Gamma-Spectroscopy

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Agenda

What is gamma spectroscopy?

studies of energy spectra of gamma rays

identification of gamma-emitting radionuclides

Interactions: Photoeffect, Compton scattering, Pair production

WInteraction of γ-rays with matter

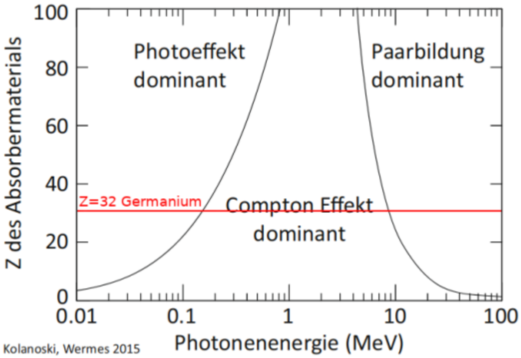


Abbildung: atomic number Z against photon energy E.

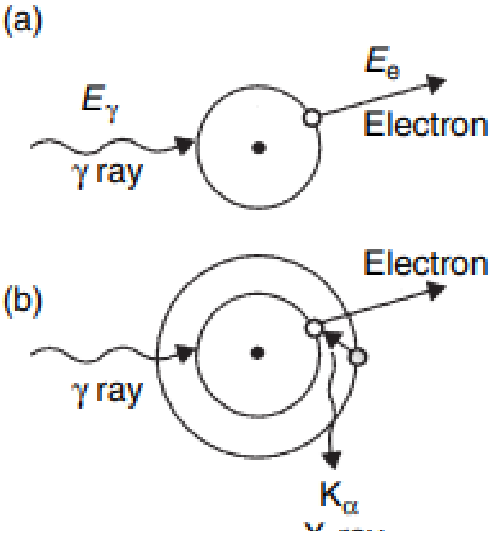
processes above ionization threshold

Gamma ray absorption →intensity loss

Material thickness dependend intensity: $N(D) = N_0 e^{-\mu D}$

D: thickness, μ: absoption coefficient, N_0: initial intensity

Photoeffect



E_γ < several 100 keV

ionizing bound electron (K-shell)

$\gamma + atom \rightarrow atom^+ + e^-$

hole is filled with electrons from higher shells recursively

energy diff. release as x-rays characteristic

rarely: photon leaves absorber. often excite more electrons inside

K-L-M-absorption edge: Quantumenergy enough to release bound electron from given shell

Compton scattering

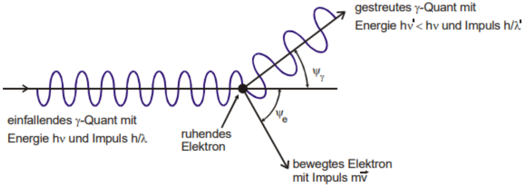


Abbildung: compton continuum

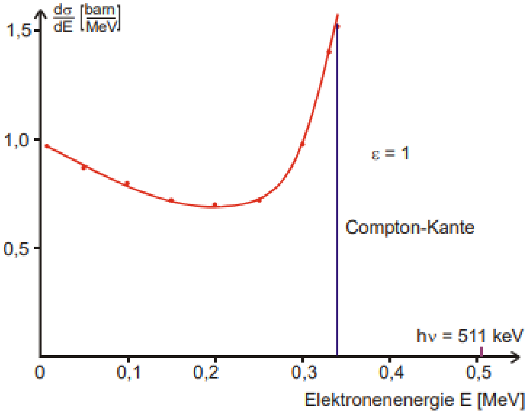
main interaction (100 keV < E < 5 MeV)

