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1. Theory & Preparation

1.1 Mössbauer effect

The process of **resonant absorption** in nuclear physics describes the phenomenon of subsequent de- and excitation of two equal atoms to the same energy levels via one γ-quant. Consider for example the radioactive decay of ^{57}Co. Via electron capture it transforms into an excited state of ^{57}Fe, which in turn emits a 14.4 keV photon upon deexcitation.

$$^{57}\mathrm{Co} + e^- \longrightarrow {}^{57}\mathrm{Fe}^* \qquad {}^{57}\mathrm{Fe}^* \longrightarrow {}^{57}\mathrm{Fe} + \gamma$$

In principle, due to the symmetry of the latter transition, one could use this emitted photon to raise another ^{57}Fe atom to the excited state. The photon is absorbed resonantly by the second atom during this process.

In reality, resonant absorption such as the Na-D-line only occurs under certain circumstances. Due to conservation laws the energy E_γ of the emitted photon does not exactly equal the transition energy E_0, but is instead shifted downward by the nuclear recoil energy. A similar analysis finds that the energy for absorption of the same atom is shifted upwards.

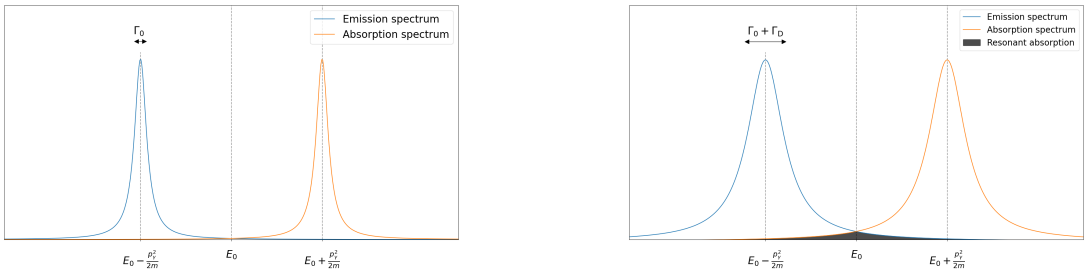
$$\underbrace{E_\gamma = E_0 - \frac{p_\gamma^2}{2m}}_{\text{Emission}} \qquad \underbrace{E_\gamma = E_0 + \frac{p_\gamma^2}{2m}}_{\text{Absorption}} \tag{1.1}$$

With the photon impulse p_γ and atom mass m. If the line width introduced by natural broadening or other effects does not exceed the energy gap, resonant absorption cannot occur (see **??**). It is also notable that the energy gap between emission and absorption spectrum can be increased by additional effects. This will be further discussed in **??**.

As it turns out, the above rules stating when resonant absorption can and cannot occur are not strictly true. Experiments in the 1960s conducted by R. Mössbauer ([**?**]) showed that resonant absorption in a crystal lattice happens much more readily than one would expect based on the previous discussion. The difference is the tight binding of the atoms in the crystal lattice. Instead of the individual atom recoiling, different phonons can be created (or destroyed) by the emission and absorption. In a sense, the entire crystal absorbs the recoil energy, effectively substituting the atom mass m in equation **??** by the mass M of the entire crystal. Because $m \ll M$, the energy gap between emission and absorption spectrum drastically decreases. This phenomenon of recoilless nuclear resonant absorption is named **Mössbauer effect**.

1.2 Mössbauer spectroscopy

To measure the the natural linewidth of ^{57}Fe with roughly 5 neV common measurement methods will fail. Even with high-resolution interferometers, some orders of magnitude are



(a) Natural broadening **(b) Natural + Doppler broadening**

Figure 1.1: (a) The natural linewidth Γ_0 is not sufficient for a sizeable overlap of both spectra. Resonance absorption is not possible. **(b)** The line width of both spectra can be increase by other effects such as Doppler broadening. In such cases the spectra with linewidth $\Gamma_0 + \Gamma_D$ can overlap and resonant absorption is possible.

still missing to resolve such lines by direct measurement of the spectrum. Therefore we take the Mössbauer effect into consideration. It is possible to measure the resonant absorption by the transition rate of the photons. The detector does not need to be energy sensitive, it is sufficient to detect the quanta in this case. The magnitude of the transition displays the overlap of the probabilities for emission and absorption (see **??**) of the natural lines. By varying the distance of the emission and absorption peaks we can make a statement about the line profile.

If the gamma radiation source is in motion a **Doppler shift** occurs and the photon energy changes. Therefor we can slightly modify the photon energy by changing the velocity of the source (see **??**).

$$\Delta E_\gamma = \pm \frac{v}{c} \cdot E \tag{1.2}$$

With the measured transmission spectrum as a function of the velocity of the source one can make qualitative as well as quantitative statements about the element. Furthermore it is possible to observe three types of nuclear interaction: isometric shift, quadrupole splitting and hyperfine magnetic splitting. The FWHM of the transmission curve corresponds to the double natural linewidth of the transition.

2. Experiment & Evaluation

2.1 Setup

The experiment consists of several components. A schematic setup can be seen in **??**. An interferometer monitors the velocity at which the Mössbauer driving unit (MDU) as well as γ-source are moving relative to the lab frame. An absorber can be placed in the beam path of the high-energy photons. Based on their energy, the γ's are either transmitted or absorbed by the target. The number of transmitted photons is counted by a 1024 channel multi-channel-scaler (MCS). The various other components of the setup (DFG, etc.) are used for calibration as well as data acquisition (DAQ) purposes, more detailed information on the individual building blocks can be taken from [**?**].

