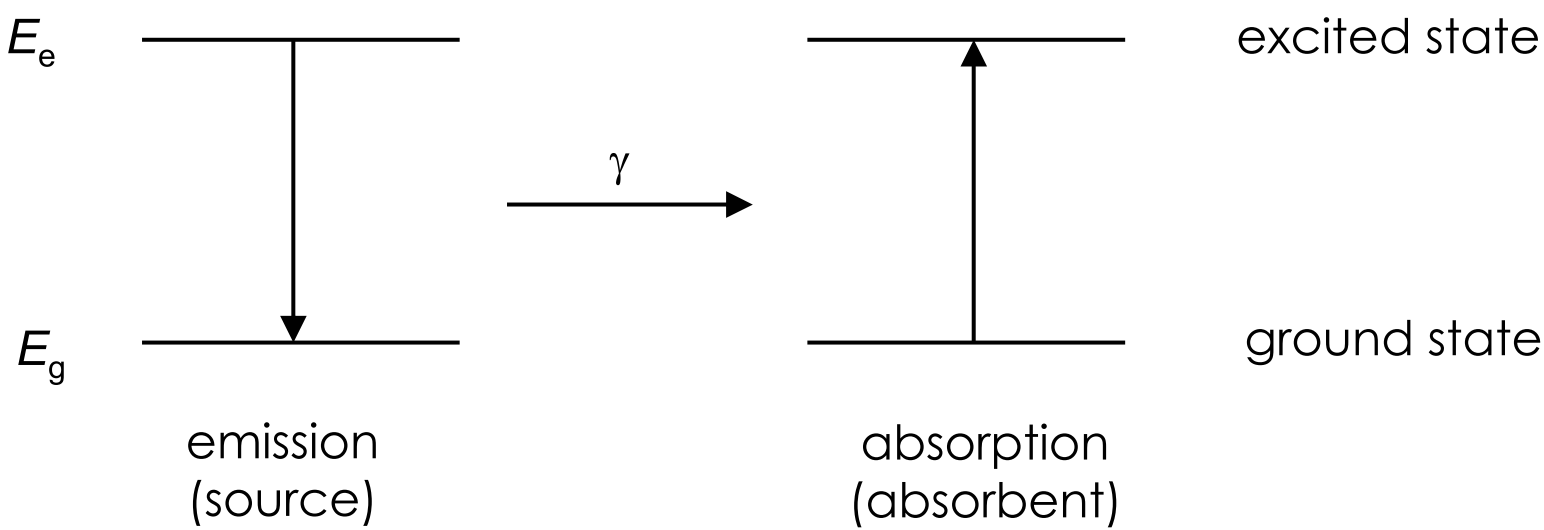
Mössbauer spectroscopy

- … spectroscopy, that is it gives information **about something** measuring the difference of the energy levels **of something** by absorption of photons

- **of something** = **nucleus**
  $\rightarrow$ requires high energy photons (γ**-ray**)

- **about something**:
  - the energy levels of the nucleus are affected by the surrounding electric and magnetic fields (**hyperfine interactions**)
  - further parameters (temperature, vibrational state of the nucleus, sample width etc.)

Mössbauer effect I.



- γ-photon will be absorbed only if the energy of the photon equals exactly* with the excitation energy of the nucleus; an **already excited identical nucleus** can be used as a source

*: we’ll see later that this is not exact

Mössbauer effect II.

- problem 1:
  - it is often complicated to use excited nucleus as a source:
    - radioactive
    - half life is too short or too long

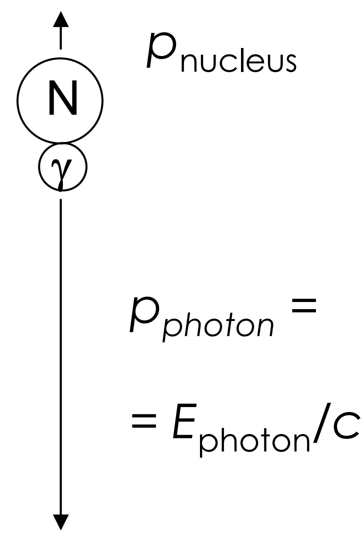
- solution 1:
  - radiation protection rules
  - in-beam technique for nucleus with short life times (one can produce the source nucleus with e.g. neutron activation process and start the Mössbauer measurement at the same time and device)

Mössbauer effect III.

- problem 2:
  - **recoil**: due to the momentum- and energy conservation rules the energy of the emitted γ-photon is not equal with the excitation energy (→ E_R **recoil energy**)

$$E_{photon} = (E_e - E_g) - E_R$$

$$E_R = \frac{p^2}{2m} = \frac{(E_{photon}/c)^2}{2m} = \frac{(E_{photon})^2}{2mc^2}$$



  - it occurs also during the absorption process!

Mössbauer effect IV.

