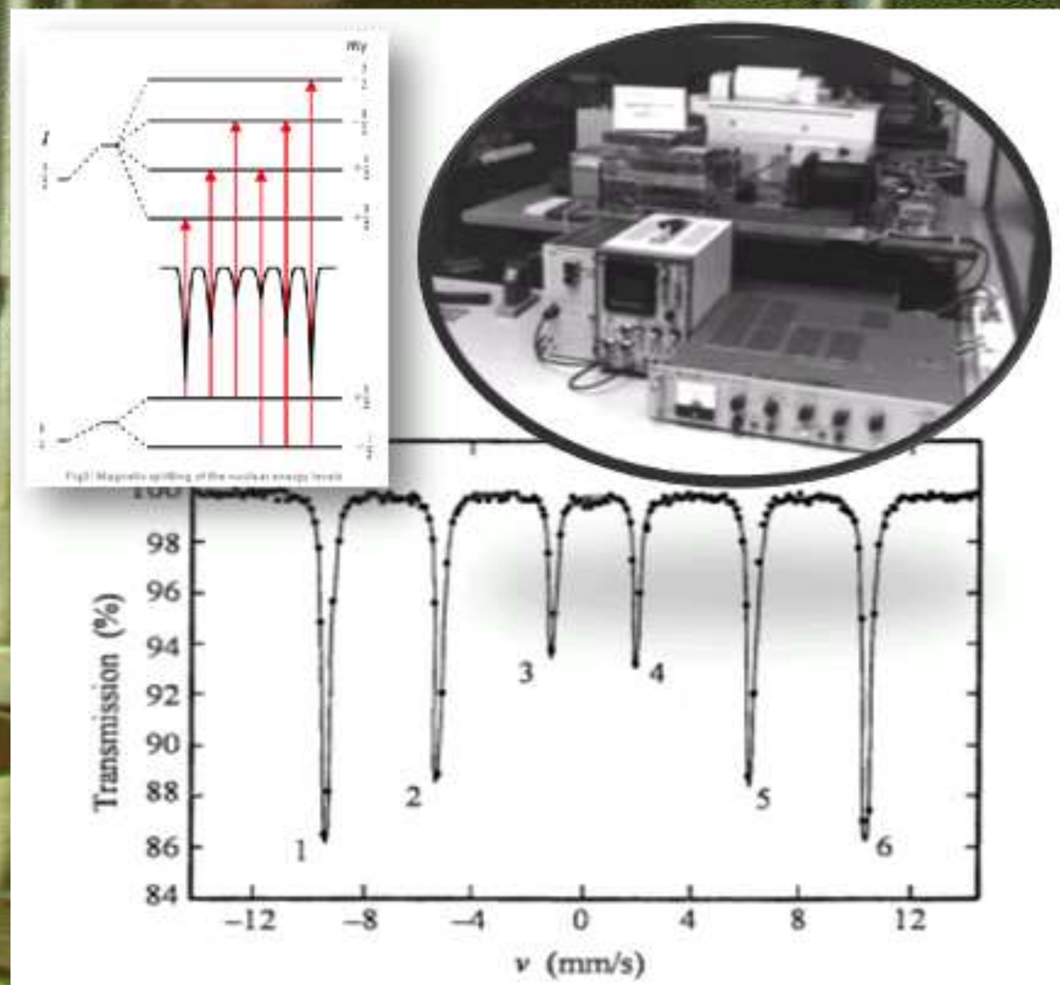
Mőβbauer Spectroscopy



Agenda: ANSEL Mössbauer Experiment

Möβbauer (Mössbauer) Spectroscopy with proportional counters:

Ultra-high-precision photon energy measurement:
Precision scanning resonant-absorption spectroscopy
with doppler-shifted photon energy, using gas amplification counters.

- Gas amplification counters, proportional counters, electronics.

- Mössbauer Principles:

  Resonant γ absorption.

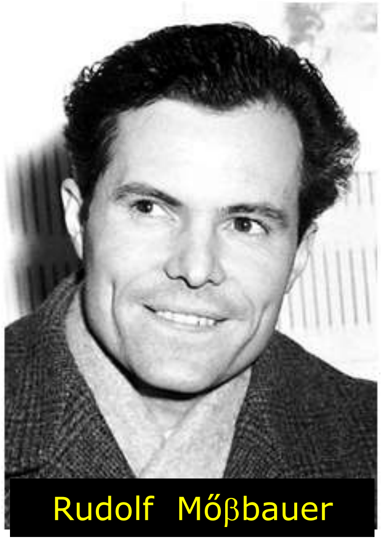
  Recoil effects in γ emission and absorption,

  Recoilless γ absorption by macroscopic samples,

- Determination of electric and magnetic HF interactions in various chemical Fe compounds

Reading Assignments:
(Knoll, LN): X ray spectroscopy with proportional counters (PC),
E_γ-dependent absorption coefficients, gas amplification counters,
Response of proportional counters to γ - and X rays, spurious peaks.

