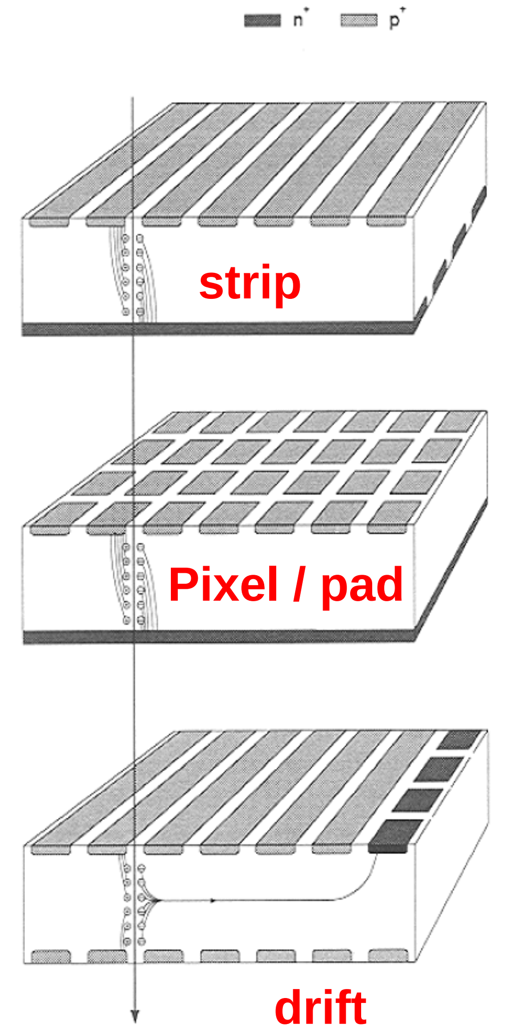
- The voltage needed to completely deplete a device of thickness d is called the depletion voltage, V_d

$$V_d = d^2 / (2\varepsilon\rho\mu)$$



Types of Silicon detectors

- Strip devices
  - High precision
  - Large active area
  - Single-sided or Double-sided
- Pixel devices
  - True 2-D measurement
  - Small areas, but high track density
- Pad devices (Big pixels / wide strips)
  - Pre-shower and calorimeters
- Drift devices



Types of Ge-detectors

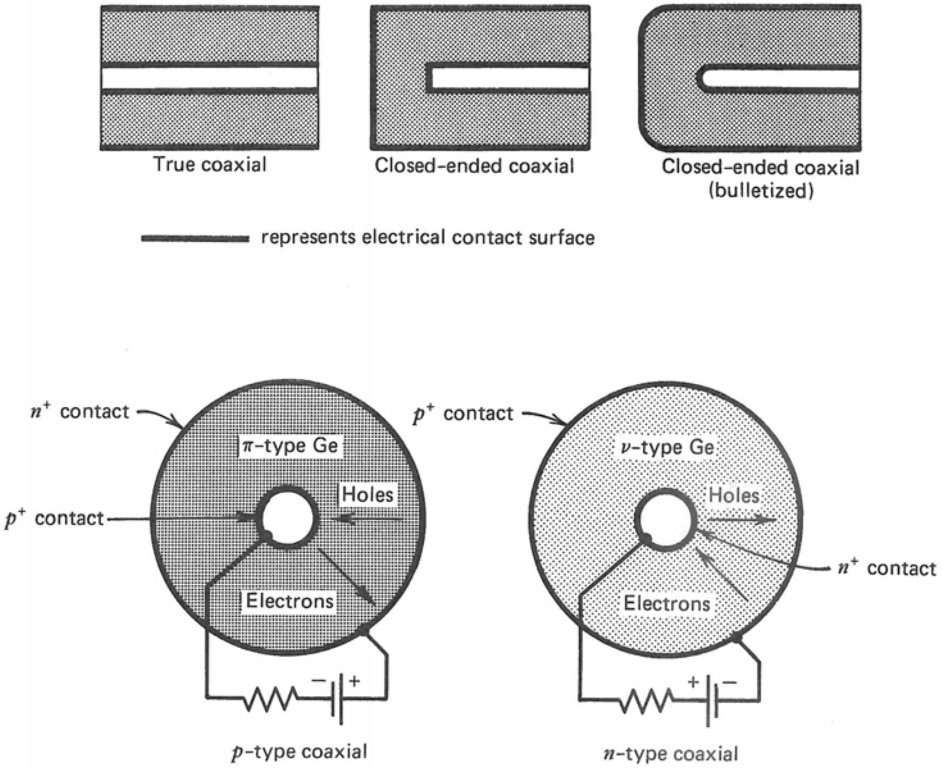
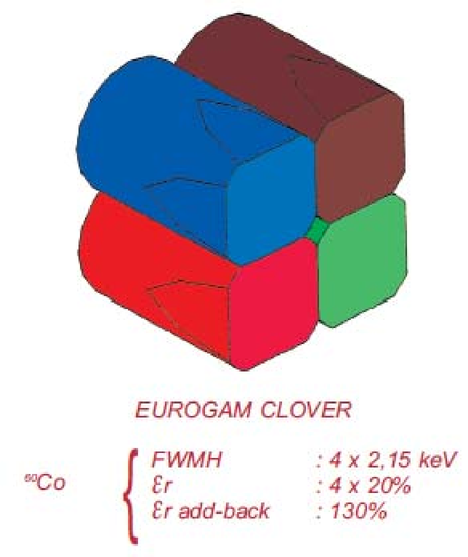


Figure 12.3 At the top are shown the three common shapes of large-volume coaxial detectors. Each represents a cross-sectional view through the axis of a cylindrical crystal. The outer electrode is extended over the flat front (left) surface in both closed-ended cases. Cross sections perpendicular to the cylindrical axis of the crystal are shown at the bottom. The HPGe material may be either high-purity *p* or *n* type. The corresponding electrode configurations are shown for each type.

Strip Ge detector

Clover Detector

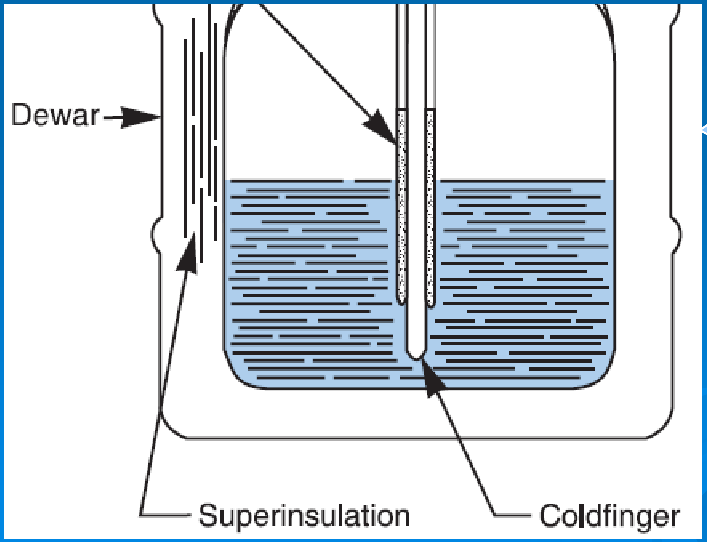
4 crystals



EUROGAM CLOVER

^{60}Co	FWMH	: 4 x 2,15 keV
	ε_r	: 4 x 20%
	ε_r add-back	: 130%

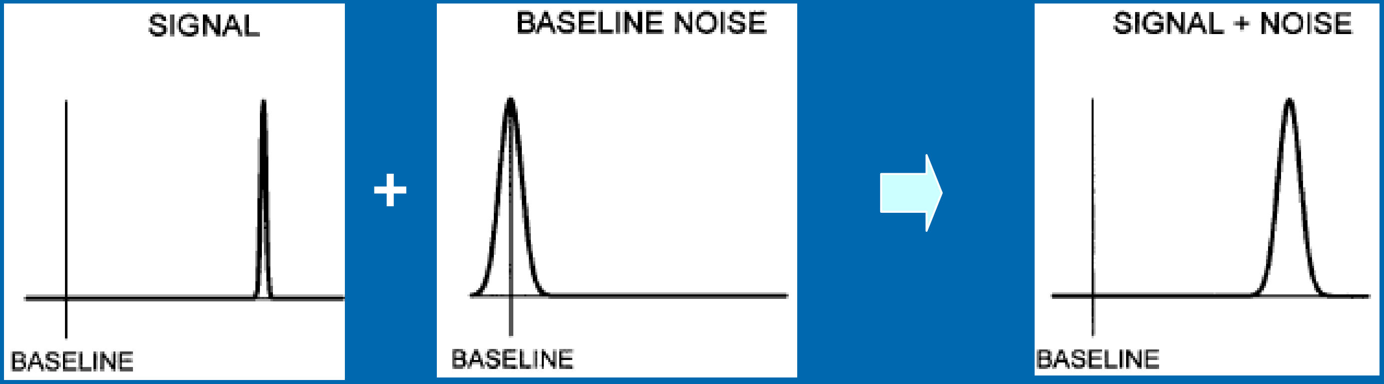
Liquid Nitrogen for cooling



Performance I

Energy Resolution

Energy Resolution



If Signal Variance << Baseline Variance
→ Electronics (baseline) noise
critical for resolution