- an energy level with a certain life time (τ_N) has an energy uncertainty of $\Gamma = \hbar / \tau_N$ which results a Lorentz-type **energy distribution** of the emitted photon :

$$I(E) = \frac{I_0}{(E - E_0)^2 + (\Gamma / 2)^2}$$

(the energy distribution is further widened by the Doppler effect of the thermal motion of the atoms)

	E_0 / eV	Γ / eV	E_R / eV
infrared	$10^{-2} - 1$	$\mathbf{10^{-5}}$	$\mathbf{10^{-12}}$
^{57}Fe Mössbauer	~14400	$\mathbf{4.6 \cdot 10^{-9}}$	$\mathbf{1.9 \cdot 10^{-3}}$

Mössbauer effect V.

- solution 2:
  - in **solid state** the nucleus is attached to the crystal $\rightarrow$ *m* becomes the mass of the whole crystal (not only one nucleus) $\rightarrow E_R \cong 0$!
    $\rightarrow$ Mössbauer effect = **recoilless nuclear resonance absorption**
  - phonon spectra (the vibrational state) of the nucleus: Mössbauer effect is only observed if phonon modes are not modified (the vibrational state of the nucleus doesn't change)
  - quantum mechanics $\rightarrow$ **Mössbauer-Lamb factor** (*f*, the fraction of the recoilless emission/absorption over all the emissions/absorptions)

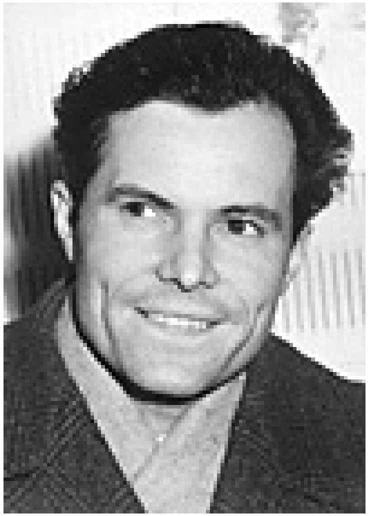
usually $$f = \exp\left[-\frac{E_R}{k\theta_D}\left(\frac{3}{2}\frac{\pi^2 T^2}{\theta_D^2}\right)\right]$$

Mössbauer effect V.b

solution 2 was discovered by Rudolf L. Mössbauer in 1958.

↓

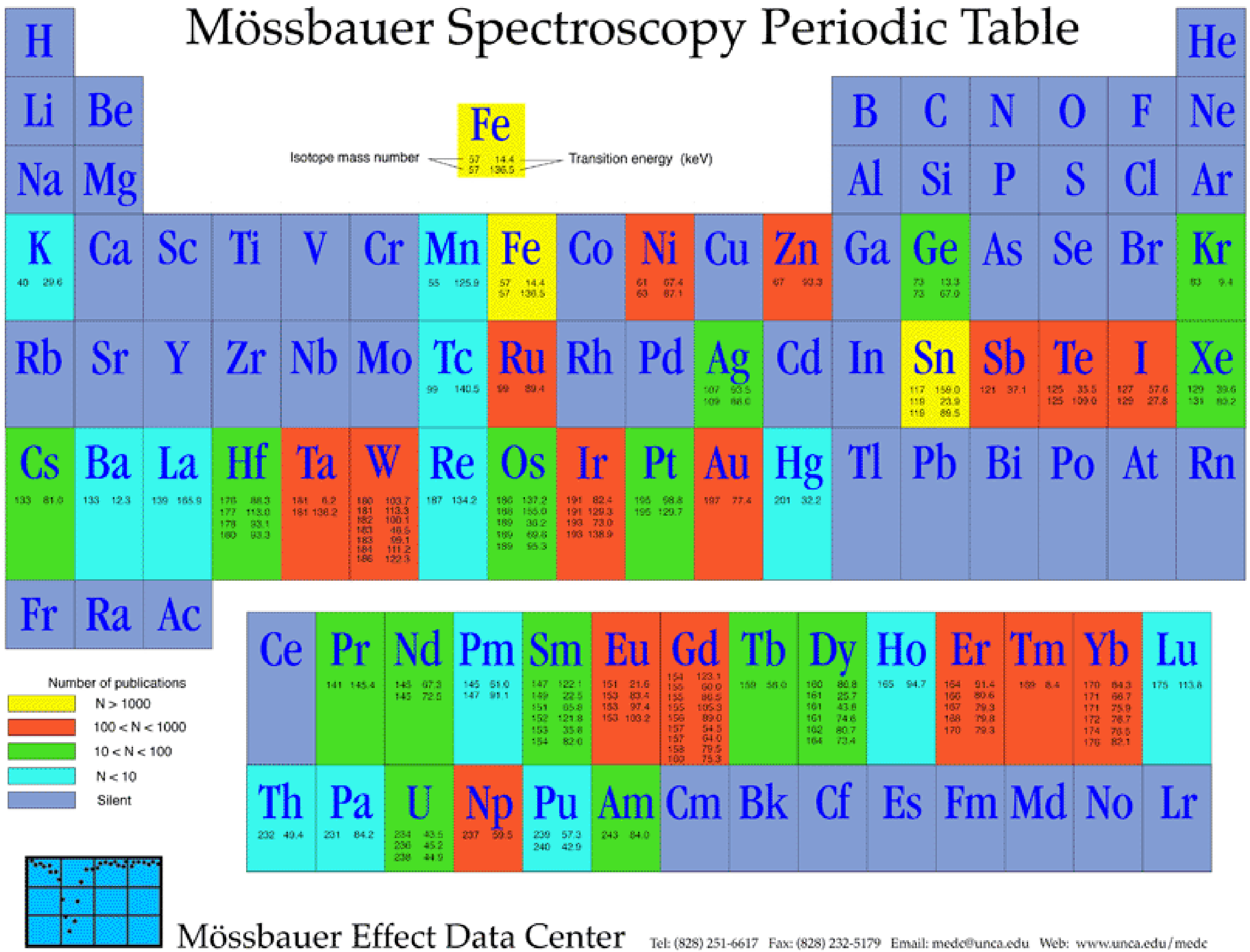
(half) Nobel prize in 1961.



