



HPGe Based Gamma-Ray Spectroscopy

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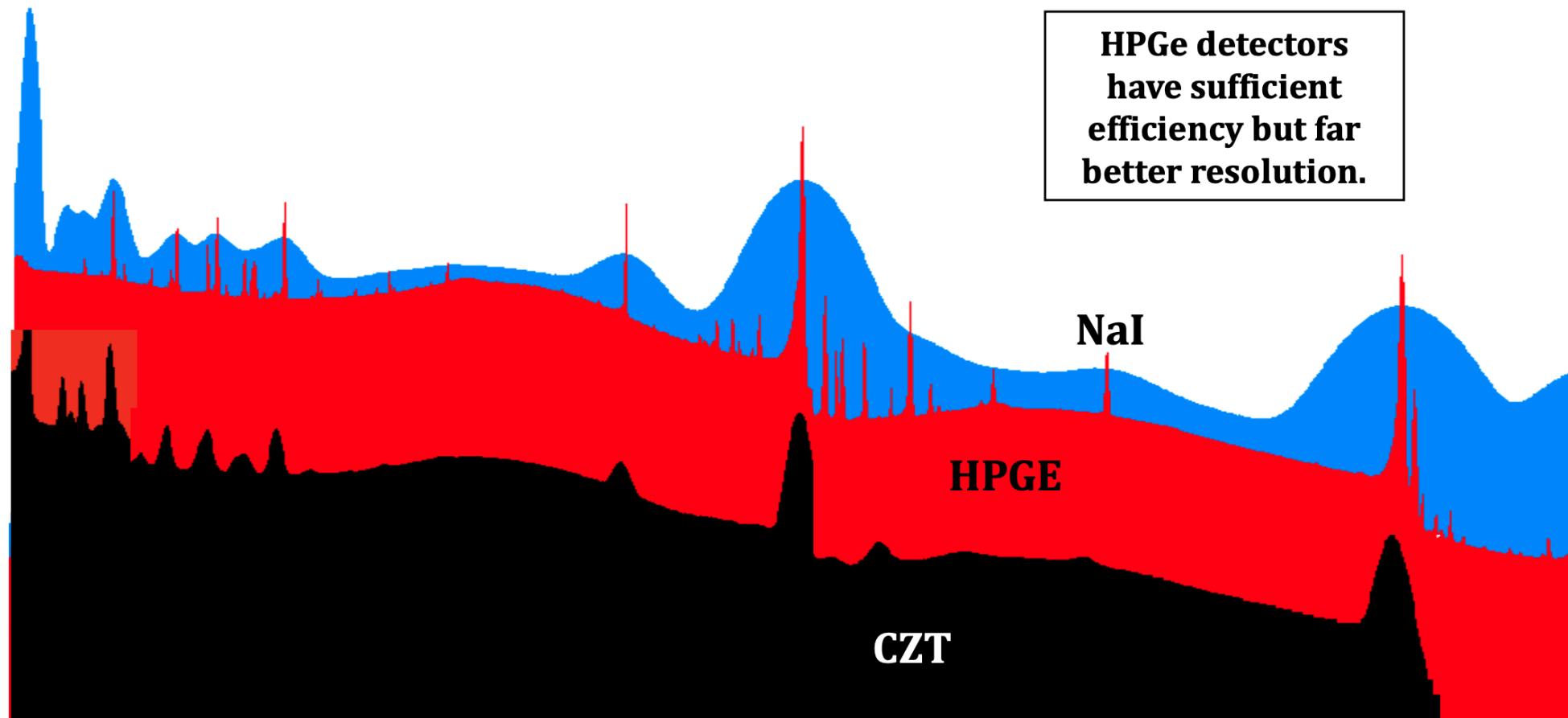
(CPNR Collaboration)

Center for Precision Neutrino Research

Chonnam National University

Introduction : Why use HPGe Detector

- Wide variety of applications that need to positively determine radioisotopes in very demanding circumstances



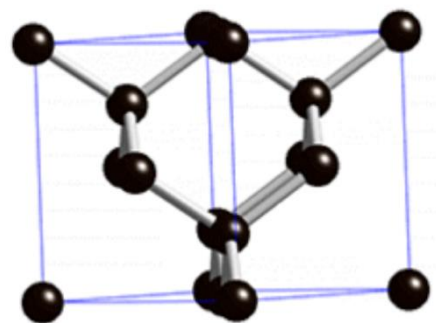
History of HPGe

- *Ge vs. Si detectors:*
 - Smaller band gap than Si (0.7 vs 1.1 eV)
 - Higher density (5.32 vs. 2.33 g/cm³) and higher Z (32 vs. 14)
 - Lower impurity (10⁹ vs 10¹² cm⁻³) allows much larger volumes to be depleted
- 1962: Pell produces first Li-drifted *Ge(Li)* detector (~1-10 cm³)
 - Limited size, permanent cooling, difficult handling, sensitive to radiation damage due to p-type, ...
- 1970's: *Ge(Li)* was replaced by High-Purity *Ge* (HPGe) detectors due to improved crystal growth processes (zone refinement and Czochralski process)
- 1990's: Large-volume HPGe detectors (10 cm diameter, 14 cm length, >800cm³); impurity concentrations down to <10⁹cm⁻³ and therefore the purest material available...

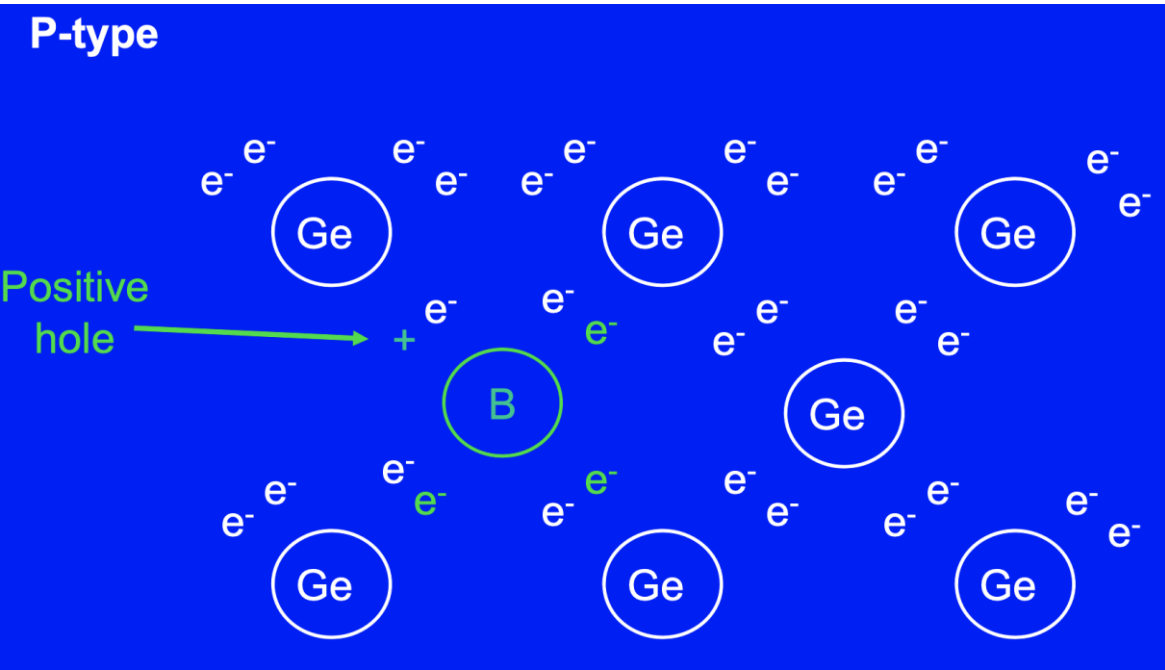
5 B 10.811	6 C 12.011	7 N 14.007
13 Al 26.982	14 Si 28.085	15 P 30.974
31 Ga 69.72	32 Ge 72.59	33 As 74.922
49 In 114.82	50 Sn 118.89	51 Sb 121.75
81 Tl 204.37	82 Pb 207.19	83 Bi 208.98



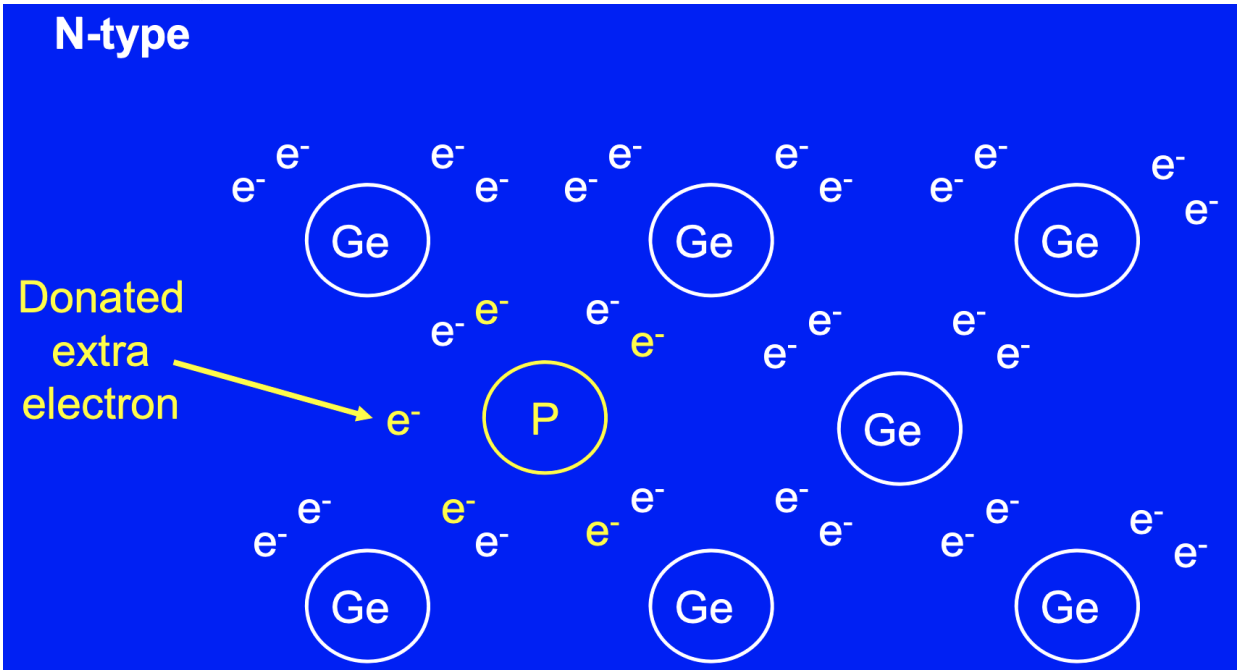
Conductivity



Acceptor Doping



Donor Doping



Resistivity and mobility

- Carrier DRIFT velocity and E-field:

$$v = \mu E$$

- $\mu_n = 1350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$: $\mu_p = 480 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

- Resistivity $\rho = \frac{1}{q(\mu_n n + \mu_p p)}$

- p-type material $\rho = \frac{1}{q\mu_p N_D}$

- n-type material $\rho = \frac{1}{q\mu N_A}$

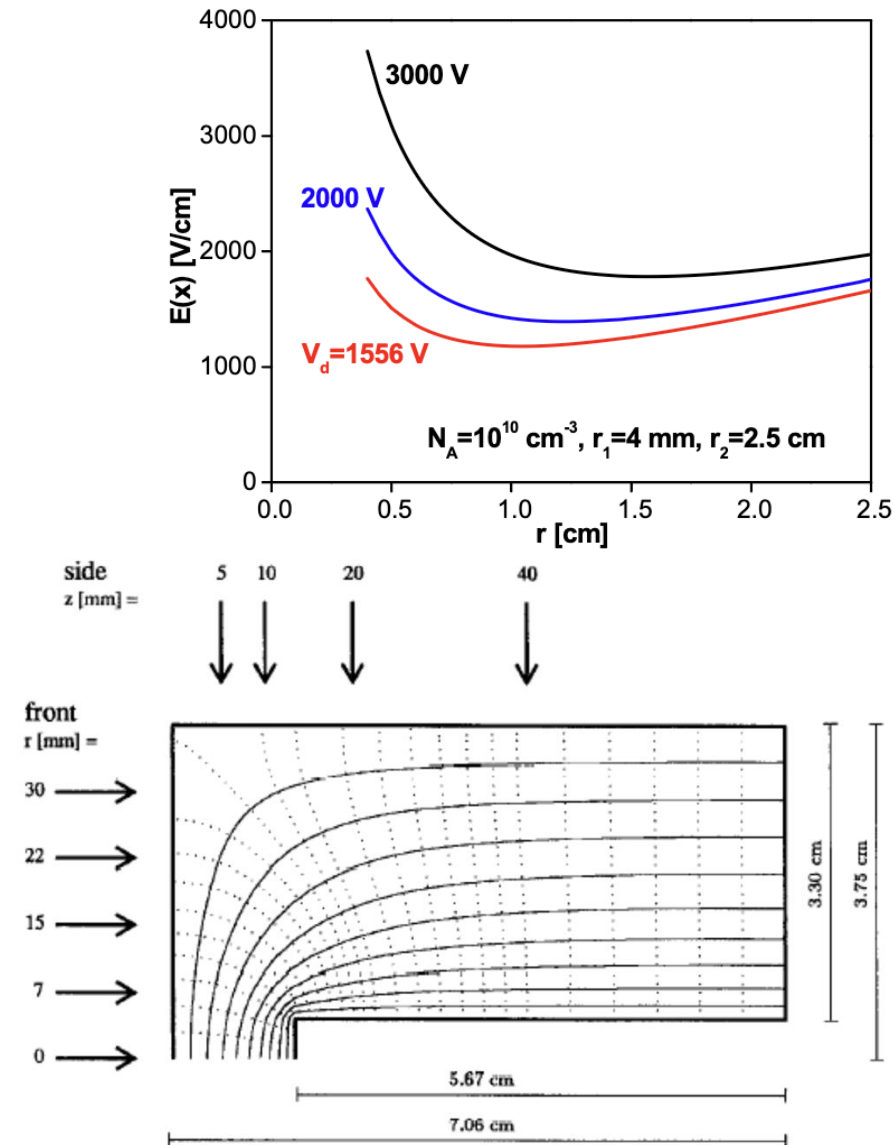
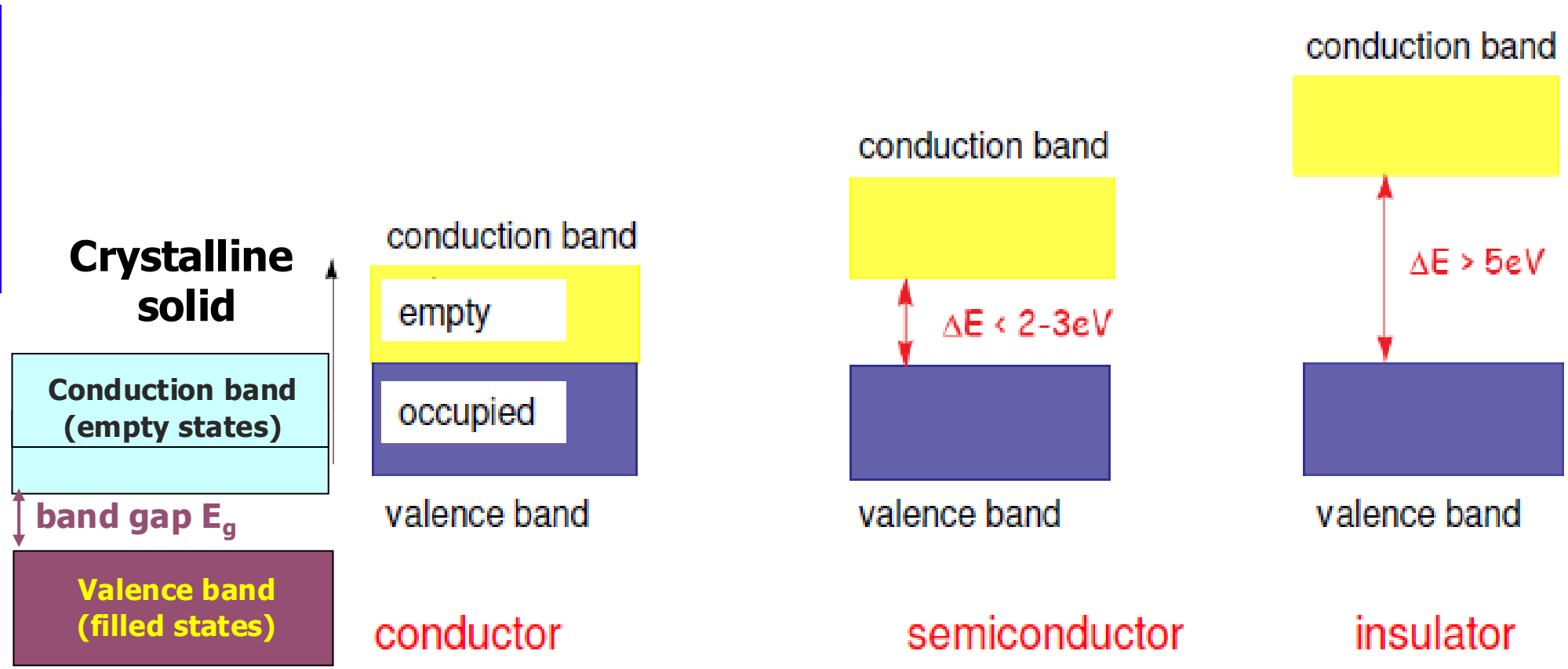
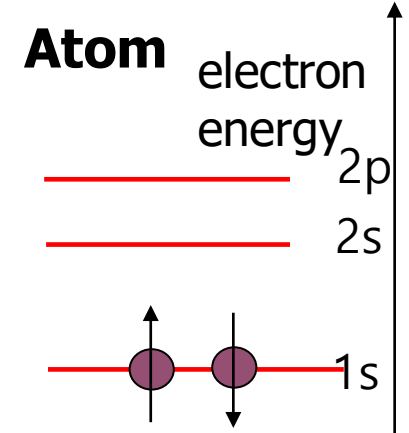
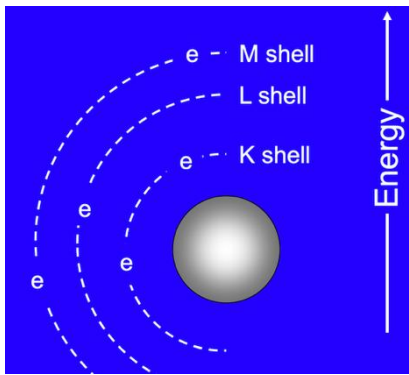


Fig. 8.11. Potential and electric field distribution of a closed-ended coaxial detector [5].