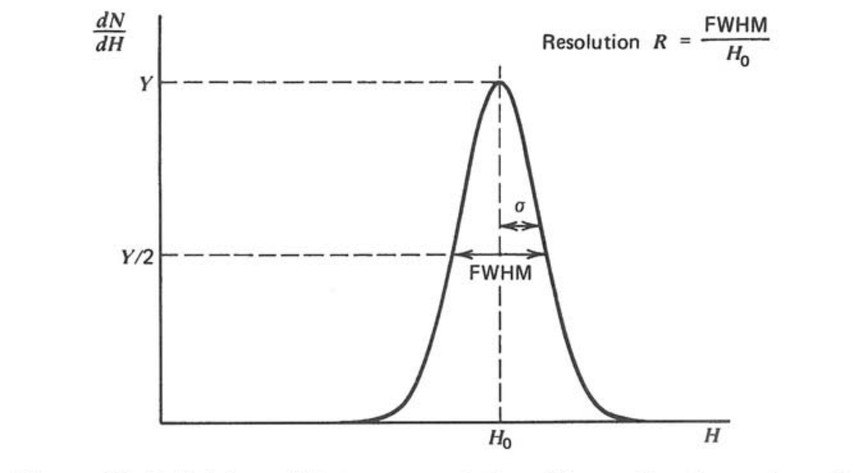
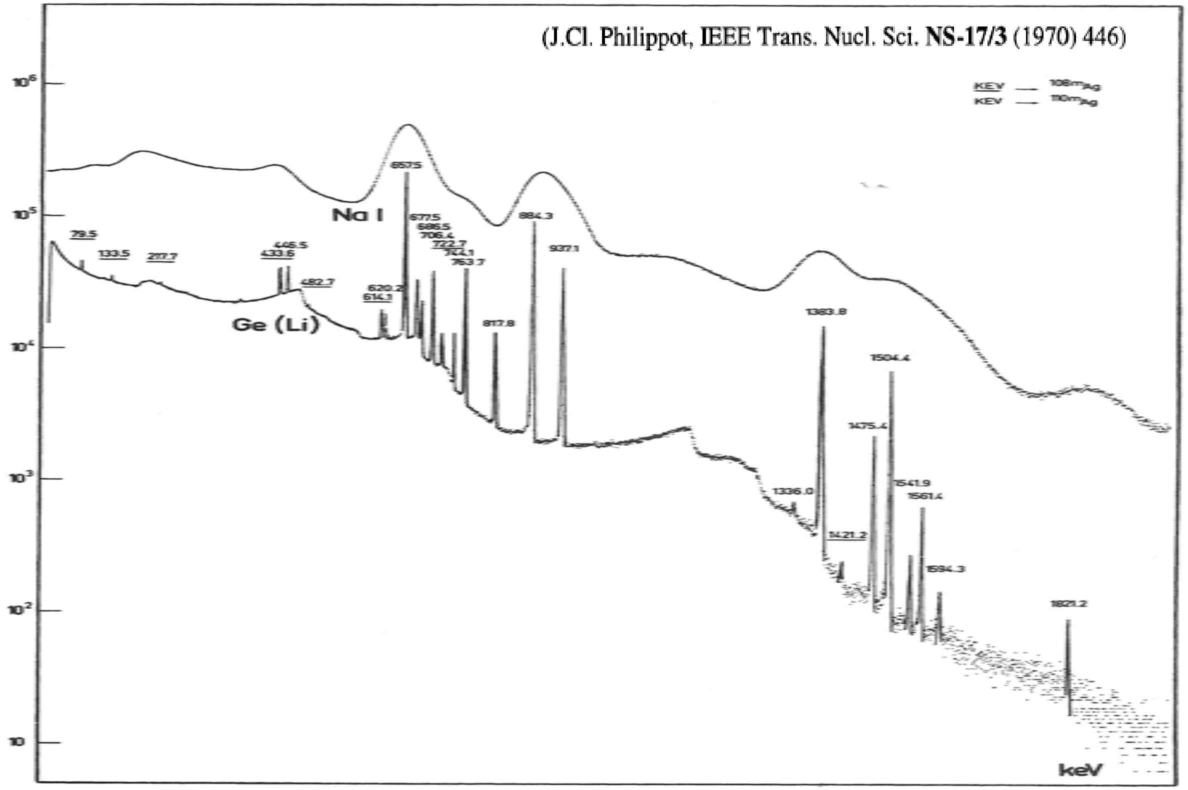


Figure 4.5 Definition of detector resolution. For peaks whose shape is Gaussian with standard deviation σ, the FWHM is given by 2.35σ.

Energy Resolution : NaI(Tl) vs Ge



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

Figure 12.7 Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector. The source was gamma radiation from the decay of ^{108m}Ag and ^{110m}Ag. Energies of peaks are labeled in keV. (From Philippot.[13])

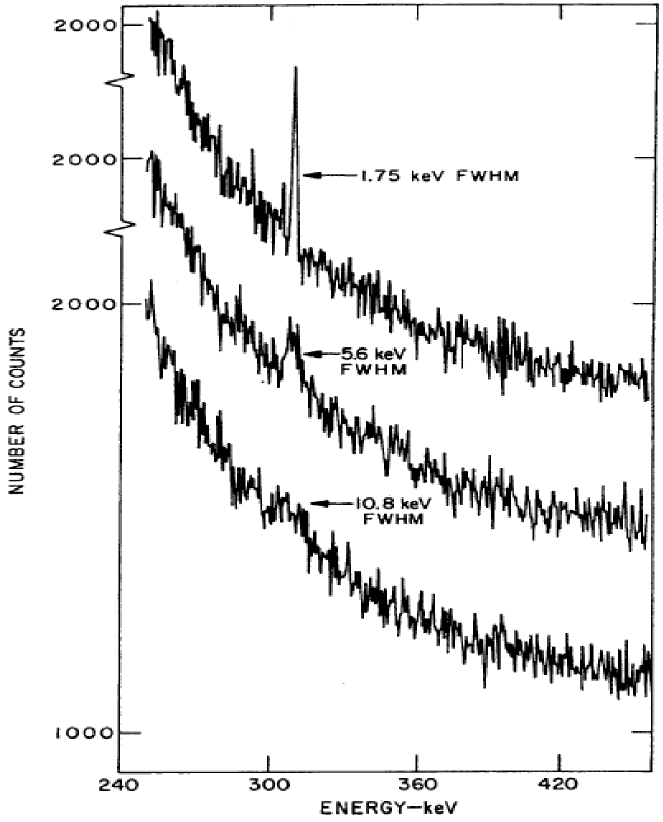
Semiconductor detector

→ **Excellent detector for energy measurement !!**

Energy Resolution

[Signal to Background Ratio (S/N)]

Signal to background ratio improves with better resolution
(signal counts in fewer bins compete with fewer
background counts)



G.A. Armantrout, *et al.*, IEEE Trans. Nucl. Sci. **NS-19/1** (1972) 107

→ **Good Energy Resolution**
→ **Higher Statistics**

We can extract

- **precise peak position,**
- **and find NEW Peaks!!**

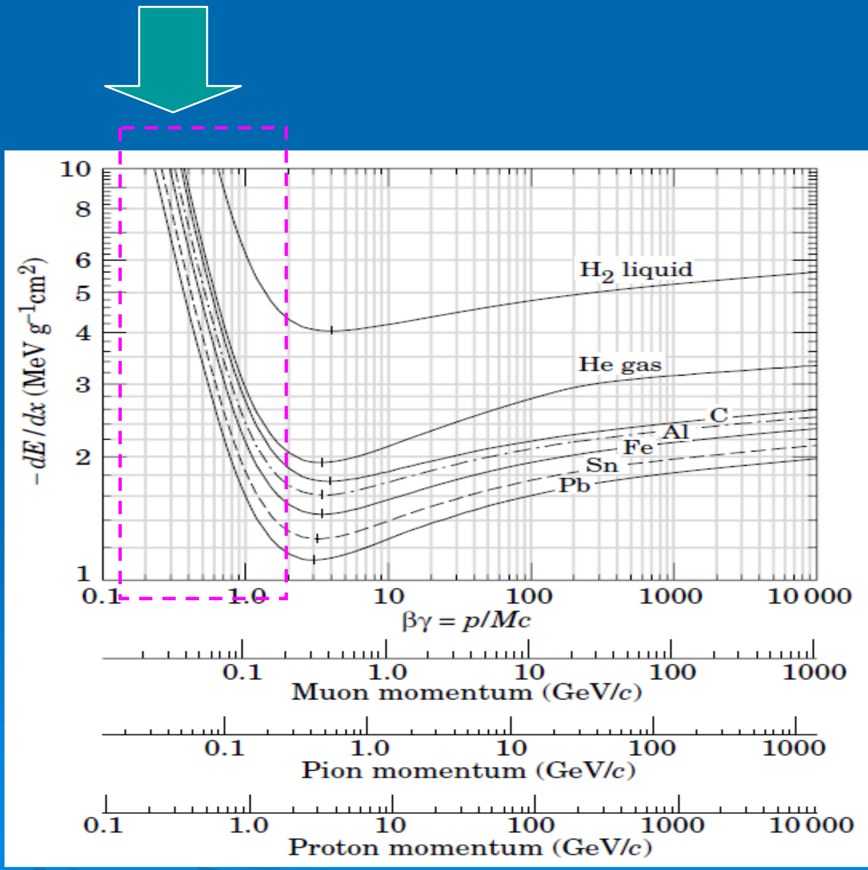
Particle Identification
[Use Difference of Stopping Power]

$$p = m_0 \beta \gamma$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2 \gamma^2\right)$$

