Fortgeschrittenen Praktikum II

Mößbauer effect

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1 Goal of the experiment

By measuring absorption of photons of the $14.4kev$ transition of Fe-57, in stainless steel and natural iron, the isomeric shift, the effective absorber thickness, the Debeye-Waller-factor of the source the lifetime of the excited Fe-57 state, the magnetic field at the location of the nucleus and the magnetic moment of the $14.4ke$V state.

2 physical principles

2.1 Interaction of Gamma radiation with matter

Photons interact with matter in three major ways[2]:

Photoelectric effect

Shell electrons of atoms absorb photons and gain its energy, leaving the potential well of the atom and exiting the shell with the energy $E_e = E_\gamma - E_B$ with E_B being the binding energy of the electron.

Compton scattering

Compton Scattering is the elastic scattering of photons at quasi free electrons ($E_B << E_\gamma$) and its wavelength $\lambda = 2\pi c/\omega$ is shifted, depending on the scattering angle φ(see figure 2.1):

$$\lambda_S - \lambda_0 = \frac{2\pi\hbar}{m_e c}(1 - cos(\varphi)) \tag{2.1}$$

Pair Production

A photon can produce a positron electron pair if it has an energy of at least $2 \cdot m_e = 1.022MeV$ the photon is lost in the processes reducing the Intensity of the photon beam. Due to those processes the intensity of electromagnetic radiation decreases exponentially with penetration depth d:

$$I(d) = I_0 \cdot exp(-\mu d) \tag{2.2}$$

where μ is the attenuation coefficient.

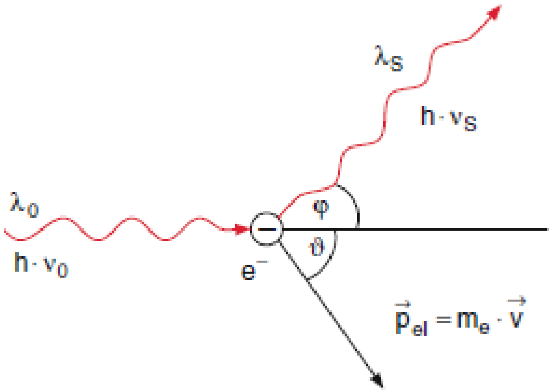

Figure 2.1: Compton effect: A photon is scattered by a (quasi) free electron changing its direction by an angle φ[2]

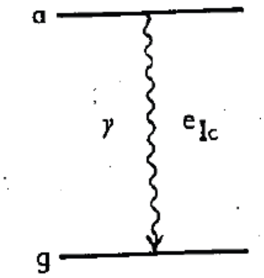

Figure 2.2: principle of spontaneous γ emission of excited nuclei. Transitioning from an excited state (E_a) to the ground state (E_g) the nucleus emits a photon with energy $E_a - E_g = \hbar\dot{\omega}$ or transmits that energy directly to an electron of the atomic shell.[1]

2.2 Gamma Decay and resonance absorption

Nuclei in excited states (energy E_a) can spontaneously transition into the ground (energy E_g) state. The energy ΔE the nucleus loses is either carried by an emitted photon (spontaneous emission) or directly gained by a shell electron (inner conversion).
In the case of spontaneous emission, the photon can be absorbed by a nucleus of the same kind which thereby transits into an excited state. This is called resonance absorption. However due to the recoil the nuclei receive this rarely happens for free atoms. Consider the rest frame of a nucleus, that means its momentum is $p_0 = 0$. Now consider this nucleus decays by emitting a photon. Since the photon carries the momentum

$$p = \frac{E_\gamma}{c} = \frac{\hbar}{c} \cdot \omega \tag{2.3}$$

with the reduced Planck constant $\hbar$ and c the speed of light, and momentum is conserved the nucleus receives a recoil equal to the photons momentum and therefore also kinetic energy or recoil energy R. The emitted photon therefore has the energy [5]:

$$E_\gamma = \Delta E - \frac{p^2}{2m} = \Delta E - \frac{(\hbar\omega)^2}{2mc^2} =: \Delta E - R \tag{2.4}$$

When the photon is absorbed the same applies: the absorbing nucleus receives the recoil R. This means for a photon to be absorbed, inducing a nuclear transition with ΔE the photon has to have the energy:

$$E_\gamma = \Delta E + R \tag{2.5}$$

In consequence the absorption spectrum is shifted relative to the emission spectrum (see fig 2.3 depending on the recoil energy R.