Conductivity

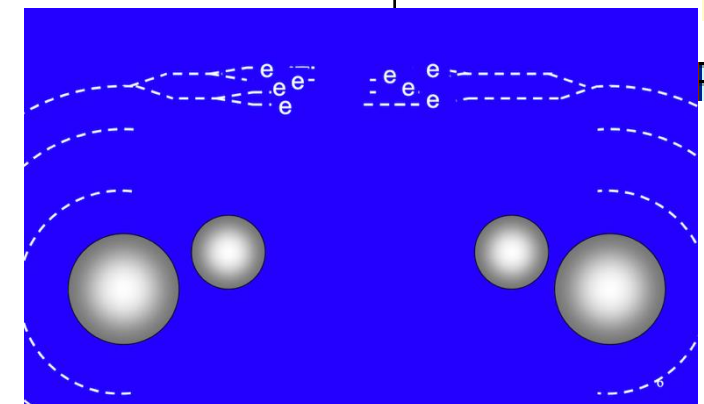


The probability that an electron occupies a certain energy level is given by the

Fermi-Dirac-Distribution:

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad \text{and for holes} \quad f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_F-E)/kT} + 1}$$

For intrinsic semiconductors (e and h concentration equal): $E_F = E_{gap}/2$



Depletion width

- Depletion Width depends upon Doping Density:
- For a given thickness, Full Depletion Voltage is:

$$W = \sqrt{\frac{2\varepsilon V}{q} \left(\frac{1}{N_D} + \frac{1}{N_A} \right)}$$

- $W = 300\mu\text{m}$, $N_D \sim 5 \times 10^{12} \text{cm}^{-3}$: $V_{fd} = 100\text{V}$

$$V_{fd} = \frac{qN_D W^2}{2\varepsilon}$$

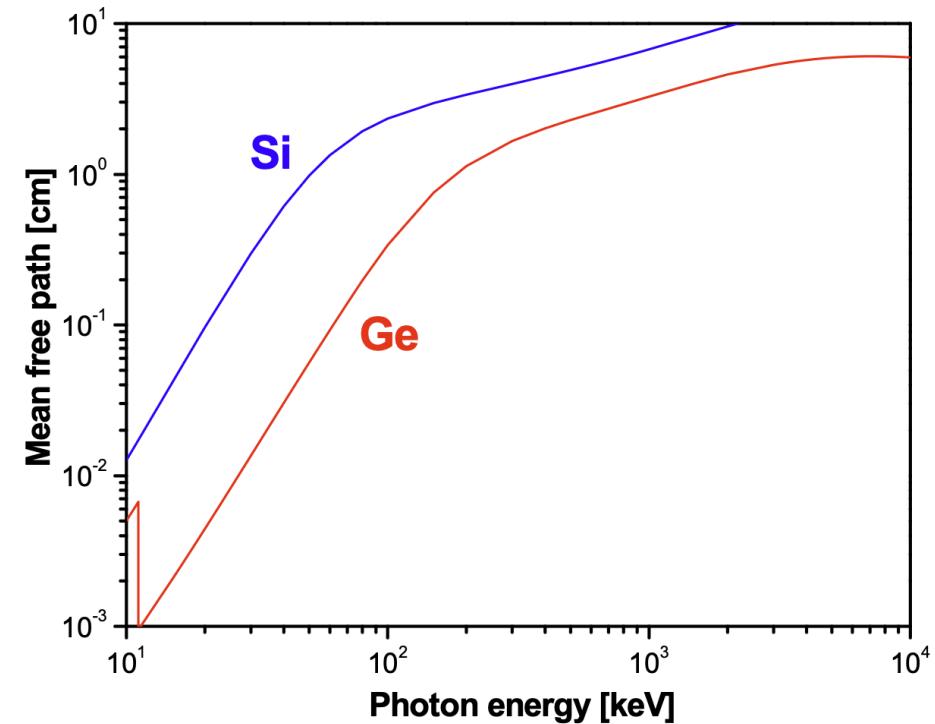


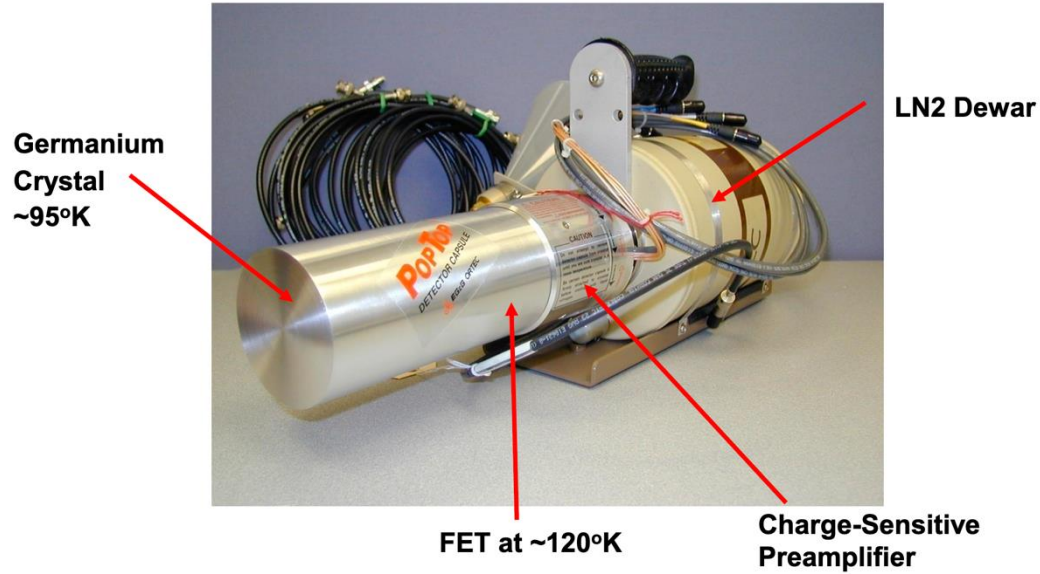
Fig. 8.1. Photon mean free paths in Si and Ge.

Capacitance

- Capacitance is due to movement of charge in the junction
- Fully depleted detector capacitance defined by geometric capacitance
- Strip detector more complex
 - Inter-strip capacitance dominates

$$C = \frac{dQ}{dV} = \sqrt{\frac{q\epsilon N_A N_D}{2(N_A + N_D)V}} = \sqrt{\frac{q\epsilon N_D}{2V}} = \sqrt{\frac{\epsilon}{2\mu\rho V}} = \frac{\epsilon}{W}$$

HPGe Detector



BROAD ENERGY GERMANIUM DETECTOR BE5030

- 50 cm² active area
- FWHM ≤ 0.50 keV @ 5.9 keV
- ≤ 0.75 keV @ 122 keV
- ≤ 2.00 keV @ 1332 keV

HPGe Application

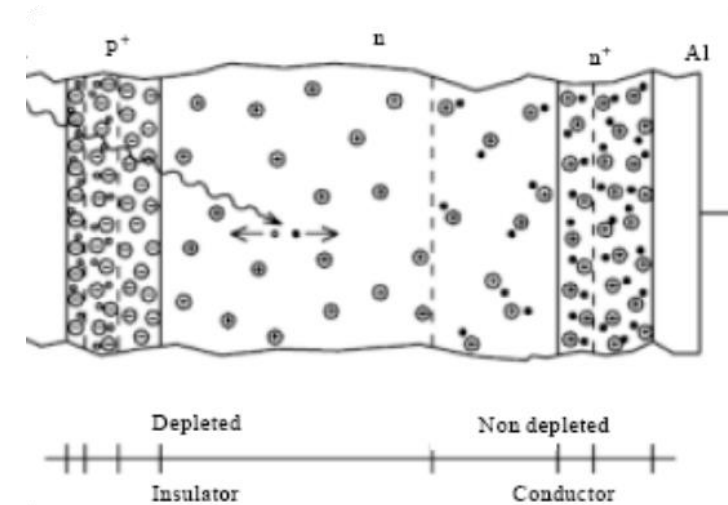
- ❑ *Study on Radionuclides*
 - ✓ *Photon Energy*
 - ✓ *Gamma-Ray Emission Rate*
- ❑ *Micro-Analysis of Element*
 - ✓ *Neutron/charged particles activation*
 - ✓ *Thermal neutron capture*
 - ✓ *Fluorescence X-ray*
- ❑ *Radiation/Radioactivity Monitoring*
- ❑ *Application to Nuclear imaging, Nuclear and High energy physics, Astrophysics and Geology*

Principle of Detector operation

- Fano factor(F)
- ✓ Average ionization energy(ϵ) necessary to create an electron-hole pair
- ✓ 2.96 eV for Ge (@ 80K) vs 3.62 eV for Si (@ 80K)

$$N = \frac{E}{W}$$

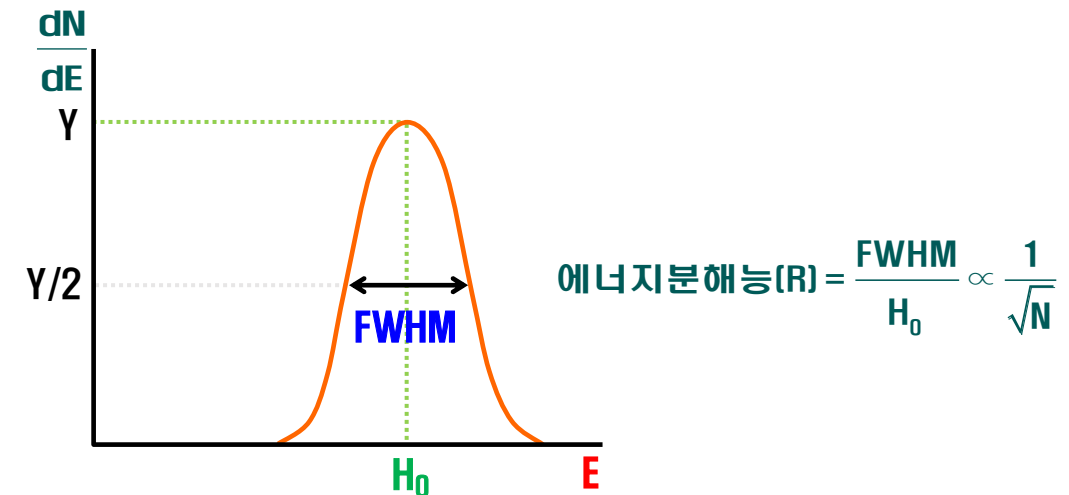
Gas 검출기의 경우 약 30 eV가 필요하므로,
Semiconductor 검출기는 동일 에너지에서 **10배 더 많은 전하**를 생성.



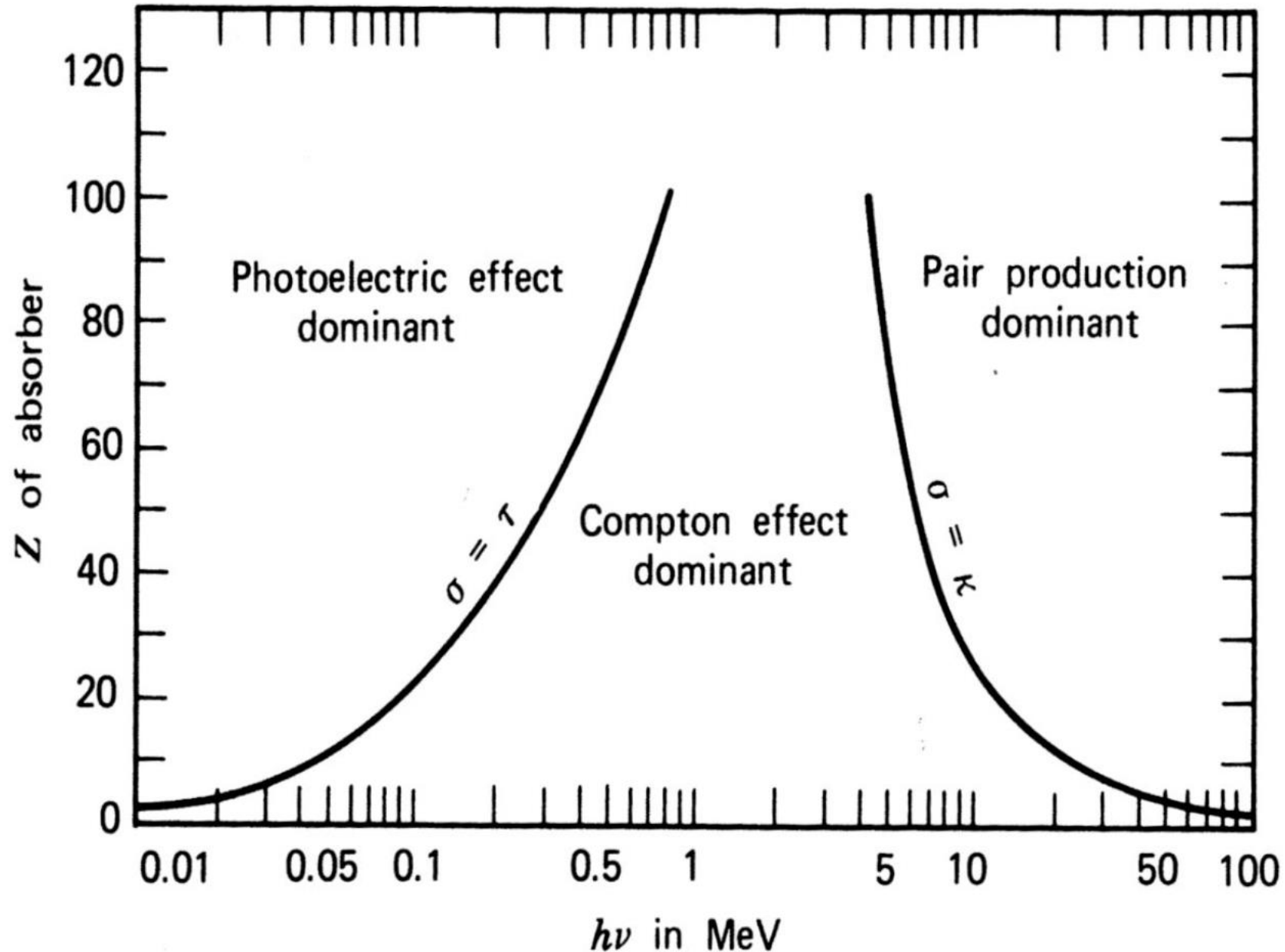
$$Variance = \overline{(n - \bar{n})^2} = F \bullet \bar{n},$$

$$\bar{n} = \frac{E_0}{\epsilon}$$

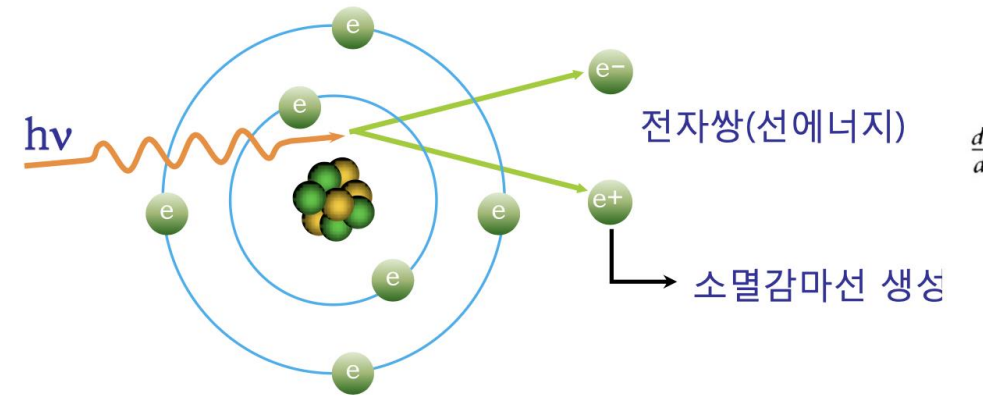
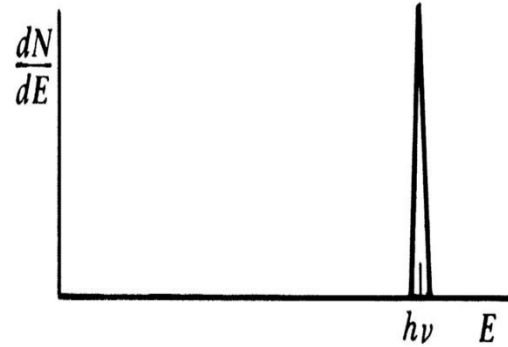
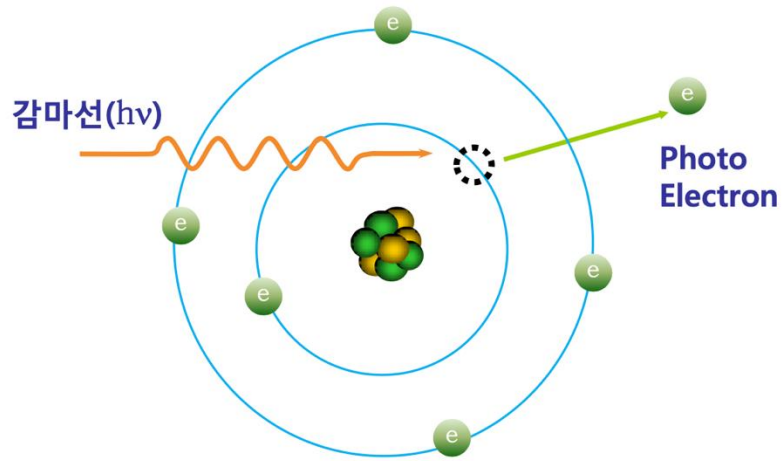
- F=0 ; no fluctuation in the # of e-h pair
- F=1 ; Poisson statistics
- Semiconductor Detector ; less than F=0.05-0.1
- Gas Detector ; F=0.2 to 0.5