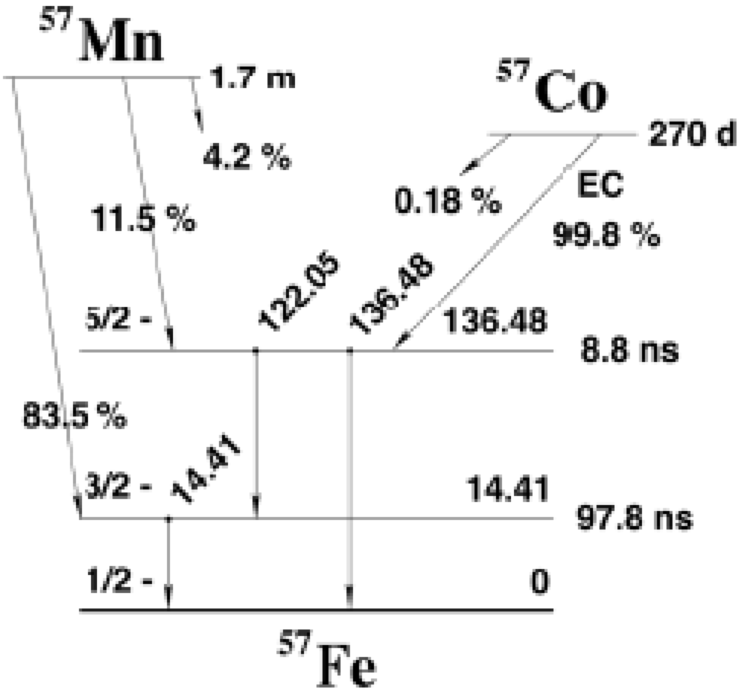
Mössbauer sources I.

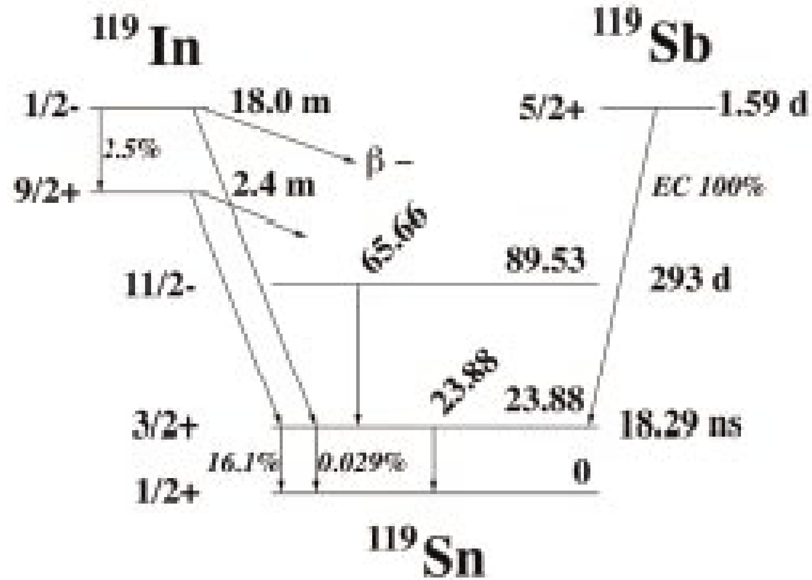
- appropriate γ-transition (end state must be ground state)
- Mössbauer-Lamb factor should be high
  - relatively low γ-energy (< 100 keV)
  - high Debye-temperature
- appropriate lifetime of the Mössbauer levels ($\tau_{1/2} \cong 10^{-7}$ s)
- appropriate lifetime of the mother isotope ($\tau_{1/2} \cong$ 1 year)

Mössbauer sources II.



Mössbauer sources III.