inelastic scattering

photons only transfers an energy fraction

cannot view full spectrum ☹

Compton scattering



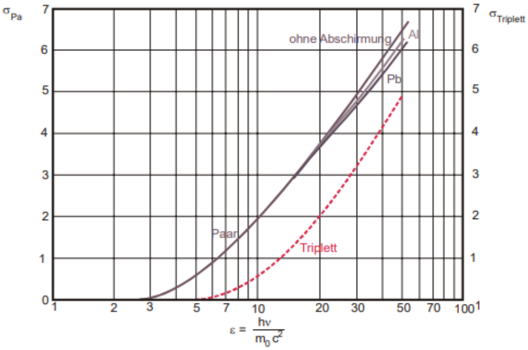
non-isotropic angular distribution

$$E_\gamma' = \frac{E_\gamma}{1+\left(\frac{E_\gamma}{511keV}(1-cos\theta)\right)}$$

$$E_{e^-} = E_\gamma\left(\frac{\frac{E_\gamma}{511keV}(1-cos\theta)}{1+\frac{E_\gamma}{511keV}(1-cos\theta)}\right)$$

extreme cases: backward scattering, light graze

Pair production



photon produces e+e- pair if E is high enough (5 MeV < E < 10 MeV)

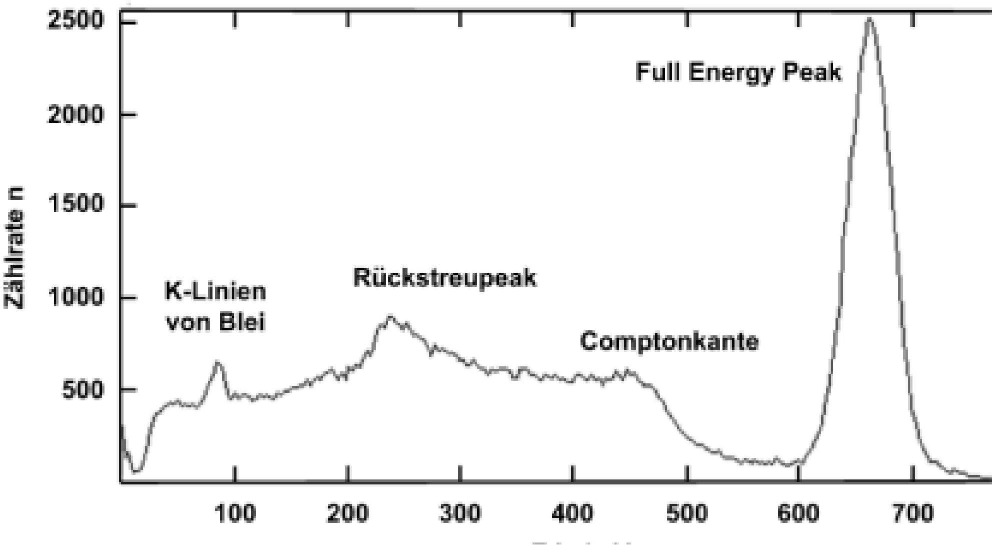
occurs in proximity of nucleus/scattering partner

photon line visible if both leptons are absorbed;

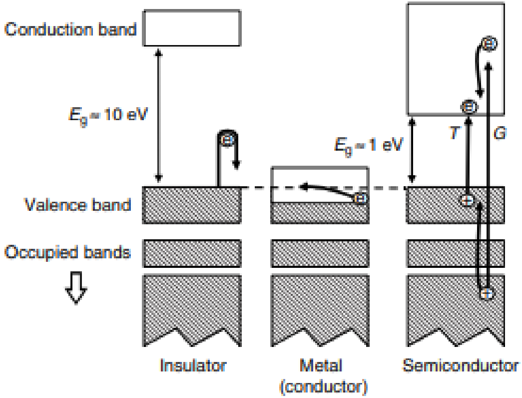
annihilation peak : 511 keV (e- mass) or doubled for both

single- and double-escape peaks

Energy spectra



Band structure

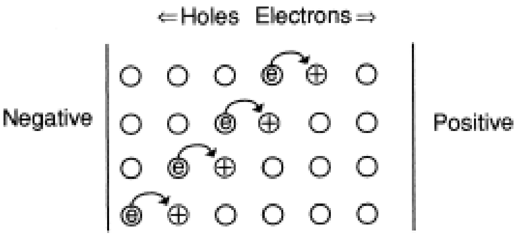


electrons in discrete/precise energy bands

valence band: outer band for chemical reactions; most inhibited

conduction band: migration of electrons

Mobility of ”Holes”