Interaction Process

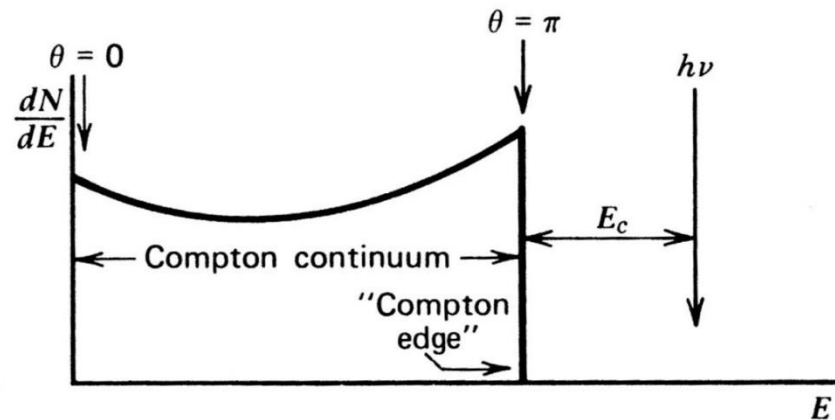
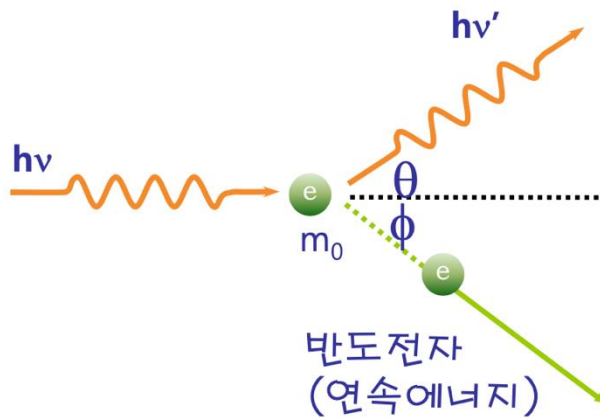


Interaction Process



$$h\nu = T^- + T^+ + 2m_0c^2$$

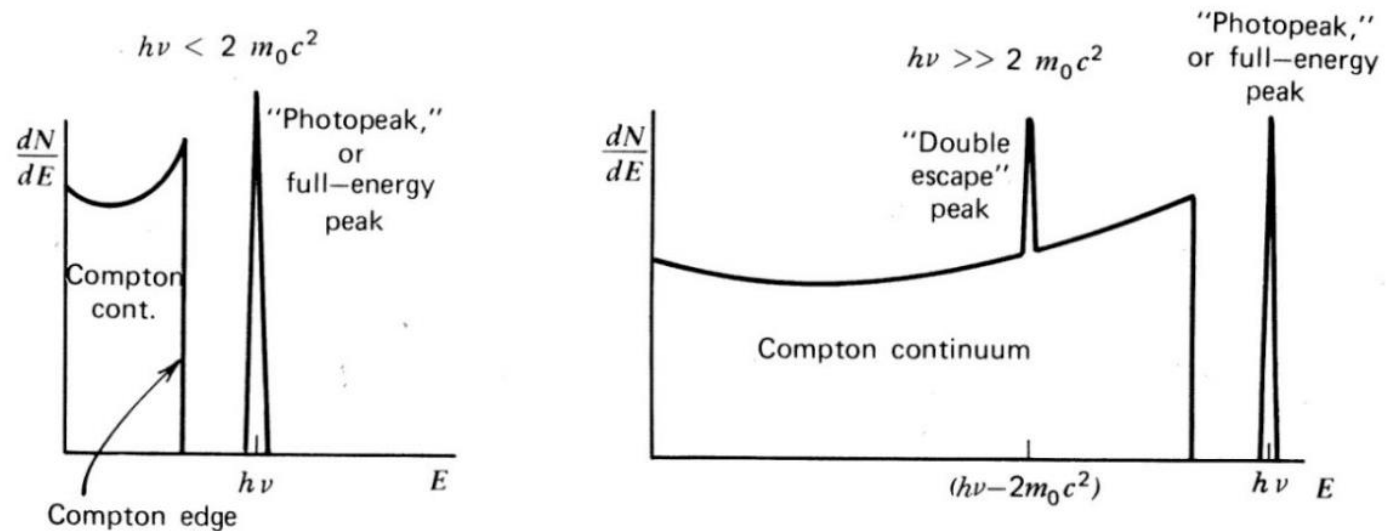
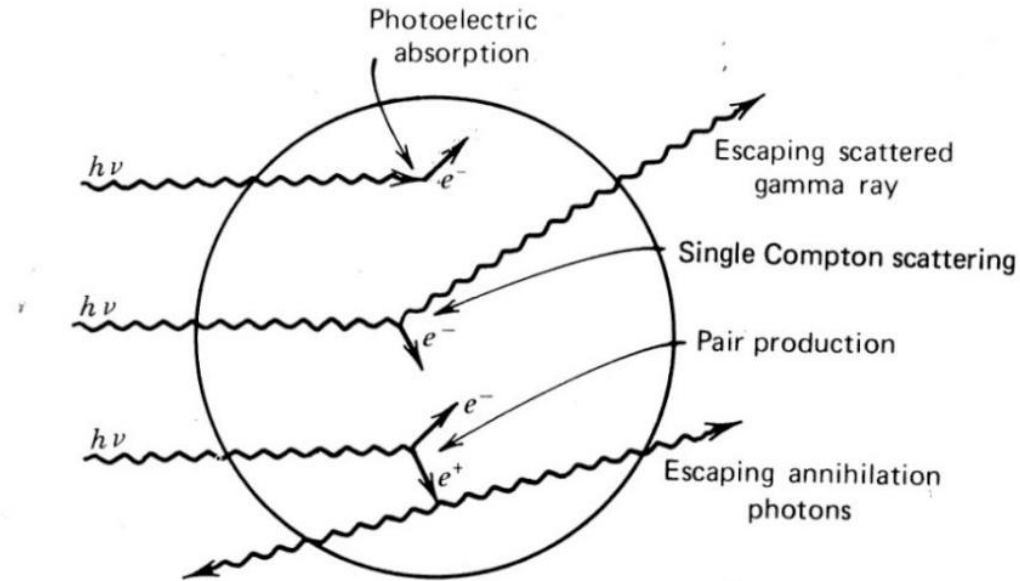
광전효과 후 감마선은 소멸됨 !!



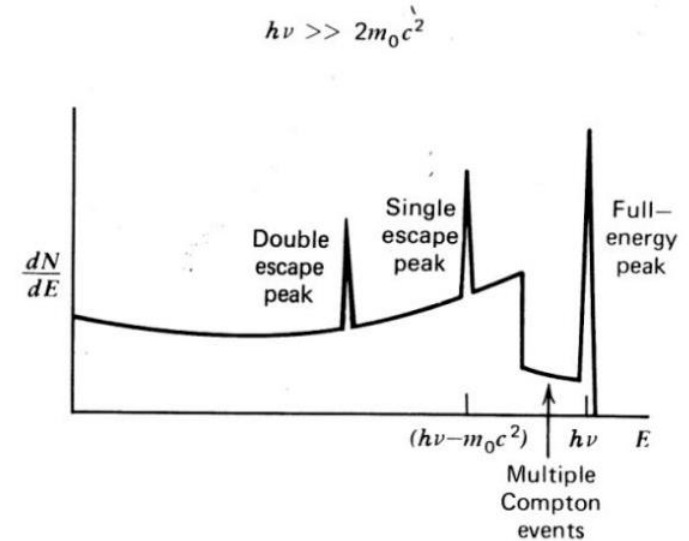
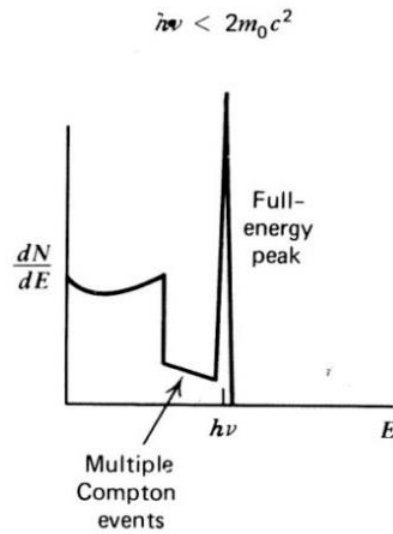
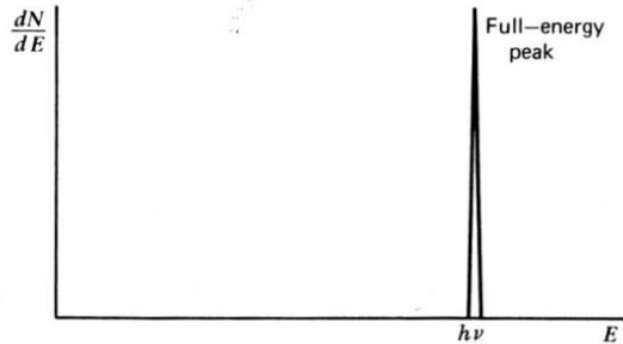
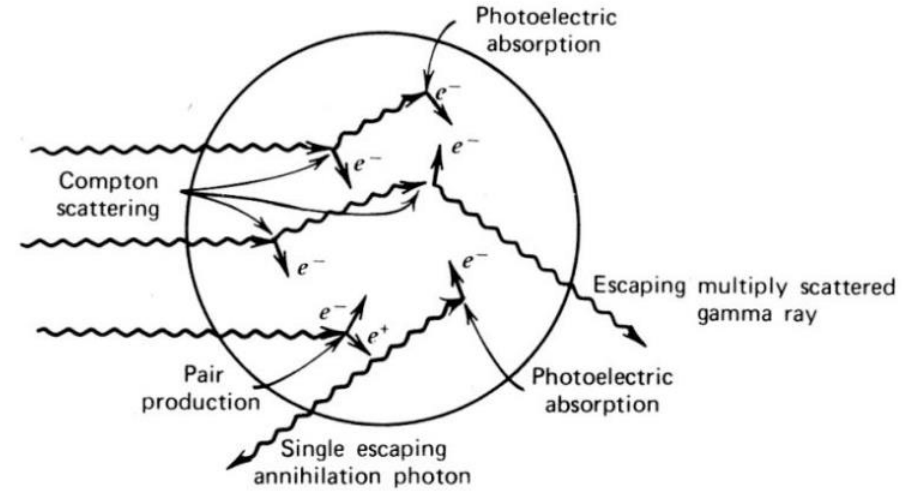
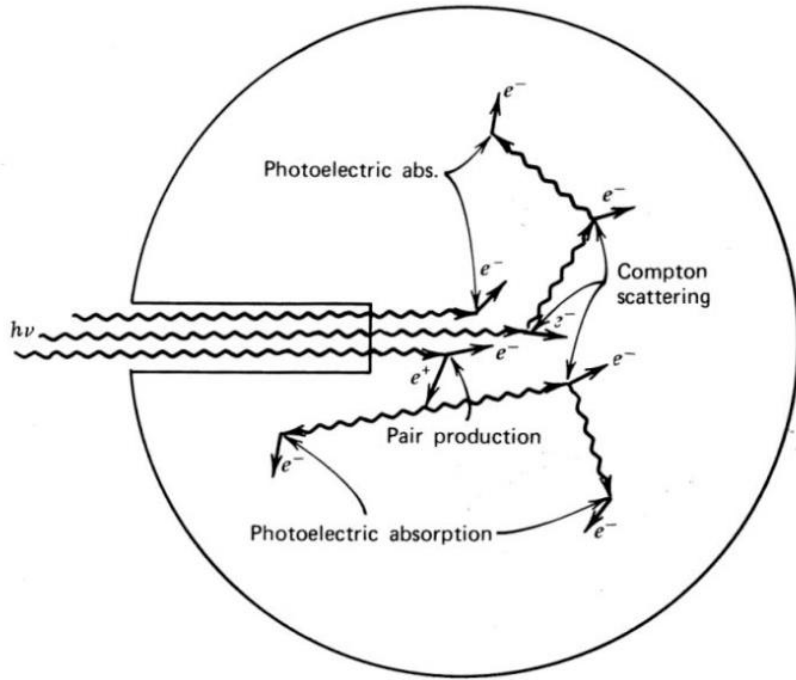
- **Photoelectric Absorption (광전효과)**
(up to several hundred keV)
- **Compton Scattering (컴프턴산란)**
(several hundred keV to 5 MeV)
- **Pair Production (쌍생성)**
(5 to 10 MeV)

컴프턴산란 후 감마선은 소멸되지 않음 !!

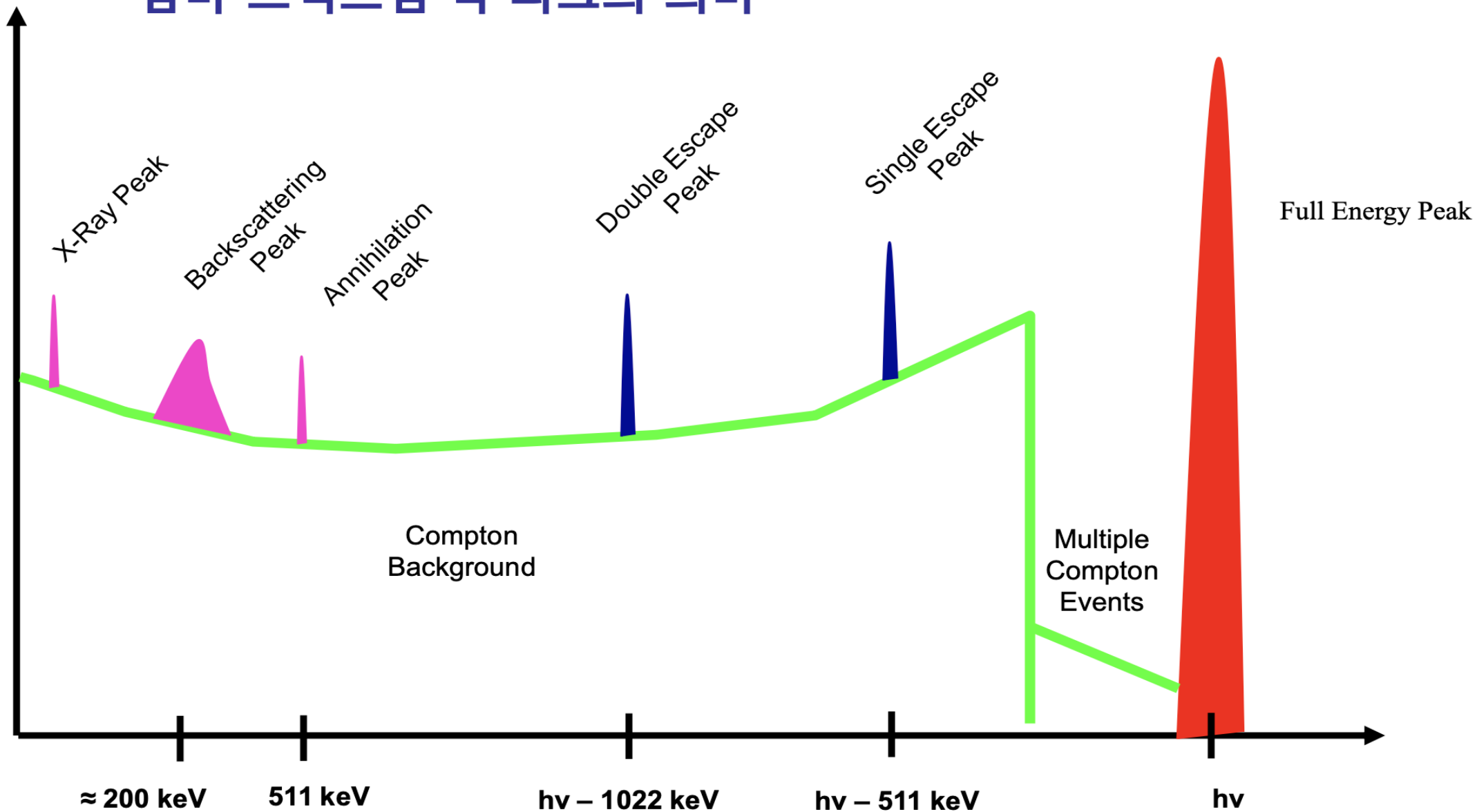
Detector Response (small)