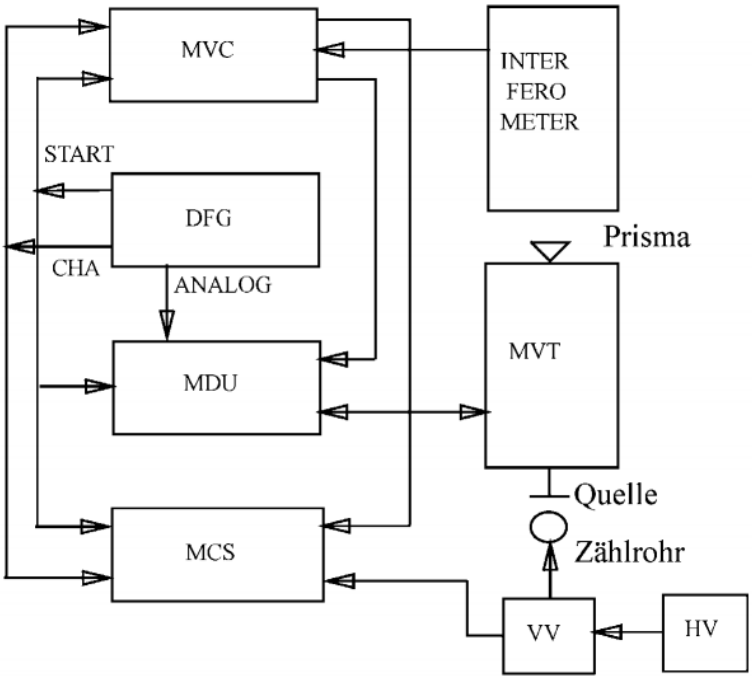


Figure 2.1: A schematic overview of the experiment components. The Mössbauer driving unit (MDU) moves the γ-source at a velocity relative to the multi-channel-scaler (MCS). The exact velocity can be controlled via a digital function generator (DFG), Mössbauer velocity transducer (MVC) and monitored by an interferometer.

2.2 Energy calibration of the MCS analyser

As described in **??**, Mössbauer spectroscopy does not rely on an extremely precise measurement of the photon energy. Due to resonant absorption it is sufficient to merely count the number of photons transmitted through an absorber to gather information about its atomic

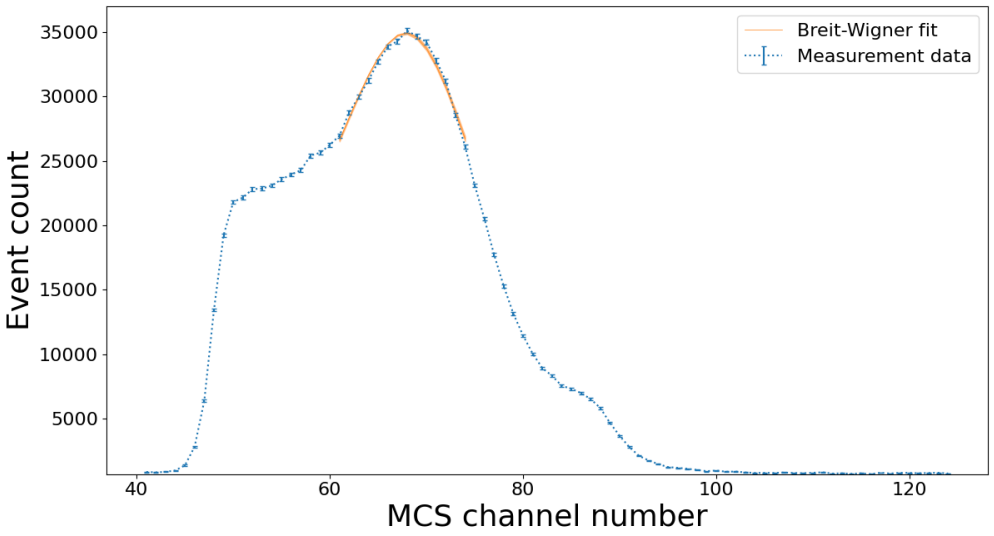


Figure 2.2: The error on the measured counts is assumed to be Poissonian. Because the amplitude A does not hold physical information other than the flux of the γ-source, uncertainties and correlations in A are neglected in the below error propagation.

energy levels and existing nuclear transitions. However, in order to allow for more detailed analysis in the following evaluation the relative difference of transition energies needs to be quantified. For this purpose as well as a proof of concept, The γ-spectrum of ^{57}Co is measured. Visible in the observed spectrum in **??** is a characteristic Lorentzian peak that reperesents the 14.4 keV resonance of the excited ^{57}Fe* state. The exact fitfunction as well as fit results are given in the below **??**

$$f(\mathcal{C}) = \frac{A}{(\mathcal{C}^2 - \omega_0^2)^2 + \gamma^2\omega_0^2} \tag{2.1}$$

$$\begin{aligned} A &= (8.68 \pm 0.36) \times 10^{10} \\ \omega_0 &= 67.84 \pm 0.08 \\ \gamma &= 23.25 \pm 0.52 \end{aligned}$$

$$\mathrm{COV}(A, \omega_0, \gamma) = \begin{bmatrix} 1.28 \times 10^{19} & 1.00 \times 10^{7} & 1.86 \times 10^{9} \\ 1.00 \times 10^{7} & 5.66 \times 10^{-3} & -6.41 \times 10^{-4} \\ 1.86 \times 10^{9} & -6.41 \times 10^{-4} & 2.75 \times 10^{-1} \end{bmatrix}$$

$$\Delta f(\mathcal{C}) = \sqrt{(\nabla f(\mathcal{C}))^T \ \mathrm{COV}(A, \omega_0, \gamma) \ \nabla f(\mathcal{C})}$$

2.3 Measuring the Mössbauer spectrum