The Mőβbauer Effect



1961 Nobel Prize in Physics.

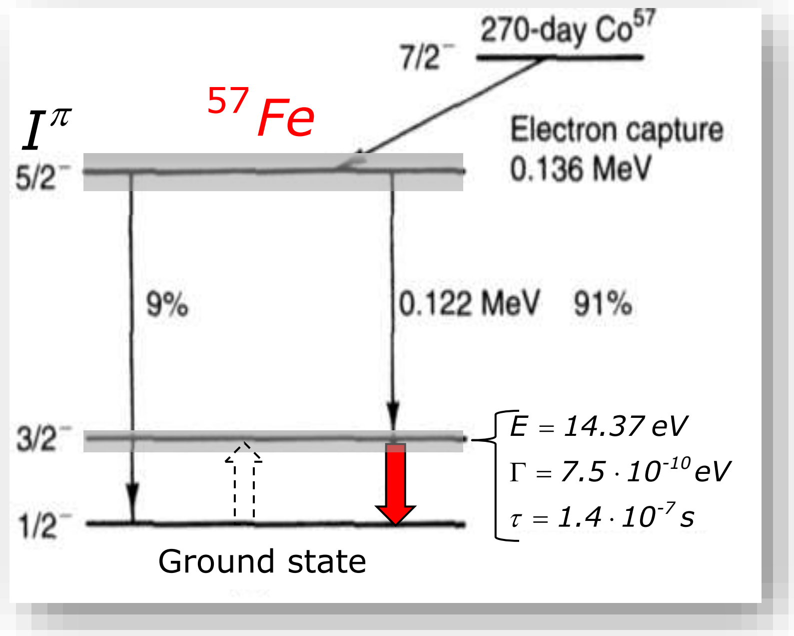
Discovered (1958) recoilless nuclear fluorescence of gamma rays in ^{191}Ir.

Famous application: proof of red shift of gamma radiation in the gravitational field of the earth (Robert Pound and Glen Rebka);
Pound–Rebka experiment was one of the first experimental precision tests of Albert Einstein's theory of general relativity.

Long-term importance:

Use of Mössbauer effect in "Mössbauer spectroscopy" testing solid-state and chemical environments via electric and magnetic hyperfine interactions between atomic electrons and nuclear charge and magnetization distributions.

Precision Absorption Spectroscopy with ^{57}Fe



^{57}Co *source emits* $14.4-keV\ \gamma-rays$

Measure scanning resonance absorption

with Doppler – tunable γ *– ray energies*

$\rightarrow$ *chemical compounds* $^{57}Fe-X(t)$

"Tunable" γ – rays

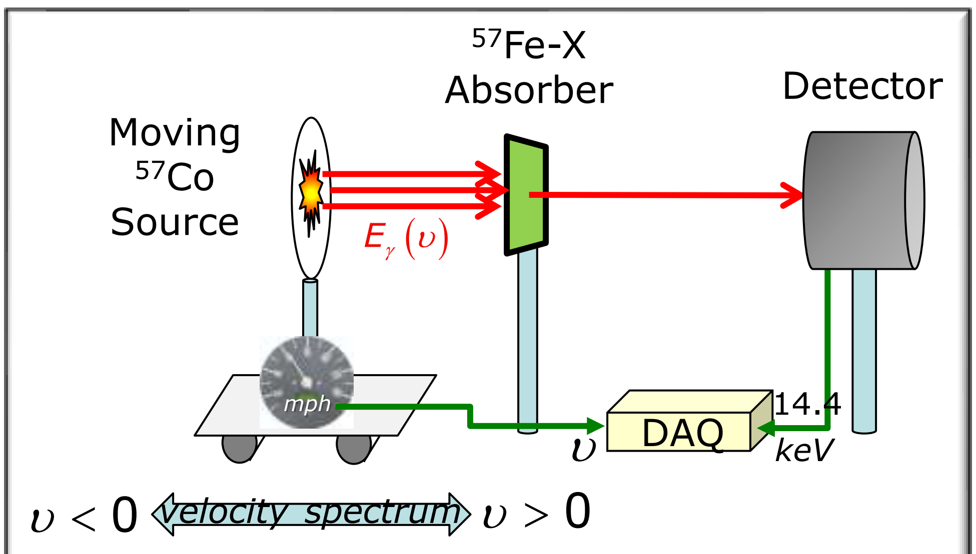
$$E_\gamma(\upsilon) \approx 14.4(1 \pm \upsilon/c)keV$$