Detector Response (Large, Intermediate)

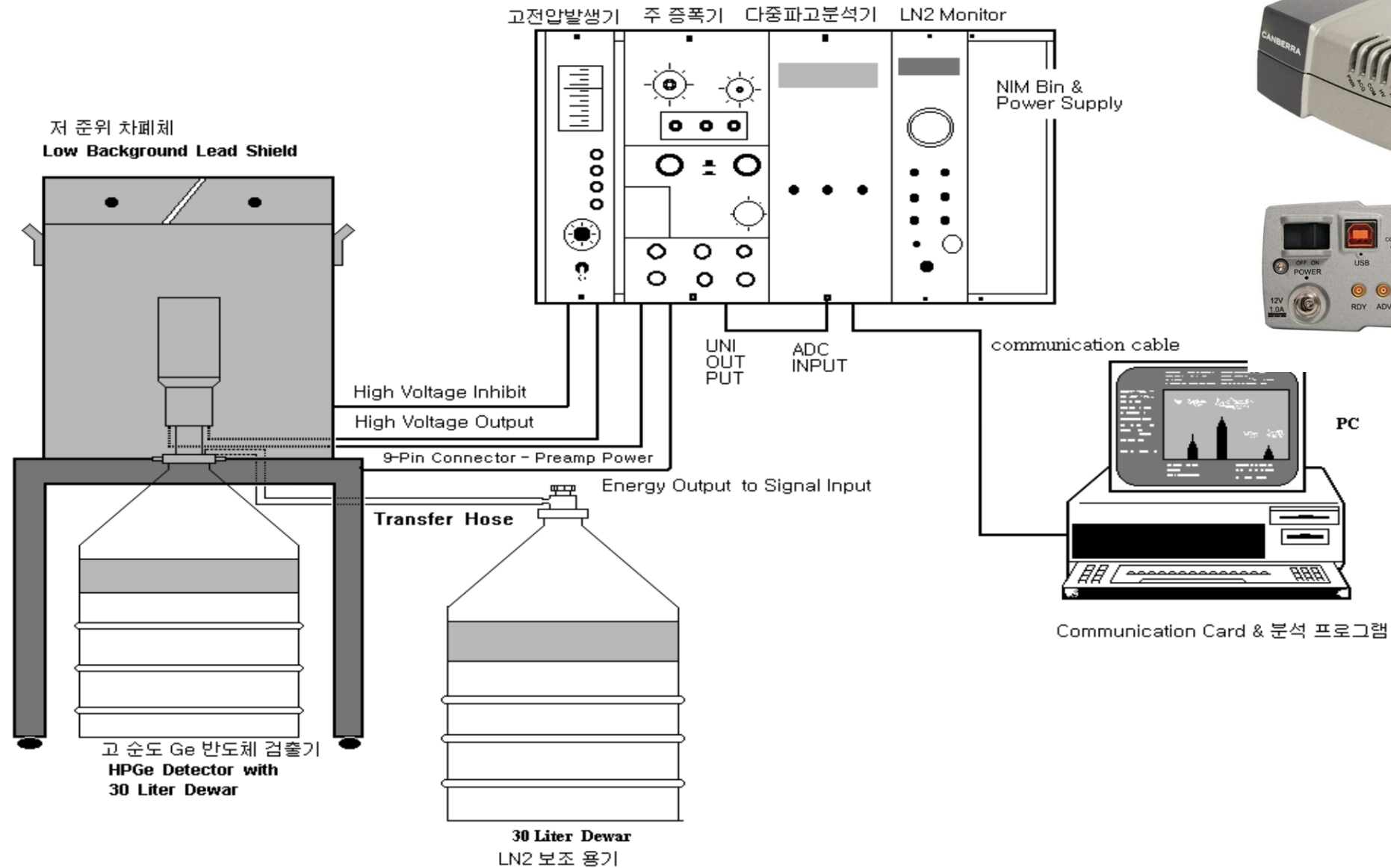


■ 감마 스펙트럼 각 피크의 의미

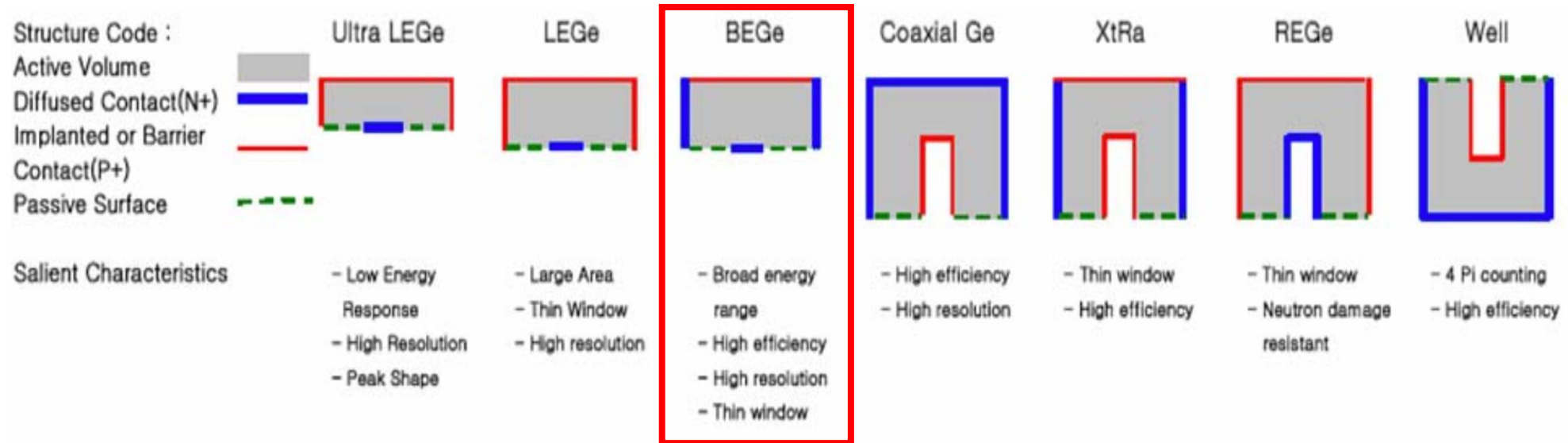


HPGe detector system configuration

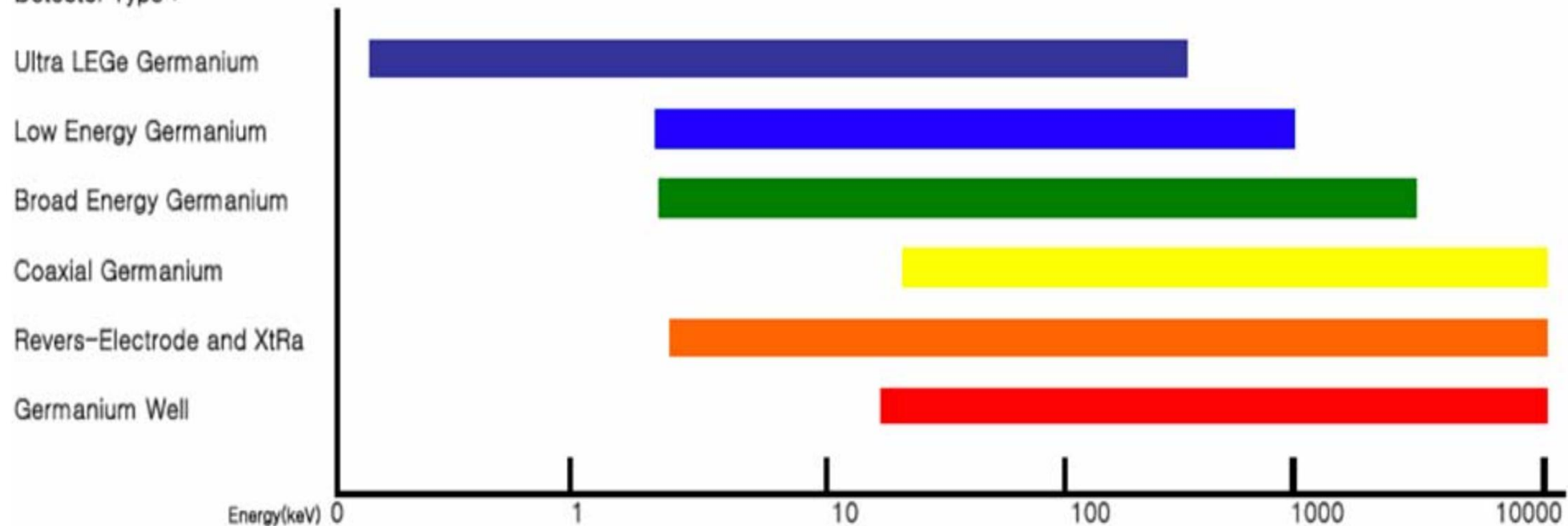
** High Purity Germanium(HPGe) Gamma-ray Spectroscopy System **



HPGe detectors types

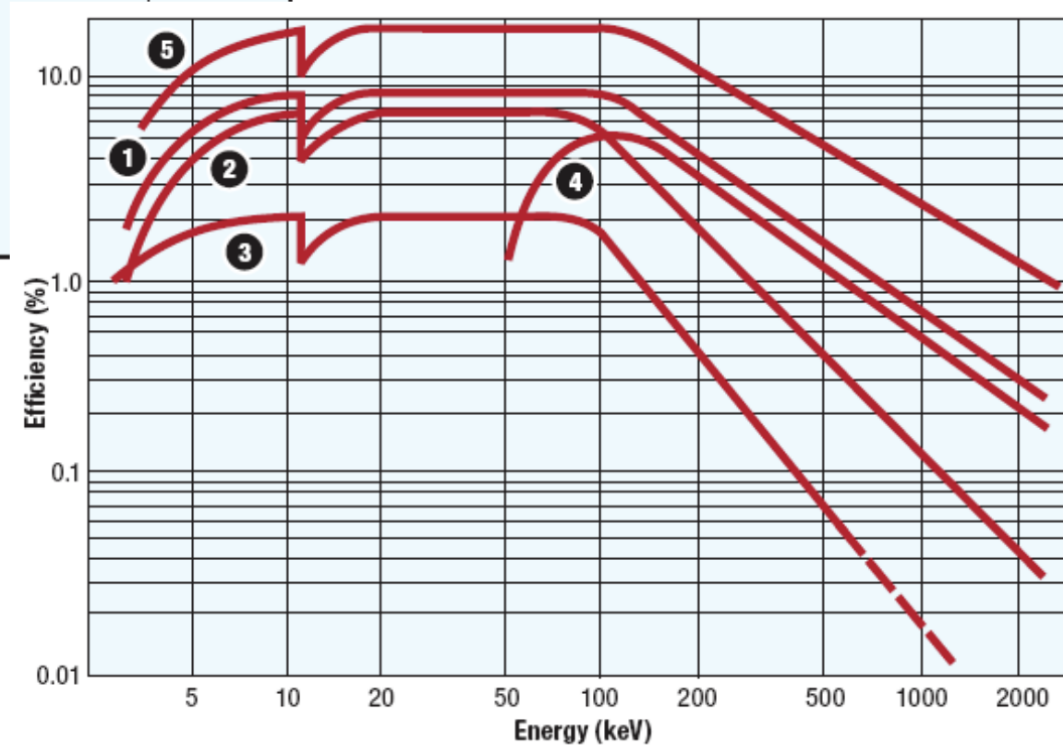
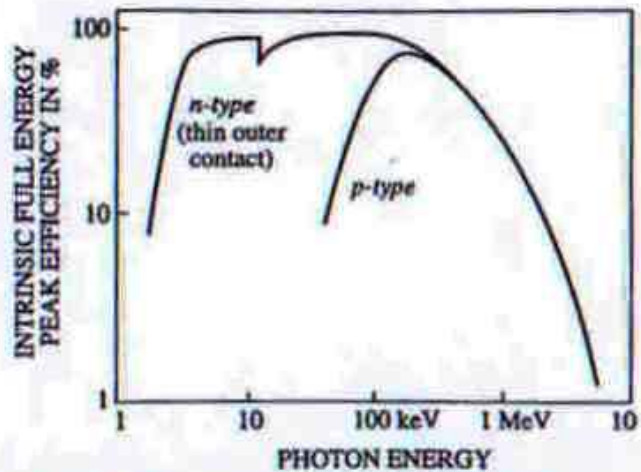
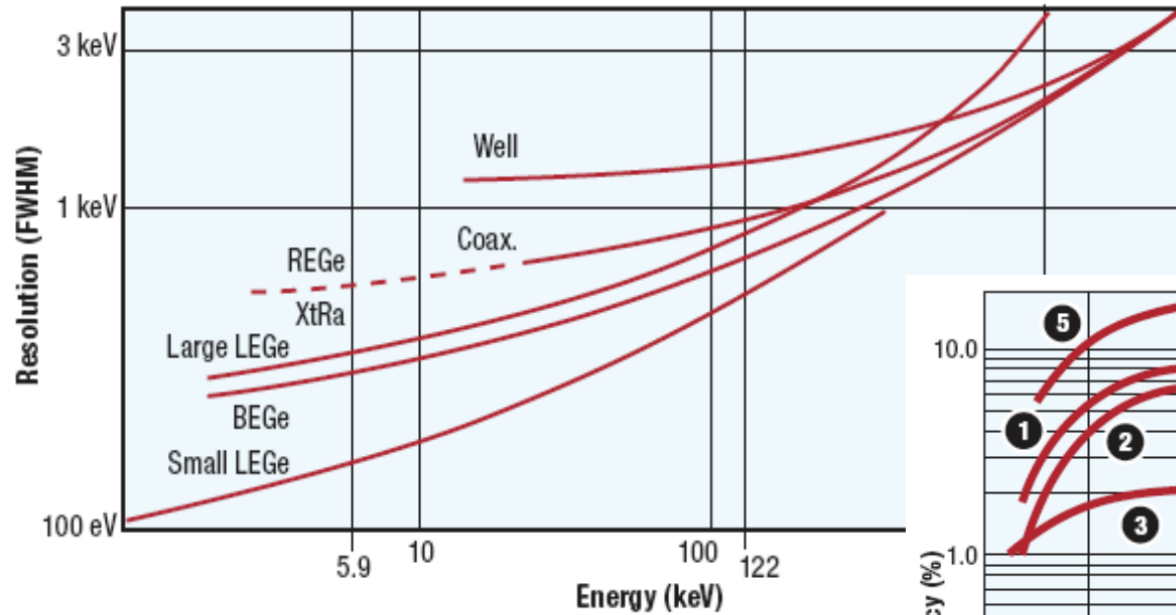


Detector Type :



Detector resolution & efficiency

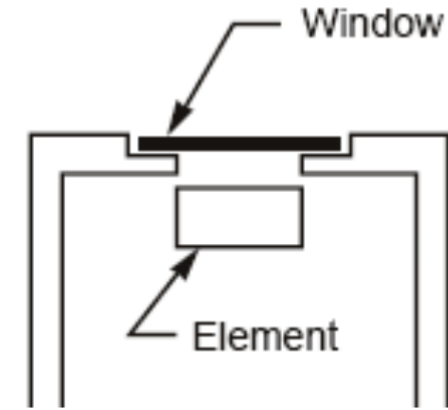
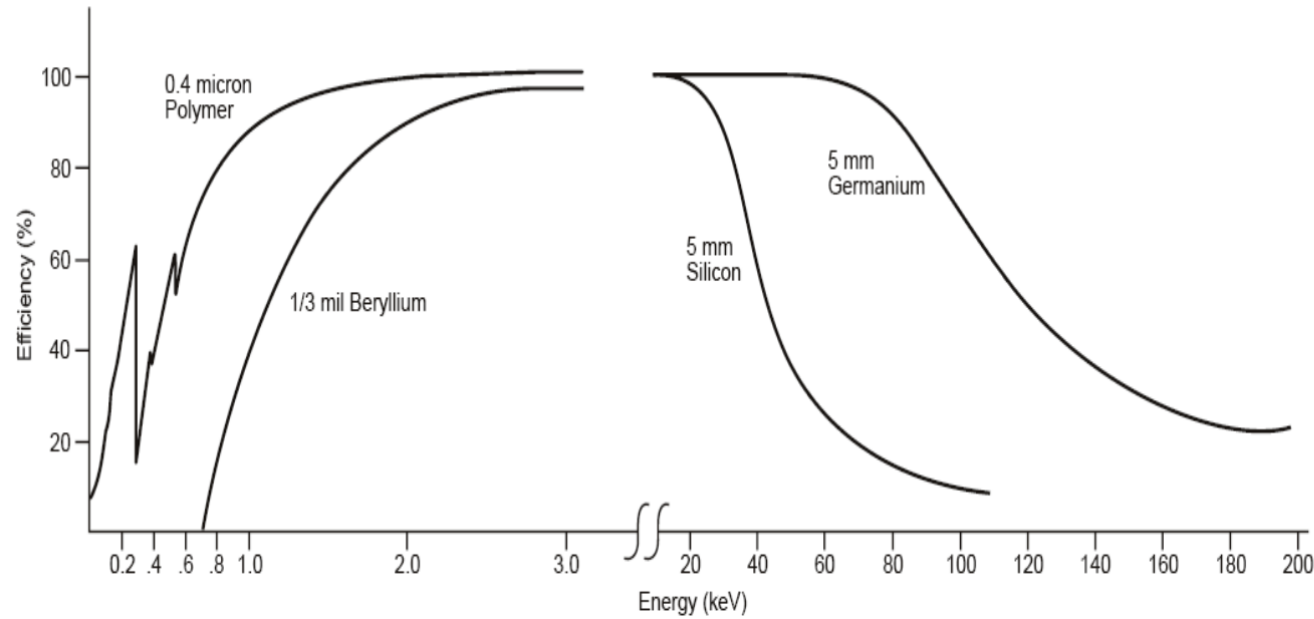
Typical Resolution vs. Energy



