Nuclear techniques in solid state research

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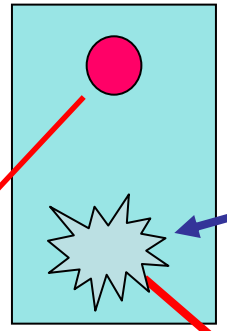
Nuclear techniques in solid state research

Radioactive probe techniques

Ion-beam analysis

Radioactive probe nuclei,
muons (μ), positrons (ß$^+$)

Scattering of
α, p, d, n, He,....



γ, ß, ...
Radiation properties mainly
modified by hyperfine interactions

Analysis of modified energy,
angular distribution, etc.

Applications of radioactive isotopes and ion beams to

- Electronic properties of impurities in metals and semiconductor
- Exchange interactions in magnetically ordered solids
- Studies of radiation damage
- Diffusion processes
- Determination of the lattice sites of dopants
- Site-selective doping of semiconductors
- Donor–acceptor interaction in semiconductors
- Hydrogen passivation and diffusion in semiconductors
- Optical studies of impurities and defects in semiconductors

Nuclear techniques in solid state research

Literature:

G. Schatz and A.Weidinger, Nuclear Condensed Matter Physics: Nuclear Methods and Applications, (Pfeiffer-Wiley,1996)

Doris Forkel-Wirth
Exploring solid state physics properties with radioactive isotopes
Rep. Prog. Phys. **62** (1999) 527–597

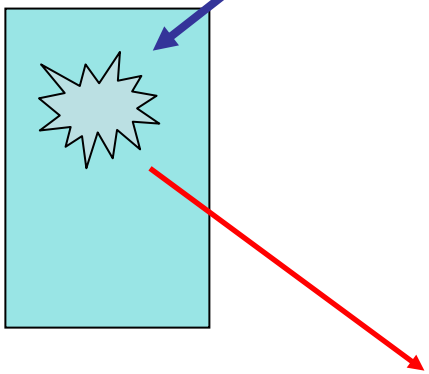
W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer

G.F. Knoll: Radiation Detection and Measurement , Wiley

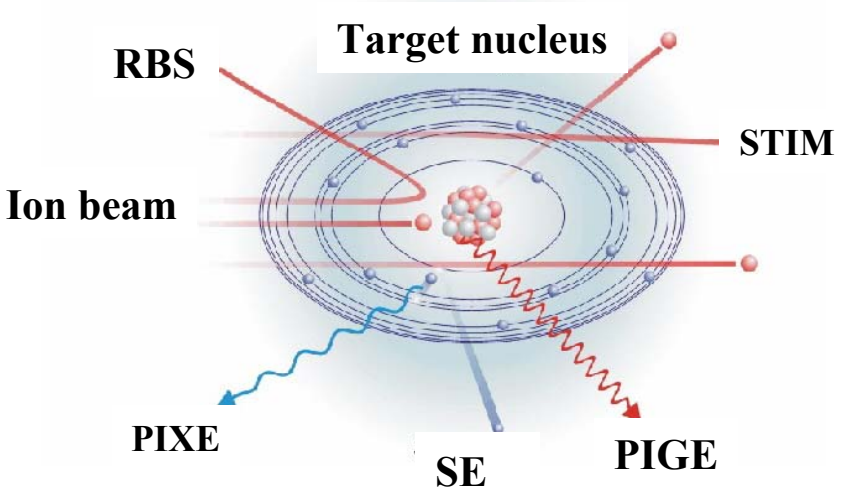
R. Röhlsberger, Nuclear Condensed Matter Physics with Synchrotron Radiation, Basic Principles, Methodology and Applications; Series: Springer Tracts in Modern Physics, Vol. 208 , 2004 ; ISBN: 3-540-23244-3

Ion-beam analysis

Scattering of
α, p, d, n, He,....



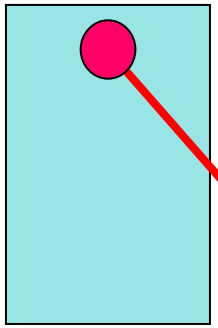
Analysis of modified energy, angular distribution, etc.



Ion Beam Techniques

RBS: Rutherford back scattering
ERD: Elastic recoil detection
PIXE: Particle induced x-ray emission
PIGE: Particle induced gamma emission
NRA: Nuclear reaction analysis
STIM: Scanning Transmission Ion Microscopy
SE: Secondary emission
Channeling

Radioactive probe techniques



γ, ß, ...

properties modified mainly by hyperfine interactions (HFI)

Hyperfine Interaction Methods

Mössbauer Effect

Perturbed angular correlations

Myon spinrotation

Nuclear orientation

$E_\gamma = E_0 \pm \Delta E$

E_0 = 10 keV – 1 MeV

$\Delta E = 10^{-6}$ eV

Hyperfine interactions:

$\Delta E/E_0 \geq 10^{-12}$

Non-HFI methods

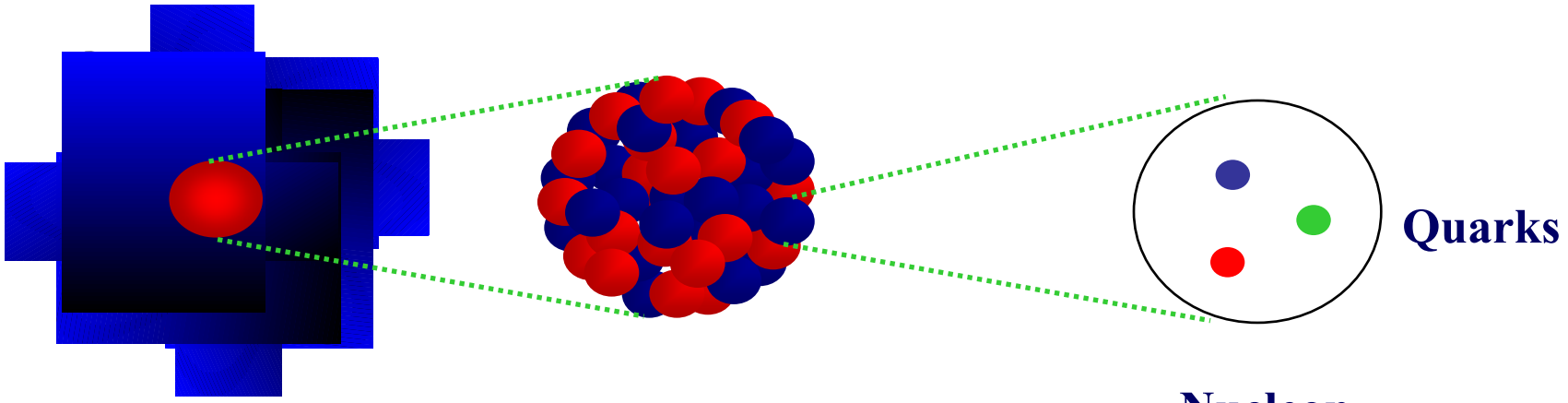
Positron annihilation, PET

Radioactive tracer, diffusion

Transmutation doping

Emission channeling

Scale and Components of Nuclei



Atom
10^{-9} m

Nucleus
10^{-14} m

Nucleon
10^{-15} m

Z protons – charge +1
N neutrons – charge 0
A = Z + N

Symbol: $^{A}_{Z}X$

Isotope: $^{N\pm n}_{Z}X$

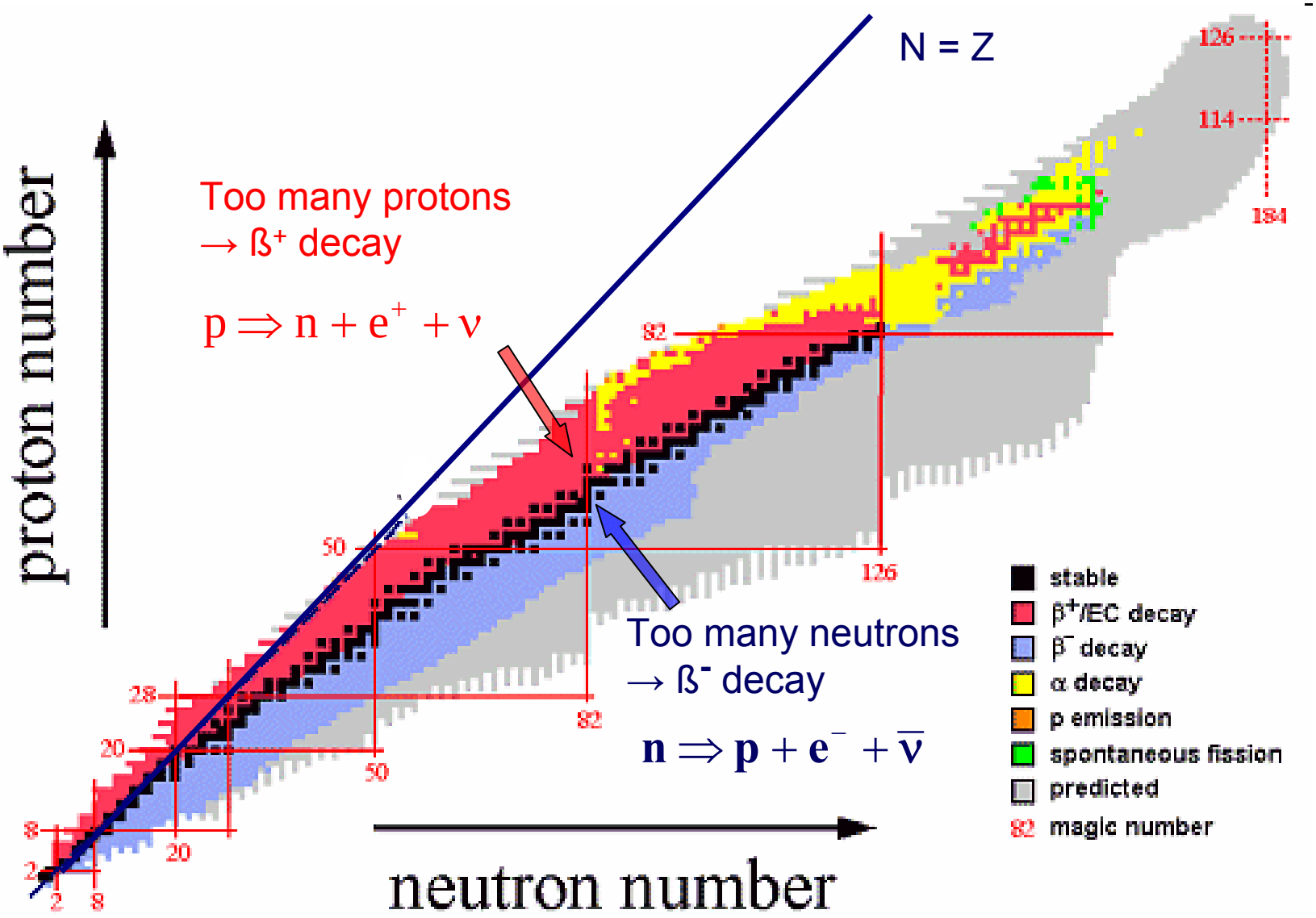
Number of nuclei

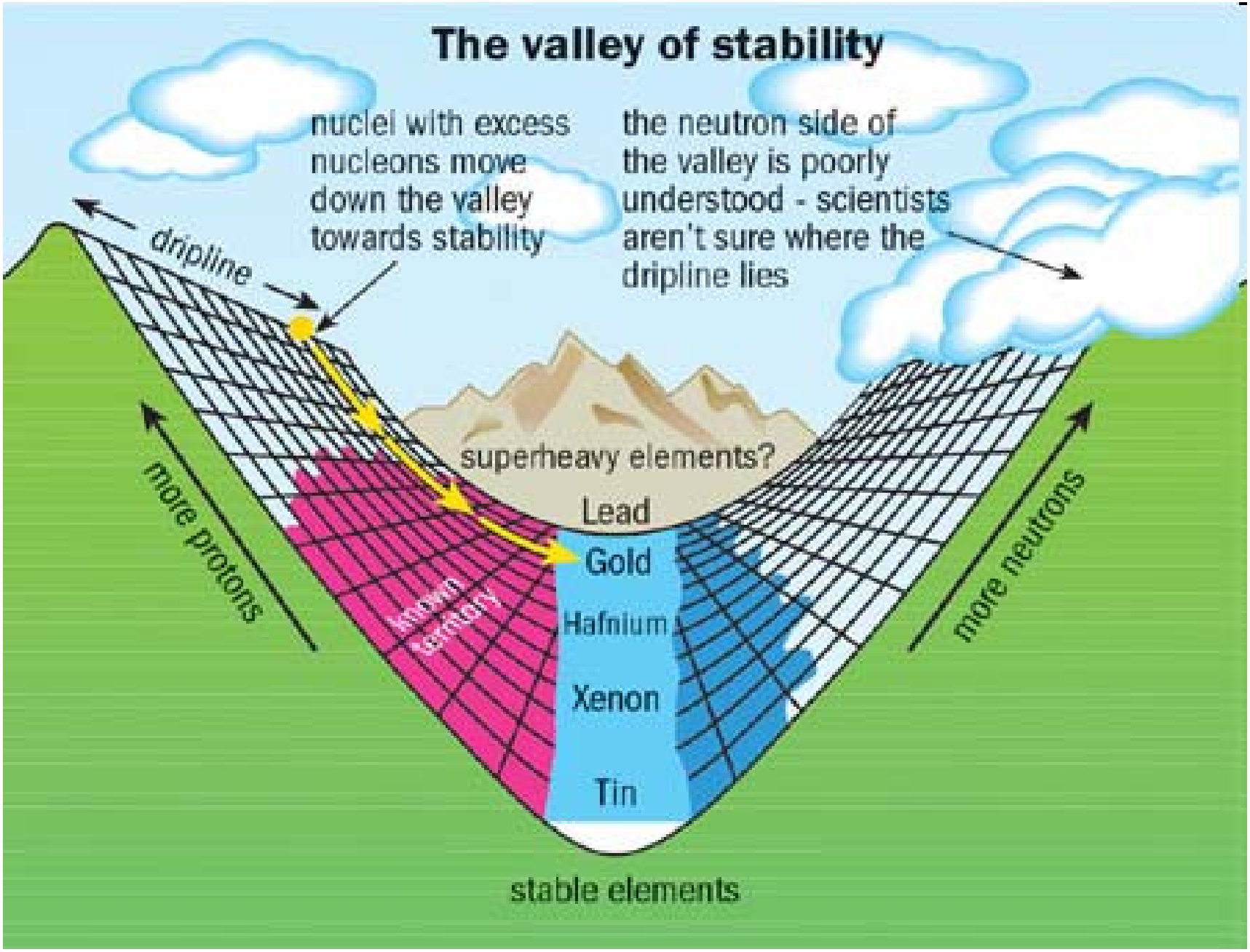
Stable nuclei	approx. 275
Nuclei occuring in nature:	approx. 300
Total number of nuclei:	approx. 2200

Main interactions:

- *Strong attractive nuclear forces between nucleons*
- *Repulsive Coulomb interaction between protons*

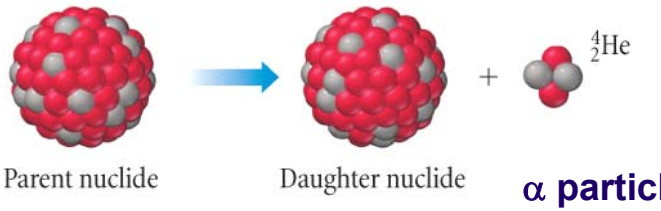
The valley of stability




The valley of stability
nuclei with excess nucleons move down the valley towards stability
the neutron side of the valley is poorly understood - scientists aren't sure where the dripline lies
dripline
superheavy elements?
Lead
Gold
Hafnium
Xenon
Tin
known territory
more protons
more neutrons
stable elements

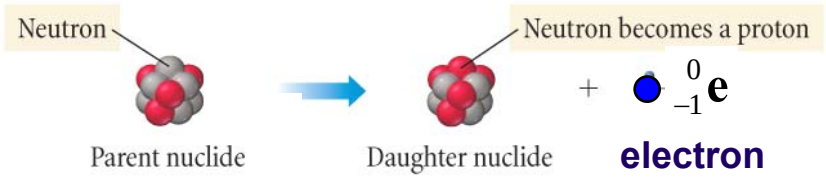
Modes of nuclear decay

α decay



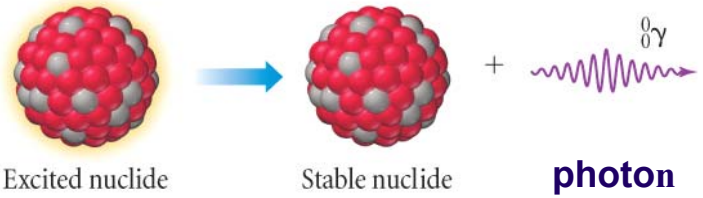
$$^{A}_{Z}X \Rightarrow {}^{A-4}_{Z-2}Y + {}^{2}_{2}He$$

β⁻ decay



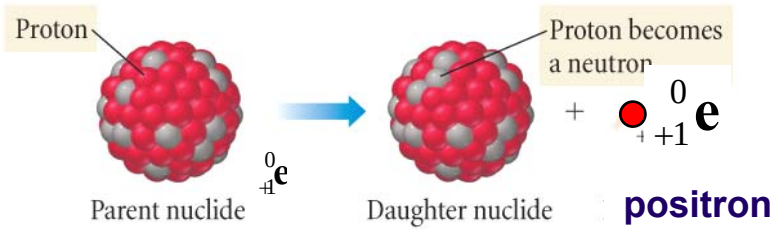
$$n \Rightarrow p + e^{-} + \bar{\nu}$$

γ decay



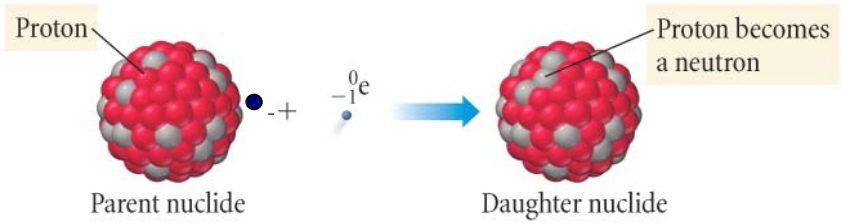
$$^{A}_{Z}X^{*} \Rightarrow {}^{A}_{Z}X + \gamma$$

β⁺ decay



$$p \Rightarrow n + e^{+} + \nu$$

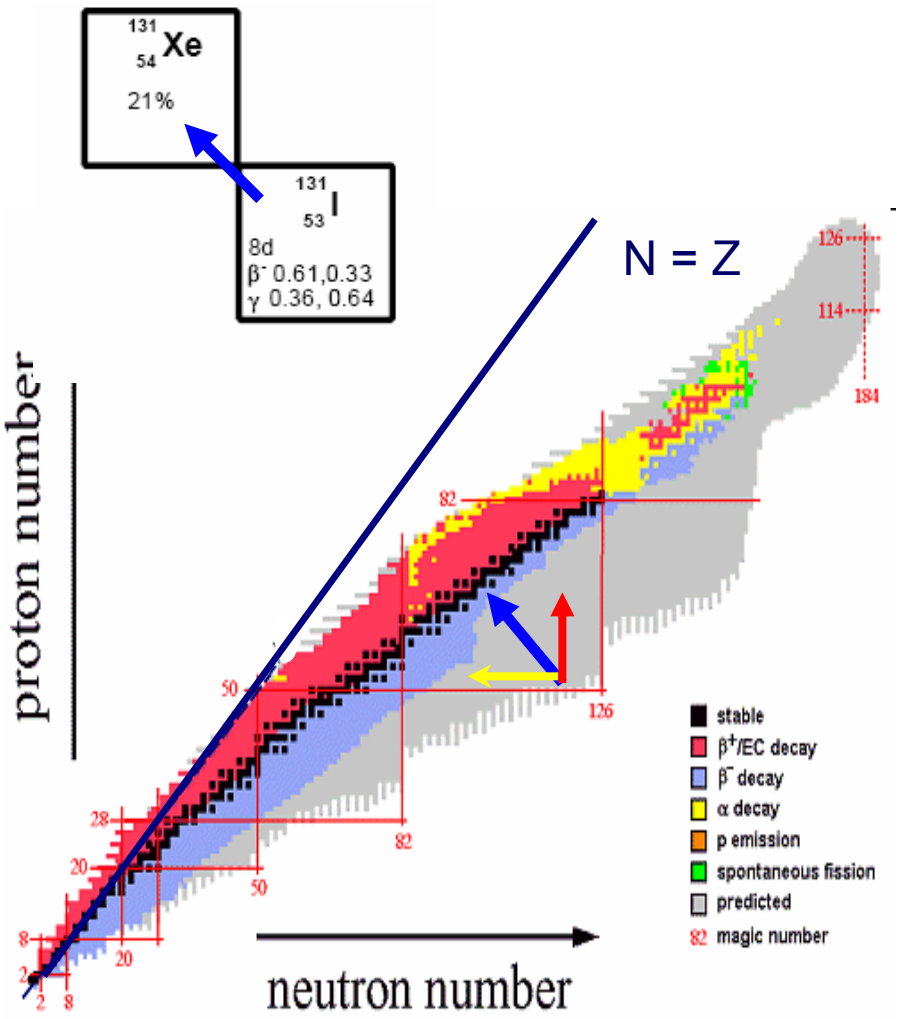
e⁻ capture

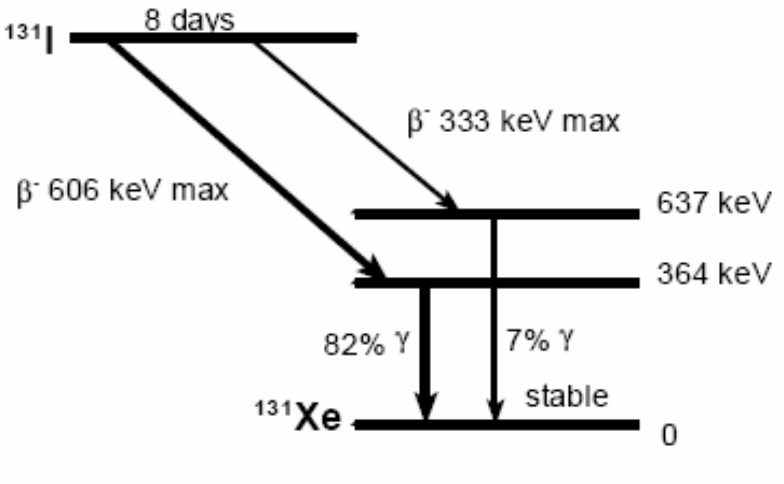


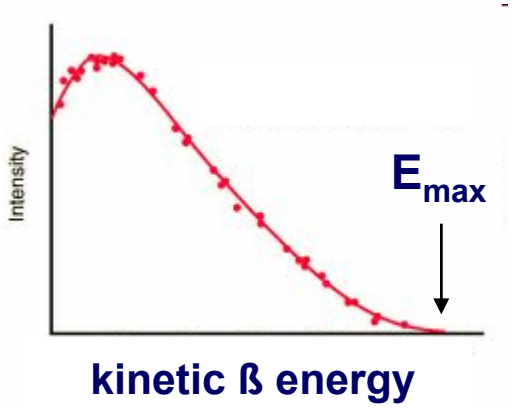
$$p + e^{-} \Rightarrow n + \nu$$

Example of a ß⁻ decay

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{Xe} + \overline{\text{neutrino}} + \text{beta particle} \; (+ \; \text{gamma ray})$$