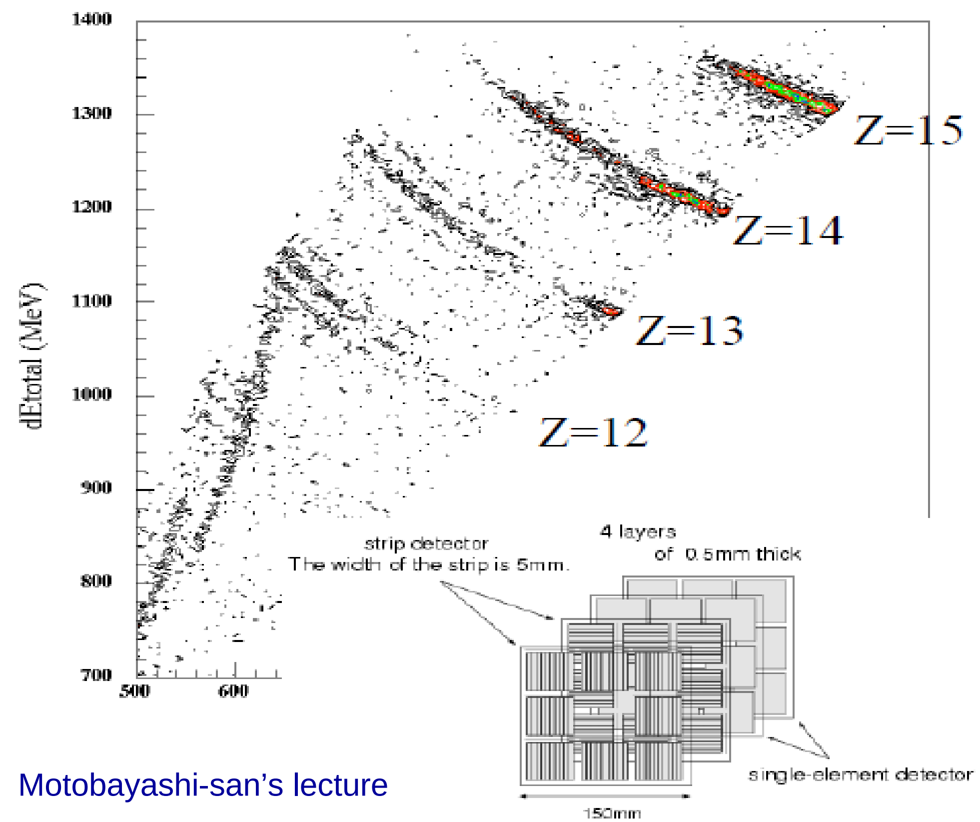
Knowing p and β gives m

For very low momenta,
we can exploit the bethe-bloch
formula for particle identification



Particle Identification

[dE-E Correlation]



Motobayashi-san's lecture

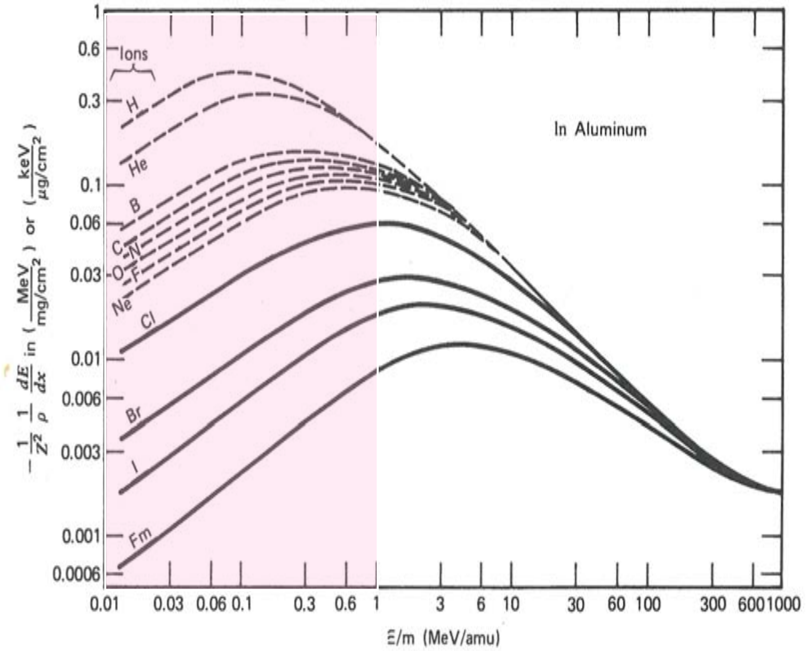


Figure 2.11 Plots showing the specific energy loss of various heavy ions in aluminum. The abscissa is the ion energy divided by its mass, and the ordinate is $-dE/dx$ divided by the density of aluminum and the square of the ion atomic number. Typical fission fragments (e.g., iodine) show a continuously decreasing $-dE/dx$ while slowing from their initial energy (~1 MeV/amu). (From Northcliffe and Schilling.[8])

Multi-layer detectors enable us to identify the particles!

Energy Resolution :

[Temperature Dependence]

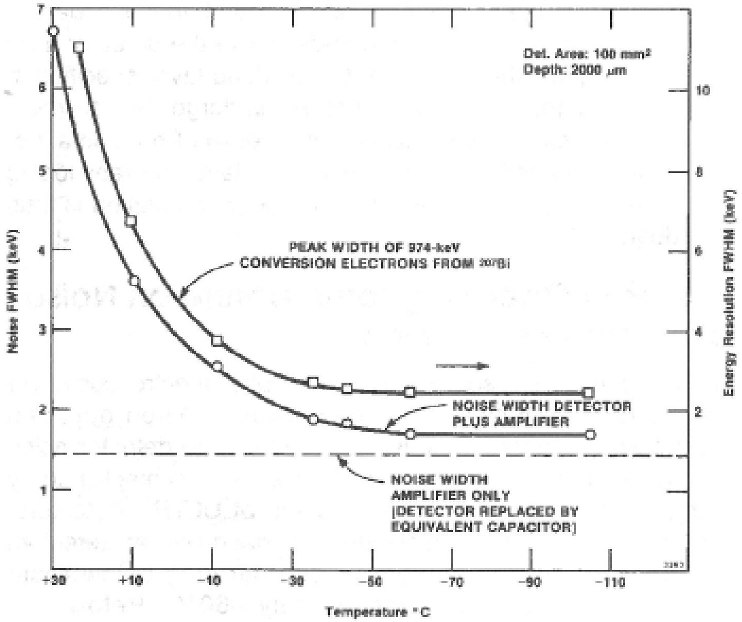


Fig. 9. Detector Noise and Electron Energy Resolution as a Function of Temperature.

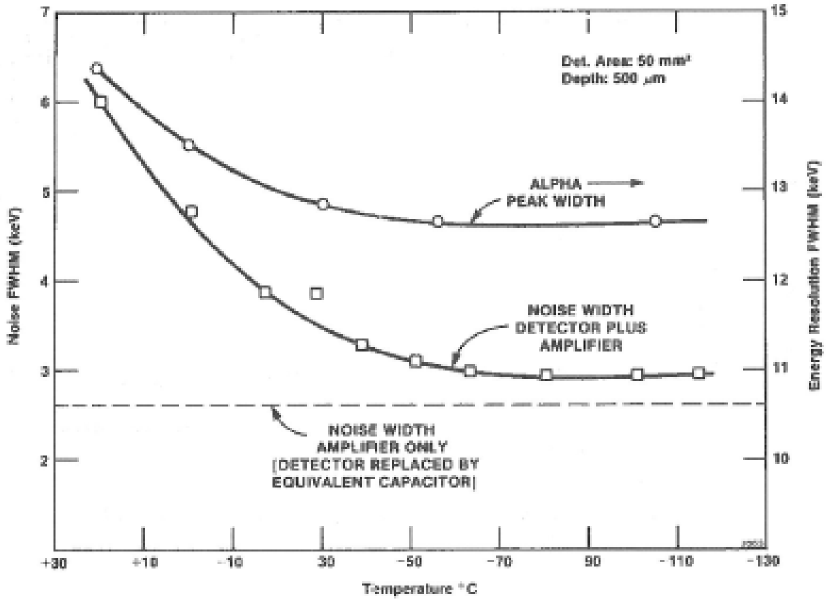
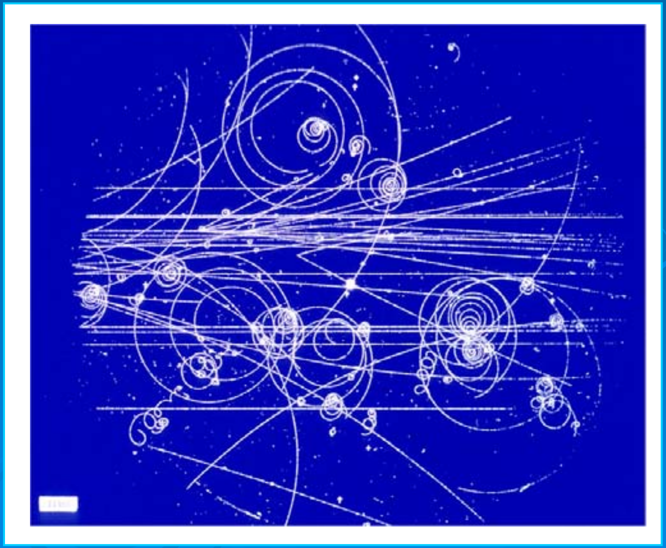


Fig. 8. Detector Noise and Alpha Energy Resolution as a Function of Temperature.

Semiconductor Detectors prefer COOLING !