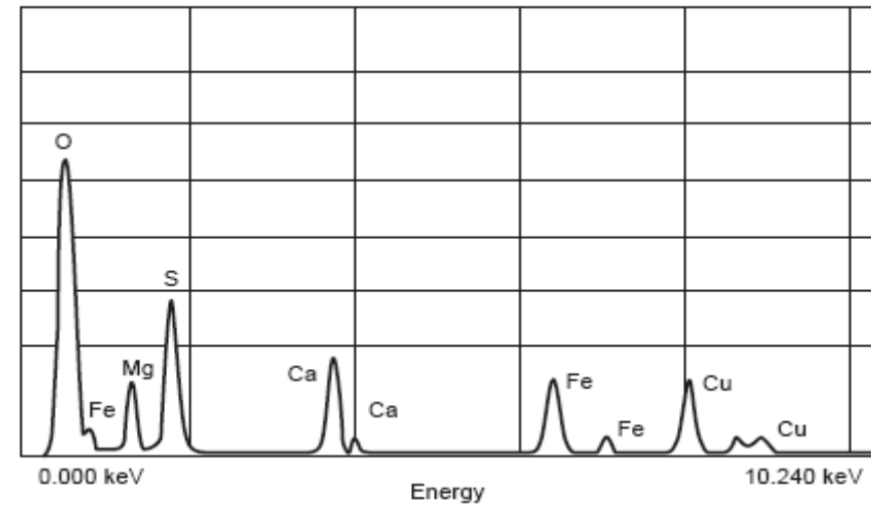
Typical absolute efficiency curves for various Ge detectors with 2.5 cm source to end-cap spacing

- ① REGe, 15% Relative Efficiency XtRa, 15% Relative Efficiency
- ② LEGe, 10 cm² x 15 mm thick
- ③ LEGe, 200 mm² x 10 mm thick
- ④ Coaxial Ge, 10% Relative Efficiency
- ⑤ BEGe, 5000 mm² x 30 mm thick

Ultra Low Energy Germanium Detector(U LEGe)

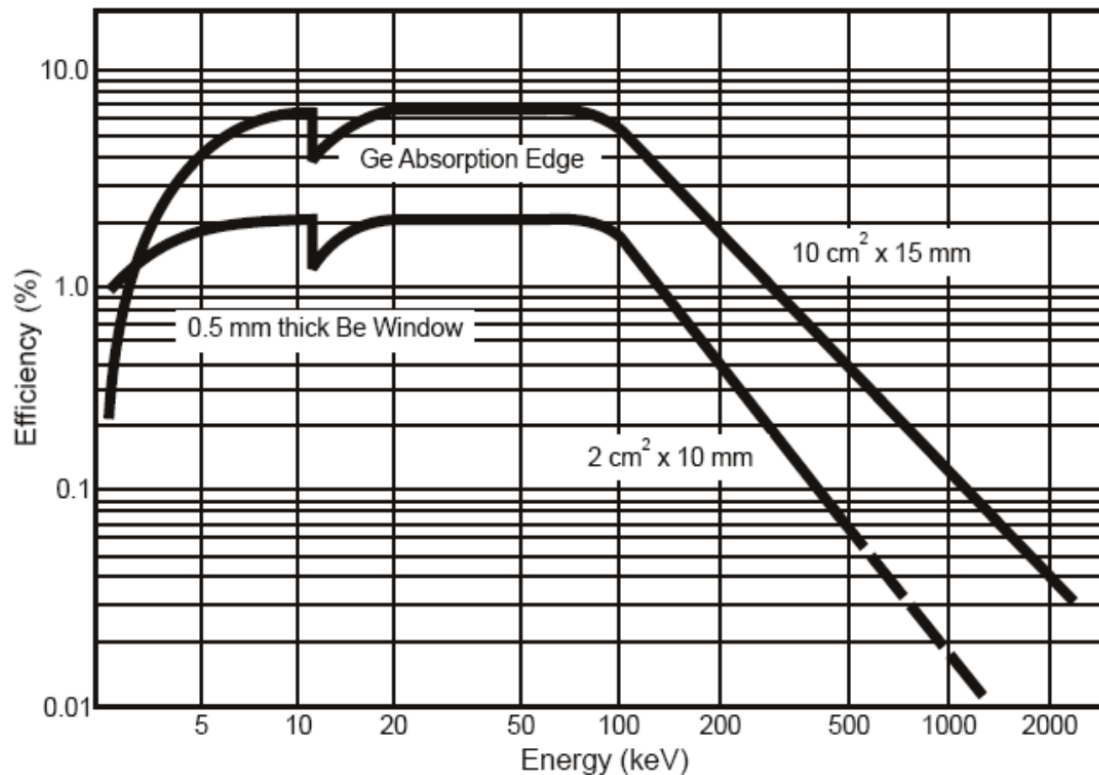
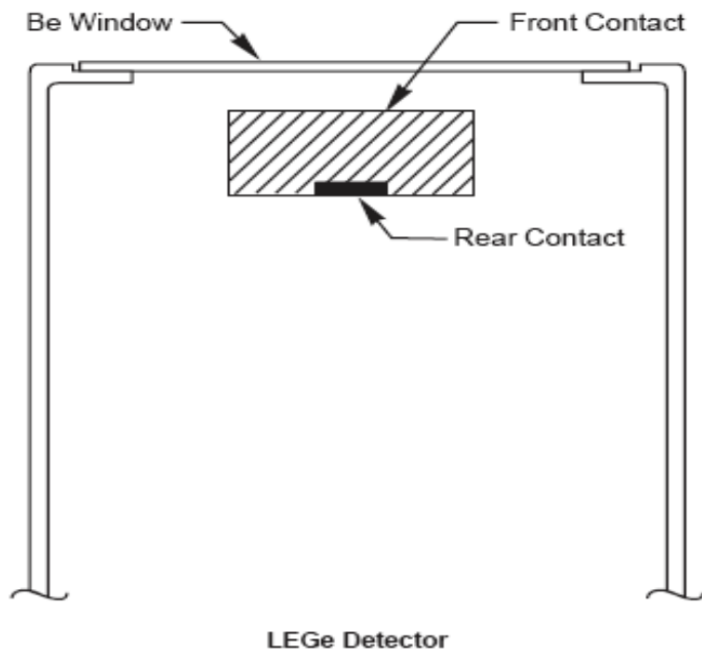


- 에너지 측정 범위 : 300 eV to 300 keV
- High Efficiency
- Low Energy Gamma 또는 X-ray 측정
- High peak/background ratio
- Optional polymer film window



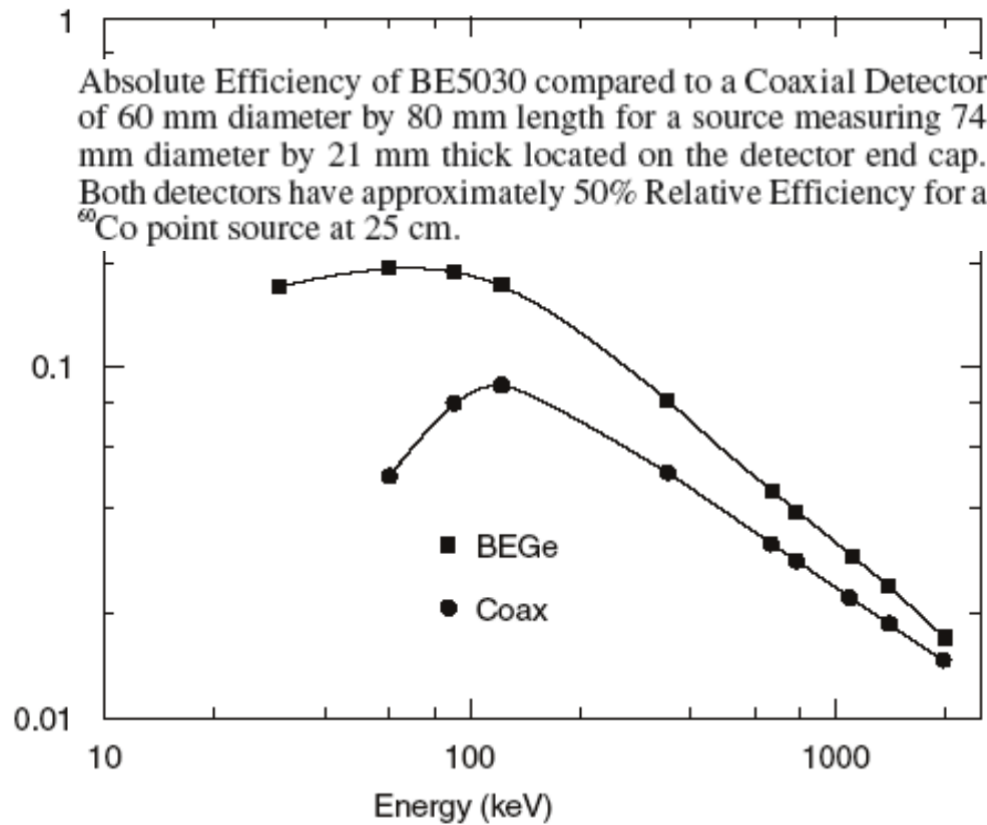
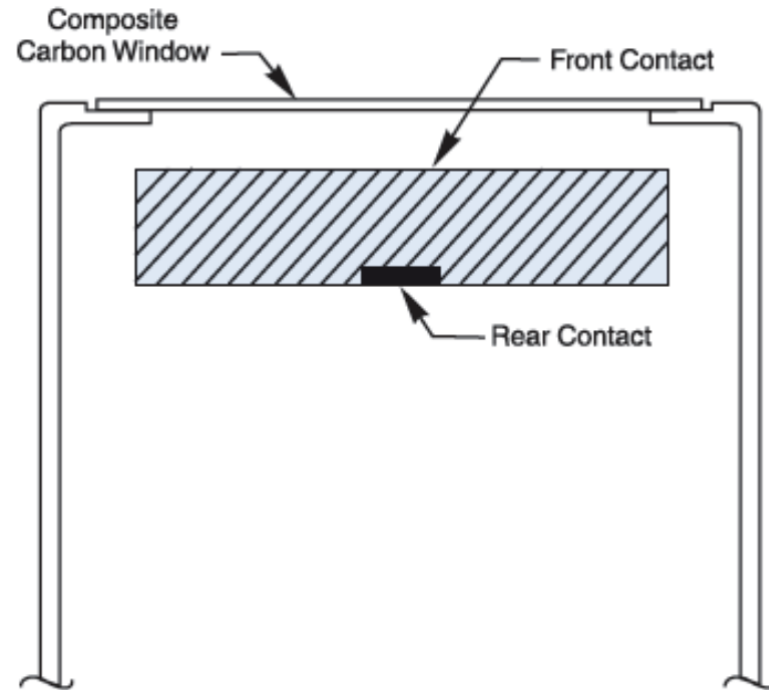
Spectrum from NIST 2063 Thin Film Standard Glass

Low Energy Germanium Detector(LEGe)



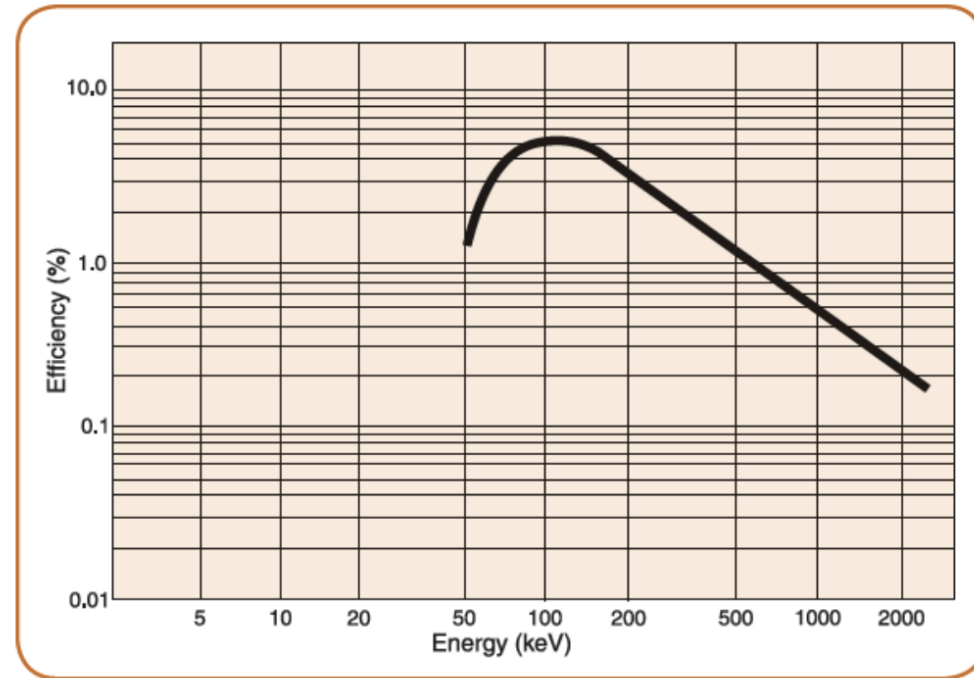
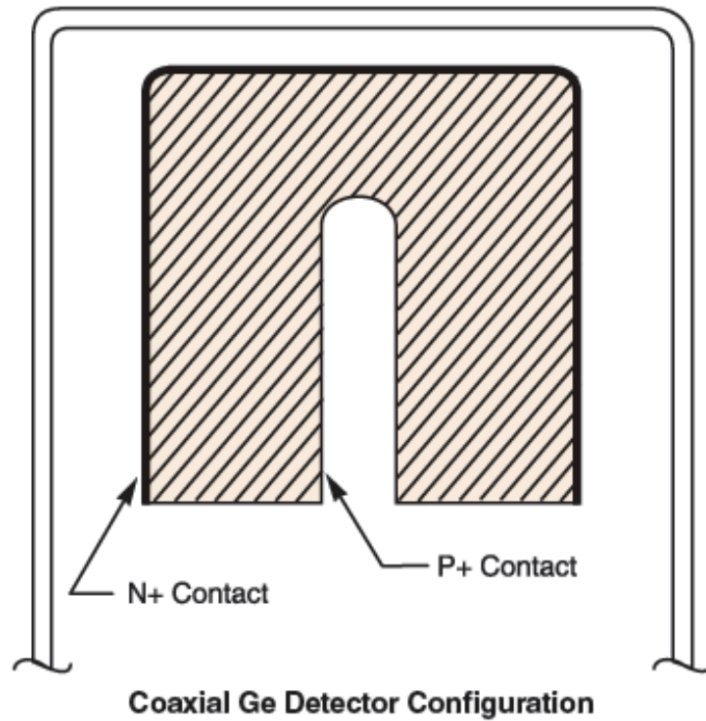
- 에너지 측정 범위 : 3 keV ~ 1MeV
- Wide range of sizes : 30mm² ~ 38cm²
- High resolution – good peak shape
- Low Energy Gamma 또는 X-ray 측정
- High energy rate capability

Board Energy Germanium Detector (BEGe)



- 에너지 측정 범위 : 3 keV ~ 3MeV
- High resolution at low energy
- High resolution at high energy
- Sample이 M.B가 아닌 검출기 위에 위치할 때 효과가 큼
- Whole Body Counting, Lung Counting System등에 효과 적임
- M.B 용기 보다는 작고 Vial 보다는 큰 시료용기의 측정시 효과 적임