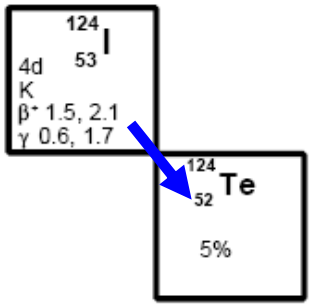


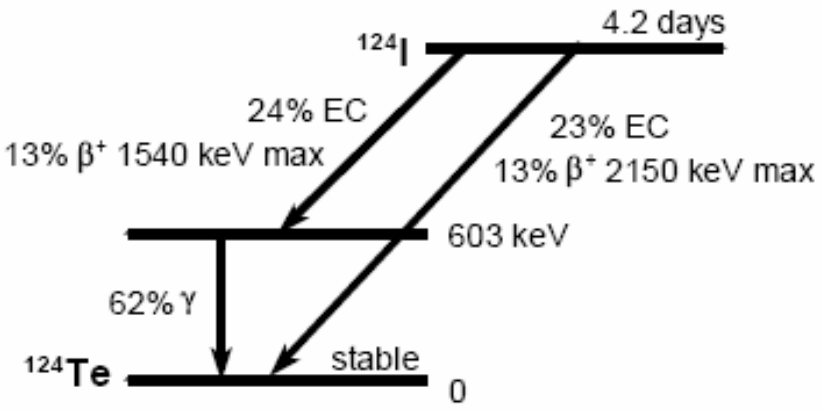


Example of a ß+/EC decay

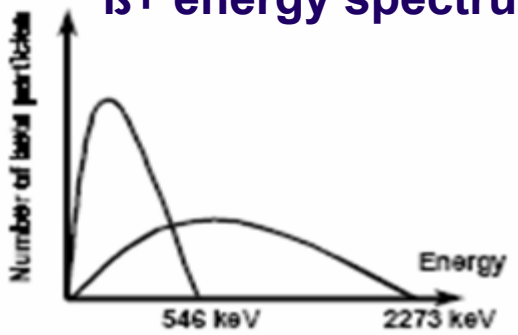
$$^{124}_{53}\mathrm{I} \longrightarrow {}^{124}_{52}\mathrm{Te} + \text{positron} + \text{neutrino} \; (+ \; \text{gamma ray})$$

$$^{124}_{53}\mathrm{I} + e^{-} \longrightarrow {}^{124}_{52}\mathrm{Te} + \text{neutrino}$$





ß+ energy spectrum



Radioactive atoms as probes in solid state research

Production by nuclear reactions

Nuclear reactors : e.g. ^{180}Hf (n,γ) ^{181}Hf, ^{116}Cd(n, γ)^{117}Cd

Particle accelerators (cyclotrons): e.g. ^{111}Cd(p,n)^{111}In , ^{75}As(α,2n) ^{77}Br

Half-lifes $T_{1/2}$:

Days: **laboratory experiments**: allows systematic studies as a function of temperature, pressure, annealing, etc

^{57}Co ($T_{1/2}$ = 270 d) $\rightarrow$ ^{57}Fe (ME source) , ^{181}Hf ($T_{1/2}$ = 43d) $\rightarrow$ ^{181}Ta (PAC source)

Isotopes commercially available

Hours: **requires nearby reactor, cyclotron, on-line mass separator**

One measurement per sample, limited possibilities of sample treatment

PAC experiments:^{111m}Cd, $T_{1/2}$ = 48 min, Emission channeling (EC) ^{24}Na, $T_{1/2}$ = 15 h

Minutes: **On-line experiments:** ME, PAC, EC equipment directly connected to accelerators or mass separators (ISOLDE @ CERN)

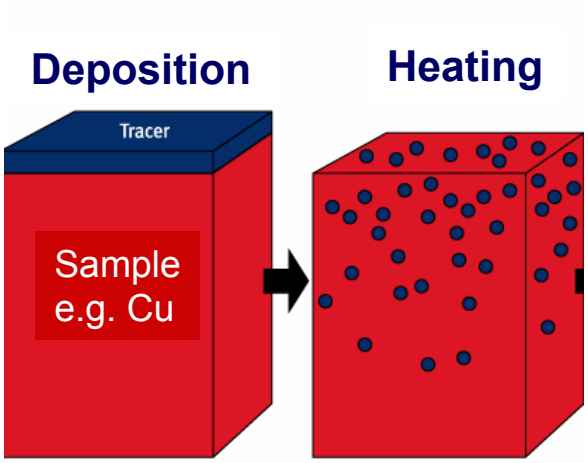
ME: ^{119}In ($T_{1/2}$ = 48 min) $\rightarrow$ ^{119}Sn, PAC: ^{79}Rb ($T_{1/2}$ = 23min) ^{79}Kr

Doping procedures

Nuclear reactions:

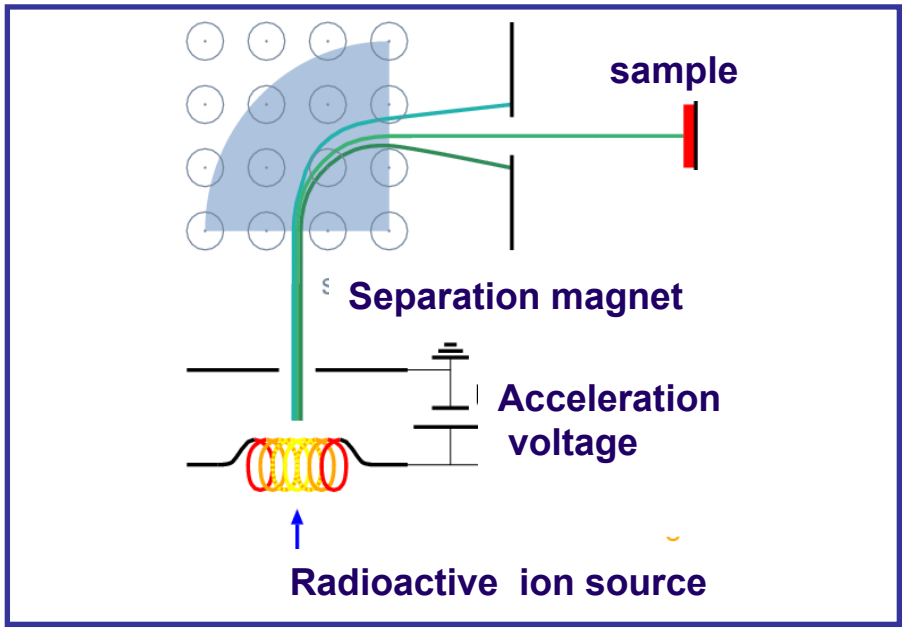
In some cases, samples can be doped via **nuclear reactions inside the material**. Examples: doping of cadmium compounds with ^{111}In via the reaction ^{111}Cd (p,n) ^{111}In and with ^{117}Cd via ^{116}Cd (n,γ) ^{117}Cd
or the production of ^{77}Br in arsenic compounds via the ^{75}As (α, 2n) ^{77}Br reaction

Diffusion



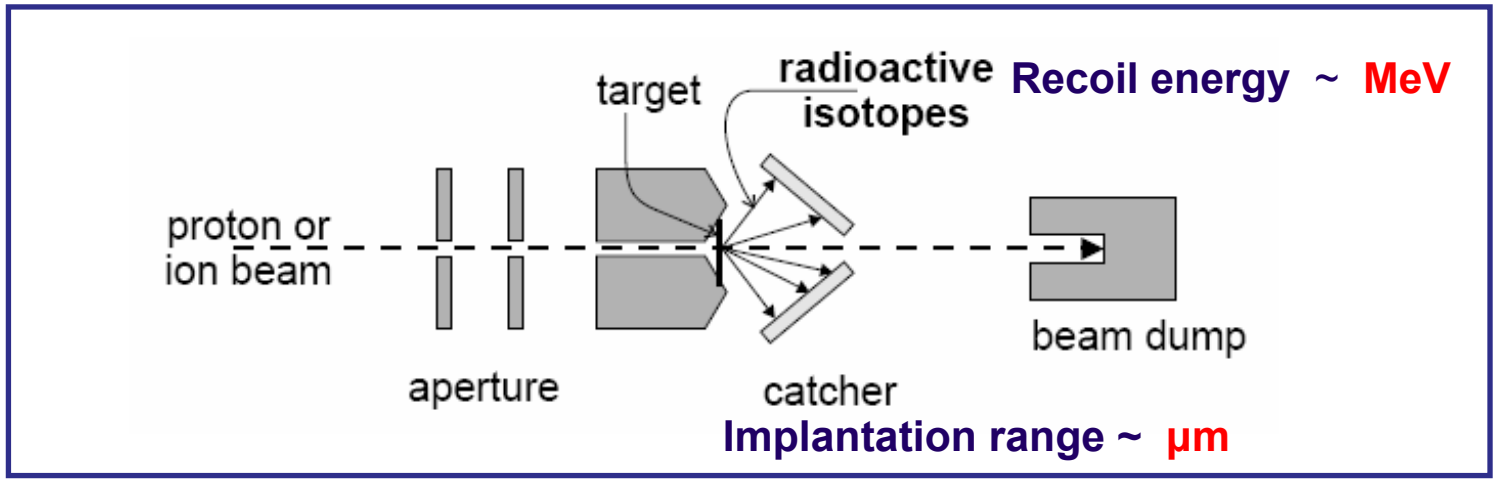
Recoil and ion implantation

Doping by ion implantation



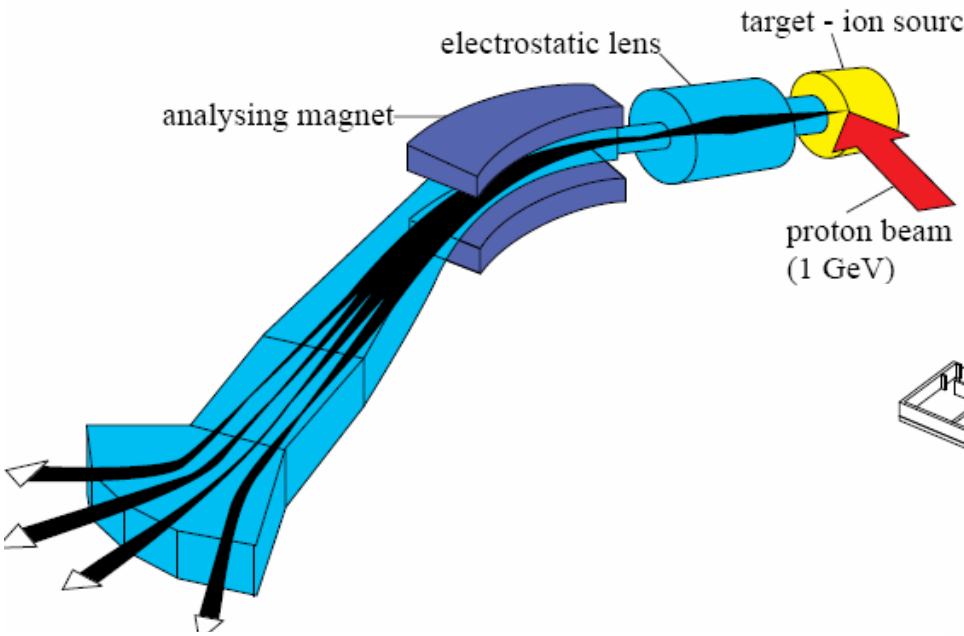
Mass separator as off-line implanter

Recoil implantation at heavy ion accelerators (e.g. VICKSI, Berlin; Pelletron, USP)