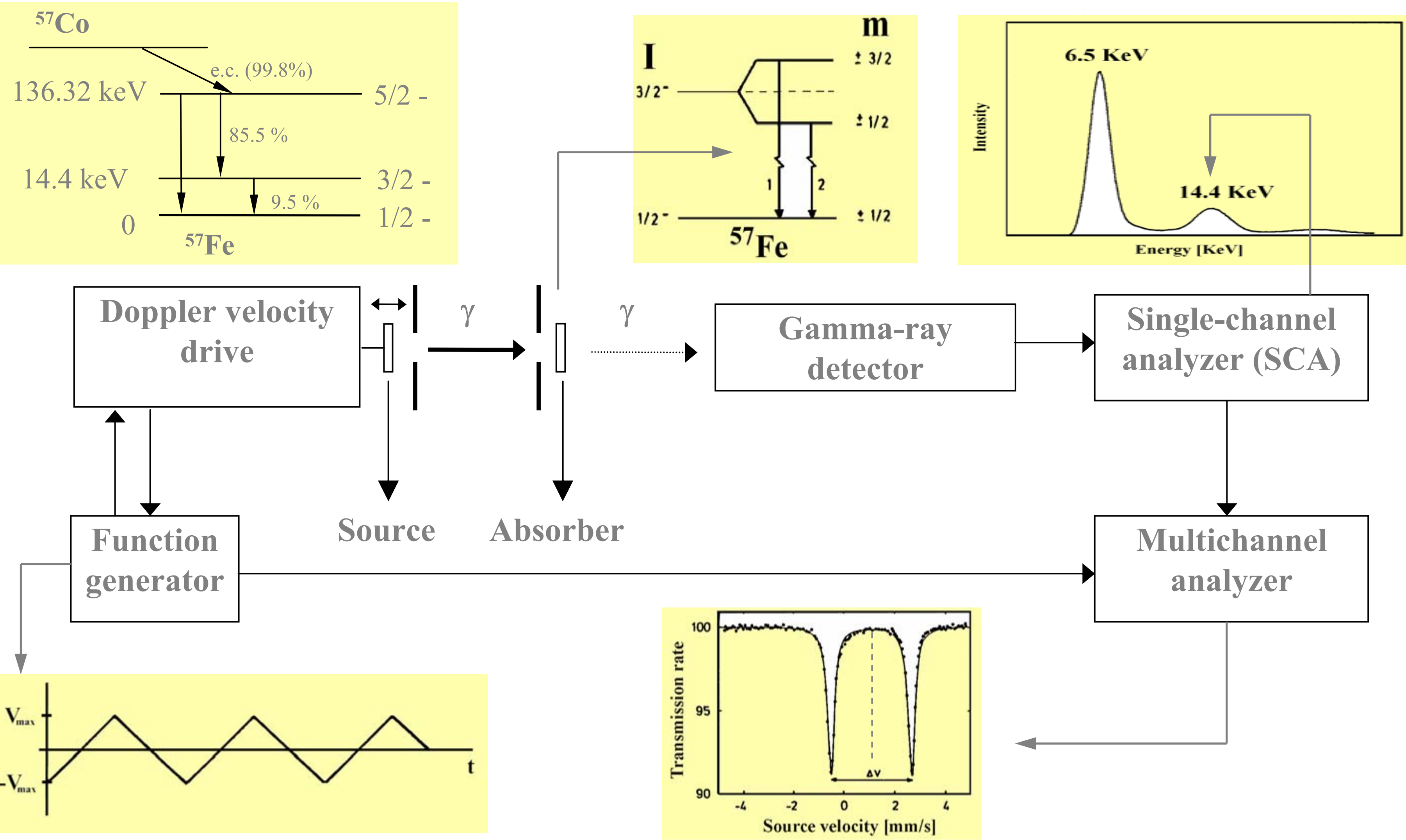
Energy scan

- **Doppler effect:**

$$E = E_\gamma \frac{v}{c}$$

- incident energy: 10^4 eV (14.41 keV for ^{57}Fe)
- line width (resolution): 10^{-9} eV
- hyperfine interactions: 10^{-8}-10^{-7} eV $\cong$ 1-10 mm/s

Mössbauer measurement



Hyperfine interactions I.

- **electric** (Coulomb) **interaction** between the charged nucleus ($\rho(\underline{r})$) and the electric field ($\Phi(\underline{r})$) at and around it

$$E_{electr} = \int \rho(\underline{r})\Phi(\underline{r})d^3r$$

- **magnetic interaction** between the magnetic dipole moment of the nucleus ($\underline{\mu}$) and the magnetic field at the nucleus ($\underline{B}$)

$$E_{magn} = -\underline{\mu} \cdot \underline{B}$$

Electric interaction I.

$$E_{electr} = \int \rho(\underline{r})\Phi(\underline{r})d^3r$$

$$\Phi(\underline{r}) = \Phi(0) + \sum_{\alpha=1}^{3}\left(\frac{\partial \Phi}{\partial x_\alpha}\right)_0 x_\alpha + \frac{1}{2}\sum_{\alpha,\beta}\left(\frac{\partial^2 \Phi}{\partial x_\alpha \partial x_\beta}\right)_0 x_\alpha x_\beta + \ldots$$

$$E_{electr} = E^{(0)} + E^{(1)} + E^{(2)} + \ldots$$

$$E^{(0)} = \Phi(0)\int \rho(\underline{r})d^3r = \text{const.}$$

$$E^{(1)} = \sum_{\alpha=1}^{3}\left(\frac{\partial \Phi}{\partial x_\alpha}\right)_0 \int \rho(\underline{r})x_\alpha d^3r = 0$$

$$E^{(2)} = \frac{1}{2}\sum_{\alpha,\beta}\left(\frac{\partial^2 \Phi}{\partial x_\alpha \partial x_\beta}\right)_0 \int \rho(\underline{r})x_\alpha x_\beta d^3r$$