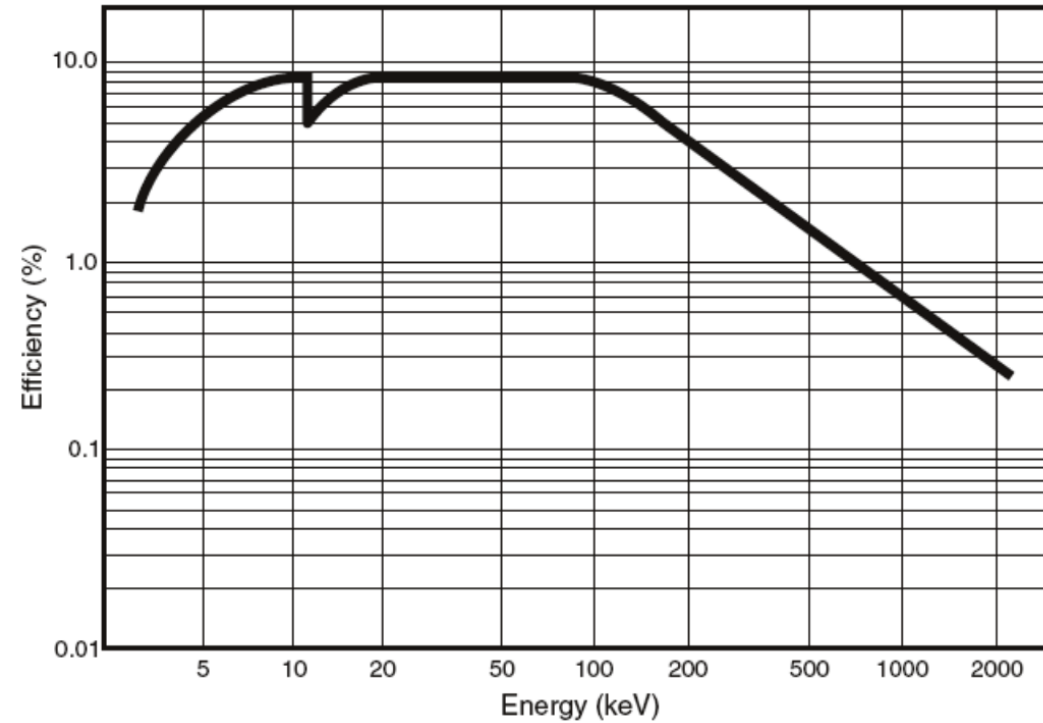
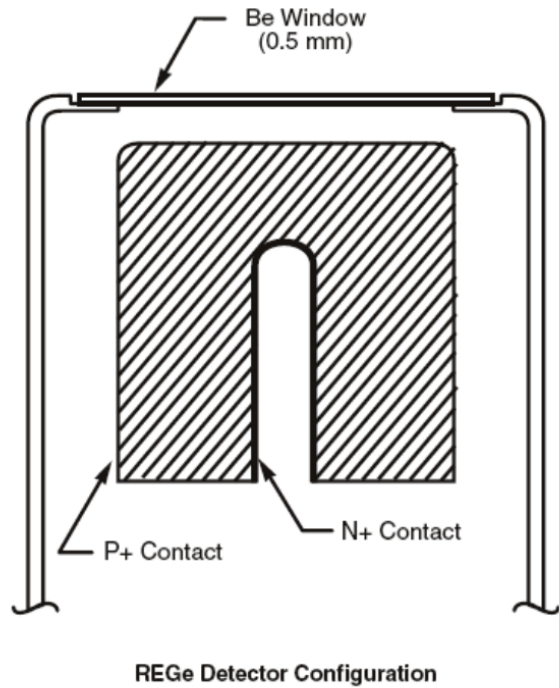
Coaxial Germanium Detector (P-Type)



Typical Absolute Efficiency Curve for 15% Detector
(25 cm detector to source spacing)

- 에너지 측정 범위 : 50keV ~ 10MeV
- 가장 보편적으로 사용되는 검출기
- Sample이 M.B 용기일 때 효과가 큼
- Inner Contact : 0.3um thick, Ion Implanted
- Outer Contact : 0.5mm thick, Diffused Lithium

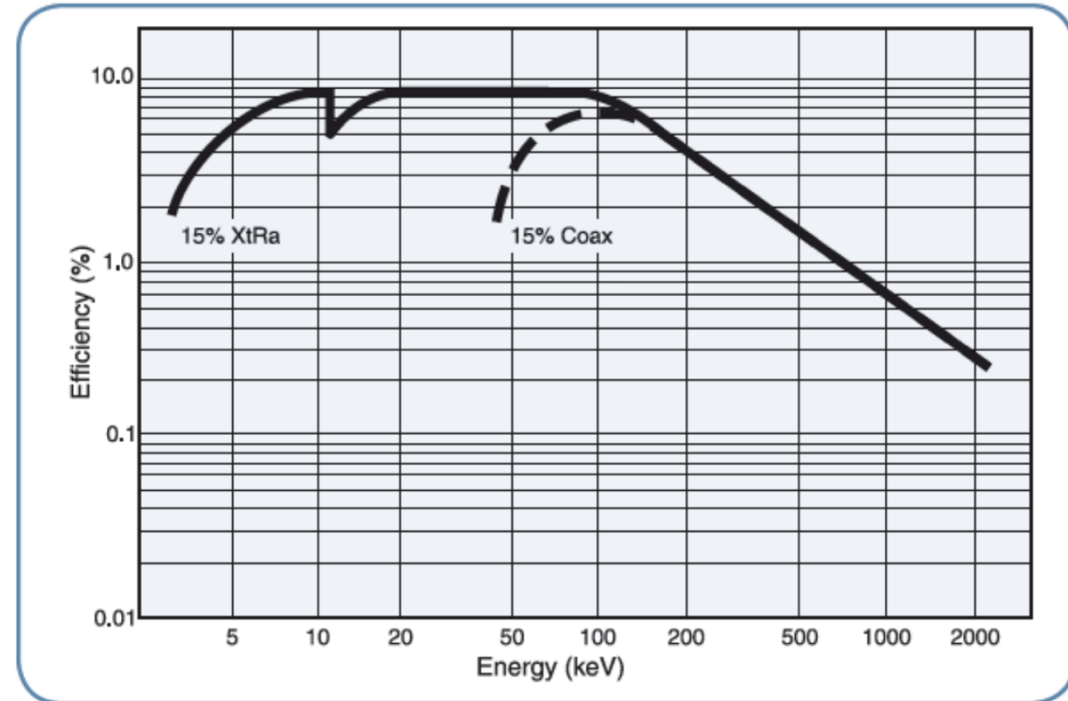
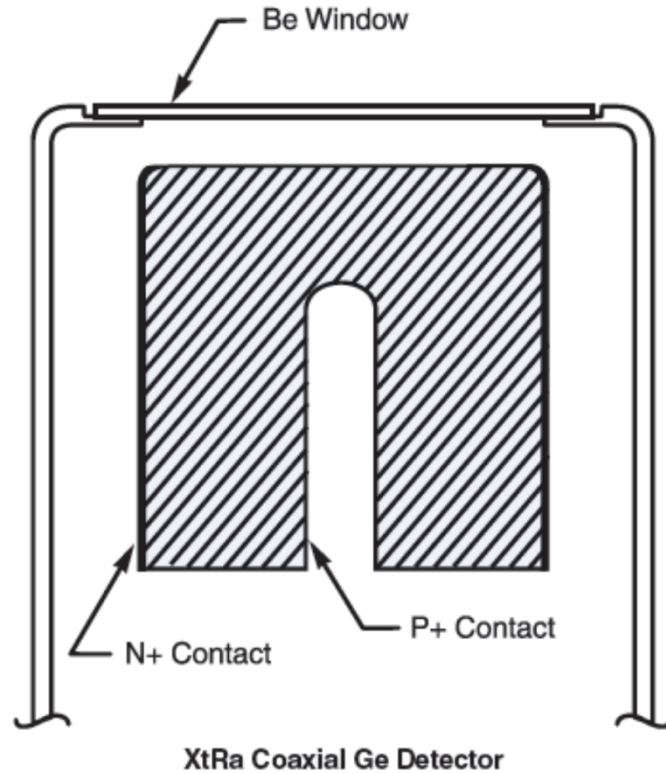
Reverse-Electrode Germanium Detector (N-Type)



Typical Absolute Efficiency Curve for 15% Detector
(2.5 cm detector to source spacing)

- 에너지 측정 범위 : 3keV ~ 10MeV
- Low Energy Gamma를 측정 할 수 있음
- Neutron 및 Charged Particles 에 의한 Damage에 강하다.
- Outer Contact : 0.3um thick, Ion Implanted
- Inner Contact : 0.5mm thick, Diffused Lithium

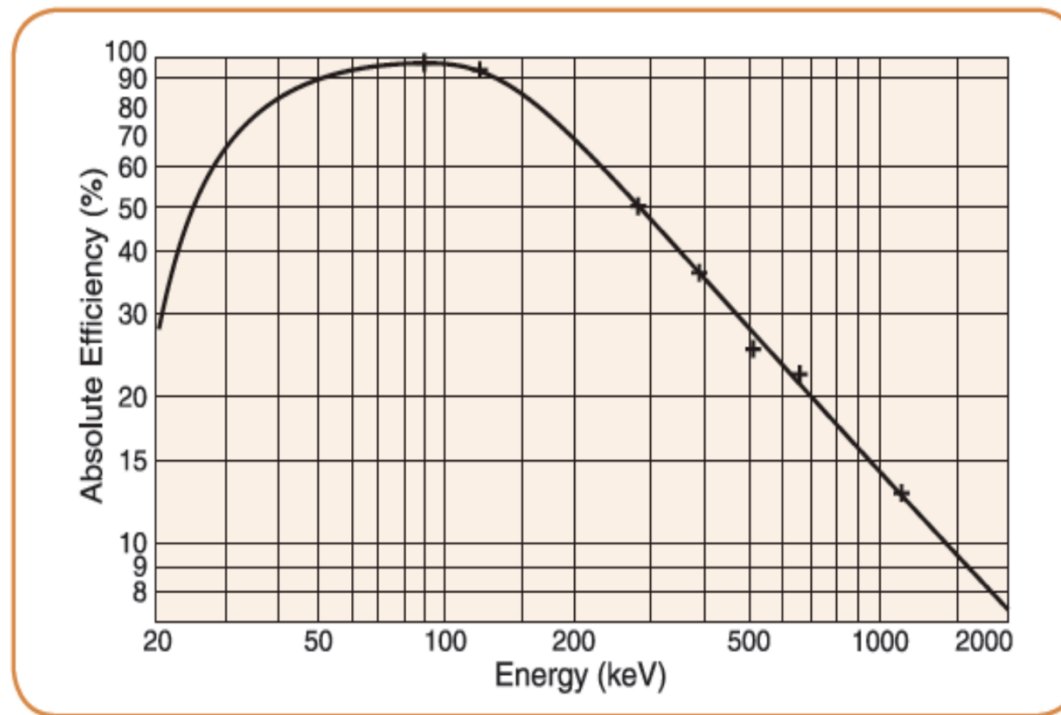
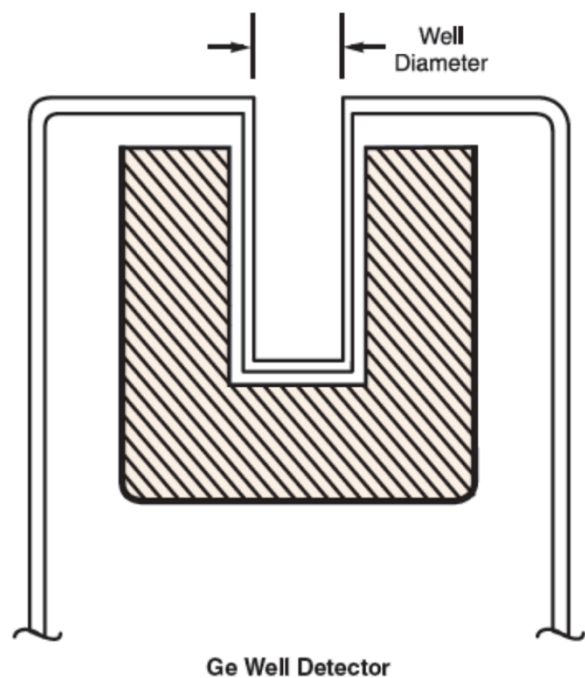
Extended Range Germanium Detector



Typical Efficiency curves comparing XtRa and Coax Detectors with detector-source spacing of 2.5 cm

- 에너지 측정 범위 : 3keV ~ 10MeV
- Low Energy Gamma를 측정 할 수 있음
- 저 에너지 감마 측정시 M.B는 큰 효과가 없음
- Outer Contact : 0.3um thick, Ion Implanted
- Inner Contact : 0.5mm thick, Diffused Lithium

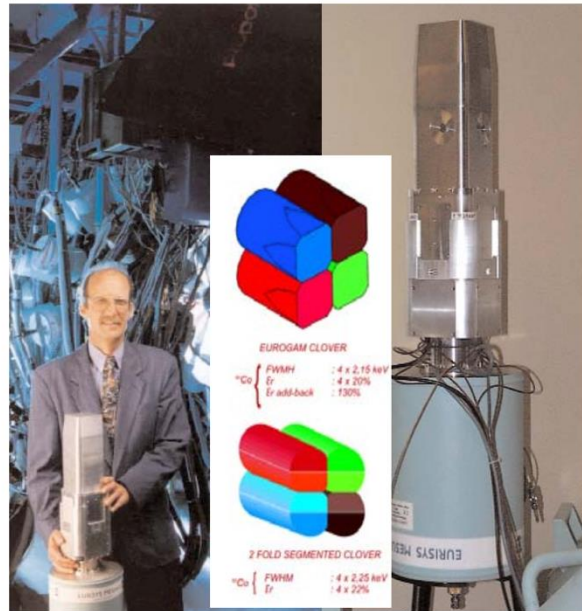
Germanium Well Detector



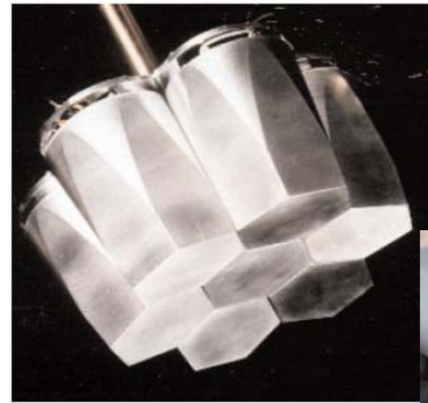
Measured efficiency of a Model GCW2522 with a mixed point standard located at the bottom of the 10 mm diameter Well.

- 에너지 측정 범위 : 3keV ~ 3MeV
- Near 4π Counting Geometry
- 시료의 양이 적은 Vial 형태의 측정에 적합함
- Well Diameter : 10mm or 16mm
- Nominal Volume : 70cc ~ 200cc

Special Germanium Detector

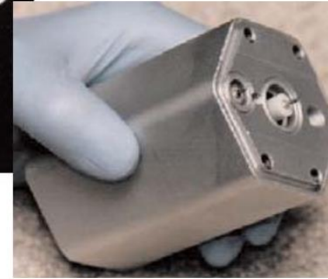


Arrangement of Four Coaxial Ge Detector

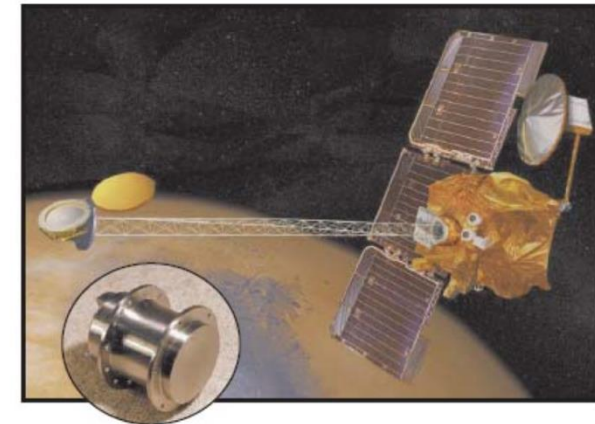


CLUSTER array for EUROBALL
(7 encapsulated HPGe detectors)

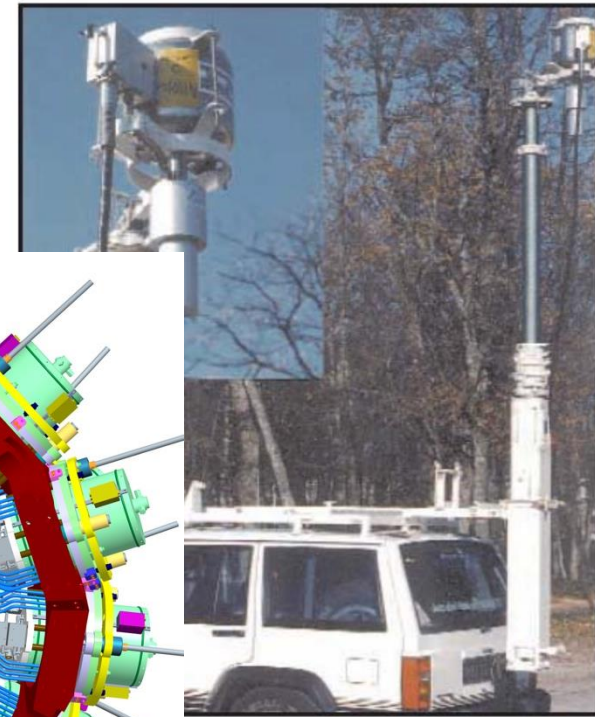
Hexagonal tapering - diam.: 70 mm - height: 78 mm
FWHM resolution: ≤ 2.3 keV
Efficiency: $\geq 55\%$
Alu wall thickness: 0.7 mm
Cap-to-Ge distance: 0.7 mm.