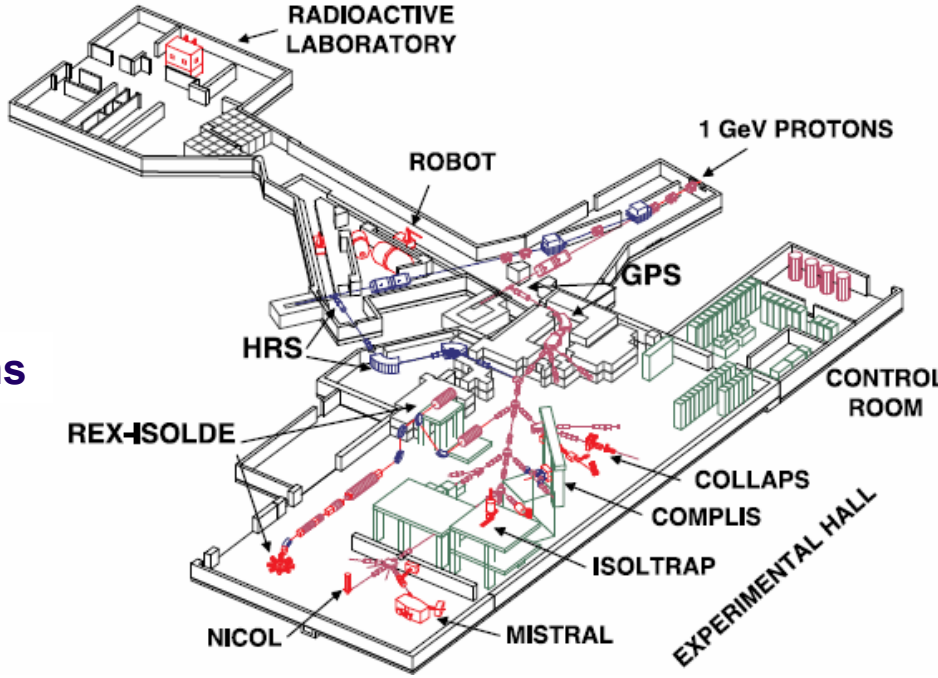
Online implantation at radioactive ion beam accelerators

ISOLDE: First On-Line Isotope Mass Separator starting in 1967



Isotope production by spallation, fission, or fragmentation reactions

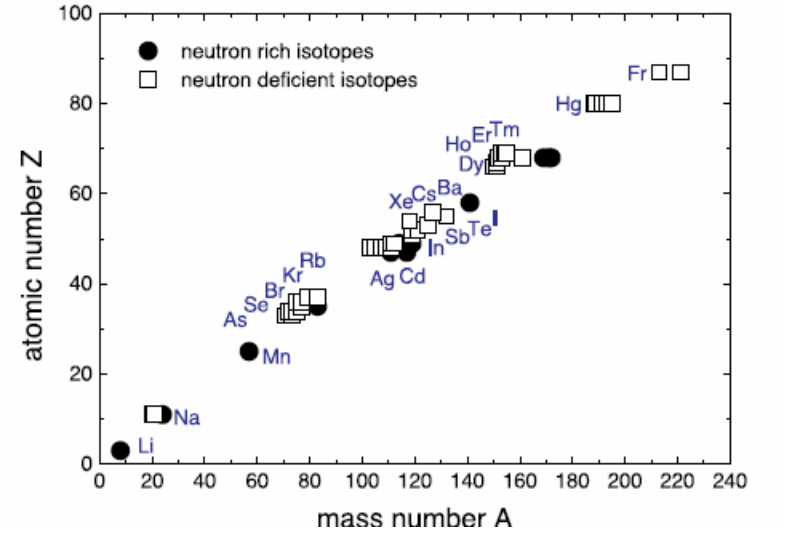
60 KeV mass separated radioactive ion beams



Elements for which radioactive beams are available at ISOLDE

GROUP IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB		IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
H																He
Li	Be										B	C	N	O	F	Ne
Na	Mg										Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
LANTHANIDES			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
ACTINIDES			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

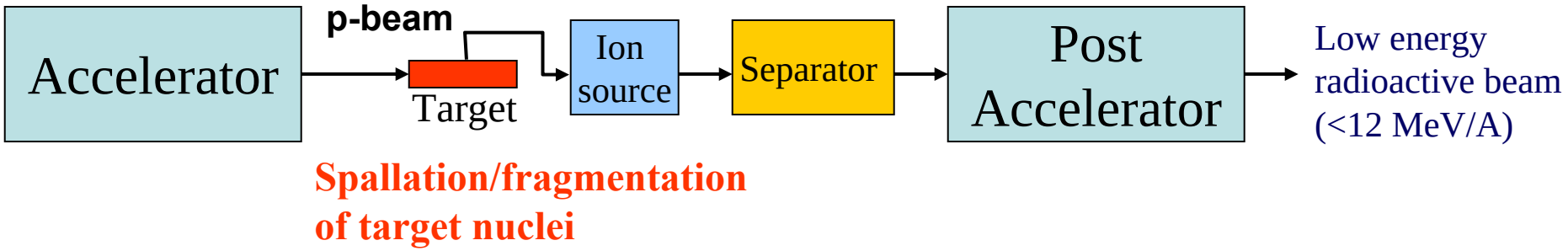
Radioactive isotopes used for solid state studies



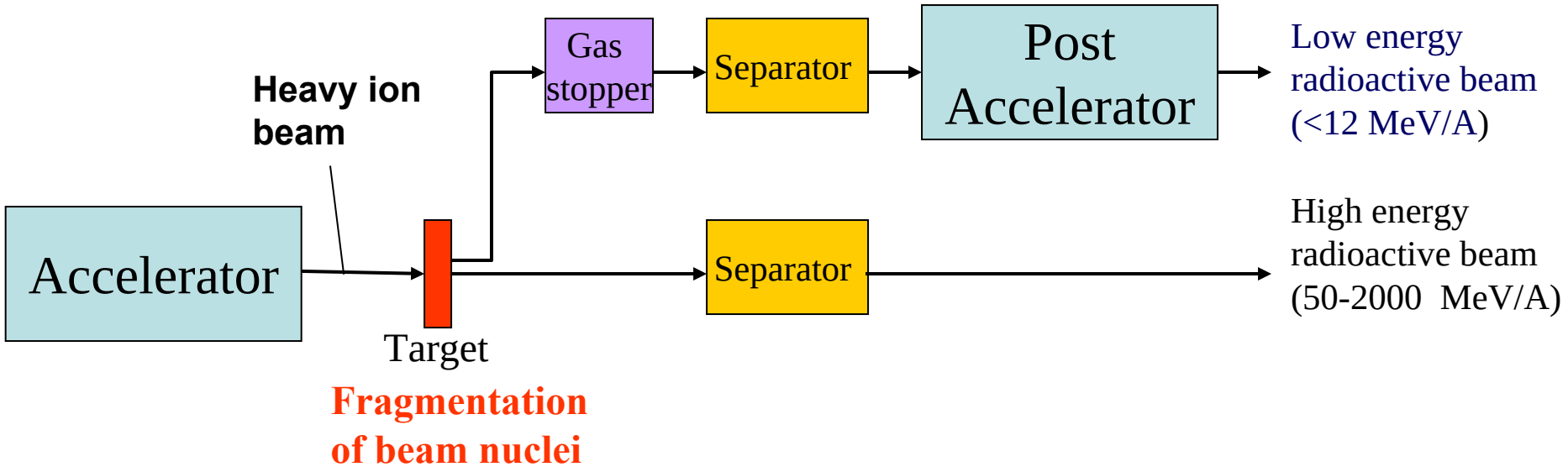
M. Forker, Nuclear Techniques in Solid State Research, CBPF 2012

Radioactive beam facilities

ISOL (ISOLDE, ISAC, Oak Ridge, Louvain-la-Neuve, …):



Fragmentation (NSCL, GSI, RIKEN, GANIL, …):



Basic concepts of radiation detection

Detector categories

<table>
<tr><th>Gas-filled detectors</th><th>Scintillation detectors</th><th>Semiconductor detectors</th><th>Other solid state detectors</th></tr>
<tr><td rowspan="2">Ionisation-chamber
(α, β)

Proportional Counter
(α,β,γ)

Geiger-Müller-Counter
(β, γ)</td><td>Solid Scintillation-Detectors
e.g. NaJ:Tl
(γ, β)

Liquid-Szintillations-Detectors
(α, β, γ)
H3, C14</td><td>Silizium-Diodes and –Single Crystals
(α, β, γ)

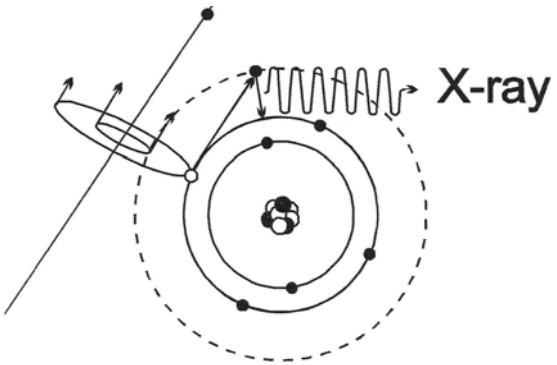
Germanium Single Crystal
(β), γ)</td><td rowspan="2">Photolumines-cence glasses
(β, γ)

Thermolumines-cence crystals
(β, γ)

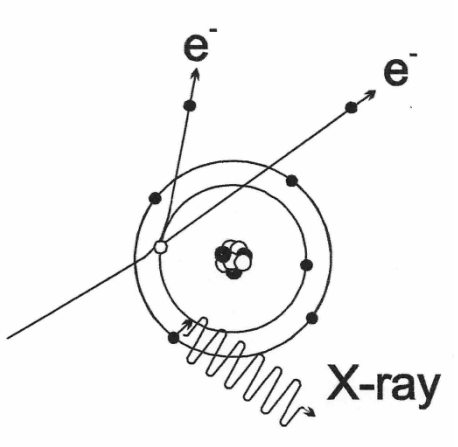
Filmemulsions
(β, γ)</td></tr>
<tr><td colspan="2">CsI(Tl) and $LaBr_3$ crystals coupled to PIN/APD photodiodes</td></tr>
</table>