positive charge ≡ hole in the band

measuring the energy relies on separating the charge carriers

electrons from valence band filling holes -> effective moving

-> conductivity

Creation of charge carriers

- excite electrons from low bands through high energies (E > E_{therm})
- redistribution of electrons-holes throughout energy-bands
- holes: top of valence band
- electrons: bottom of conduction band
- external field: charge carriers migrate towards respective electrode

- number of electron-hole pairs $n = E_{\text{abs}}/\epsilon$
- ϵ: average energy needed to create electron hole pair
- E_{abs}: absorbed gamma ray energy

resolution and suitable semiconductors

resolution $\propto$ n -> detector needs specific properties

- large absorption coefficient (high atomic number Z)
- low ϵ: to produce many electron-hole pairs
- allow good Mobility (trapping inside semiconductor lattice)
- pure crystal structure (traps for charge carriers)
- cannot be too expensive

Why Germanium as detector material?

Material	Atomic number	Operating temperature	Band gap (eV)[a]	ε (eV)[a,b]	Density ($g\,cm^{-3}$)	Mobility($cm^2\,V^{-1}\,s^{-1}$)[a]	
						Electrons	Holes
Si	14	RT	1.106	3.62	2.33	1350	480
Ge	32	Liquid N_2 (77 K)	0.67	2.96	5.32	3.6×10^4	4.2×10^4
CdTe	48, 52	RT	1.47	4.43	6.06	1000	80
CdZnTe	48, 30, 52	RT	1.57	4.64	5.78	1000	50–80
HgI_2	80, 53	RT	2.13	4.22	6.30	100	4
GaAs	31, 33	RT	1.45	4.51	5.35	8000	400
TlBr	81, 35	−20 °C	2.68	?	7.56	—	—
PbI_2	82, 53	—	2.6	7.68	6.16	8	2
GaSe	31, 34	—	2.03	6.3	4.55	—	—
AlSb	13, 51	—	1.62	5.05	4.26	—	—
CdSe	48, 34	—	1.75	?	5.74	—	—

[a] Values are given at 77 K for Ge and 300 K otherwise.
[b] Electron–hole creation energy.

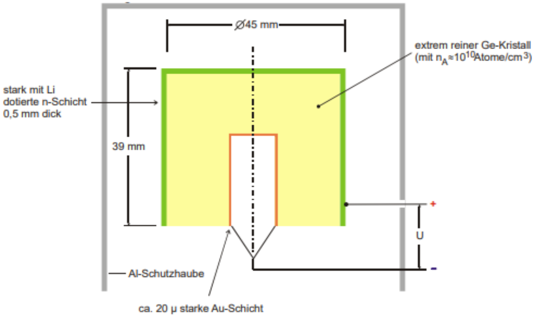
Silicon: highly pure, low-priced, low atomic number (low energy photons)

Germanium: higher Z -> good for higher energy gamma radiation

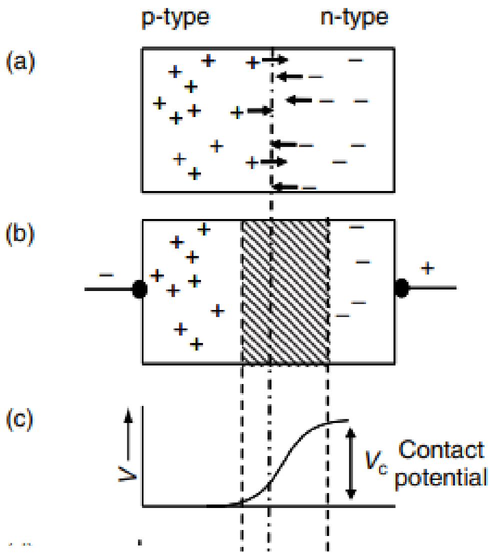
improvements reduced resolution to ≈ 1.8 keV

low temperature -> reduce leakage current

Why Germanium as detector material?