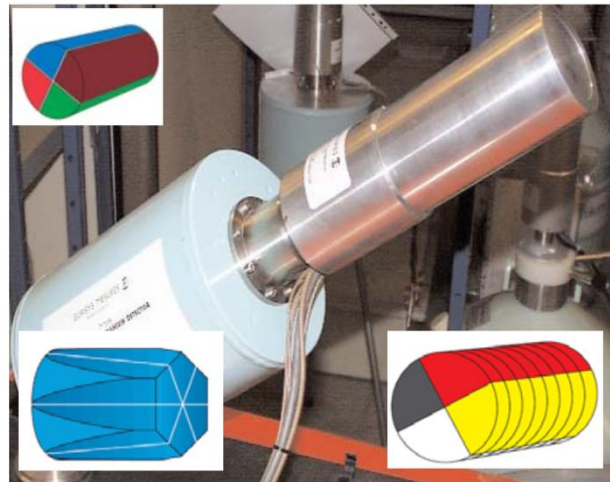
Encapsulated Detector



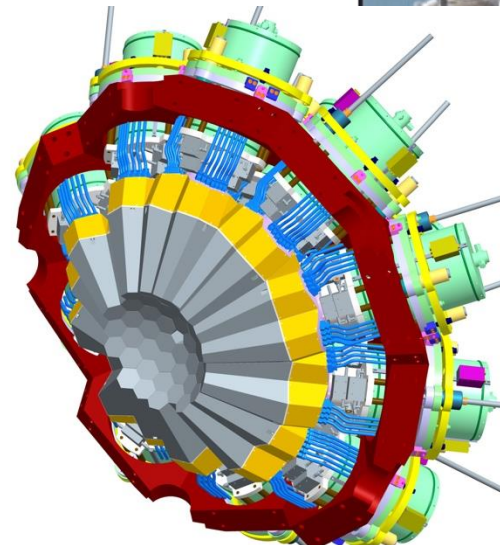
Encapsulated HPGe detector for the Mars Odyssey Spatial Mission.



detector mounted on a 8-meter telescopic mast for measurements of contaminated areas.



Segmented Coaxial Detectors



저온유지장치(Cryostat)

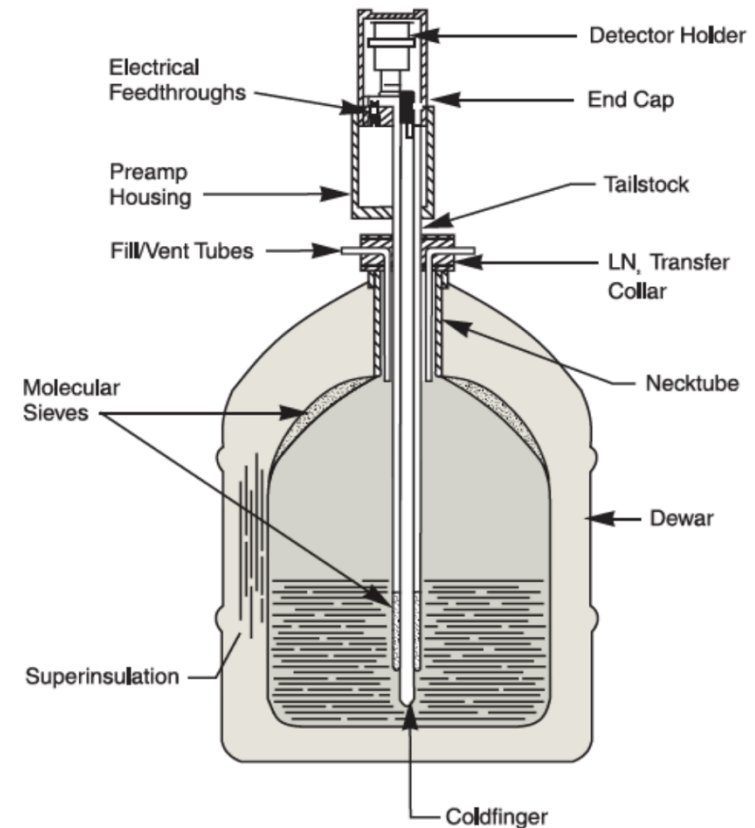
◆ 저온유지장치(Cryostat)의 기능 및 종류

동작 온도: 약 77 ~ 80 K (-196°C)

- ✓ 공핍층 내에서 열적으로 생성된 전자.정공쌍에 의한 누설전류는 공핍층의 체적에 비례하고 온도를 낮게 하면 감소한다. → 액화질소로 Ge를 냉각 시키는 이유.
- ✓ 분자체(Molecule Sieve)는 액체질소와 닿는 순간부터 검출기 내부의 불순물 Gas(헬륨 등)들을 흡입하여 검출기 내부가 청정 상태가 되도록 만들어 준다. → 액체질소를 충전 하고 최소 4시간 동안 냉각 시키는 이유.

✓ 종류

- Slimline
- Flanged
- Portable
- Convertible
- Electrically Cooled
- Ultra Low-Background



Model 7500SL Vertical Dipstick Cryostat

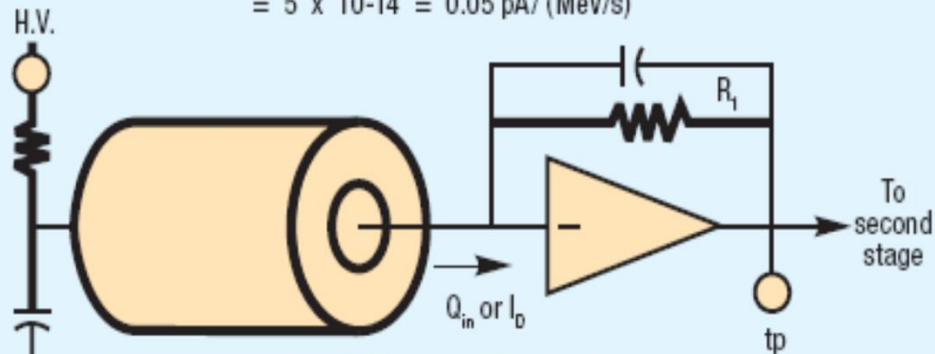
전치 증폭기 (Pre-Amplifier) – RC Feedback

- ▶ 보편적으로 가장 많이 사용
- ▶ 저, 중 준위의 시료 측정에 사용

Charge carriers produced by Ge per unit energy deposited = 1/2.98

$$\text{Detector Current} = \text{Energy Rate} \left(\frac{\text{eV}}{\text{s}} \right) \times \frac{\text{charge (Q)}}{\text{energy (eV)}} \times \underbrace{1.6 \times 10^{-19} \frac{\text{Coulombs}}{\text{Q}}}_{\text{Charge per charge carrier}}$$

$$\begin{aligned} \frac{\text{Detector Current (A)}}{\text{Energy Rate (MeV/s)}} &= 10^6 \times \frac{1.6 \times 10^{-19}}{2.98} \\ &= 5 \times 10^{-14} = 0.05 \text{ pA / (MeV/s)} \end{aligned}$$



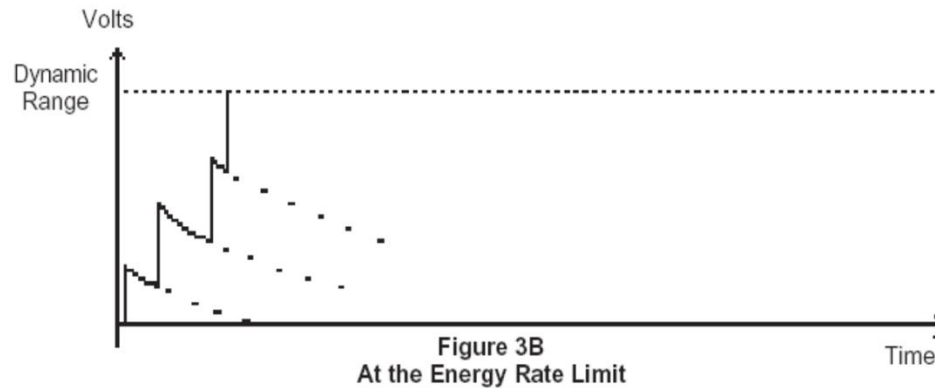
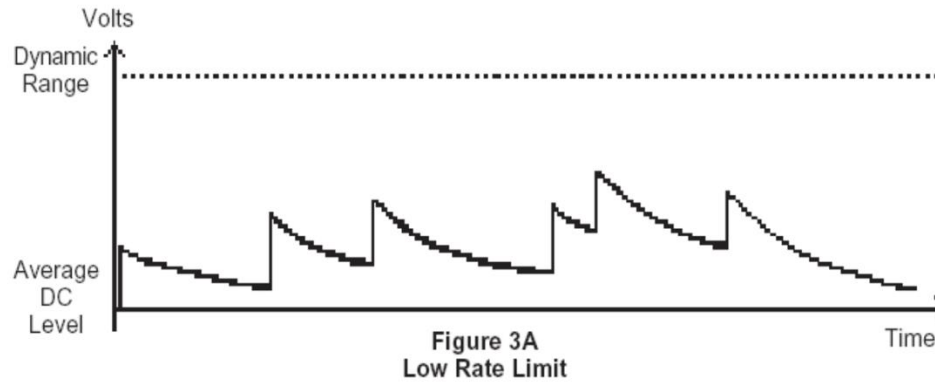
The energy rate limit of RC preamplifiers is a function of feedback resistor value (R_f) and dynamic range.

$$V_{tp} = I_0 \times R_f$$

Assuming $V_p = 20 \text{ V (max)}$

$$\text{Energy Rate Limit (MeV/s)} = \frac{400\,000}{R \text{ (Gigohms)}} \text{ MeV/s}$$

For 2 Gigohms - Limit is 200 000 MeV/s
For 0.5 Gigohms - Limit is 800 000 MeV/s



Resolution vs. Feedback Resistor

Experimental Results with Detector Model GC-1019

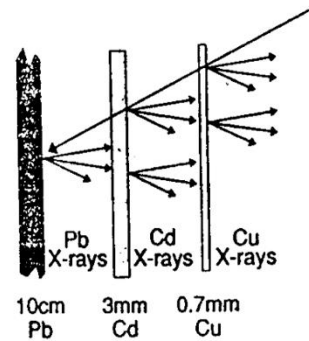
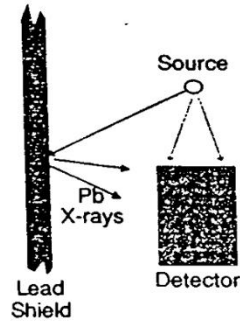
Resistor Value	⁵⁷ Co (122 keV FWHM)	⁶⁰ Co (1332 keV FWHM)
2 Gigohm	1.00	1.81
1 Gigohm	1.02	1.85
0.5 Gigohm	1.08	1.93
0.2 Gigohm	1.25	2.13



차폐체 (Lead Shield)

▶ 감마선과 차폐체의 상호작용

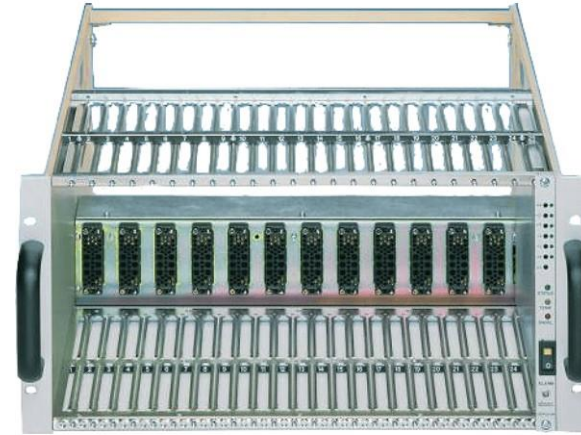
Lead X-ray 및 우주선과의 상호작용으로 광전자 효과, Compton 산란 (후방산란-Backscattering), 전자쌍 생성 등의 상호작용이 발생한다. 이를 막기 위해 10cm Lead Shield 내부에 추가로 약 3mm 정도의 카드뮴 판 및 약 0.7mm 정도의 동판 또는 주석 판을 설치 한다.



NIM Bin & Power Supply

◆ 검출기의 동작 전압 공급

- ① 고순도 반도체 검출기의 작동에 필요한 고 전압을 공급하기 위한 것
- ② 반도체 검출기의 경우 검출기와 전치 증폭기의 첫째 단의 FET를 보호하기 위하여 전압을 천천히 상승, 저하 시켜야 한다. 이러한 보호 회로는 전치 증폭기 단에 고 전압 Filter(시정수가 큰 RC회로)를 설치 하여 전압을 인가 하는 방식이 많이 사용되고 있다.
- ③ 반도체 검출기의 동작전압은 대개 $\pm 3\text{kV} \sim \pm 5\text{kV}$ 정도인 것이 보통이다.



Canberra Power Supply Preview Chart				
Model	Bias	Current	Applications	Physical
3002D	$\pm 3\text{ kV}$	10 mA	Nal, Gas Proportional, Si(Li), HPGe	2-Wide NIM
3102D	$\pm 2\text{ kV}$	1 mA	Nal, SSB, PIPS, GM, Gas Proportional Si(Li), HPGe	1-Wide NIM
3106D	$\pm 6\text{ kV}$	300 μA	HPGe	1-Wide NIM
3125 (Dual Unit)	$\pm 5\text{ kV}$ $\pm 2\text{ kV}$	100 μA 300 μA	Nal, SSB, oPIPS, GM, Gas Proportional Si(Li), HPGe	1-Wide NIM



1) NIM Format (Nuclear Instrumentation Module)

- 미국에서 규정한 표준규격
- 국제적으로 통용되고 있음
- Size, 전원, 신호의 표준규격

2) NIM Unit을 장착하고 직류전원을 공급

- ### 3) 직류전원 공급장치는 뒤쪽 하단부
- 각 Unit에 DC $\pm 6\text{V}(10\text{A})$, $\pm 12\text{V}(3\text{A})$, $\pm 24\text{V}(1.5\text{A})$ 를 공급

Spectroscopy Amplifier

◆ 신호의 증폭 및 정형

- ① 신호증폭 : Gain치 변화로 증폭치 변화(Coarse Gain, Fine Gain, Super Fine Gain)
- ② 신호정형 : 전치 증폭기의 출력신호의 빠른 상승시간(Rise Time)과 느린 하강시간의 신호를 정형하고 신호 대 잡음비(S/N 비)를 개선 시키기 위하여 신호를 선형적으로 증폭($\pm 10V$ 이하)시키는 역할을 수행
- ③ Pulse Shaping (Pre-amplifier 신호모양 변화)
 - Pre-amplifier의 날카로운 신호는 피크 높이 직접 측정에 불리
 - Pre-amplifier 신호의 중첩 시 피크 높이 직접 측정 불가



2025

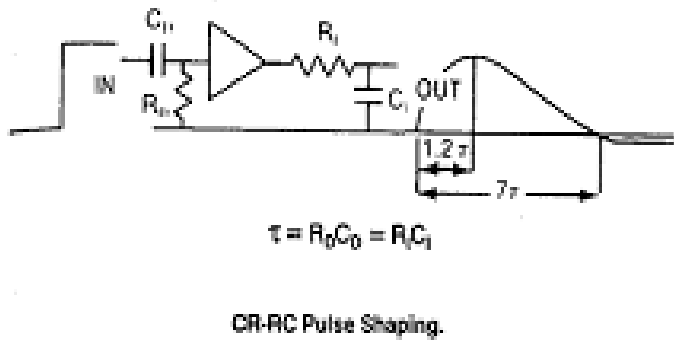
- ✓ 보편적으로 가장 많이 사용 함
- ✓ AFT (Auto Fine Tuning) 기능 장착
- ✓ Auto BLR 기능
- ✓ PUR 기능



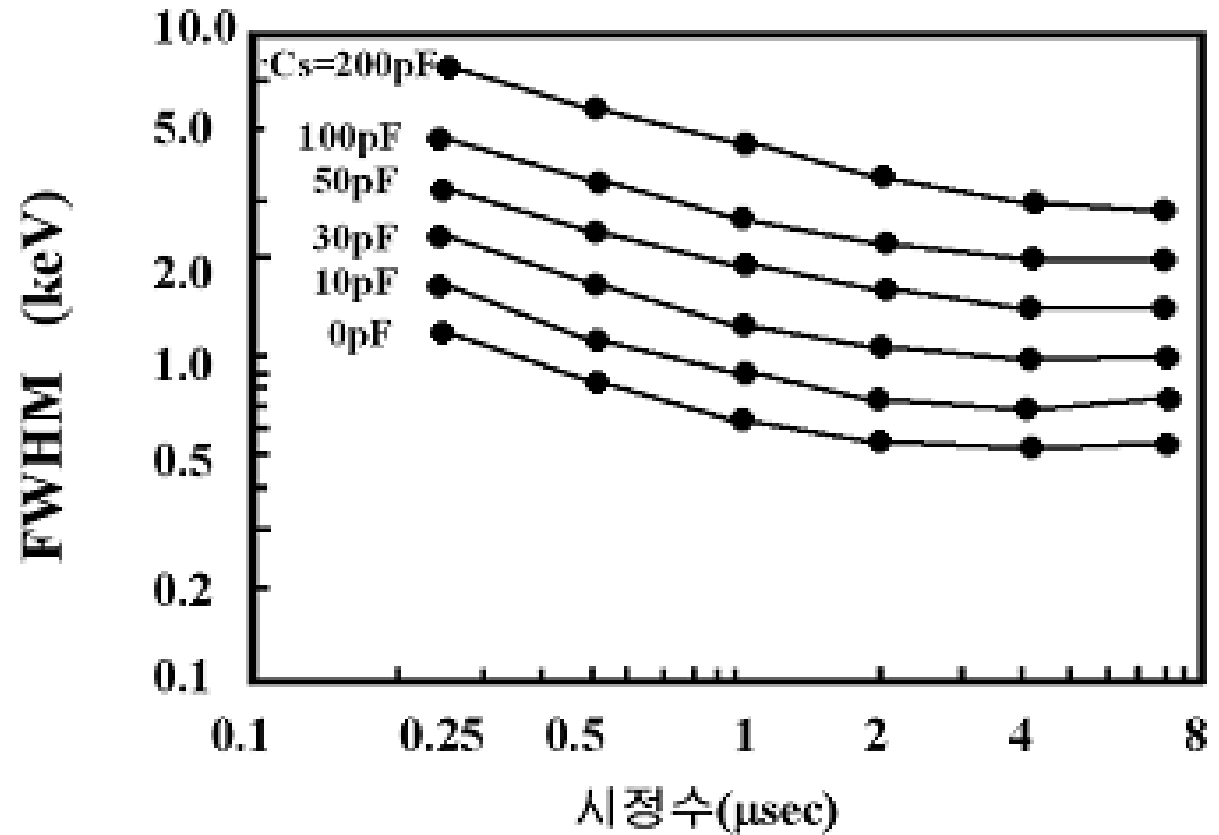
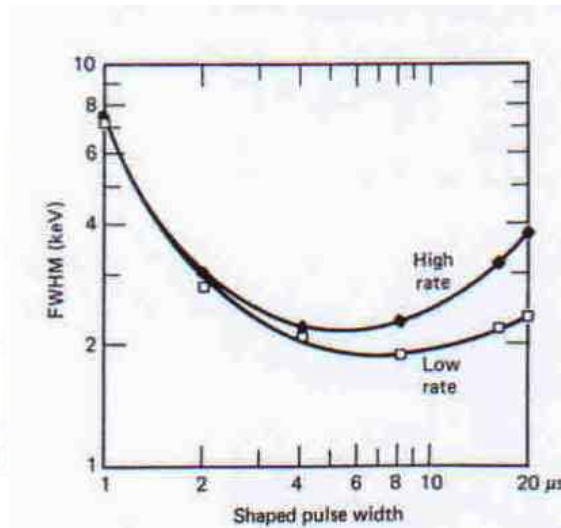
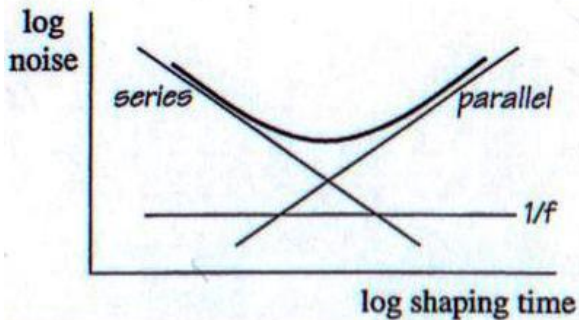
2024

