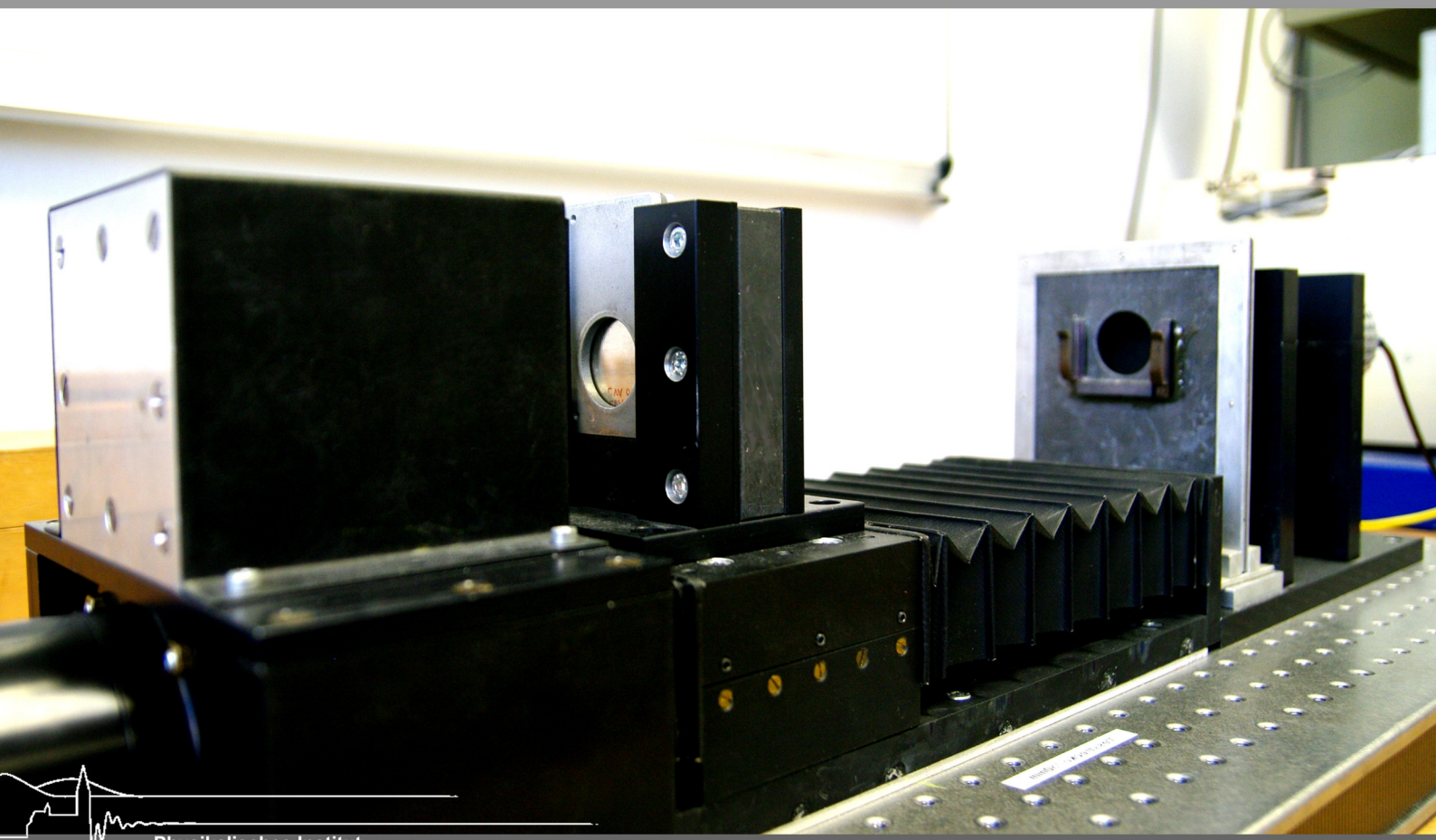
Universität Freiburg

Instructions

Advanced Lab Courses

Part II



Physikalisches Institut

Advanced Lab Courses II

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Mößbauer-Effect

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1 Preamble

1.1 Experimental Goal

Absorption lines in stainless steel and natural iron are to be measured with the help of the Mößbauer effect. This is done utilising an iron source emitting a narrow line at 14.4 keV. Unfortunately, the width of the line cannot be measured accurately due to the bad energy resolution of the used scintillation counter. In the experiment 'Short Lifetimes' of the advanced lab courses I, the time between population and depopulation, the lifetime, of the 14.4 keV state of ^{57}Fe was measured with a time-to-pulse converter. However, with the Mößbauer effect the change in transmission as function of the velocity due to Doppler shift of the energy of photons traversing a resonant absorbing sheet is measured. Thus the lifetime of the state can be inferred. Chemical shifts can be measured as well as magnetic fields at the nucleus.

2 Background

2.1 Basic Principles of the Mößbauer-Effect

A nucleus emitting a particle in a decay will experience a recoil which depends on its mass and the momentum of the emitted particle. The energy transferred on the nucleus reduces the energy of the emitted particle and changes the form of the line spectrum of the decay. If the nucleus is embedded in a crystal lattice the momentum has to be absorbed by the whole crystal. This reduces the energy loss of the emitted particle.

Preparation:

- How large is the momentum and energy transfer to a free iron nucleus due to the 14.4 keV transmission?
- How does this change, if the mass of 1 mol of iron is assumed as the mass of the nucleus?

The bonds in the crystal are not arbitrary large, hence, the recoil can also be absorbed by the emitted photon if the exact energy of the photon is transferred on the crystal. If the energy of the emitted radiation is lower than this energy, a phonon can be excited with a non-zero probability. The phonon spectrum can be predicted by different models.

Preparation:

- What is the Einstein model of a crystal? What is the Debye model of a crystal?