Electric interaction II.

$$E^{(2)} = E_M + E_Q$$

$$E_M = \frac{e}{6\varepsilon_0}\left|\Psi(0)\right|^2 \int \rho(\underline{r}) r^2 d^3 r = \frac{Ze^2}{6\varepsilon_0}\left|\Psi(0)\right|^2 \left\langle r^2 \right\rangle$$

$$E_Q = \frac{e}{6}\sum_{\alpha} V_{\alpha\alpha} Q_{\alpha\alpha}$$

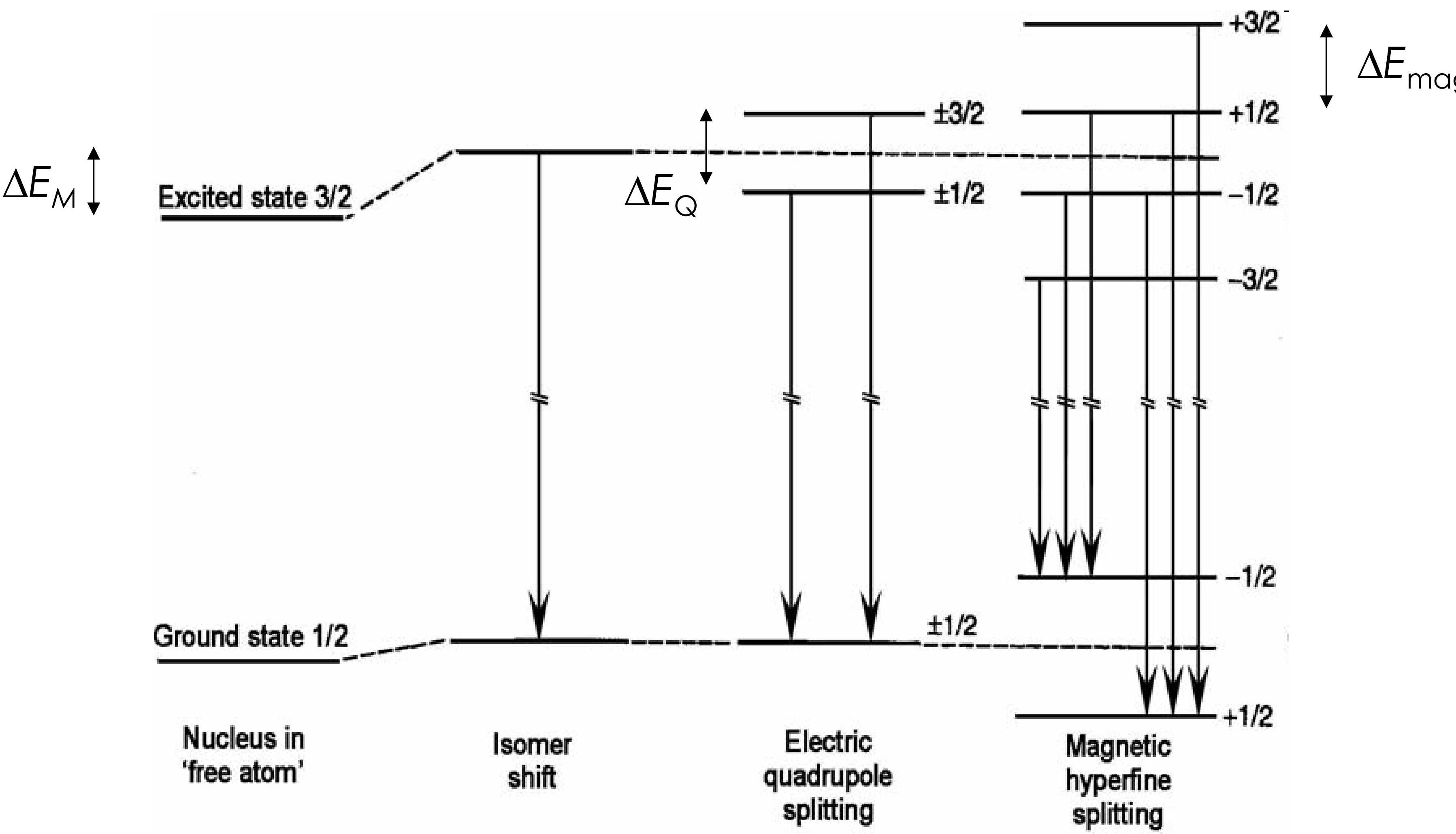
Magnetic interaction

$$E_{magn} = -\underline{\mu} \cdot \underline{B}$$

$$E_{magn} = -\gamma \; B_z \hbar m$$

$$\Delta E_{magn} = -\gamma \; B_z \hbar = -g \mu_N B_z$$

Hyperfine interactions II.



Mössbauer parameters I.