- ✓ GI (Gated Integrator) 기능 내장
- ✓ 고 계수율(High Activity) 시료 측정에 적합 함
- ✓ Auto BLR 기능
- ✓ PUR 기능

Linear Amplifier



CR-RC회로를 이용한 파형정형

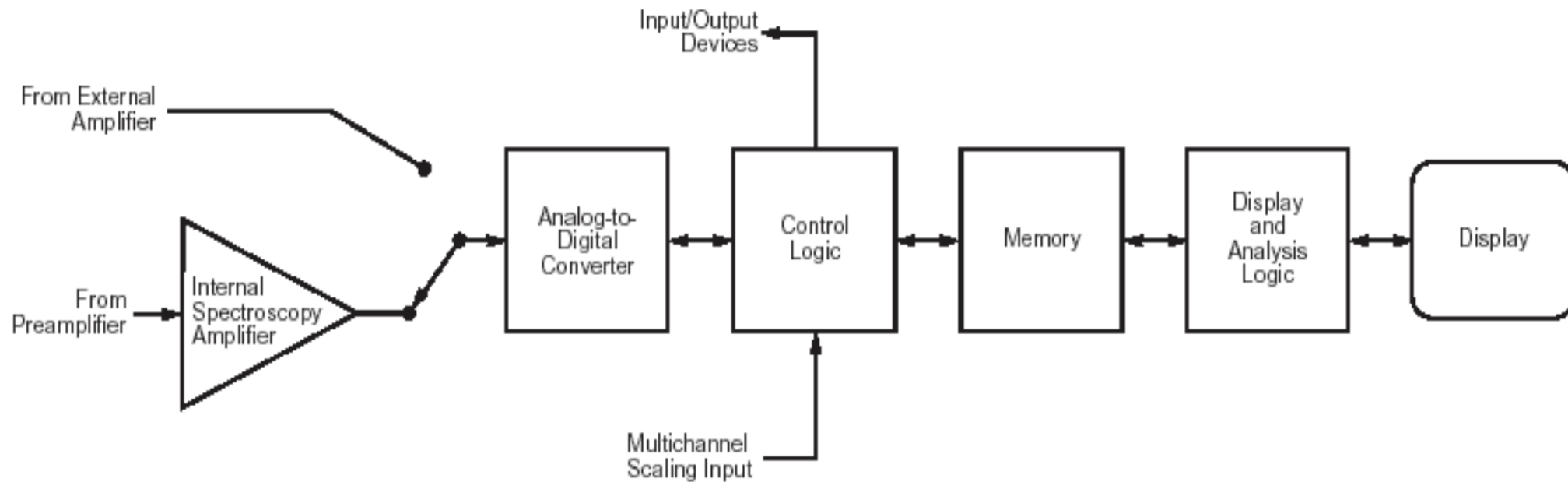


주증폭기의 Shaping time과 반치폭과의 관계

Multi-Channel Analyzer (MCA)

◆ 기능

- ▶ 증폭기의 출력 펄스를 Digital 신호로 변환하여 신호의 크기 별로 분류하여 메모리에 저장
- ▶ ADC 와 Memory로 구성 되며 Stand-alone Type은 여기에 Display 장치를 내장
- ▶ 근래에는 DSP (Digital Signal Processing)를 이용한 Digital 방식의 일체형 형태의 MCA들도 있으며, 사용하고자 하는 목적에 따라 다양하게 선택 할 수 있다.

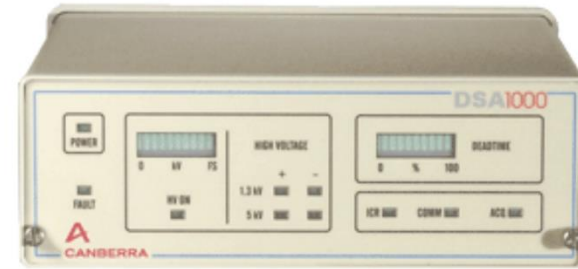


Multichannel Analyzer Functional Block Diagram

Integrated Digital Spectrum Analyzer

◆ Digital Spectrum Analyzer

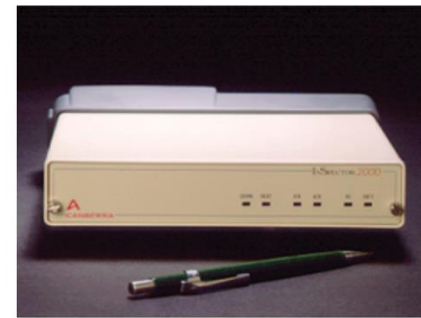
- ▶ DSP (Digital Signal Processing) 기반의 일체형
- ▶ Digital Amplifier 내장
- ▶ High Voltage Power Supply : +/- 5000V 내장
- ▶ 16K Multichannel Analyzer 내장
- ▶ PHA and MCS 측정 모드 지원
- ▶ On-board data backup 기능 지원
- ▶ Digital Oscilloscope 기능 내장
- ▶ HPGe, NaI(Tl), CdTe 등 기타 검출기에 모두 적용이 가능함
- ▶ 통신 방식 : Ethernet/USB or USB only 선택 가능



DSA-1000



DSA-2000

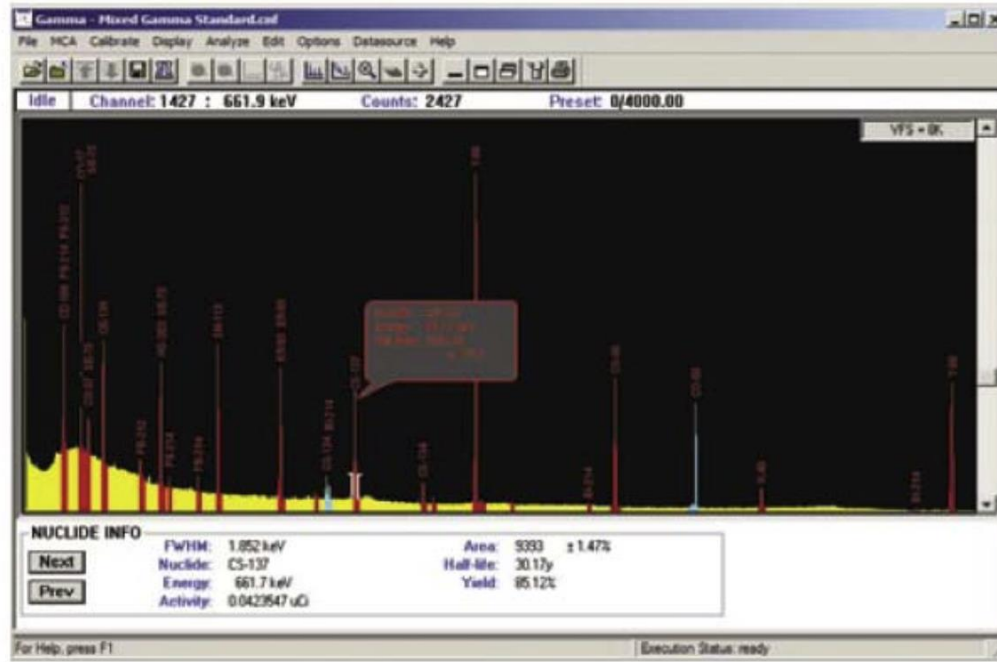


Inspector-2000 (Portable)



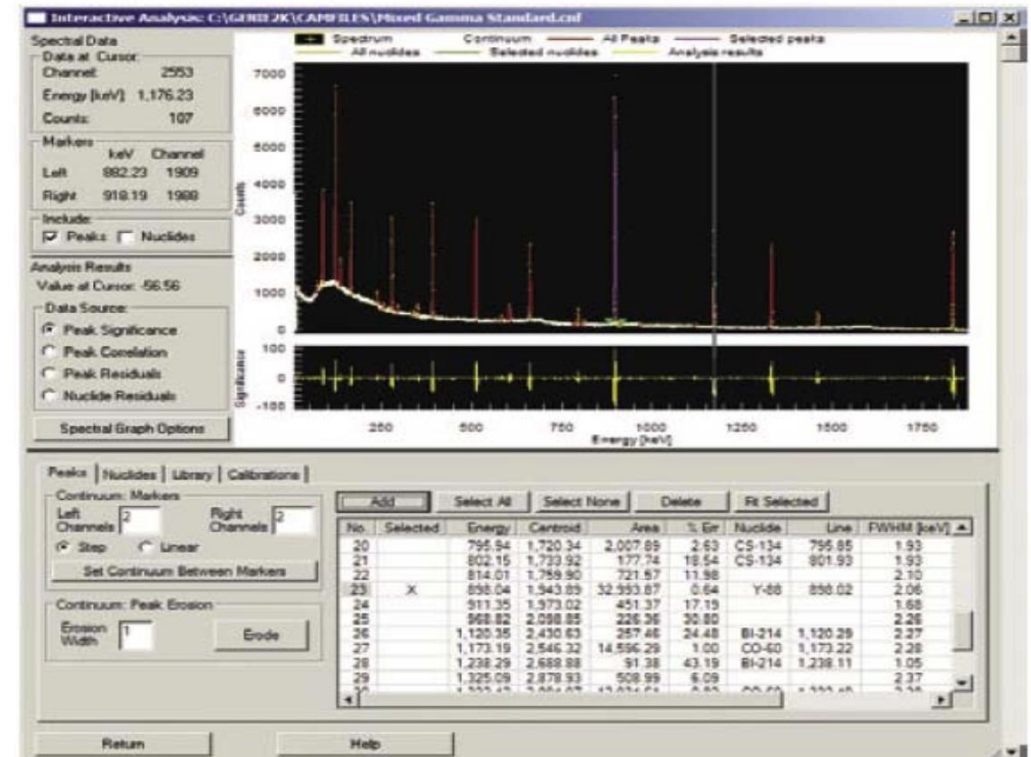
DSA - LX

Gamma-ray Spectroscopy Analysis Software



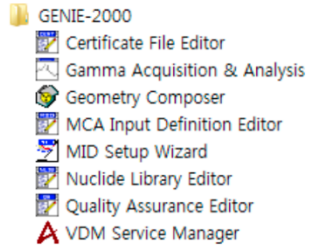
- ◆ Genie-2000 Basic Spectroscopy
 - Hardware 제어 및 측정
 - Energy/Resolution Calibration
 - 정성분석 (핵종 판별)

- ◆ Genie-2000 Gamma Option
 - Efficiency Calibration
 - 정량분석 (Activity Calculation)



GENIE-2000 프로그램 운영

GENIE-2000



■ 분석 소프트웨어(GENIE-2000)

: GENIE-2000을 설치하면 Gamma Acquisition & Analysis를 비롯하여 다양한 관련 프로그램이 설치 된다.

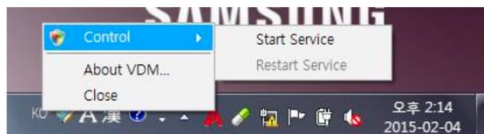
■ 주요 사용 프로그램

분류	내용	확장자
VDM Service Manager	- GENIE-2000 프로그램 사용 시 항상 구동되어야 하는 가상 데이터 관리자	-
MCA Input Definition Editor	- 사용하고 있는 MCA의 정보를 기록/저장(필수)	*.MID
Nuclide Library Editor	- 감마핵종 라이브러리 파일 생성(에너지 교정 시 유용)	*.NID
Certificate File Editor	- 교정 시 사용하는 표준물질 인증서 파일 생성(효율 교정 시 유용)	*.CTF
Gamma Acquisition & Analysis	- 실시간 측정 데이터를 분석	*.CNF

GENIE-2000의 파일 확장자

분류	설명	저장 폴더
.cnf	스펙트럼 파일	C:\WGENIE2K\CAMFILES
.mid	MCA의 정보 저장 DB 파일	C:\WGENIE2K\MIDFILES
.cal	교정 정보가 저장 된 파일	C:\WGENIE2K\CALFILES
.nlb	핵종 라이브러리가 저장 된 파일	C:\WGENIE2K\CAMFILES
.ctf	인증서 파일	C:\WGENIE2K\CAMFILES
.asf	Analysis Sequence가 저장 된 파일	C:\WGENIE2K\CTFILES
.rpt	Report가 저장 된 파일	C:\WGENIE2K\WREPFILS

VDM Service Manager?



Back up

The energy resolution of the HPGe photon spectroscopy system is governed by the variation in the number of charge carriers, variation in the charge carrier collection, and the contribution of electronic noise. Hence, the FWHM of a peak in the spectrum can be represented as

$$W_T^2 = W_D^2 + W_X^2 + W_E^2$$

where W values on the right-hand side are peak widths expected due to carrier statistics, carrier collection and electronic noise.

The variation in the number of the charge carriers is given by

$$\frac{W_D}{E_\gamma} = 2.355 \frac{\sqrt{F} \delta N}{N} = 2.355 \frac{\sqrt{F}}{\sqrt{N}} \Rightarrow W_D^2 = (2.355)^2 F \frac{E_\gamma^2}{N} = (2.355)^2 F w E_\gamma$$

where E_γ is the photon energy, N is the number of e-h pairs, F is the **Fano** factor, and w is the energy required for creating a electron-hole pair. If the **Fano** factor is assumed to be 0.1, the equation predicts the W_D value of 1.3 keV at 1.33 MeV when the w value of 3 eV is used.

The contribution of the second term is due to incomplete charge collection and becomes important for large volume or low electric field detectors.

The last term represents the broadening effects of all electronics following the detector. This component can be measured with a precision pulser as discussed in the pulse processing chapter. The pulser output is fed to the test input of the preamp and it undergoes exactly the same path as that of the actual signal from the detector.

Fig. 8.15 shows the contribution of each component as a function of the photon energy. At low energies, electronic noise and charge collection are relatively important while the additional broadening due to carrier statistics becomes significant at higher energies.

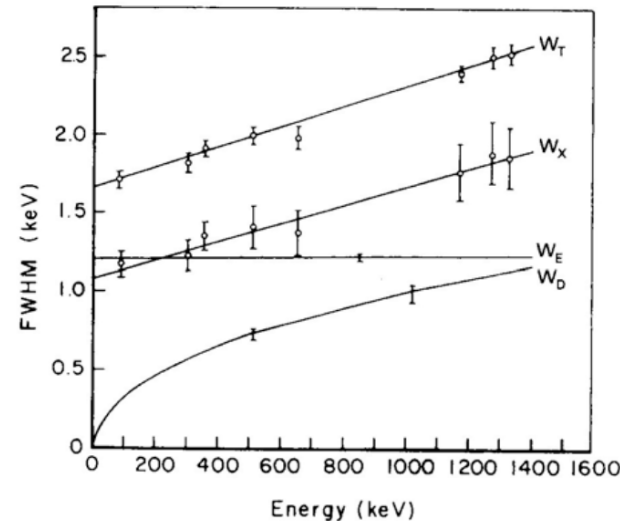


Fig. 8.15. Dependence of resolution on photon energy.

Peak to Compton Ratio = A / B

A: the channel counts of 1332.5 keV

B: the average channel count in the Compton continuum between 1040 and 1096 keV

1332.5 keV (Co60)

The P to C ratio is analogous
to a Signal to Noise ratio.