Interaction processes of charged particles in matter

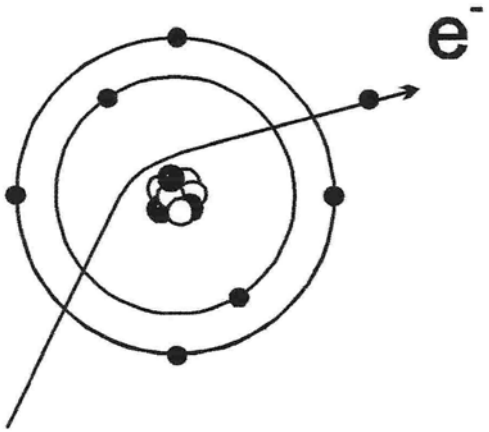
Inelastic collision: excitation



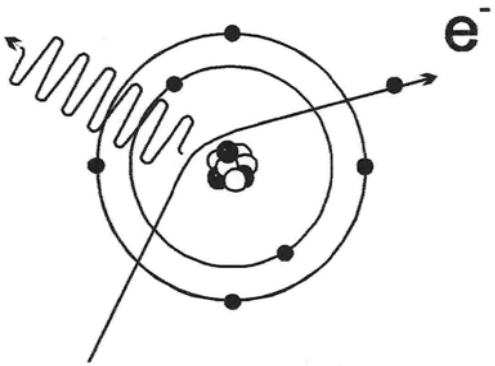
Inelastic collision: ionisation



Elastic collision

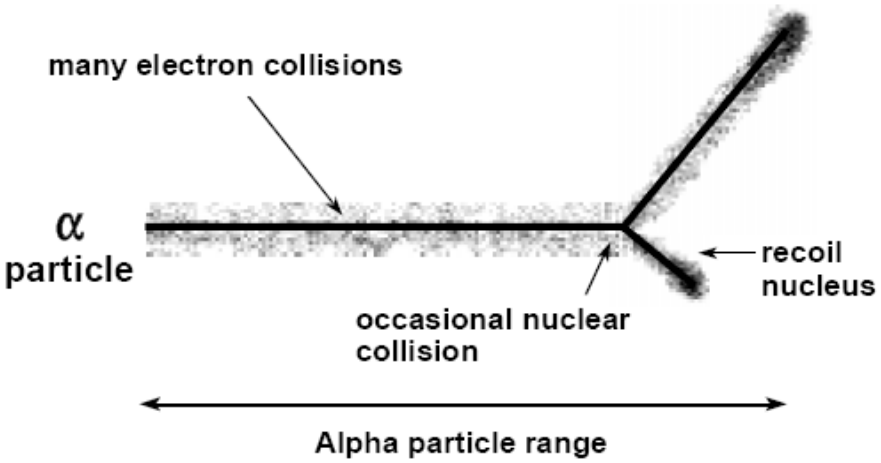


Bremsstrahlung

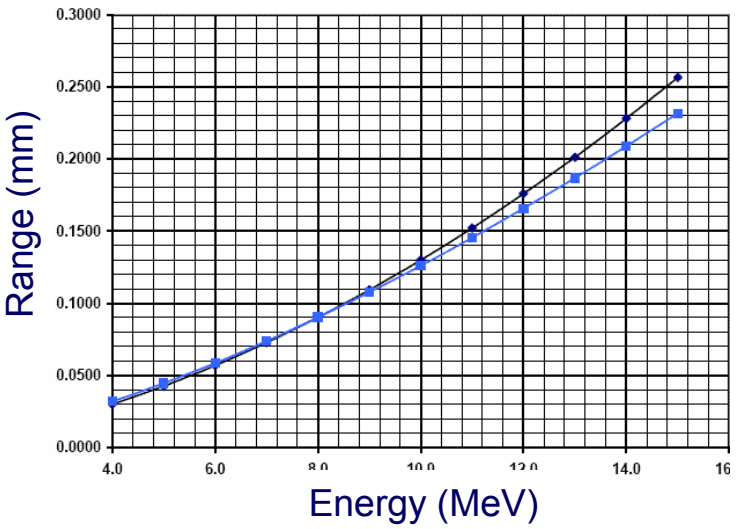


Alpha particles in matter

Interaction pattern



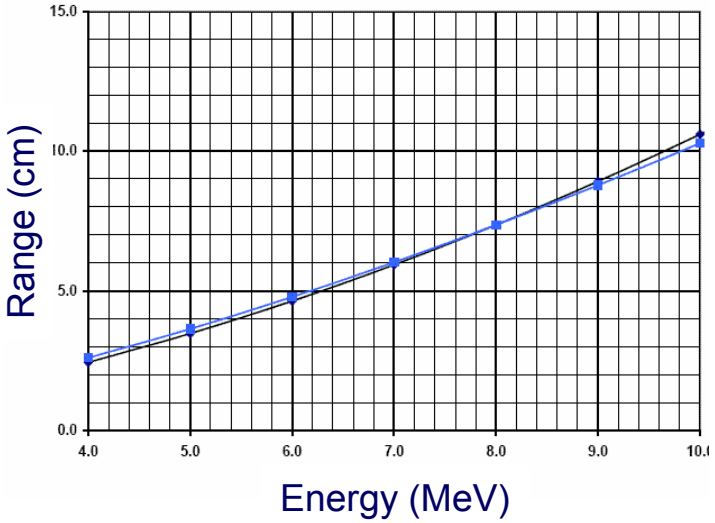
Alpha range in water



Cloud chamber photograph

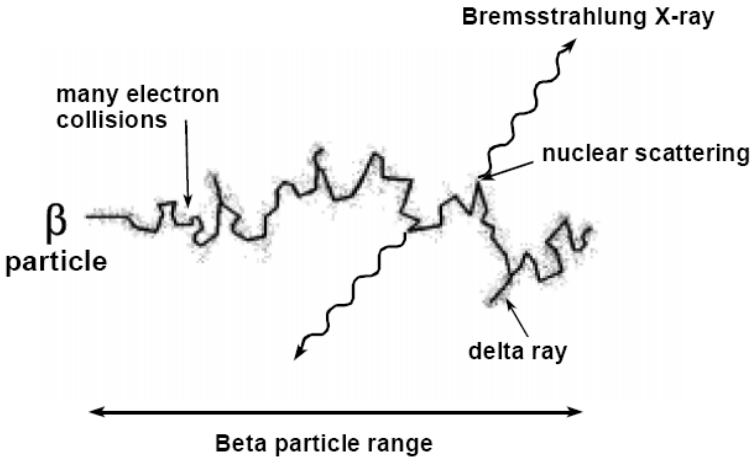


Alpha range in air

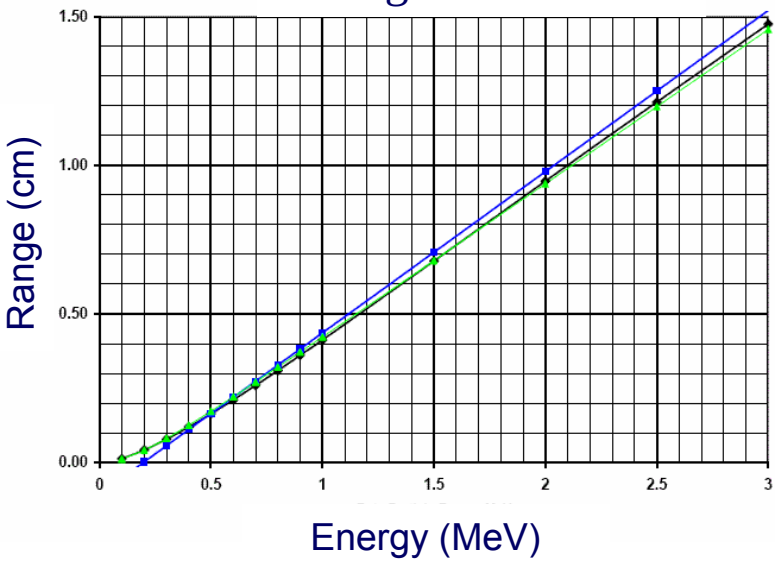


Electrons (ß-) in matter

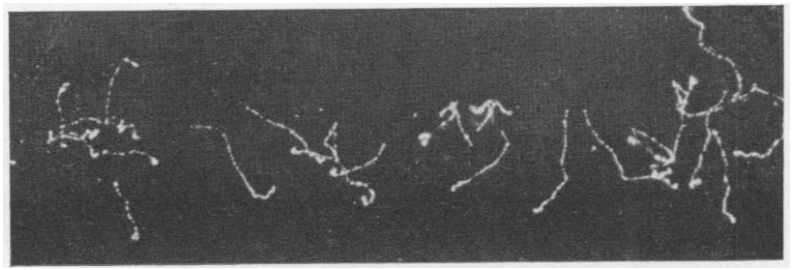
Interaction pattern



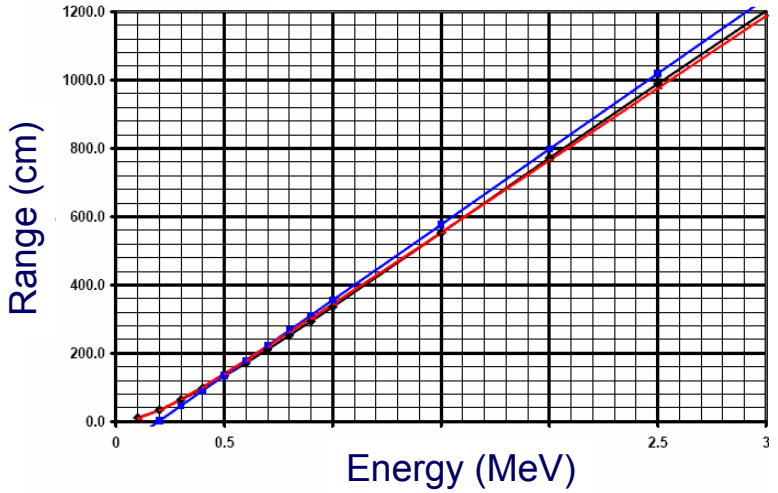
ß- range in water



Cloud chamber photograph



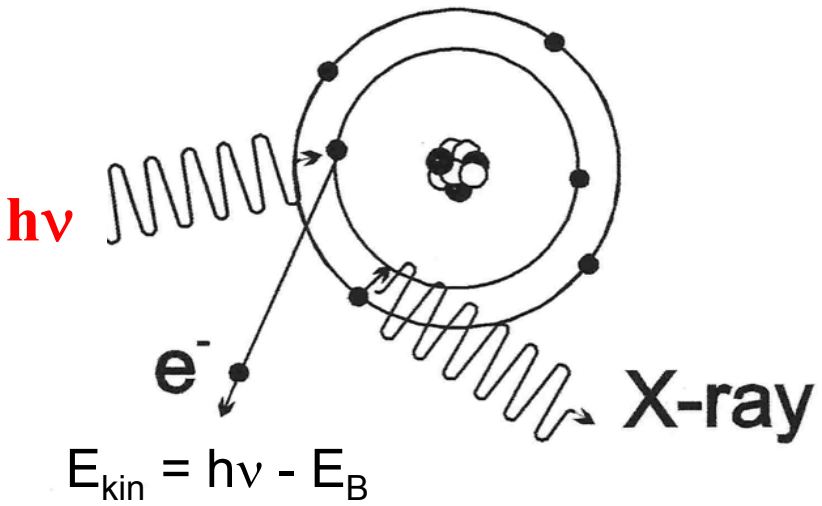
ß- range in air



Interaction of photons (γ-rays) in matter

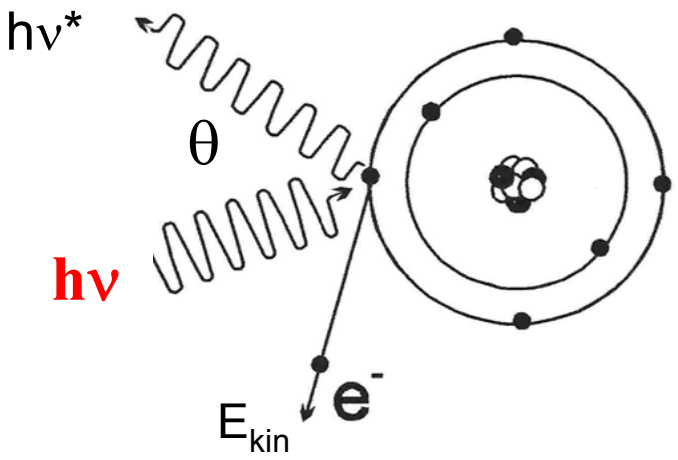
Processes : Photo effect, Compton effect, Pair production, Raleigh scattering