Performance II

Position Measurement



Bubble chamber (CERN)

Position Measurement

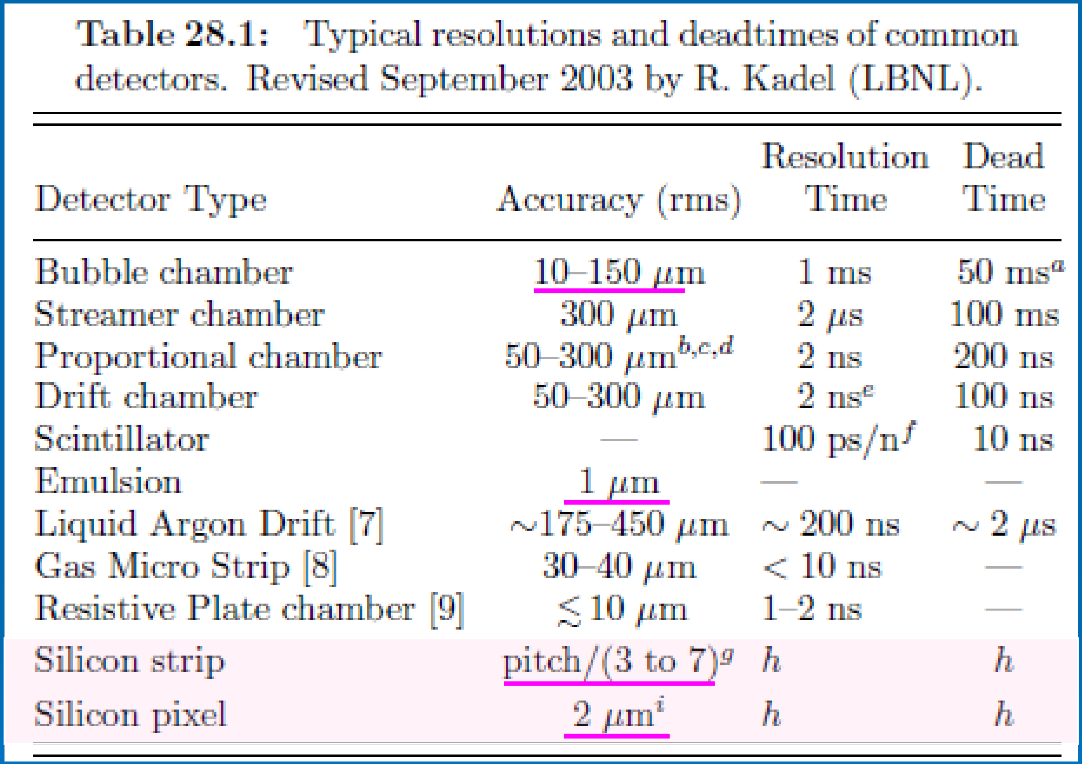
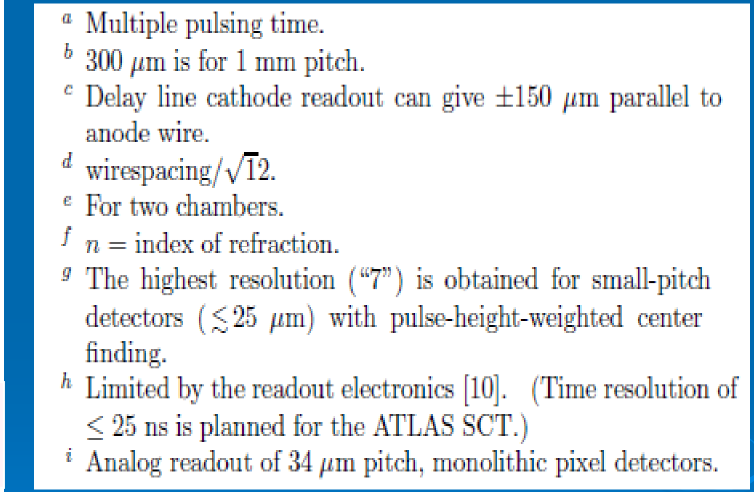


Table 28.1: Typical resolutions and deadtimes of common detectors. Revised September 2003 by R. Kadel (LBNL).

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [7]	~175–450 μm	~ 200 ns	~ 2 μs
Gas Micro Strip [8]	30–40 μm	< 10 ns	—
Resistive Plate chamber [9]	$\lesssim$ 10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	[h]	[h]
Silicon pixel	2 μm[i]	[h]	[h]



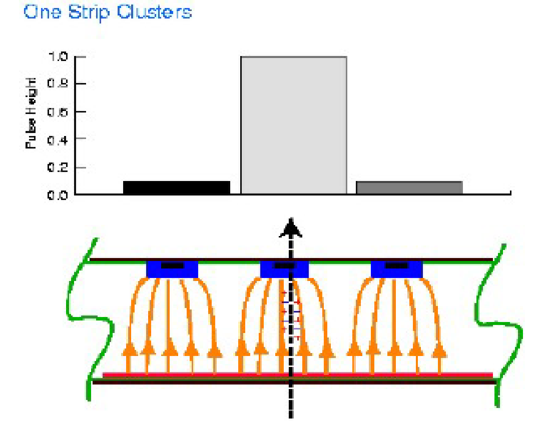
[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give ±150 μm parallel to anode wire.
[d] wirespacing/$\sqrt{12}$.
[e] For two chambers.
[f] n = index of refraction.
[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 μm) with pulse-height-weighted center finding.
[h] Limited by the readout electronics [10]. (Time resolution of $\lesssim$ 25 ns is planned for the ATLAS SCT.)
[i] Analog readout of 34 μm pitch, monolithic pixel detectors.

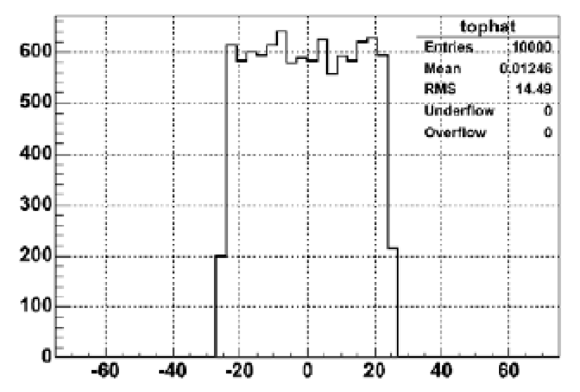
Silicon Detectors

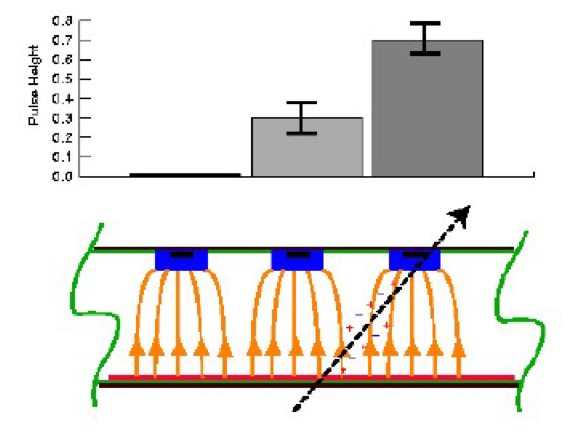
- very good position resolution.
- works under high magnetic field.
- high rates and triggering.