- (chemical) isomer shift:

$$\delta = \left(\Delta E_M\right)_e - \left(\Delta E_M\right)_g$$

- quadrupole splitting:

$$\Delta = \Delta E_Q$$

- magnetic field:

$$B_z = \frac{\Delta E_{magn}}{-g\mu_N}$$

Mössbauer parameters II.

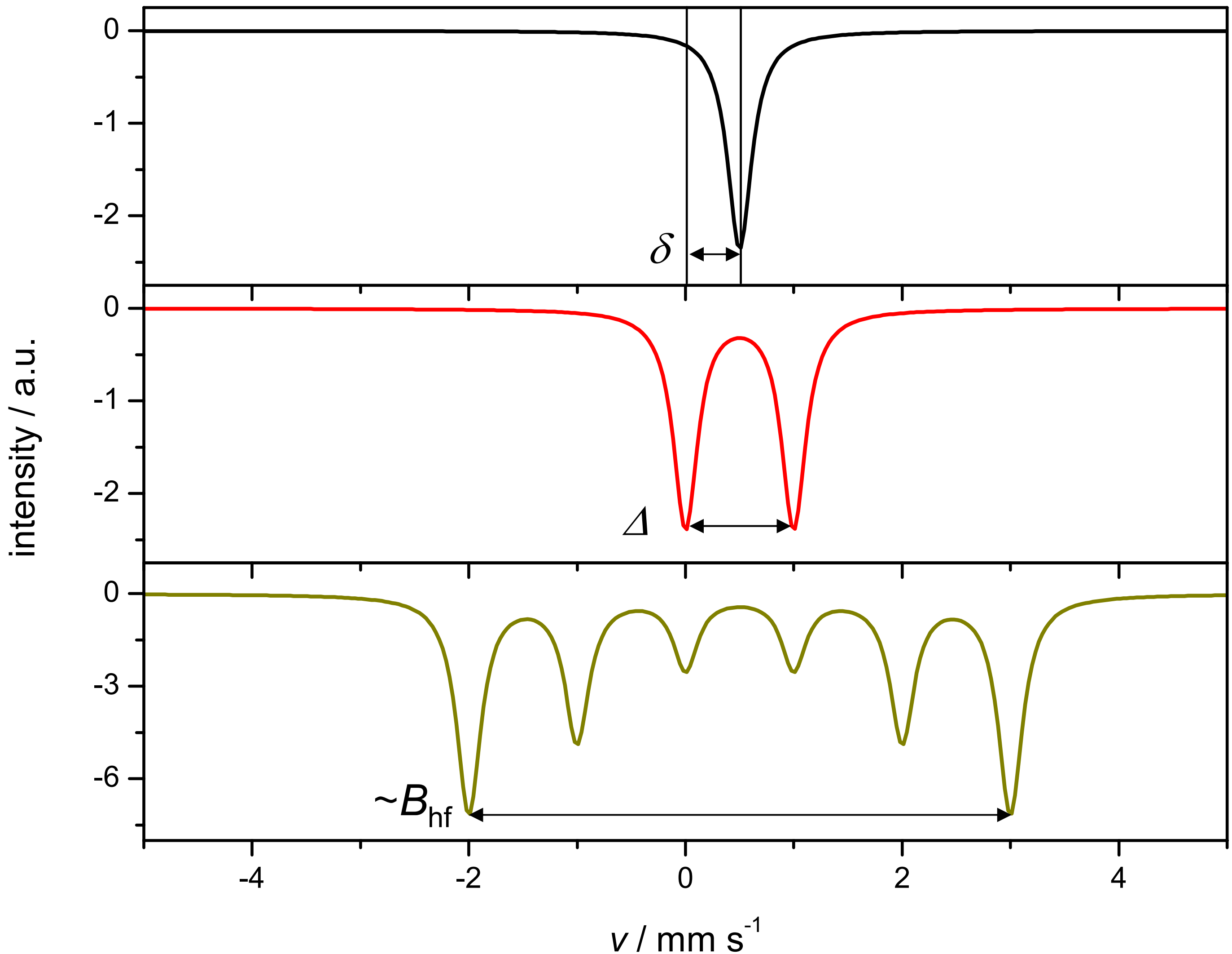
- line width (Γ), usually full width at half maximum (FWHM)

- relative (to the base line) area of the lines (~ *f*)