- What is the form of the decay spectrum in the Einstein model? What is it in the Debye model? What is the Debye temperature? What is its relation to a 'normal' temperature? Why is the thermal temperature of a crystal important? Why did Mößbauer perform the experiment with cooling?

Through the addition of radioactive atoms in a crystal, a relative line width of $\mathcal{O}(10^{-13})$ can be reached. With this narrow line width one can even account for the energy loss of a photon in the gravitational field of the earth, which would otherwise be impossible due to (thermal) Doppler or recoil broadening.

But how should such a narrow line be measured? Here one uses the same effect in the absorption as is used in the emission to measure an absorption line, the resonant absorption. An absorber is mounted on a sledge which can be moved with a few mm/s towards and away from the source. The Doppler shift due to the movement of the sledge leads to a shift in the photon energy the absorber 'sees'. Hence, the photon is absorbed with different probabilities at different velocities. The line can then be reconstructed by plotting the rate of not absorbed particles behind the absorber against the velocity (i. e. the energy).

Preparation:

- Which orders of magnitude are relevant?

- How much smaller is the natural line width than for example the optical measured line width of a vapour discharge lamp? (Lifetime $\leftrightarrow$ Line width)
- How large is the energy loss (in units of the line width) of a photon travelling an upward distance of 10 m in the near earth gravitation field? How large is the Doppler shift at velocities of 10 mm/s?

2.2 General Background

In addition to the basic principles of the Mößbauer effect amongst others you should know about:

- Interaction of gamma radiation with matter.
- Theory of operation of the detector:
  What is a scintillator? What different types of scintillators are there? Which of them can be utilised to measure energy? Where are the limits of the energy measurement, where do the sources of uncertainty lie? What is the relation between crystal size and resolution? Are there additional effects in the crystal?
- Statistics and uncertainty propagation.

3 Experimental Setup

The absorbers have to be mounted on a sledge that can be moved by a linear motor. Via a motor steering software the sledge can be moved with velocities from 0.01 mm/s to 10 mm/s. DO NOT USE HIGHER VELOCITIES!