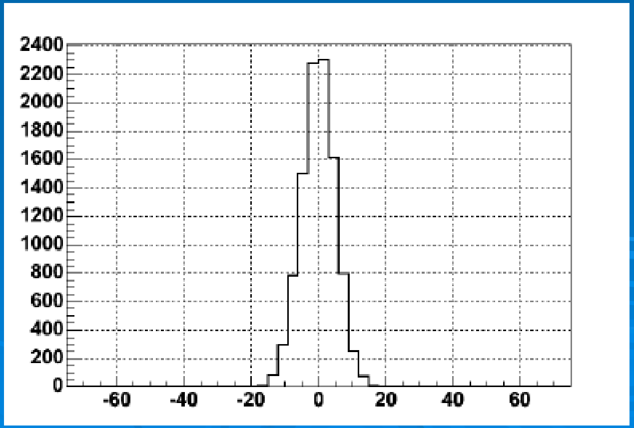
Position Measurement

$\sigma = \text{pitch}/\sqrt{12}$

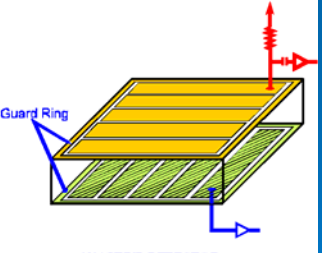


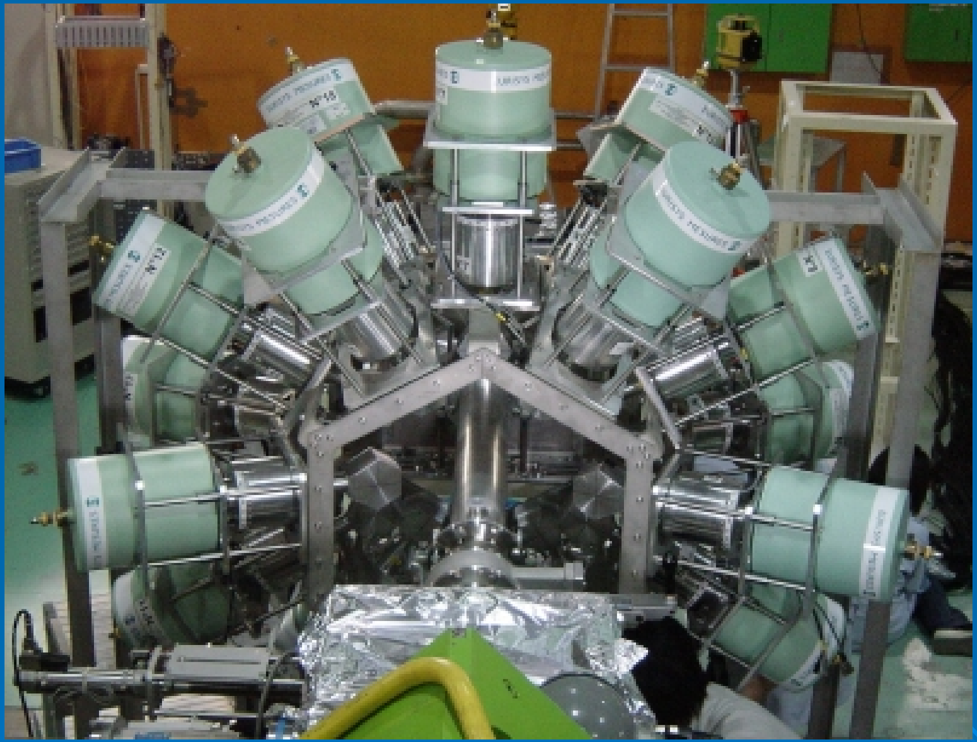






Position Sensitive Ge detectors





Ge detector array (GRAPE)
CNS, Univ. of Tokyo

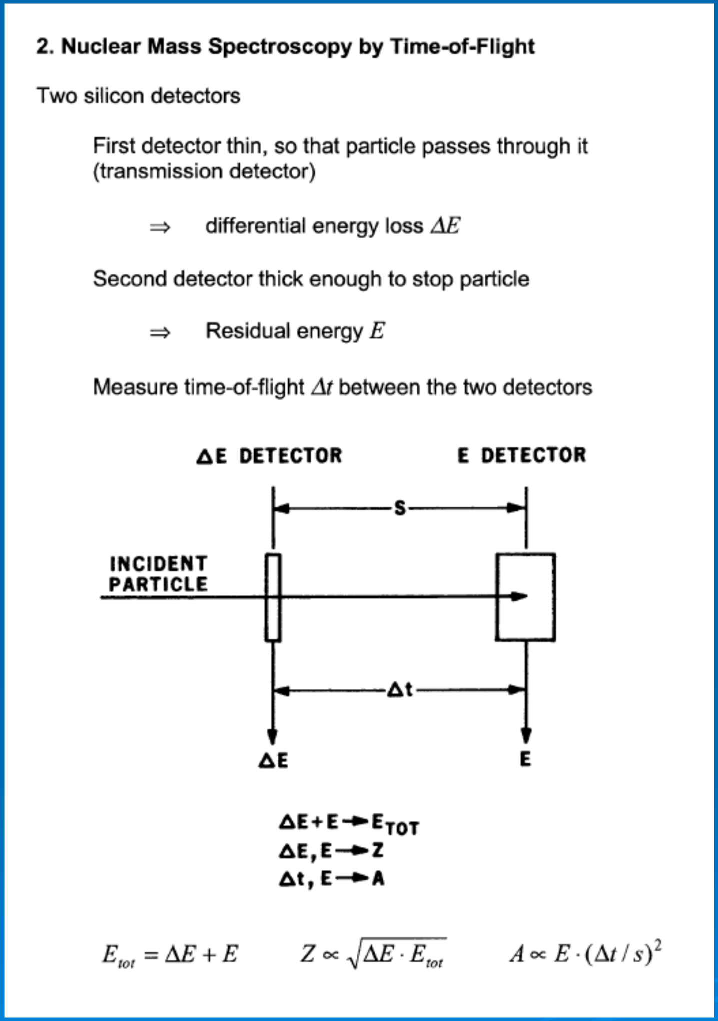
Performance III

Timing Measurement

Silicon detector

- Electrons ~10ns/300um
- Holes ~ 25ns/300um

Timing Measurement



2. Nuclear Mass Spectroscopy by Time-of-Flight

Two silicon detectors

First detector thin, so that particle passes through it (transmission detector)

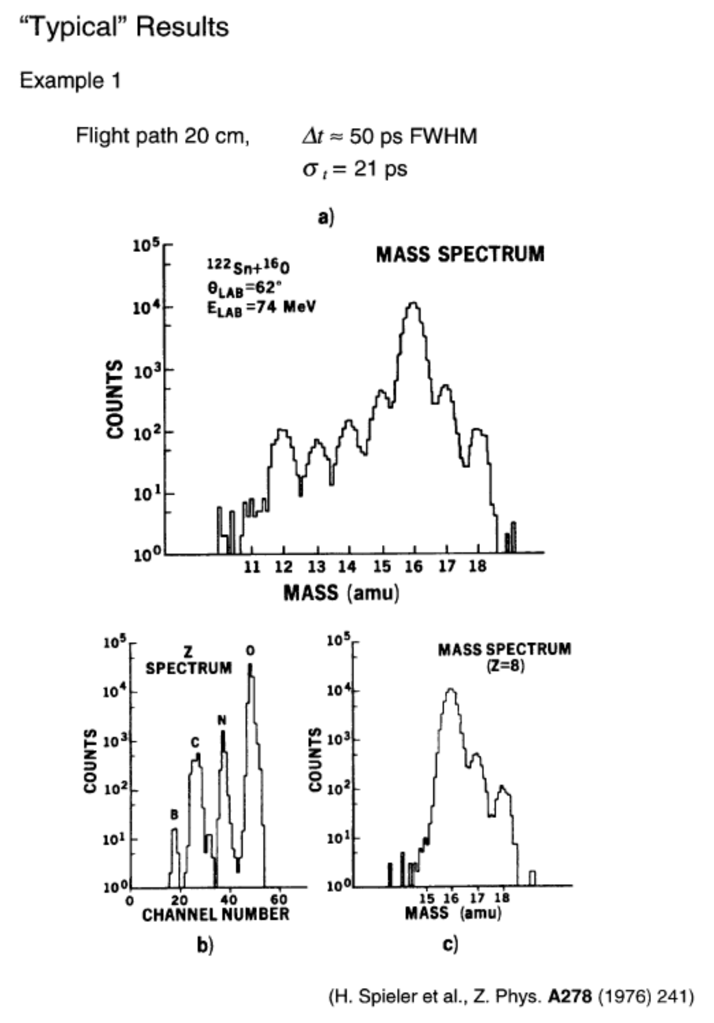
⇒ differential energy loss ΔE

Second detector thick enough to stop particle

⇒ Residual energy E

Measure time-of-flight Δt between the two detectors

$$E_{tot} = \Delta E + E \qquad Z \propto \sqrt{\Delta E \cdot E_{tot}} \qquad A \propto E \cdot (\Delta t / s)^2$$



"Typical" Results

Example 1

Flight path 20 cm, $\Delta t \approx 50$ ps FWHM

$\sigma_t = 21$ ps

(H. Spieler et al., Z. Phys. **A278** (1976) 241)

Electronics

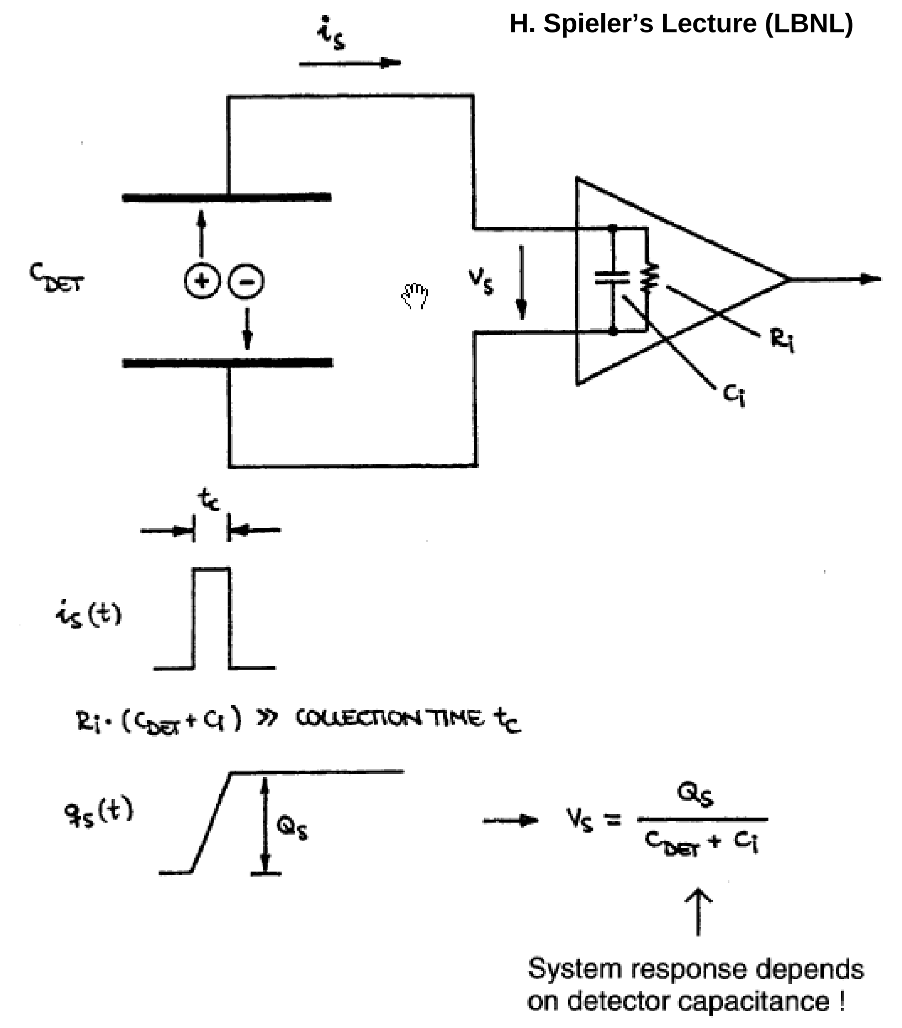
Electronics

- Noise is a big issue for Silicon/Ge detectors. At 22000 e- for a 300 um thick silicon sensor, the signal is relatively small. Signal losses can easily occur depending on electronics, stray capacitances, coupling capacitor, frequency etc.