$^{57}Co\ \gamma$ *– source*

moving with velocity υ

emits precisely controlled

Doppler – shifted $E_\gamma(\upsilon)$



Resolving power $\Gamma/E_\gamma = 3\cdot10^{-13}$

γ *detectors* : $\Gamma_{FWHM}/E_\gamma \sim 10^{-3}-10^{-2}$

Resonant γ Absorption

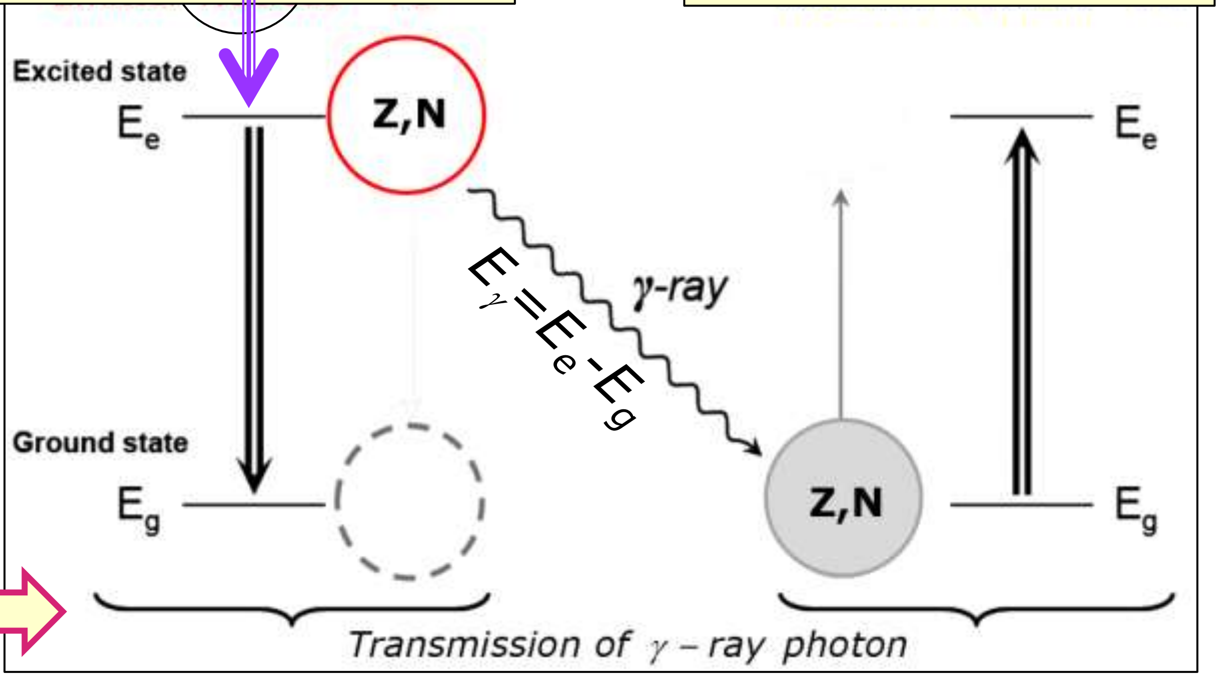
Absorption of radiation= competition of various interactions of photons with (atomic, nuclear) constituents of structured material ("absorbers") →

Absorbance ($\ln I_0/I_x$) = sum of statistical probabilities per constituent.

Mass absorption coefficient (photons) : $\mu\left(E_\gamma\right) = \sum_n \mu_n\left(E_\gamma\right)$

^{57}Co→^{57}Fe Source

^{57}Fe-X Absorber



Special case: Nuclear Resonant Absorption

$\mu_\nu(E_\gamma)=\mu_{res}(E_\gamma)$

Breit–Wigner Resonance

$$\mu_{res}(E_\gamma) \propto \frac{\left(\Gamma_{res}/2\right)^2}{\left(\Gamma_{res}/2\right)^2 + \left(E_\gamma - E_{res}\right)^2}$$

Resonance parameters E_{res}, Γ_{res}

Here : $E_{res} = E_e - E_g$

Free nucleus : $E_\gamma \neq E_e - E_g$ *Recoil effects*

Spectroscopy Challenge: γ Energy Shift due to Nuclear Recoil

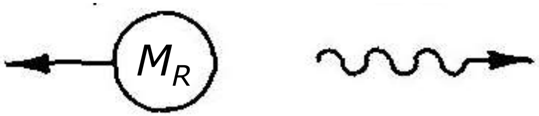
Emission and absorption of γ-rays by nuclei in motion (thermal lattice vibrations, recoil effects due to γ emission) → **Doppler effect** both in emission and absorption.

→ γ emission or absorption energy is different from nominal transition energy! $E_\gamma \neq E_i - E_f$

Nominal transition energy $h\nu_{if} = (E_i - E_f) = E_\gamma + E_R$ (photon and nuclear recoil)