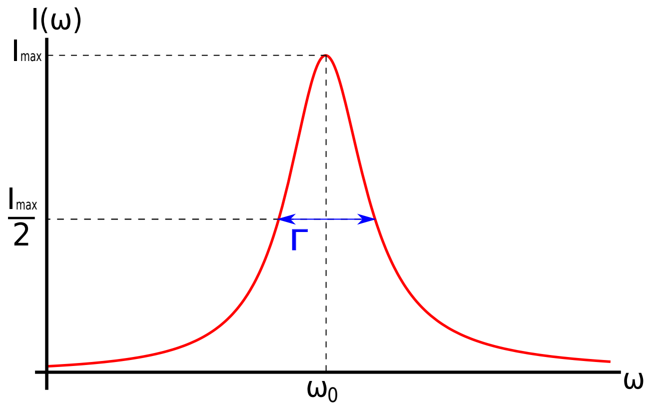

Figure 2.3: Lorentz distribution: $I(\omega) \propto \frac{1}{(\omega-\omega_0)^2+(\Gamma/2)^2}$

2.3 Doppler shift

Due to thermal motion the emitting nucleus and the absorbing nucleus have relative velocity v, shifting the frequency via Doppler effect:

$$E_\gamma^{'} = E_\gamma(1 + \frac{v}{c}) \tag{2.6}$$

So the energy is changed by:

$$E_\gamma^{'} - E_\gamma = E_\gamma \frac{v}{c} \tag{2.7}$$

2.4 Mößbauer effect

The Mößbauer effect is the name for the phenomenon of *recoilless emission* (or absorption). Revisiting equation 2.4 one an see that the recoil energy $R = \frac{(\hbar\omega)^2}{2mc^2}$ is inversely proportional to the mass of the nucleus. In a solid it is possible for the whole lattice the absorb the recoil therefore increasing the recoiled mass enormously, so that $R \approx 0$[1]. This effect means atoms that shows this behavior (In this experiment Fe-57) can emit photons, that can be reabsorbed by atoms of the same kind.

[1] this is a simplified description, for a more detailed one see [5] and [1]

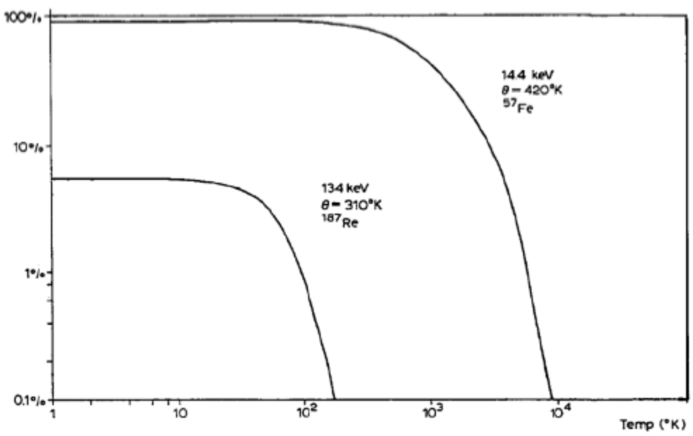

Figure 2.4: Debye factor as a function of temperature in Fe-57 and Re-187. At room temperature Fe-57 has a ratio of recoilless emission absorption of 0.91

2.5 Debye-Waller factor

The Debye-Waller factor is the ratio of recoilless absorption.

$$f = exp\left[-\frac{3R}{2k \cdot \Theta_D}\left(1 + \frac{4T^2}{\Theta_D^2}\int_0^{\Theta/T}\frac{xdx}{e^x - 1}\right)\right] \tag{2.8}$$

Where R is the recoil energy, k the Boltzmann constant, Θ_D the Debye temperature. If the temperature is low $T << \Theta_D$ this can be simplified to:

$$f \approx exp\left[-\frac{3R}{k \cdot \Theta_D}\left(\frac{3}{2} + \frac{\pi^2 T^2}{\Theta_D^2}\right)\right] \tag{2.9}$$

2.6 Isomer shift

Since electrons of an atomic shell are kept within the coulomb potential of the nucleus their potential energy depends on the charge distribution in the nucleus. Transitioning to an excited state affects this distribution therefore also affecting the potential energy of the electrons. This change in energy shifts the frequency that an absorbed photon must have to induce the transition[1].

2.7 Hyperfine splitting

The nucleus has magnetic moment (μ_I) and spin I. In a surrounding magnetic field H the energy level splits into $2I + 1$ sub-energy levels. The sub-sates are characterized by the magnetic quantum number $m_I = -I, I + 1.., I - 1, I$ and the energy difference induced is:

$$E_{HFS} = \frac{\mu_I m_I H}{I} \tag{2.10}$$

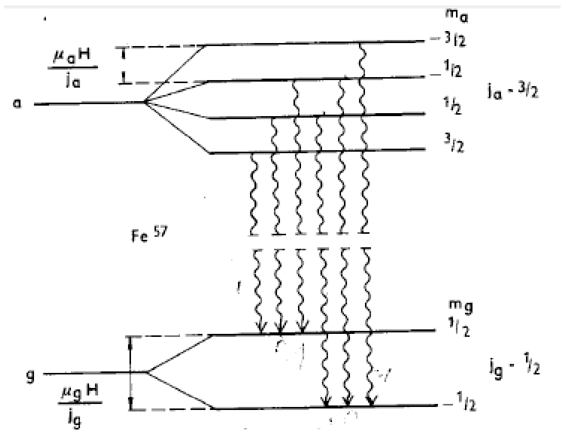

Figure 2.5: Hyperfine splitting for Fe-57 in magnetic field H for the ground state g ($I_g = 1/2$) and the excited state ($I_a = 3/2$).[1]