  - Improve energy resolution
  - Allow a low detection threshold

Electronics

[Signal Integration on Input Capacitance]



H. Spieler's Lecture (LBNL)

System response depends on detector capacitance !

Energy Deposit ∝ Charge Qd
However,

☆Detector capacitance C_{DET} may vary within a system or change with bias voltage.

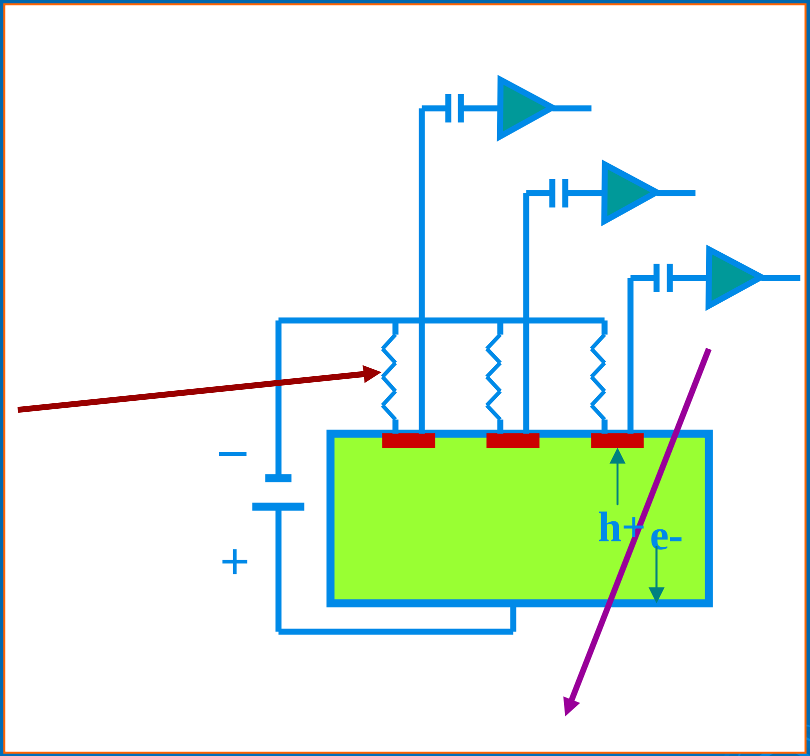
☆Variation of charge collection in time T_c

Make system whose gain (dV_{out}/dQ_S) is independent of detector capacitance.

Charge sensitive preamp !

Charge Collection

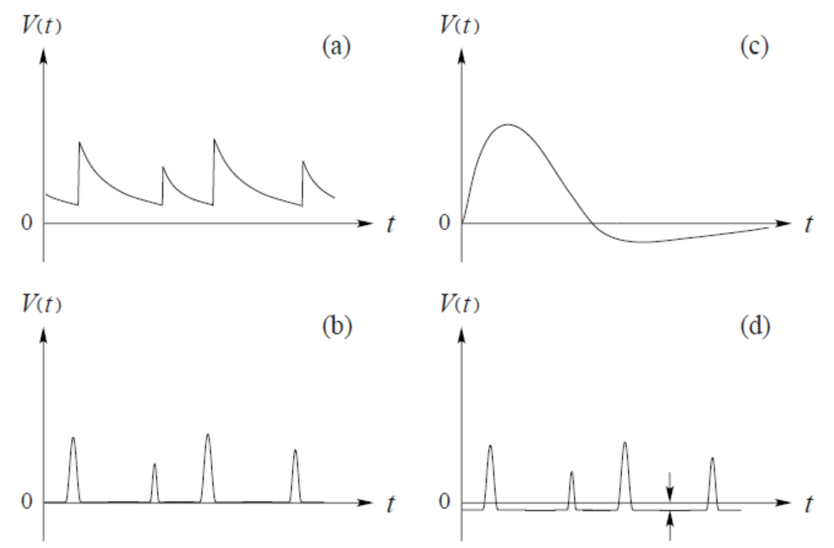
- **Isolation of each strip using high impedance bias connection**
  - → Collect / measure charge on each strip



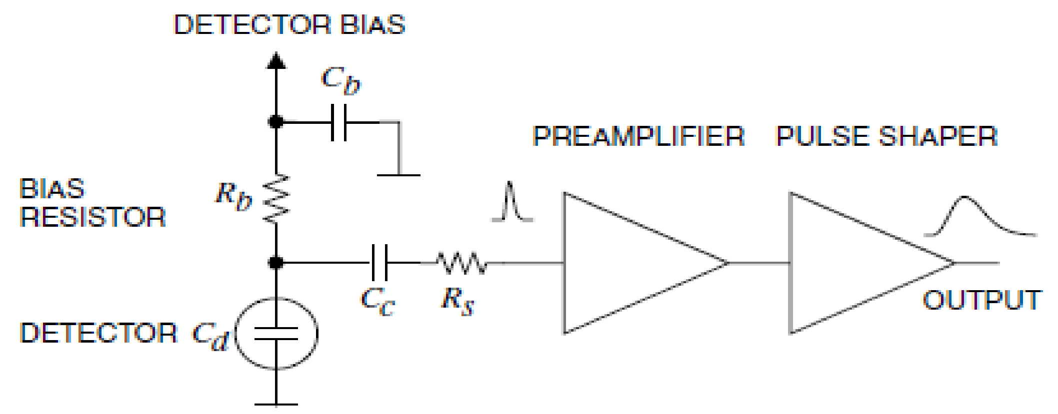
- **AC couple input amplifier (usually)**
  - → **Avoid large DC input currents**

Signals

- (a) Output of preamp
- (b) Output of shaping amp
- (c) Undershoot
- (d) Base-line shift



The output of preamplifier : rapidly rising step, followed by a slow exponential decay.
Amplitude of the step = energy of the detected radiation
Exponential decay time = feedback resistor in parallel with the feedback capacitor.



Shaping Time

Dominated by

Voltage noise ← → **Current noise**

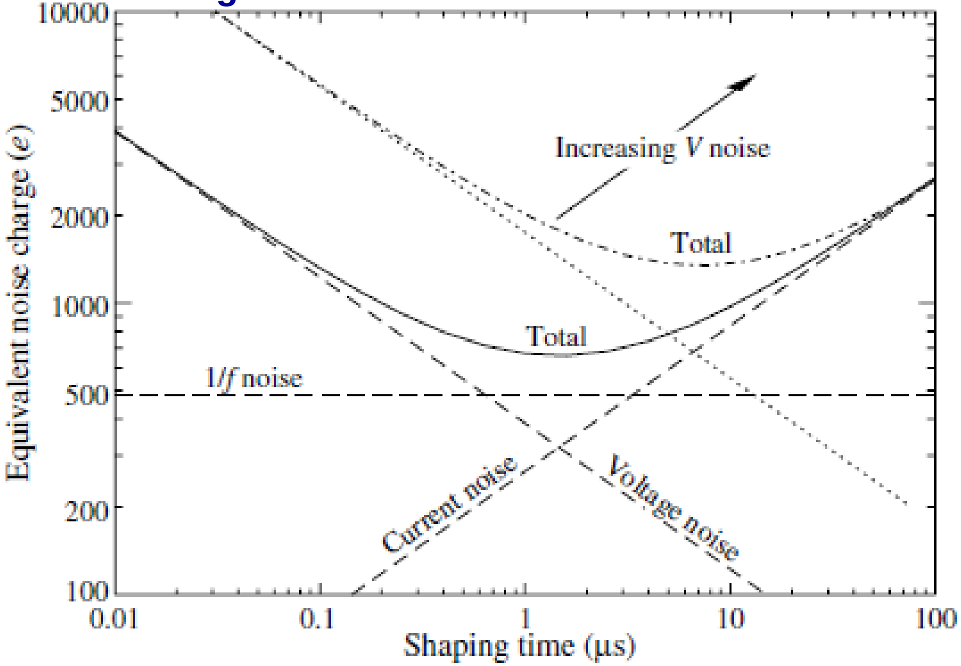
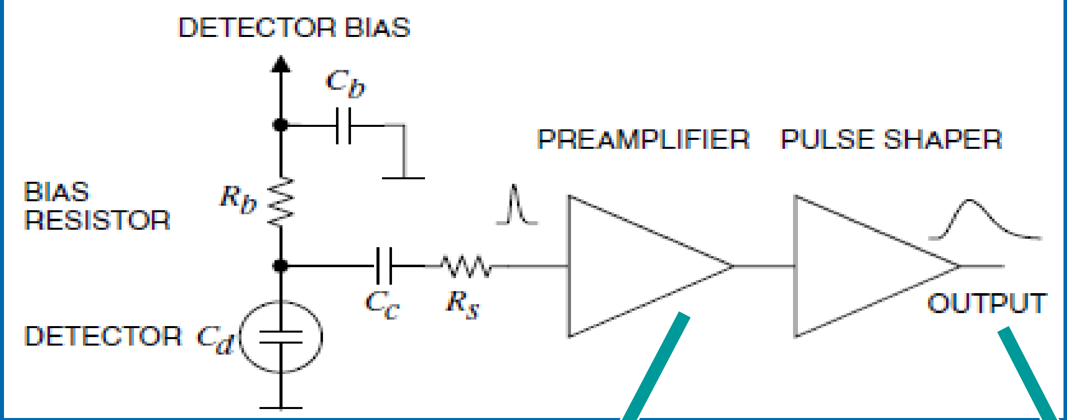


Figure 28.20: Equivalent noise charge *vs* shaping time. Changing the voltage or current noise contribution shifts the noise minimum. Increased voltage noise is shown as an example.