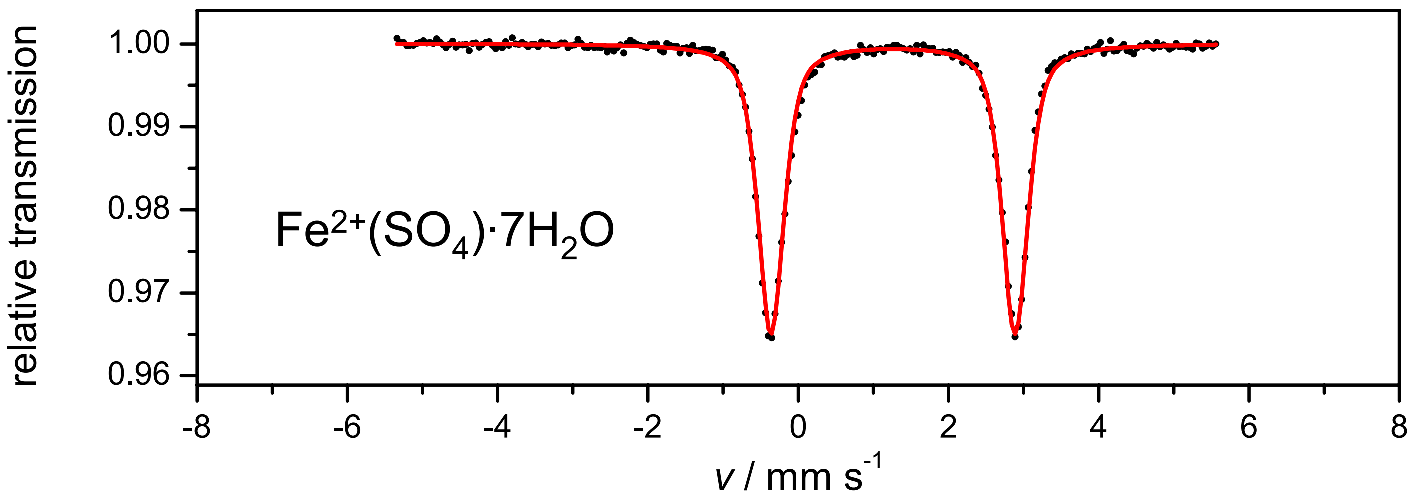
- relative (to other lines) line intensities

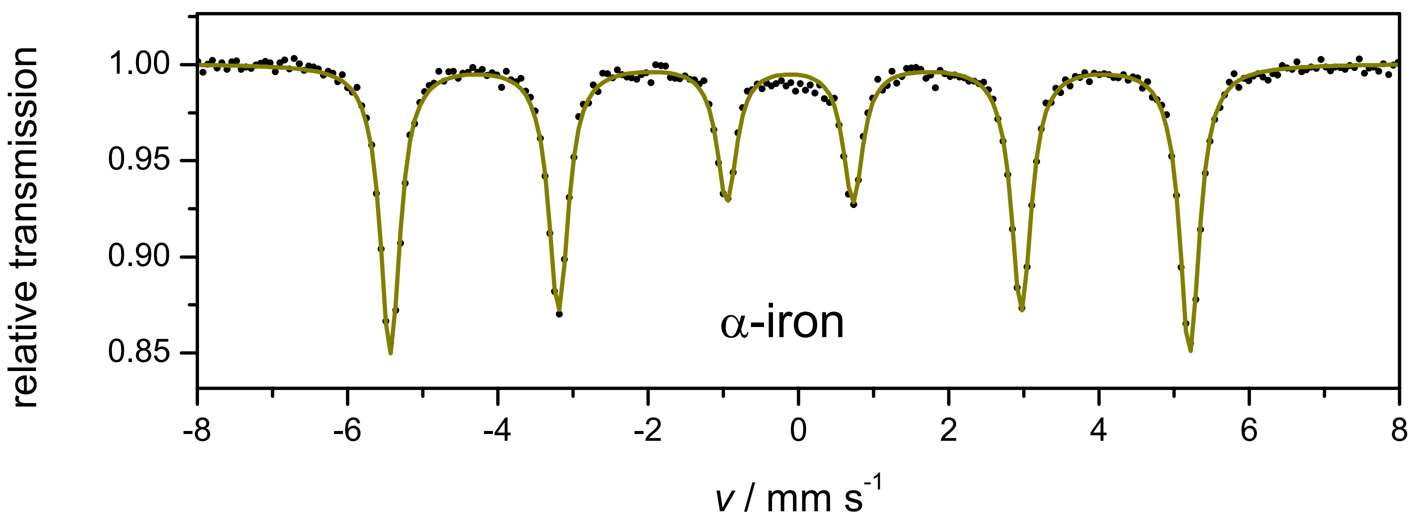
\+ temperature dependence

Mössbauer spectra I.