The transition $m_a \to m_g$ emits photons with energy ω:

$$E_\gamma(m_a, m_g) = E_0 - \left(\frac{\mu_a m_a}{I_a} - \frac{\mu_g m_g}{I_g}\right) H \tag{2.11}$$

3 Experimental procedure

3.1 Method

To measure the absorption spectra of stainless steel and natural iron, we irradiate the samples with the 14.4keV γ-radiation emitted by a radioactive source. To vary the frequency a motor is used to move the absorber relative to the source (Doppler shift see 2.7). By repeating this measurement for different absorber velocities a spectrum is recorded.

3.2 Setup

The setup consists of the γ source, the absorber on a track, the motor used to move the absorber at constant speeds relative to the source and as the photon detector a scintillator is used. The light signal of the scintillator turned into an electric signal by a photomultiplier. This signal is amplified and shaped in the amplifier. The amplifier has two exits, one of which is connected to a single channel analyzer (SCA). If the signal pulse is within an adjustable window the SCA sends a standardized signal and enables the linear gate, which is also connected to the amplifier via a delay to ensure simultaneity of the signals. If the linear gate is enabled when it receives a signal from the amplifier it transmits the amplifier signal to the multichannel analyzer (MCA), which is read out with a Computer. The second output of the SCA is connected to a counter, which also can be read out with the Computer.

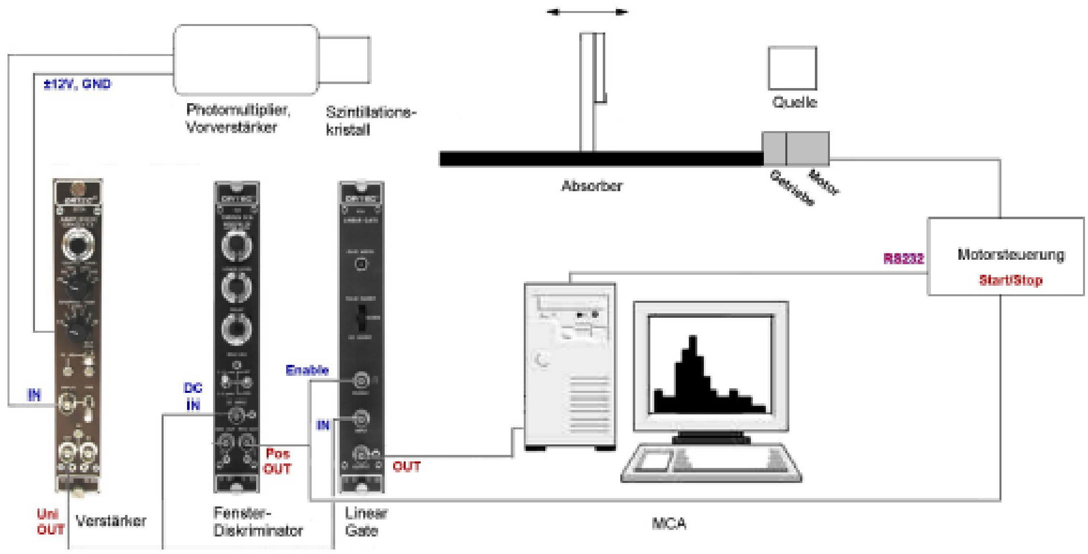

Figure 3.1: Overview of the experimental setup

3.3 The source Co-57

^{57}Co decays via electron capture with a branching ratio of 99.8% and a half life of 270d into an iron in an excited state ^{57}Fe*. This state decays with a half life of 9ns an branching ratio of 88% into the $14.4keV$ excited state which finally decays to the ground state (Branching ratio for $\gamma - decay$ is 10%) 3.2.

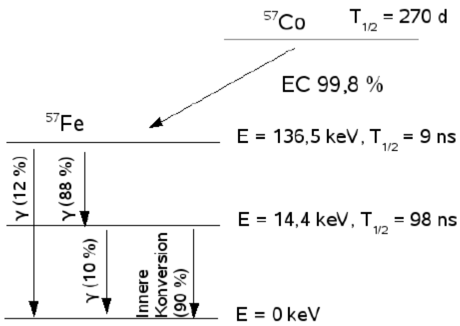

Figure 3.2: decay series of Cobalt-57

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