PRL667

Optimization is required in shaping time, ~ 1 μs

Electronics : Pile-up



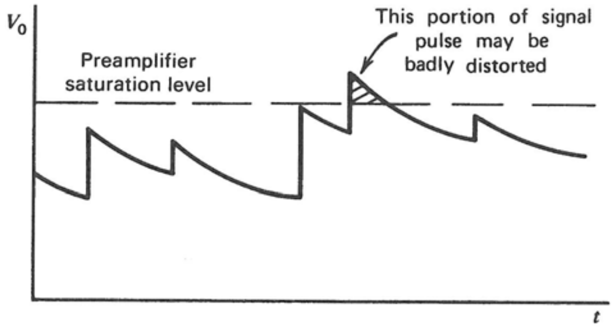
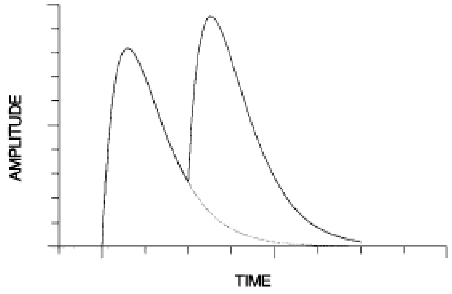
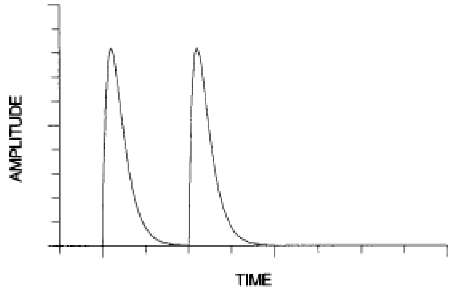


Figure 17.3 The pile-up of pulses within the preamplifier at high rates. If the saturation level of the preamplifier is exceeded, some pulses can be seriously distorted.

Pulse pile-up distorts amplitude measurement

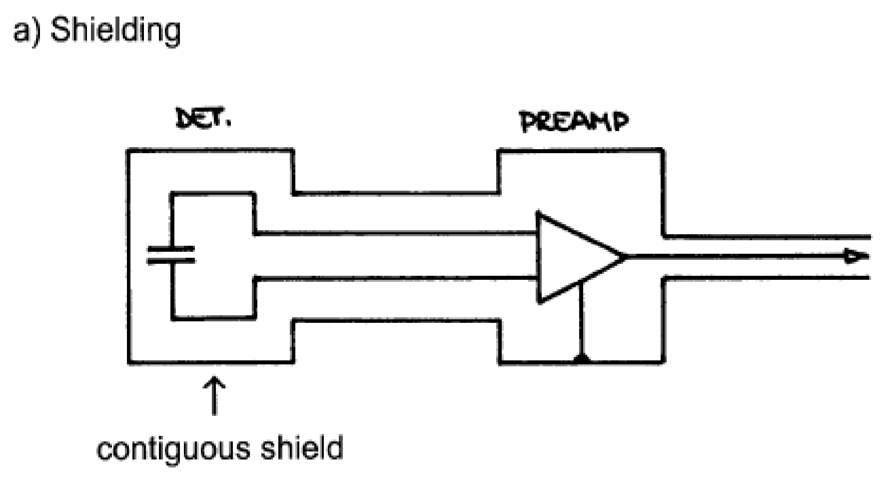


Reducing pulse shaping time to 1/3 eliminates pile-up.

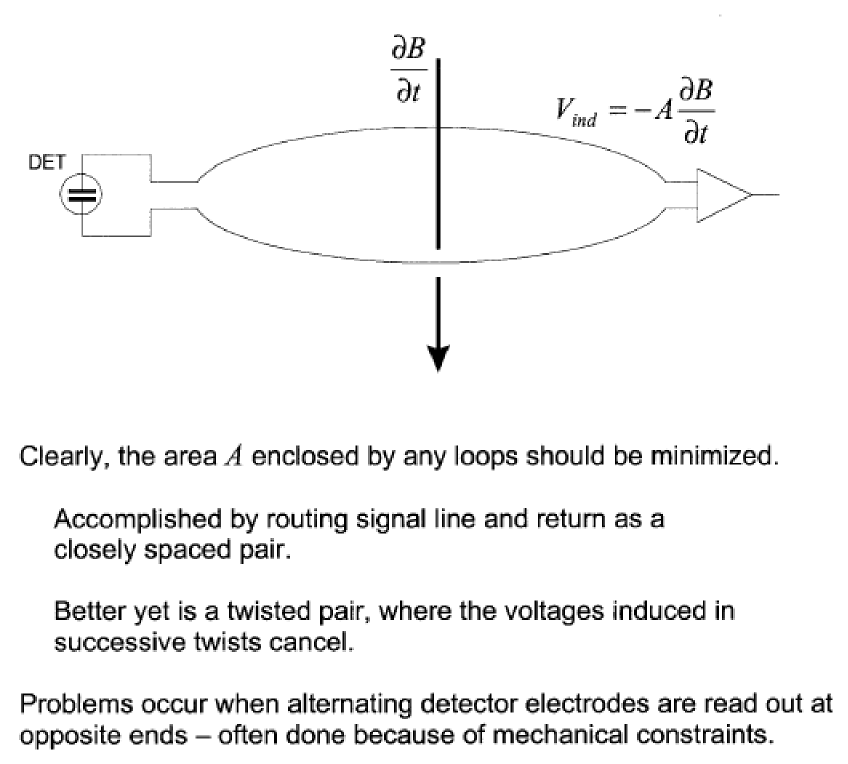


Shielding and Loops

H. Spieler (LBNL)



a) Shielding



$\frac{\partial B}{\partial t}$

$V_{ind} = -A\frac{\partial B}{\partial t}$

Clearly, the area A enclosed by any loops should be minimized.

Accomplished by routing signal line and return as a closely spaced pair.

Better yet is a twisted pair, where the voltages induced in successive twists cancel.

Problems occur when alternating detector electrodes are read out at opposite ends – often done because of mechanical constraints.

Operation

How to use them

Operation

DELICATE Devices

- HV should be increased SLOWLY..
  - Check its maximum HV value and Polarity (+/-)
  - Check the current in HV module and its signal carefully.
  - If something is wrong, stop the operation and investigate the reason.

- Shock / vibration may destroy the detector.
  - Careful handling.

- Silicon detectors
  - Only the support frame can be touched.
  - Silicon detector hates moisture.
  - Sensitive to photons (light) … Operate in dark place.

- Ge-detector
  - Liquid nitrogen is required to cool the detector down.

Summary

- Semiconductor detectors based on the simple principle of the p-n junction.
- Si is typically used for charged particle & X-ray
- Ge is used for γ ray spectroscopy.

Friday afternoon, Practical training using Ge detector (by Watanabe-san)

I wish you all the best for enjoying
your stay in JAPAN !!

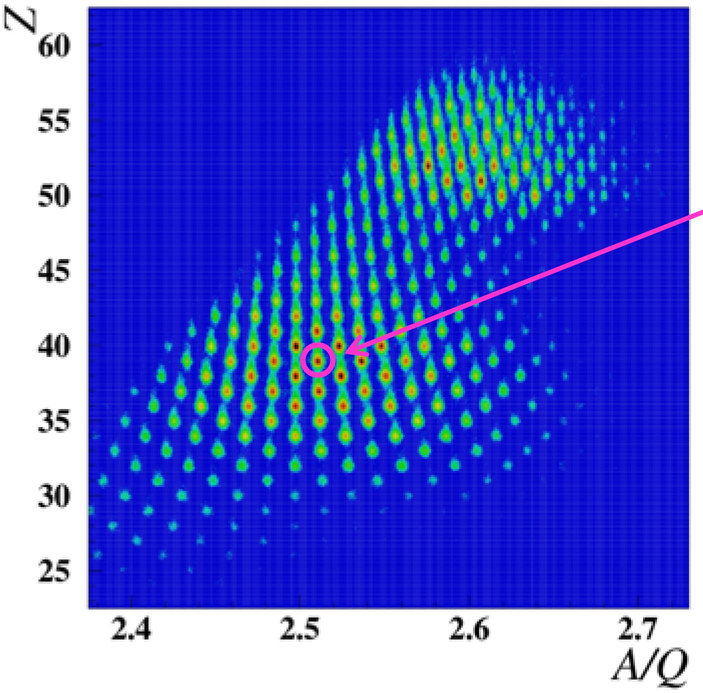
References

- SLAC Lecture
  - http://www-group.slac.stanford.edu/sluo/lectures/Detector-Lectures.html
- Silicon Detector by Paula Collins
  - http://lhcb-doc.web.cern.ch/lhcb-doc/presentations/lectures/CollinsItacuruca03-2nd.pdf
- REVIEW OF PARTICLE PHYSICS, Phys. Letters B 667 (2008).
- EG&G ORTEC, Modular Pulse-Processing Electronics and Semiconductor Radiation Detectors.
- GLENN F. KNOLL, Radiation Detection and Measurement.