Recoil in γ emission

$p_R = -E_\gamma / c$ $\quad p_\gamma = E_\gamma / c$



Nuclear recoil

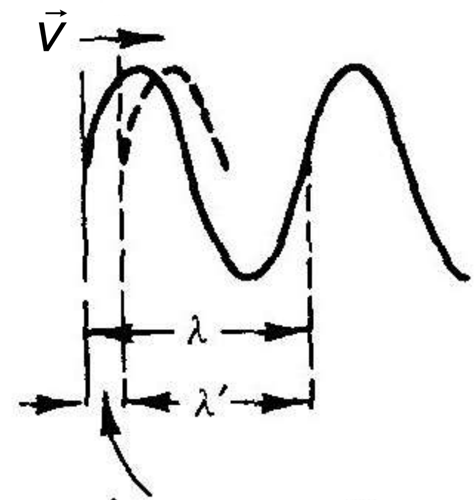
$v_R = -h\nu_\gamma / M_R c$

Recoil in γ absorption

$v_{Ri} = p_R / M_R$

$p_\gamma = h\nu_\gamma / c$

$v_{Rf} = \left(p_R - h\nu_\gamma / c\right) / M_R$



$vt = v\frac{\lambda}{c}; \lambda' = \lambda(1 - \frac{v}{c})$

Emitter velocity v
→ λ red(blue) shift
for stationary observer

Typical recoil velocities $\upsilon_R \sim \left(10^3 - 10^5\right) cm/s$

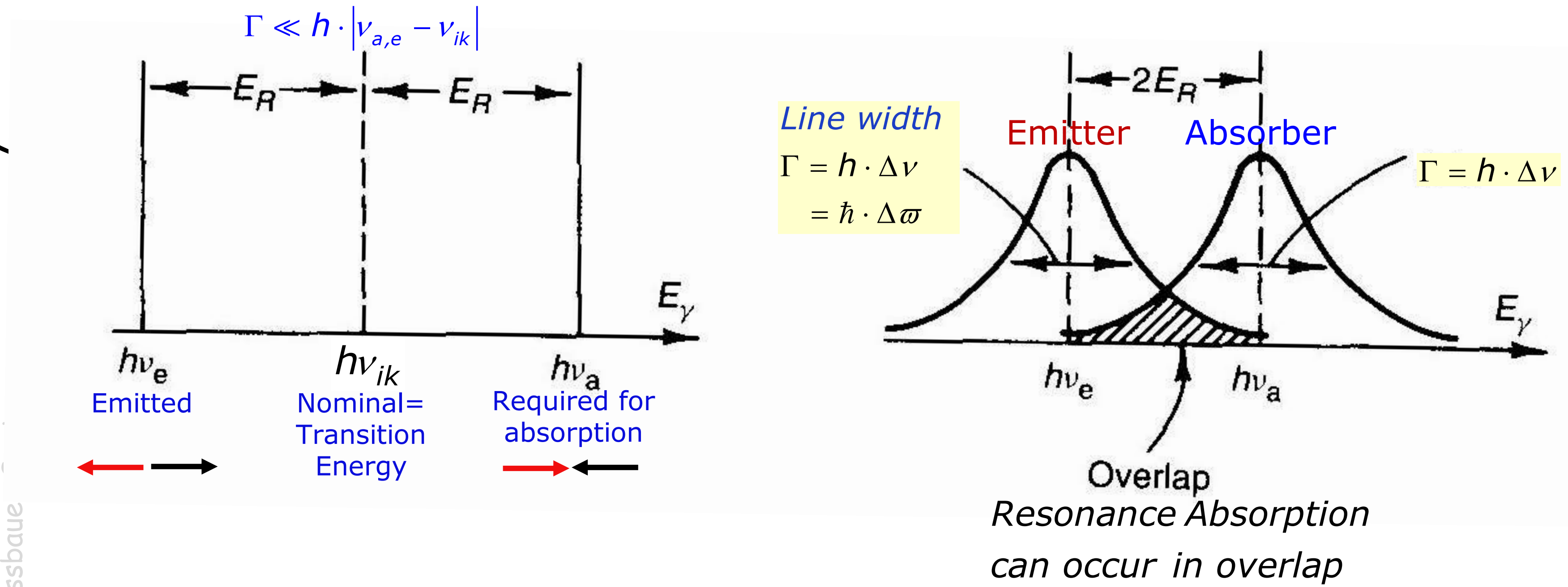
Doppler Shift : $E_\gamma(\upsilon) \approx h\nu_{ik} \cdot (1 \pm \upsilon/c)$

⇨ $\pm$ *sign : ν blue or red shift*

Resonant Emission/Absorption of γ-Rays

Quantum Effect: System absorbs electromagnetic radiation strongly if γ energy $h\nu_{ik}$ equals a system energy level difference: $h\nu_{ik} = (E_i - E_k)$ For absorption, the lower level *(i, k)* must be occupied, the other empty.

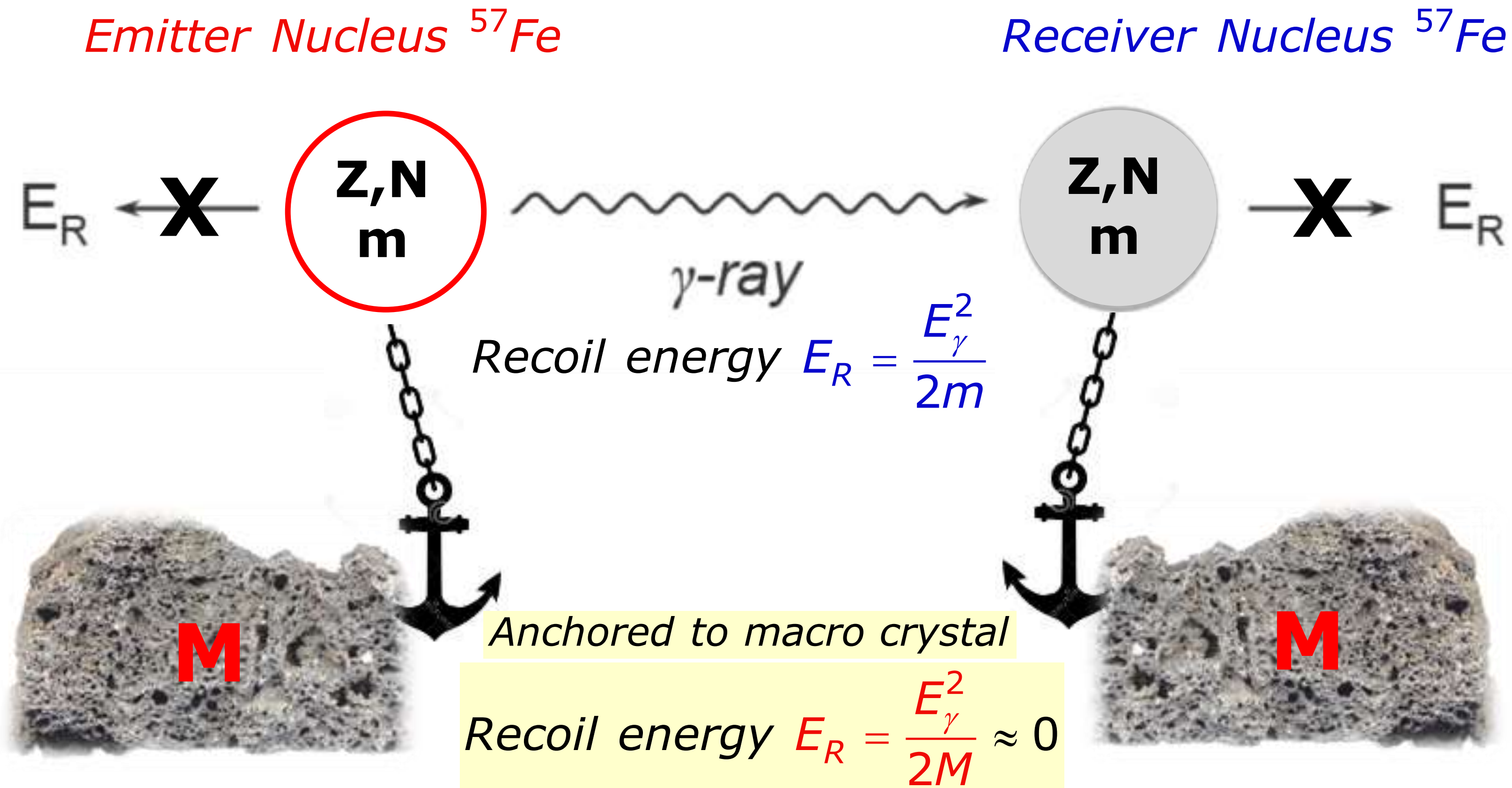
→ **Use for scanning level scheme *{En}***