Photo effect



$E_{kin} = h\nu - E_B$

Compton effect

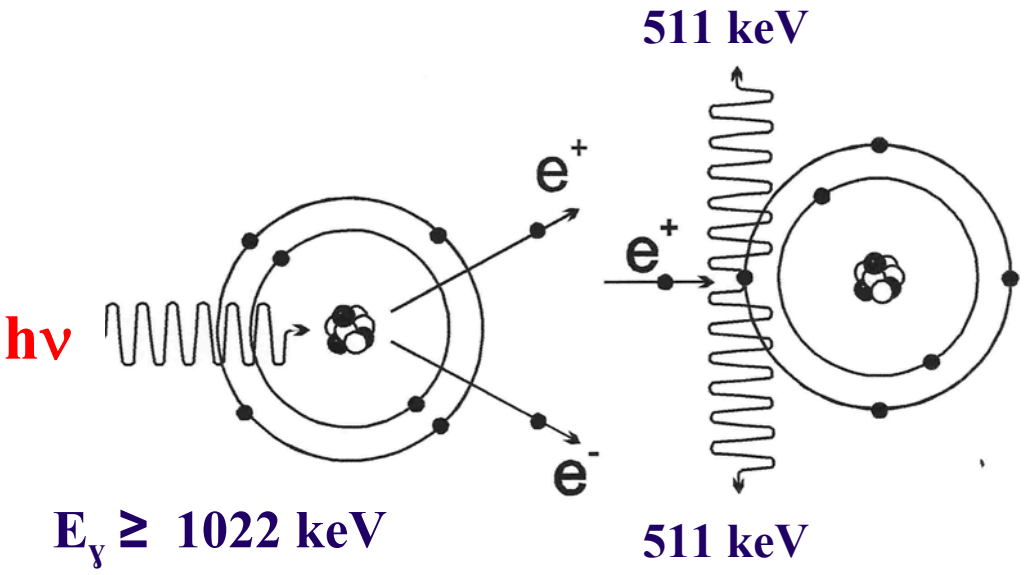


Photons posses momentum !!!

Confirmation of the particle-like character of photons predicted by Einstein

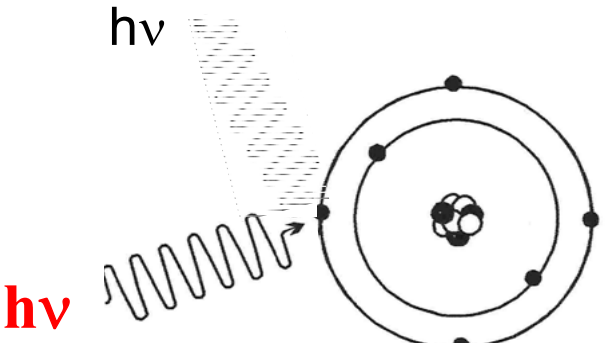
Interaction of photons (γ-rays) with matter

Pair production

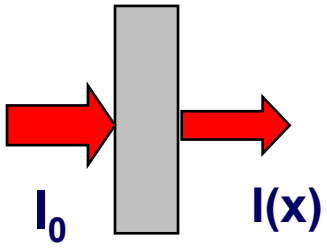


annihilation

Raleigh (elastic) scattering

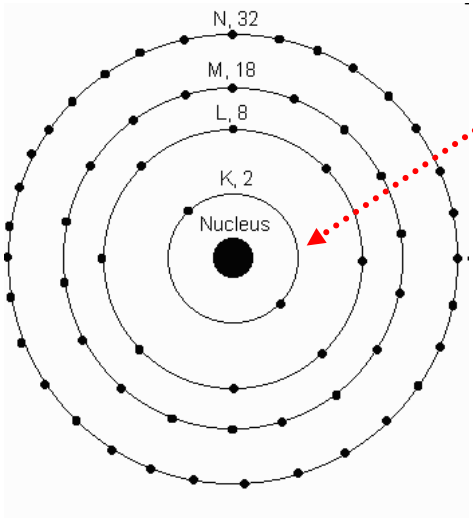


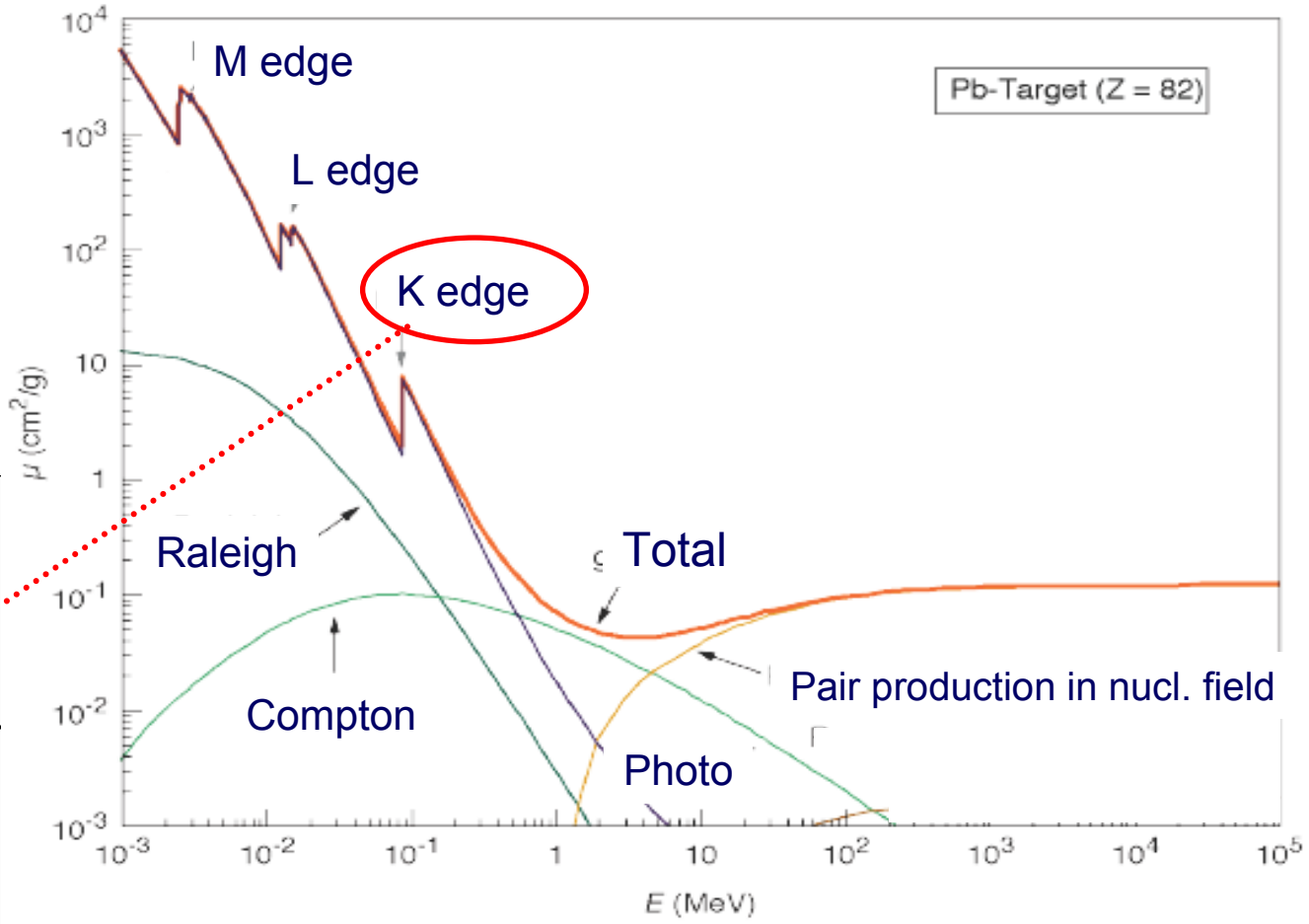
Absorption of photons in matter



$$I(x) = I_0 \exp(-\mu x)$$

Absorption coefficient

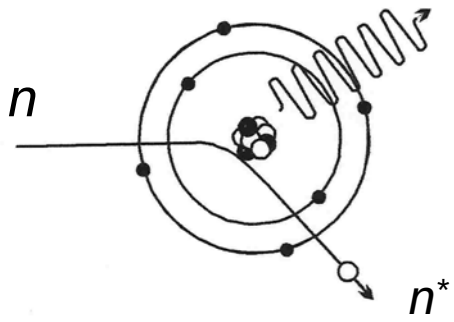




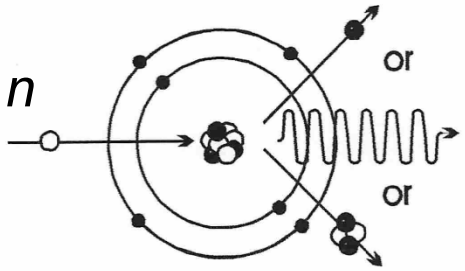
K ,L ,M edge: The absorption increases abruptly when the photon energy exceeds the binding energy of the K-, L-, M-electron