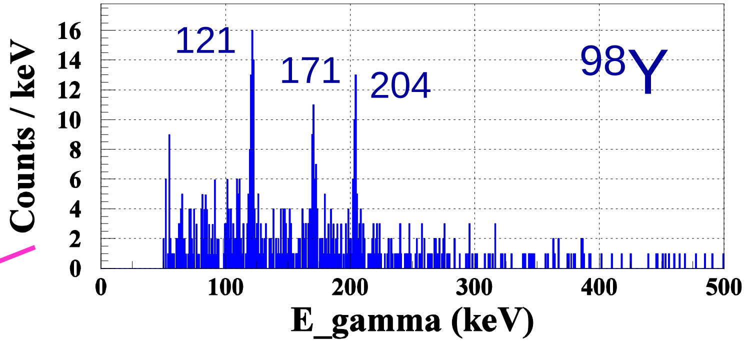
Particle Identification (PID)

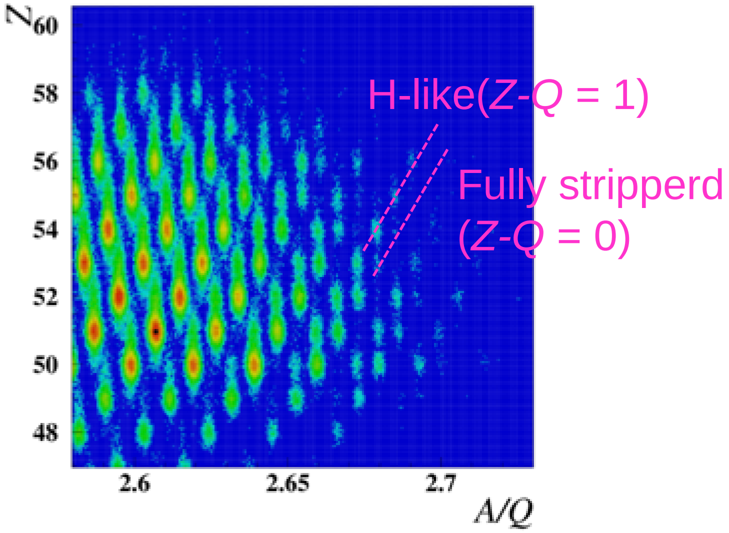
Isomeric states as Flag of PID

^{238}U (345 MeV/A) + Pb (1.5 mm)
Bρ = 6.99 Tm
without energy degrader



Confirmation by γ-rays from ^{98}Y isomeric state

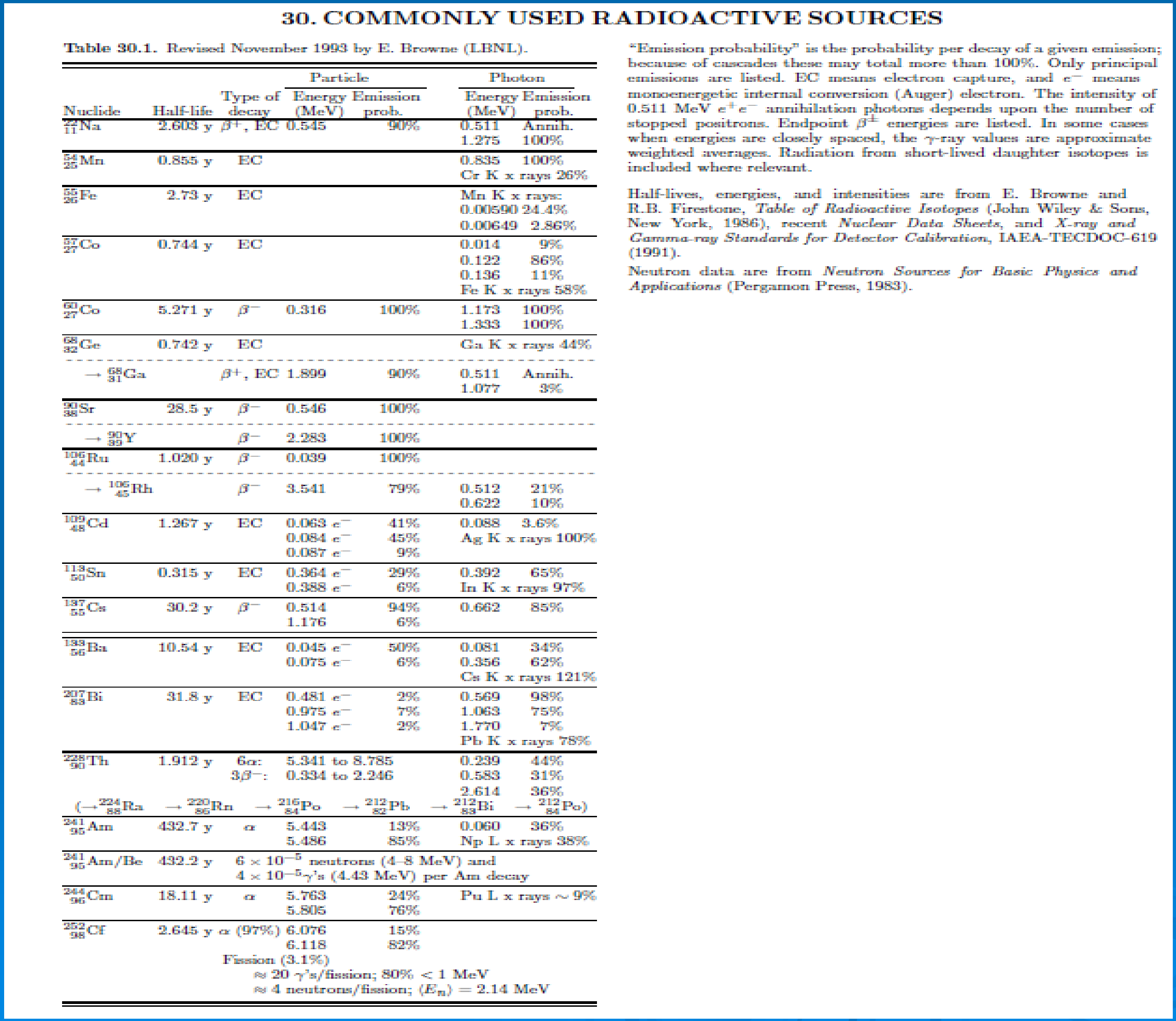




from Fukuda-san

Energy Calibration

PRL667



30. COMMONLY USED RADIOACTIVE SOURCES

Table 30.1. Revised November 1993 by E. Browne (LBNL).

			Particle		Photon	
Nuclide	Half-life	Type of decay	Energy (MeV)	Emission prob.	Energy (MeV)	Emission prob.
$^{22}_{11}$Na	2.603 y	β^+, EC	0.545	90%	0.511 1.275	Annih. 100%
$^{54}_{25}$Mn	0.855 y	EC			0.835 Cr K x rays	100% 26%
$^{55}_{26}$Fe	2.73 y	EC			Mn K x rays: 0.00590 0.00649	 24.4% 2.86%
$^{57}_{27}$Co	0.744 y	EC			0.014 0.122 0.136 Fe K x rays	9% 86% 11% 58%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173 1.333	100% 100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K x rays	44%
$\rightarrow$ $^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511 1.077	Annih. 3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
$\rightarrow$ $^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
$\rightarrow$ $^{106}_{45}$Rh		β^-	3.541	79%	0.512 0.622	21% 10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^- 0.084 e^- 0.087 e^-	41% 45% 9%	0.088 Ag K x rays	3.6% 100%
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^- 0.388 e^-	29% 6%	0.392 In K x rays	65% 97%
$^{137}_{55}$Cs	30.2 y	β^-	0.514 1.176	94% 6%	0.662	85%
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^- 0.075 e^-	50% 6%	0.081 0.356 Cs K x rays	34% 62% 121%
$^{207}_{83}$Bi	31.8 y	EC	0.481 e^- 0.975 e^- 1.047 e^-	2% 7% 2%	0.569 1.063 1.770 Pb K x rays	98% 75% 7% 78%
$^{228}_{90}$Th	1.912 y	6α: $3\beta^-$:	5.341 to 8.785 0.334 to 2.246		0.239 0.583 2.614	44% 31% 36%
($\rightarrow$ $^{224}_{88}$Ra $\rightarrow$ $^{220}_{86}$Rn $\rightarrow$ $^{216}_{84}$Po $\rightarrow$ $^{212}_{82}$Pb $\rightarrow$ $^{212}_{83}$Bi $\rightarrow$ $^{212}_{84}$Po)						
$^{241}_{95}$Am	432.7 y	α	5.443 5.486	13% 85%	0.060 Np L x rays	36% 38%
$^{241}_{95}$Am/Be	432.2 y	6×10^{-5} neutrons (4–8 MeV) and 4×10^{-5} γ's (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763 5.805	24% 76%	Pu L x rays	$\sim$ 9%
$^{252}_{98}$Cf	2.645 y	α (97%) Fission (3.1%) $\approx$ 20 γ's/fission; 80% $<$ 1 MeV $\approx$ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV	6.076 6.118	15% 82%		

"Emission probability" is the probability per decay of a given emission; because of cascades these may total more than 100%. Only principal emissions are listed. EC means electron capture, and e^- means monoenergetic internal conversion (Auger) electron. The intensity of 0.511 MeV e^+e^- annihilation photons depends upon the number of stopped positrons. Endpoint $\beta^{\pm}$ energies are listed. In some cases when energies are closely spaced, the γ-ray values are approximate weighted averages. Radiation from short-lived daughter isotopes is included where relevant.

Half-lives, energies, and intensities are from E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York, 1986), recent *Nuclear Data Sheets*, and *X-ray and Gamma-ray Standards for Detector Calibration*, IAEA-TECDOC-619 (1991).

Neutron data are from *Neutron Sources for Basic Physics and Applications* (Pergamon Press, 1983).

End

谢谢。