Always present thermal motion: Large velocities of emitters and absorbers, broad line shapes destroy resonance requirement, → absorption patterns are washed out at large ***T***.

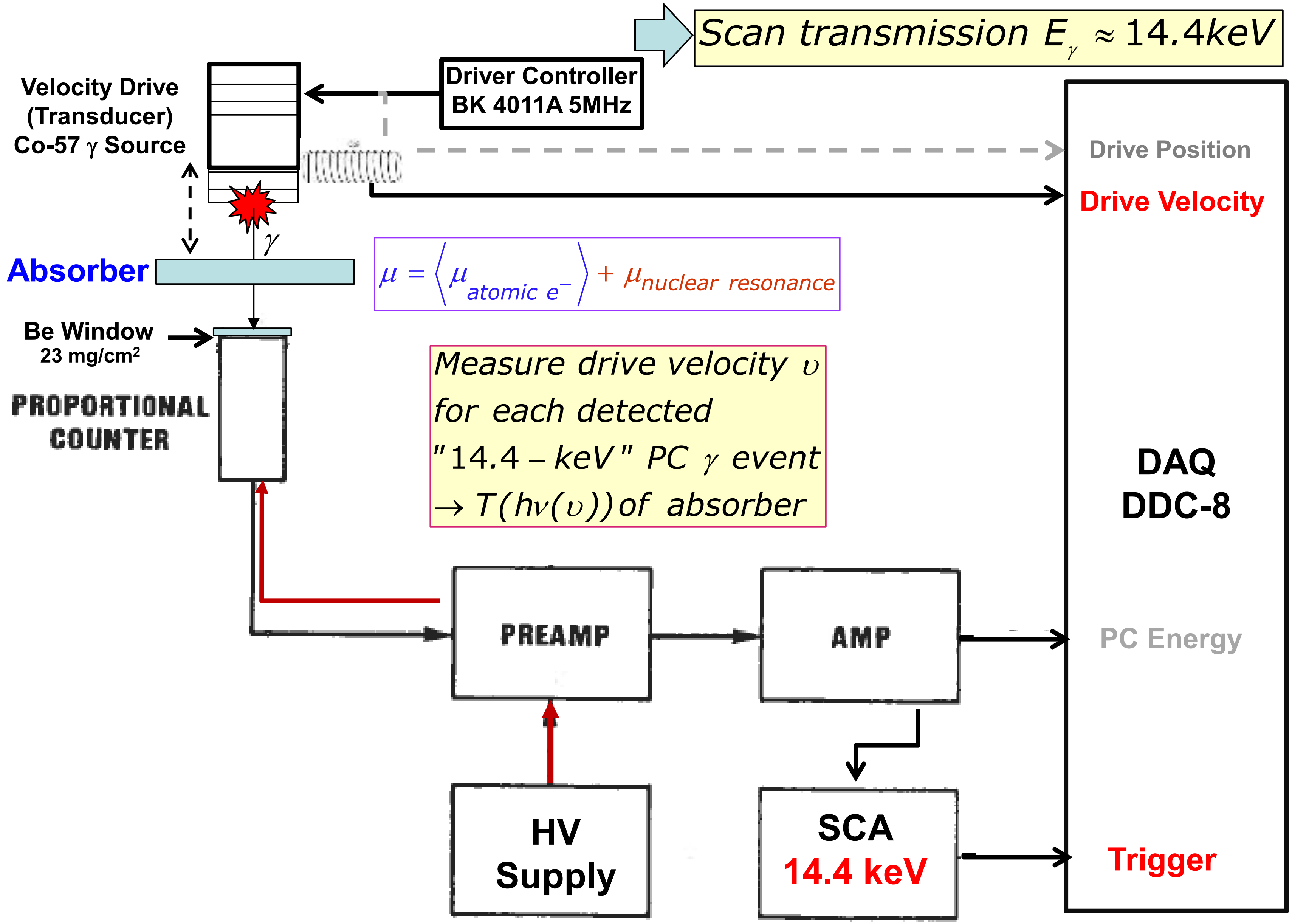
Recoilless Emission/Absorption

Momentum-energy transfer to nucleus (mass *m*) changes effective γ energy → Loss of resonance condition

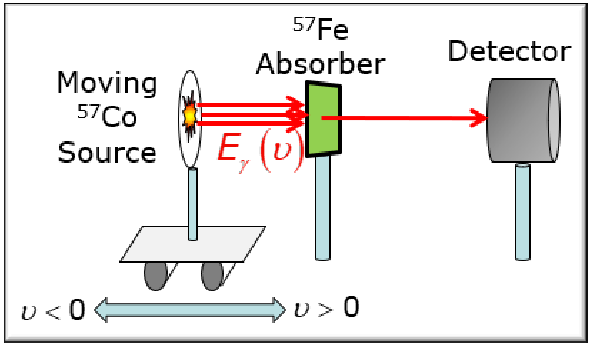


Momentum-energy transfer to nucleus embedded in macro crystal lattice is negligible → Resonance condition retained