Neutron interactions with matter

Inelastic scattering of neutrons

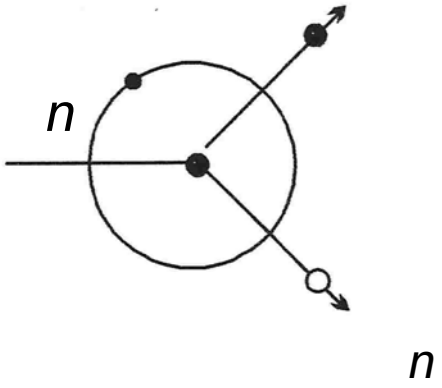


Nuclear reaction

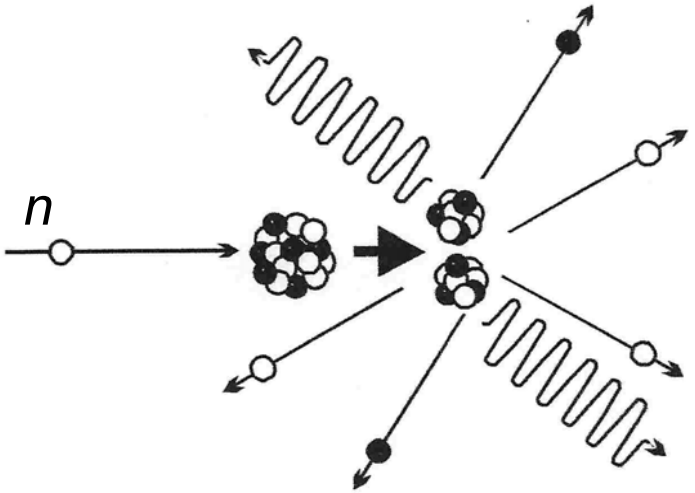


$^{10}B+n \rightarrow {}^{7}Li+\alpha$

Elastic scattering of neutrons

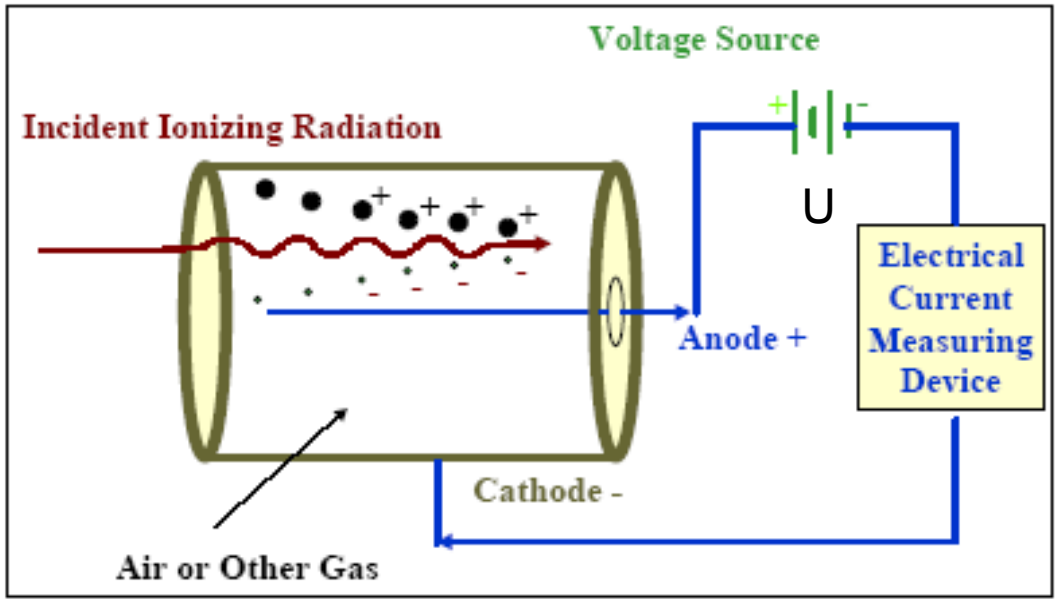


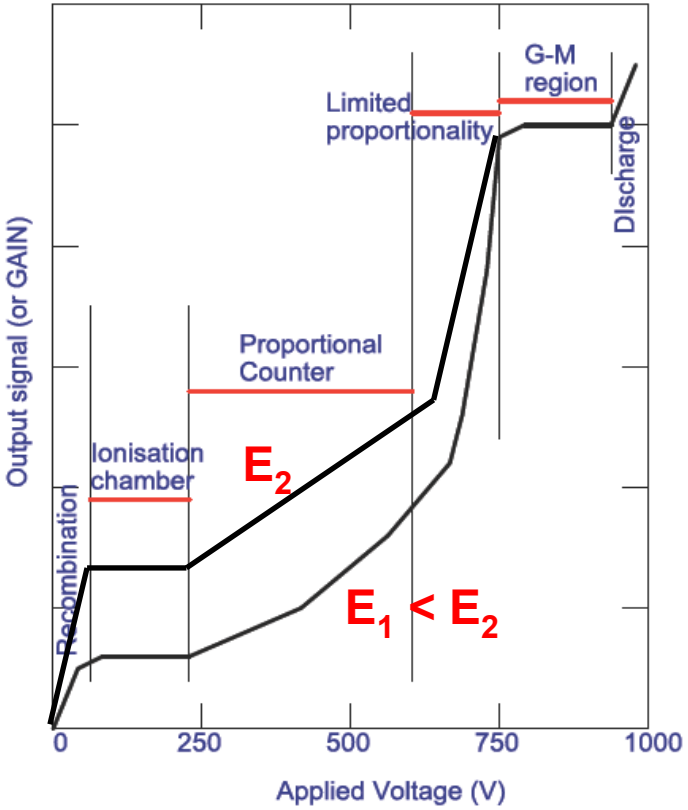
Fission



Gas-filled detectors

Principle: Incident radiation ionises the gas, producing electron-ion pairs.
These charges are collected by applying a voltage *U* between anode and cathode

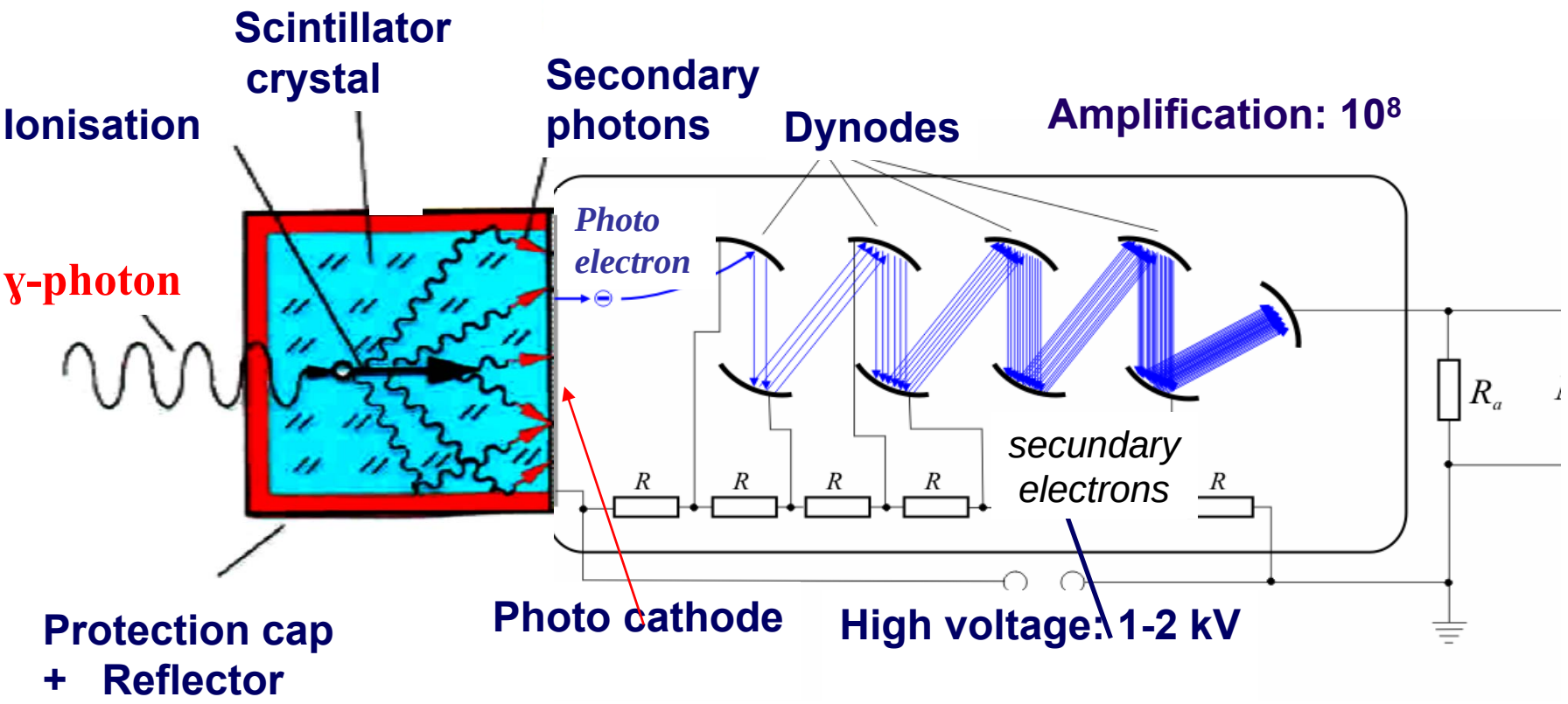




E_{ion} (Ar) = 15 eV

With increasing U:
Ionisation chamber → Proportional counter → Geiger Müller counter

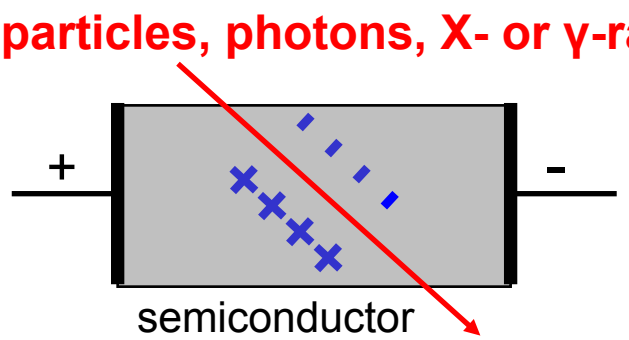
Scintillation detector: Scintillation crystal + photomultiplier

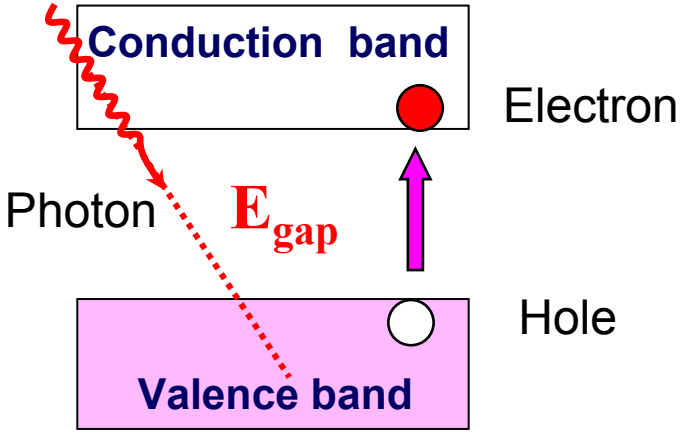


Scintillators: NaI(Tl), CsI(Tl), BaF_2, BGO,…..; Plastic: Anthracene,…

Photo cathodes: Ag-O-Cs, GaAs:Cs, Sb-Cs, Bialkali (Sb-K-Cs, Sb-Rb-Cs),..

The principle of semiconductor detectors





- The incident radiation produces electron-holes pairs in a semiconductor band structure.
- As in a ionisation chamber, these mobile charge carriers are collected by applying a voltage to the electrodes
- Charge losses by **recombination** must be avoided. This requires *Intrinsic Semiconductors* of very high purity

- **Principal advantage** compared to gas-filled and scintillation detectors is the much higher number of charge **carriers/keV** . This results in a much better energy resolution

Material	E_{gap} (eV)
Ge	0.67
Si	1.0
GaAs	1.42
C (Diamant)	5.5

Energy resolution
$\Delta E/E \propto N^{-1/2}$,
N = number of particles/γ

Energy resolution of scintillation and semiconducting detectors

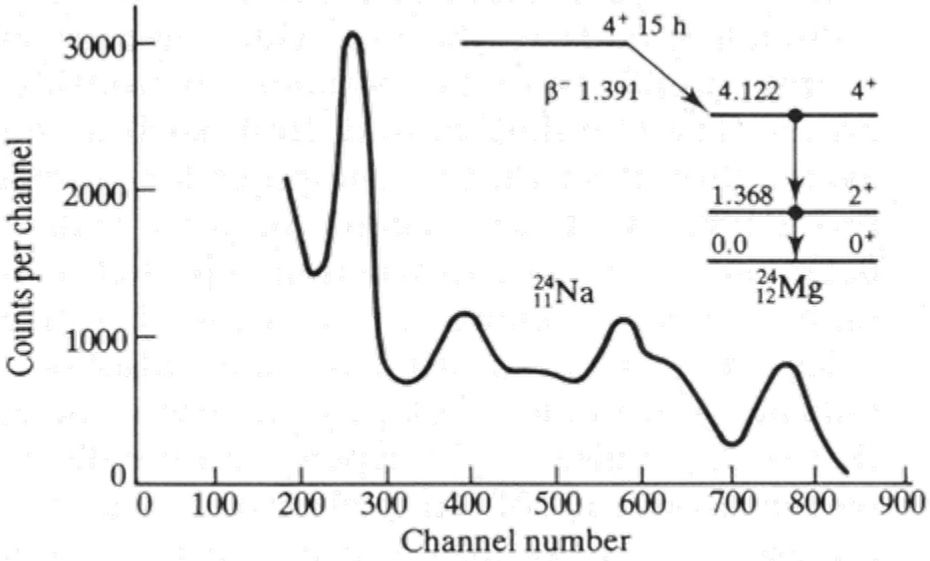
scintillation detector
NaJ(Tl) + photo mult.