Semiconductor detector



p-n or M-S junctions possible

electrodes form a metal-semiconductor junction

impurities: p-type (acceptor states), n-type (donator states)

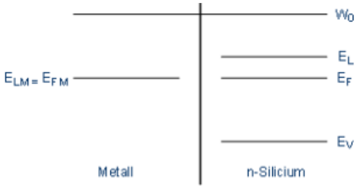
solid detection material for full energy deposition inside

doping: adding energy states -> narrowing the band gap

maximising the depletion zone -> hinder recombination -> reconstruct energy of the event

probability of thermal excitation:
$p(T) = T^{3/2} exp(-E_g/2k_bT)$

Metal-Semiconductor junction



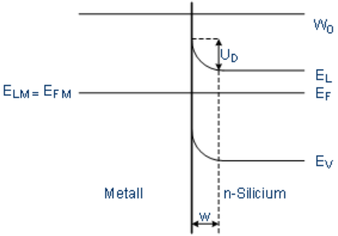
W_0: vacuum level, E_L: conduction band, E_F: fermi energy

E_V: valence band, E_{LM}: energy level in metal, E_{FM}: fermi energy in metal

electrons can migrate from Semiconductor to metal since E-level is lower

probability of finding electrons in conduction band gets lower

Metal-Semiconductor junction (n-Si)



migrated charge carriers form depletion zone and lower fermi level

additional e^- must overcome the Schottky-barrier to flow into Metal

fermi levels in metal and semiconductor equalize via diffusion process

Why is this junction used over p-n?

Si-Schottky diodes are substantially faster changing from forward bias to reverse bias

-> switching action: 10 - 100 GHz possible because no ”holes” in metal

low forward voltage drop (0.15 - 0.45V) p-n: 0.6 - 0.75 V

But: higher reverse leakage current

How to semiconductor

- p and n doped areas
- charge carriers diffuse and recombinate
- surface is charge carrier poor zone
- acceptor in p, donator in n. electric field hinders carriers
- the bigger the zone the better the seperation -> more U_g
- seperation before recombination $\rightarrow$pulse $\rightarrow$quatification of energy
- only possible if generated in depletion zone (charge carrier poor zone)
- depletion zone big -> reverse voltage and doping material
- asymmetric doping (equation)
- noise: electrons randomly passing reverse voltage, also cool detector
- veto region with alu case (E_{min} = 40 – 50 keV)
- Li in Ge for n, Au in Ge for p

Evaluation of gamma spec

PRO:

- quite cheap in material costs
- relatively fast result evaluation
- multinuclide analysis (distinct lines visible for all nuclides)
- non-destructive for emitter (radiation hardness of detector given)
- remote measurement

CONTRA:

- often less sensitive
- require large sample masses (if not gamma rays from space)

Table of interesting radio nuclides

Radionuclide	Gamma Ray Energy (keV)	Gamma Intensity
Na-22	1274.5	1.0
	511.0 (annihilation)	1.8
K-40	1460.8	0.11
Cr-51	320.1	0.098
Co-57	122.1	0.855
Fe-59	1099.2	0.565
	1291.6	0.432
Co-60	1173.2	1.0
	1332.5	1.0
Zn-65	1115.5	0.507
Ga-67	93.3	0.357
	300.2	0.16
Mo-99	739.6	0.128

Summary

Quellen

https://onlinelibrary.wiley.com/doi/book/10.1002/9780470861981
V18_Anleitung.pdf
https://www.nrc.gov/docs/ML1122/ML11229A699.pdf
https://www.electrical4u.com/schottky-diode/

Backup

Attenuation egde for caesium iodine (CsI)

2 K-lines and 2 L-lines