Mőβbauer Experiment DAQ Setup



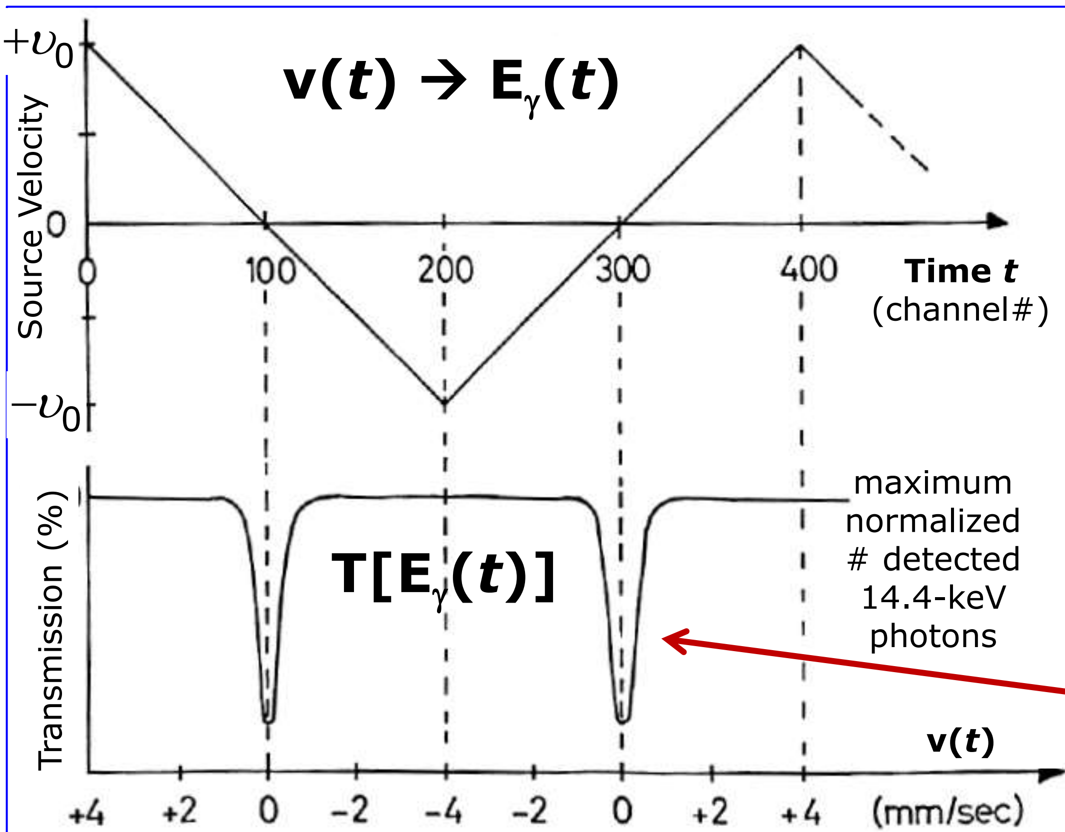
Precision Absorption Spectroscopy



$$\text{Tunable } E_\gamma(\upsilon) = 14.4(1 \pm \upsilon/c)\,keV$$

$$\text{Lower transmission for } E_\gamma(\upsilon) = E(\langle {}^{57}Fe \rangle)$$

$$\langle {}^{57}Fe \rangle = {}^{57}Fe \in \text{Absorber lattice}$$



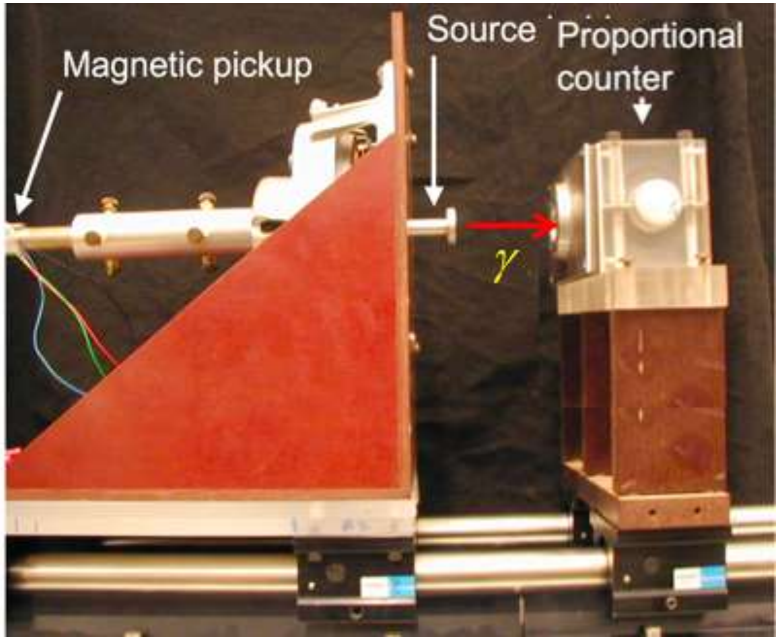
Example *linear velocity* drive:
Identical source & absorber
Phases (crystal lattices) and no external electric or magnetic fields

$$\upsilon(t) = \upsilon_0 \cdot (t_0 \pm t);\ t \in [nT, (n+1)T]$$

$$\rightarrow dN/dt \propto dN/d\upsilon$$

Minimum transmission = Maximum (resonant) no − field absorption at $E(\langle {}^{57}Fe \rangle) = E_\gamma(\upsilon = 0)$