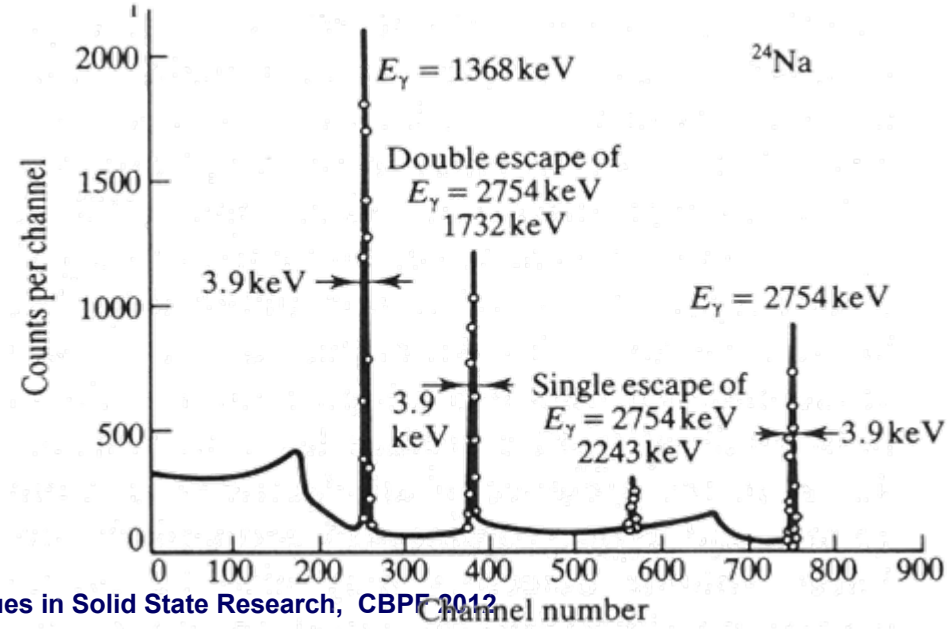
ΔE/E~10 %

Energy resolution
$\Delta E/E \propto N^{-1/2}$,
N = number of particles/ɣ

semiconducting detector
HP Ge

ΔE/E~1.5 %

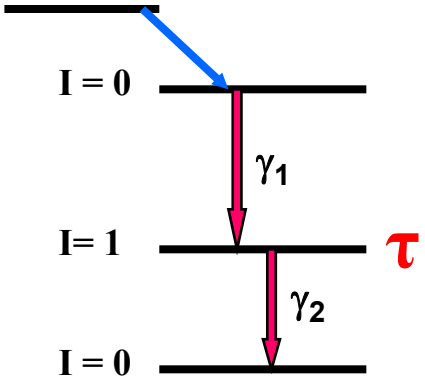


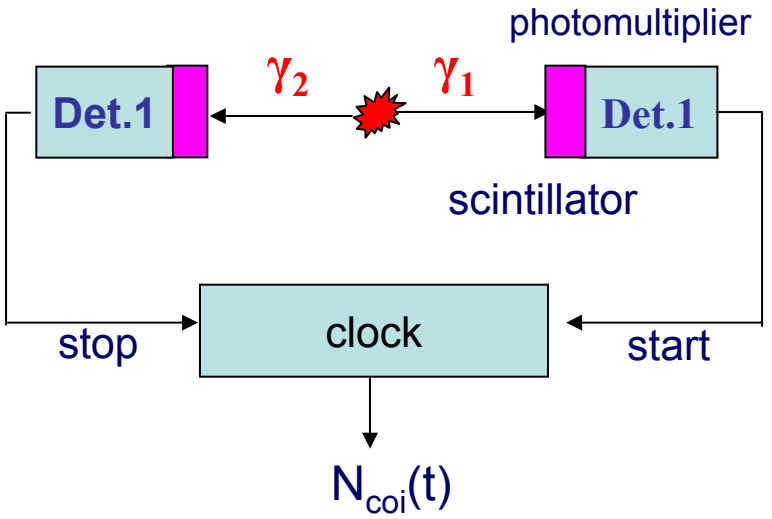


Lifetime measurements

Important parameter: **the time resolution** of coincidence spectrometers

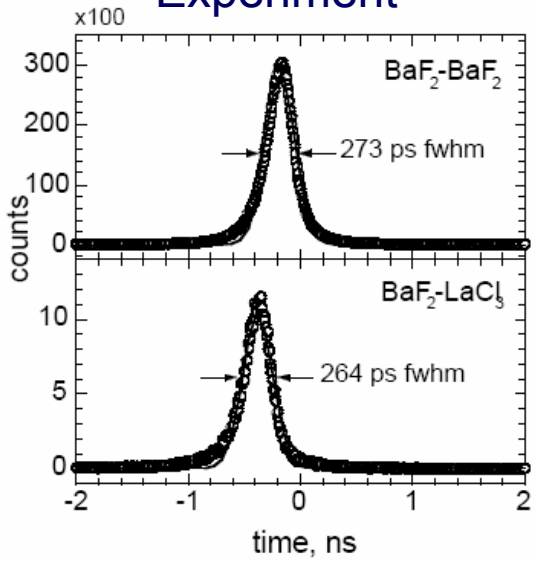
Decay



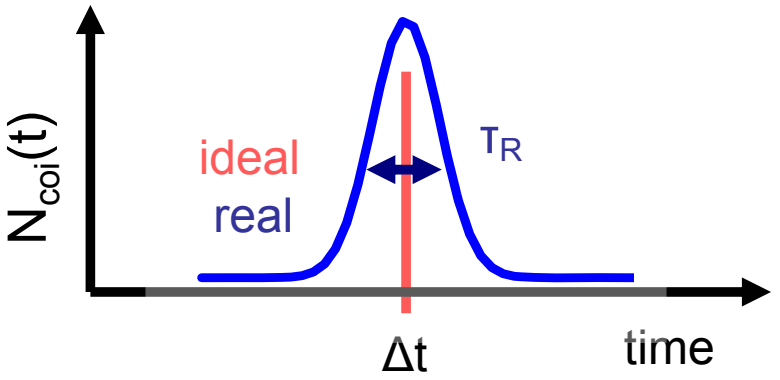


Consider : γ_1 and γ_2 with delay Δt

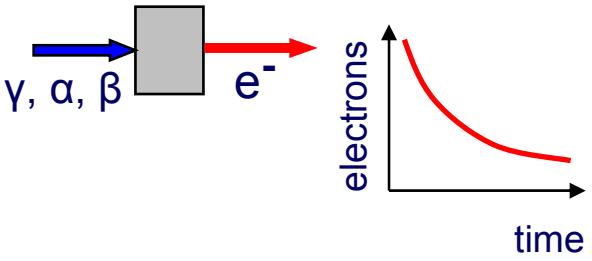
Experiment



Coincidence spectrum



Scintillators for lifetime measurements



Short decay time = Fast time response

HgI_2, PdI_2,CuI

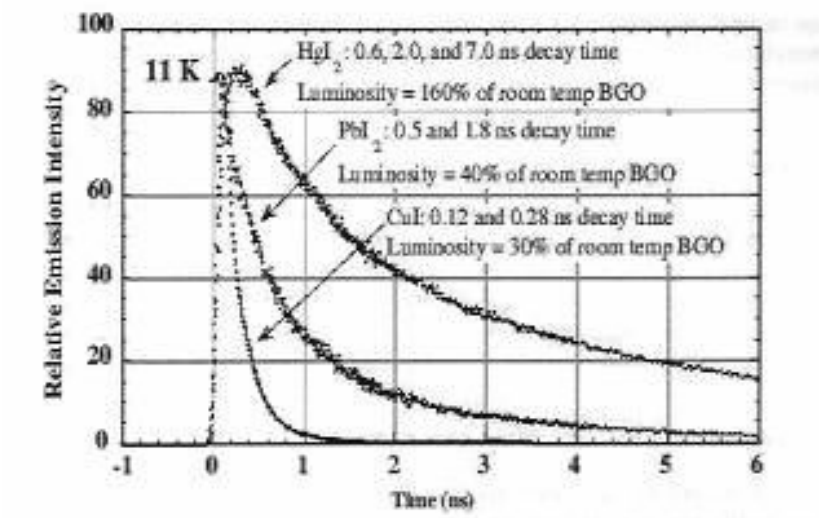
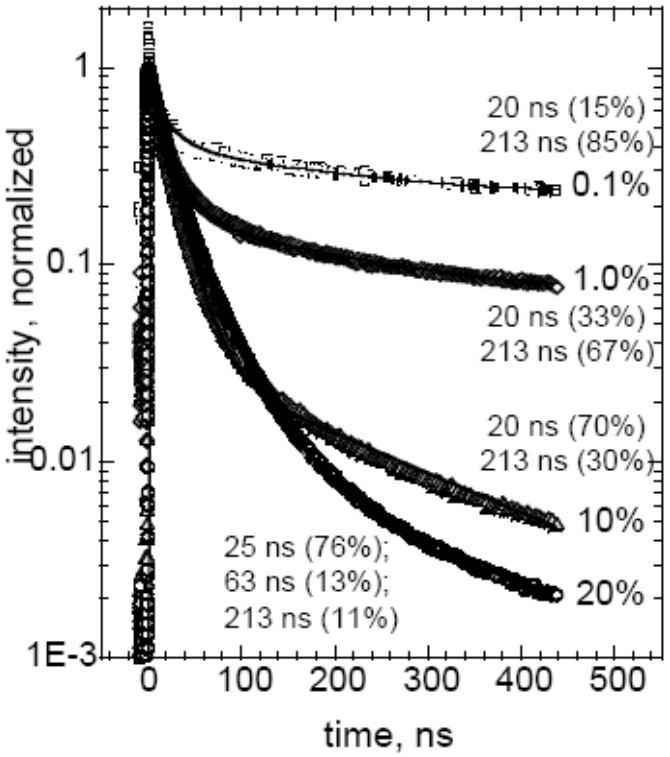


Figure 6.1.5: Time profile of scintillation pulse for three different scintillation materials (34).

$LaCl_3$(Ce)



K.S. Shaha,*, J. Glodoa, M. Klugermana, L. Cirignanoa, W.W. Mosesb, S.E. Derenzob, and M.J. Weberb
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Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Important inorganic scintillator materials used in nuclear physics and nuclear medicine

Property	NaI(Tl)	BGO	LSO(Ce)	GSO(Ce)	CsI(Tl)	BaF_2	Plastic†
Density (g/cm^3)	3.67	7.13	7.40	6.71	4.51	4.89	1.03
Effective atomic number	50	74	66	59	54	54	12
Decay time (nsec)	230	300	40	60	1000	0.8, 620*	2
Photon yield (per keV)	38	8	20–30	12–15	52	10	10
Index of refraction	1.85	2.15	1.82	1.85	1.80	1.56	1.58
Hygroscopic	Yes	No	No	No	Slightly	No	No
Peak emission (nm)	415	480	420	430	540	225, 310*	Various

*BaF_2 has two components: a fast-decaying component and a slow-decaying component.
†Typical values—there are many different plastic scintillators available.
BGO, $Bi_3Ge_4O_{12}$; GSO, $Gd_2(SiO_4)O$:Ce; LSO, $Lu_2(SiO_4)O$:Ce.

Energy resolution
$\Delta E/E \propto N^{-1/2}$,
N = number of particles/γ

Detection efficiency

Time resolution

Energy resolution