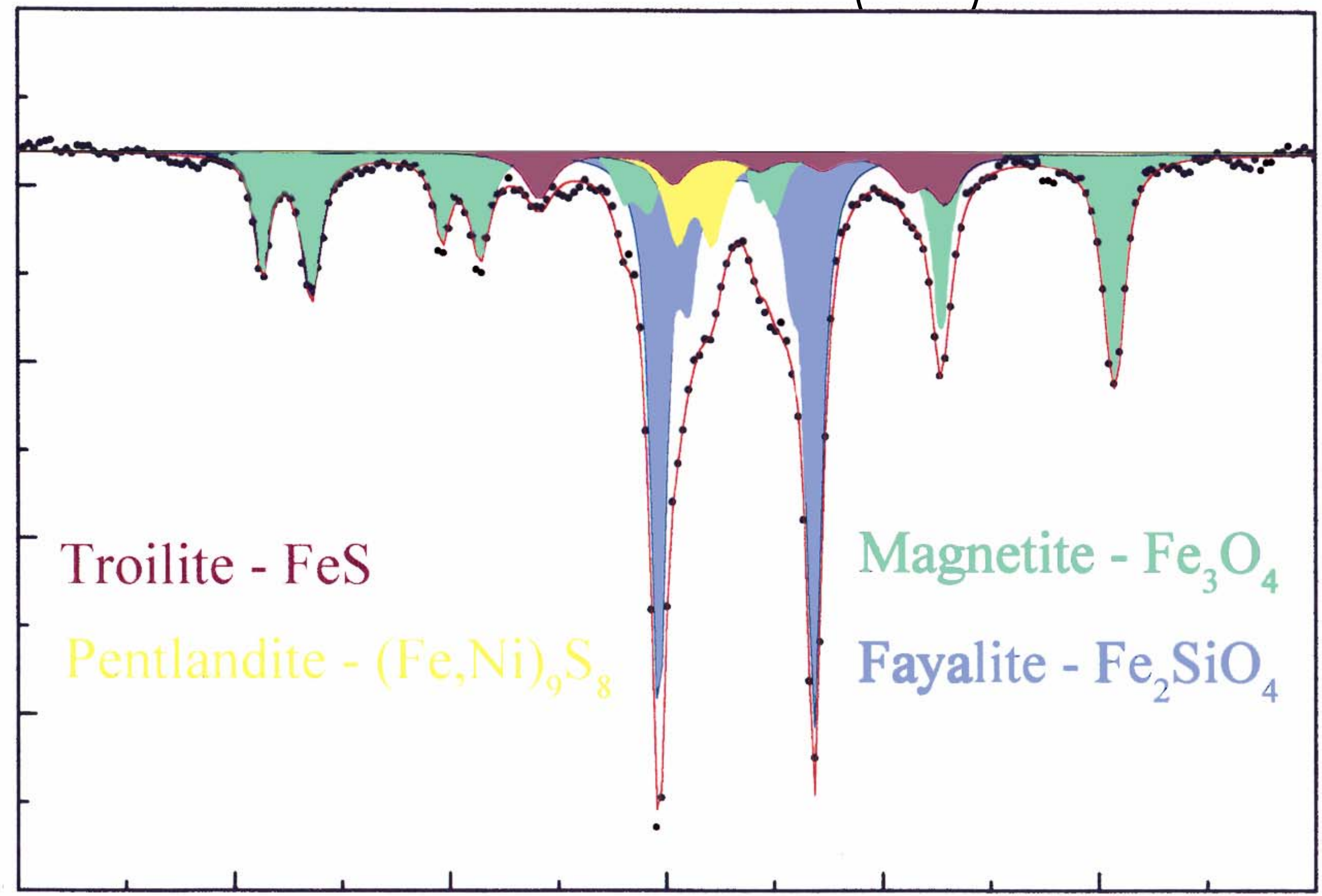
Mössbauer spectra II.





Applications I.

Meteorite from Kaba (HUN)



Applications II.

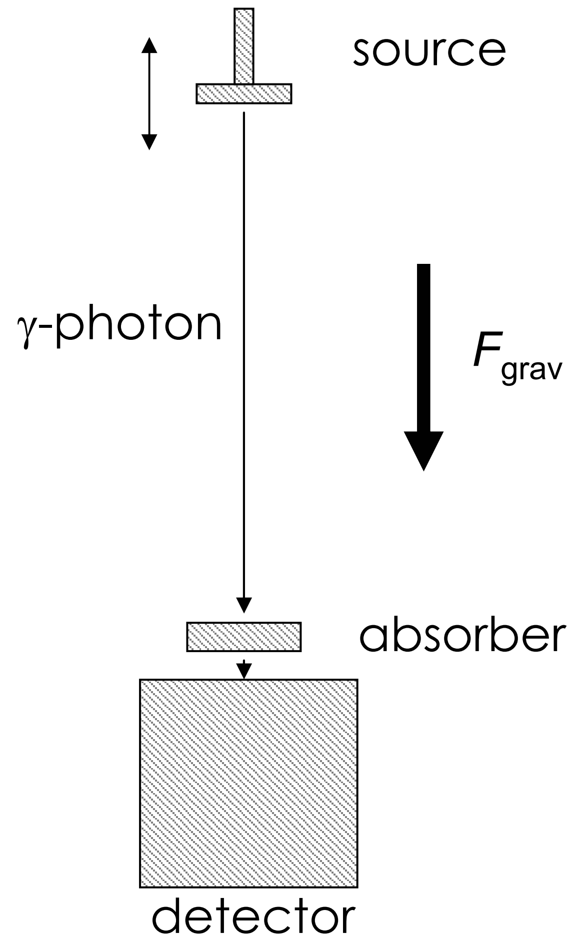
- determination of gravitational shift:
  - additional kinetic energy of the photon from the gravitational force:

$$E_{kin} = E_{pot} = mgh = \frac{E_\gamma}{c^2} gh$$

  - E_{kin} results (gravitational) shift (δ_g) of the Mössbauer line:

$$\frac{E_\gamma}{c^2} gh = E_\gamma \frac{v}{c} \rightarrow v = \delta_g = \frac{gh}{c}$$

  - δ_g is in the order of 10^{-3} mm/s if h = 30 m, which is well measurable



Applications III.