ANSEL Mőssbauer Drive/Setup

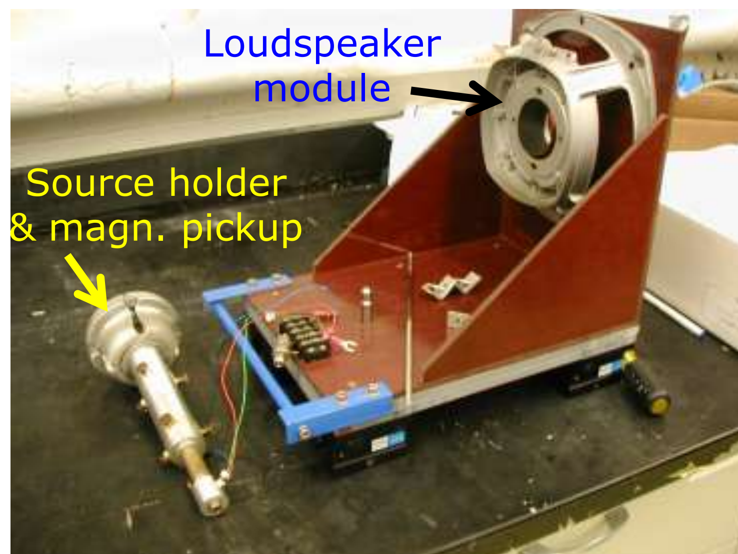


ANSEL drive has non-linear, sinus-type velocity profile defined by function generator controlling electro-magnet

$$\upsilon(t) = \upsilon_0 \sin(2\pi t/T) \rightarrow dN/dt \not\propto dN/d\upsilon$$

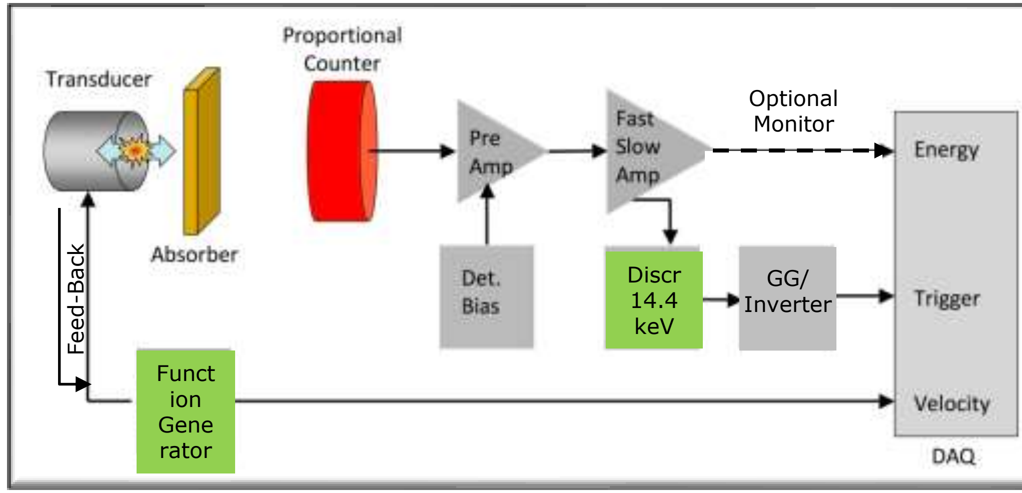
$$\textit{Velocity signal } 1\,mm/s \triangleq 16\,mV$$

Drive velocity profile is highly stable and precise. Auto-correction via electronic feedback to function generator from magnetic induction pickup.



ANSEL Mőssbauer Experiment

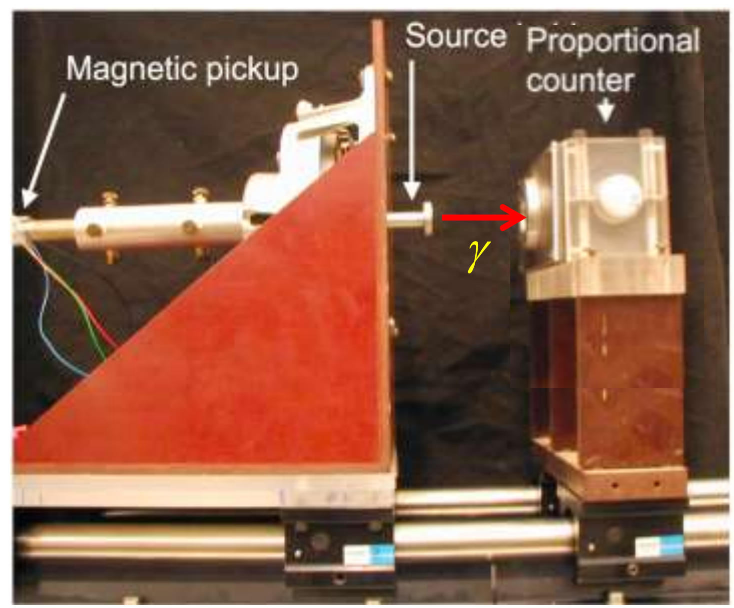
Ultra-sensitive, scanning γ absorption spectroscopy → measuring precisely energy levels of nuclei
in the fields of atomic electrons/lattice.



Scanning of Doppler-shifted γ- ray absorption energies using a moving ^{57}Co → ^{57}Fe 14.4-keV γ source.
^{57}Fe-XX absorbers = samples studied.

Precision (resolving power) of audio drives

$$\frac{\Delta E_\gamma(\upsilon)}{E_\gamma} = \frac{\Delta\upsilon}{c} \sim \frac{mm}{s}\cdot\left(3\cdot 10^8\,\frac{m}{s}\right)^{-1} \sim 10^{-12}$$



Accessible effects:

- Isomer shift (el. monopole interaction)
- Quadrupole splitting (el. dipole interaction)
- Magnetic hyper-fine splitting (magnetic dipole interaction)

→ Nuclear diagnostic instrument

Suitable X Ray Calibration Sources

^{133}Ba atomic X rays		Energy keV		Photons per 100 disint.	
XL	(Cs)	3,8 — 5,7		16,0 (8)	
$XK\alpha_2$	(Cs)	30,625		34,0 (4)	} $K\alpha$
$XK\alpha_1$	(Cs)	30,973		62,8 (7)	}
$XK\beta_3$	(Cs)	34,92	}		
$XK\beta_1$	(Cs)	34,987	}	18,2 (2)	$K'\beta_1$
$XK\beta_5''$	(Cs)	35,245	}		
$XK\beta_5'$	(Cs)	35,259	}		

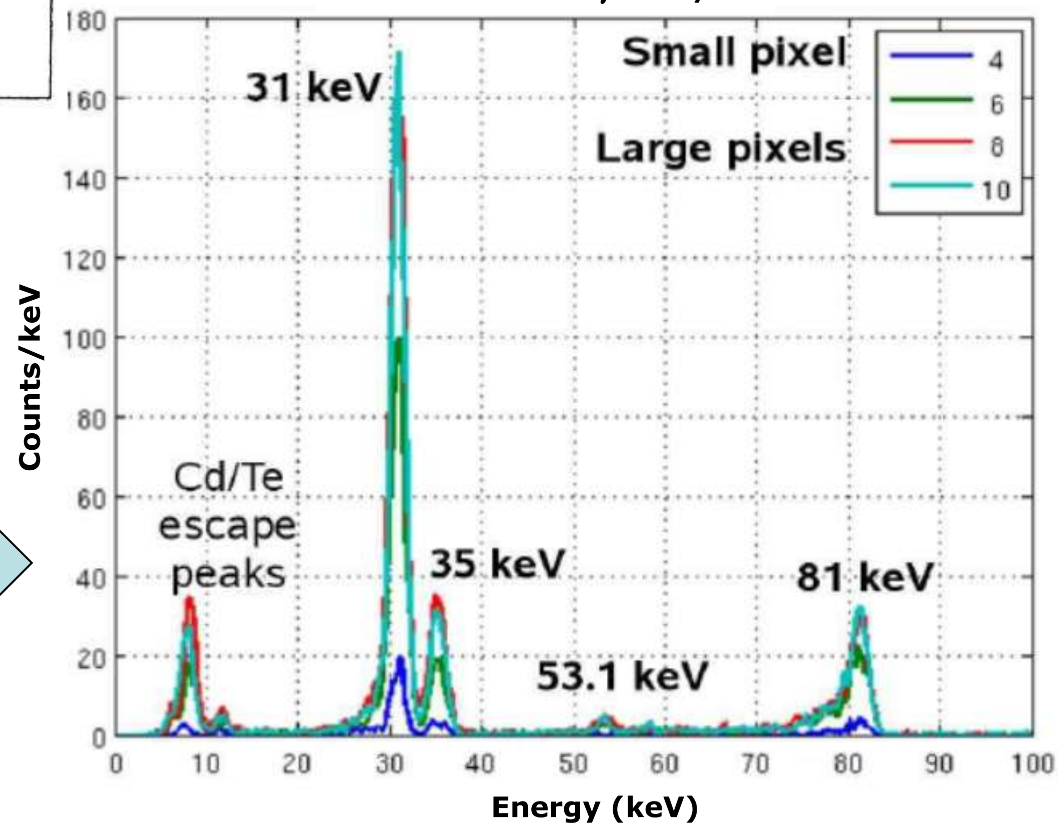
Calibration needed in the *l.e.* range
$0\ keV \le E_\gamma < 100\ keV$ → X rays

E.g. use ^{133}Ba, ^{109}Cd, ^{241}Am, K_α and K_β X ray energies/intensities

Find ı$^{60}Co\ \gamma, X-rays$ a on data sheets (internet)

Barium-133 photon spectrum, low-energy region, obtained with a solid-state detector (patterned CdTe crystal, used on ESA Solar Orbiter). O. Grimm et al. J. Instr. 7. C12015. 10.1088/1748-0221/7/12/C12015.

^{133}Ba X and γ-rays



Intro to MB Principles/ANSEL Setup/Tasks

Experimental and analytical tasks

- Set up electronics for PC
- Calibrate PC for very low γ energies (absorber method)
- Identify characteristic spectral features of PC

- Adjust transducer frequency to mechanical drive resonance
- Measure transducer velocity (interpret spectral features, absorber method)

- **Goals/Theory**: Hyperfine interactions → Lifting of level degeneracy through interaction with external fields
- Functionality of ANSEL setup for scanning absorption spectroscopy
- Explain/interpret shape and specific features of velocity spectra:
  1) no absorbers or non-resonant ("background") absorption,
  2) resonant absorption for specific Fe compound absorbers,
  3) method of background correction.
- Deduce isomer shift, electric quadrupole and magnetic HF interaction energies and related nuclear electric/magnetic moments for given chemical Fe environments.