The steering software automatically starts and stops the counters after a few millimetres of movement. This delay ensures that a stable velocity is reached before the counting starts. The photons transmitted through the absorber are registered by a scintillating crystal. The output signal of the photo multiplier is amplified and fed into the input of a window discriminator. A downstream linear gate lets the scintillator signal through if the window discriminator gives a signal. The goal is to adjust the window discriminator such that only photons of the 14.4 keV line of the iron compound gives a signal at the output. The gate can be set on 'DC Inhibit' (for details consult the manual of the gate) for the calibration. Discrimination happens in the mode 'Norm' and one can check, that the window is set correctly or adjust it accordingly.

Preparation:

- With which alternative experimental setups could one also measure the Mößbauer effect?

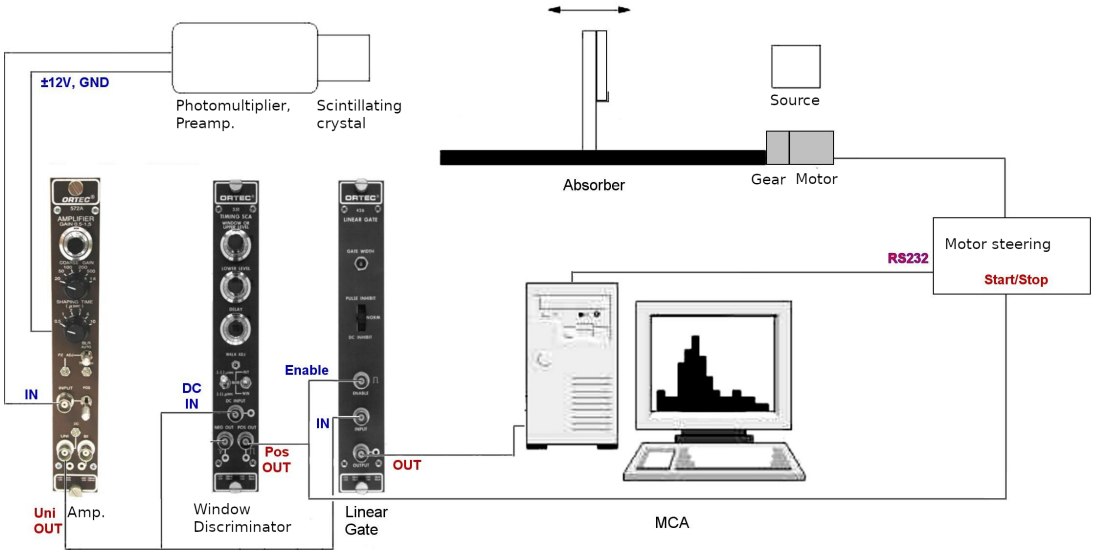


Figure 3.1: Schematic of the experimental setup.

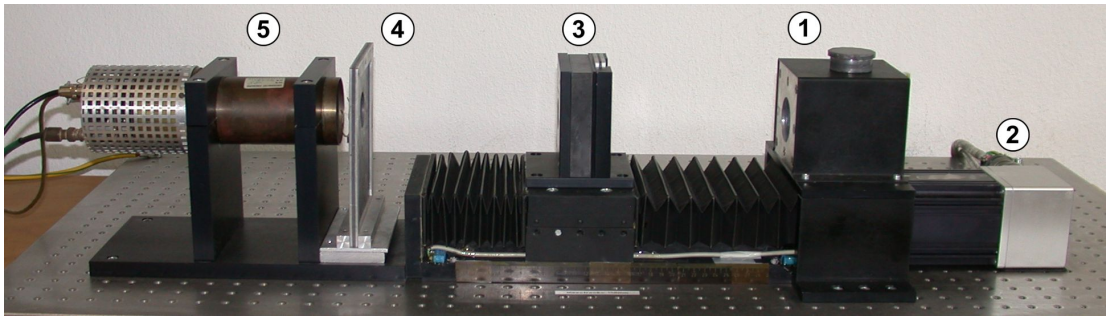


Figure 3.2: ① ^{57}Co source ② Motor (without gear) ③ Sledge with target holder ④ Radiation screen ⑤ NaJ scintillator

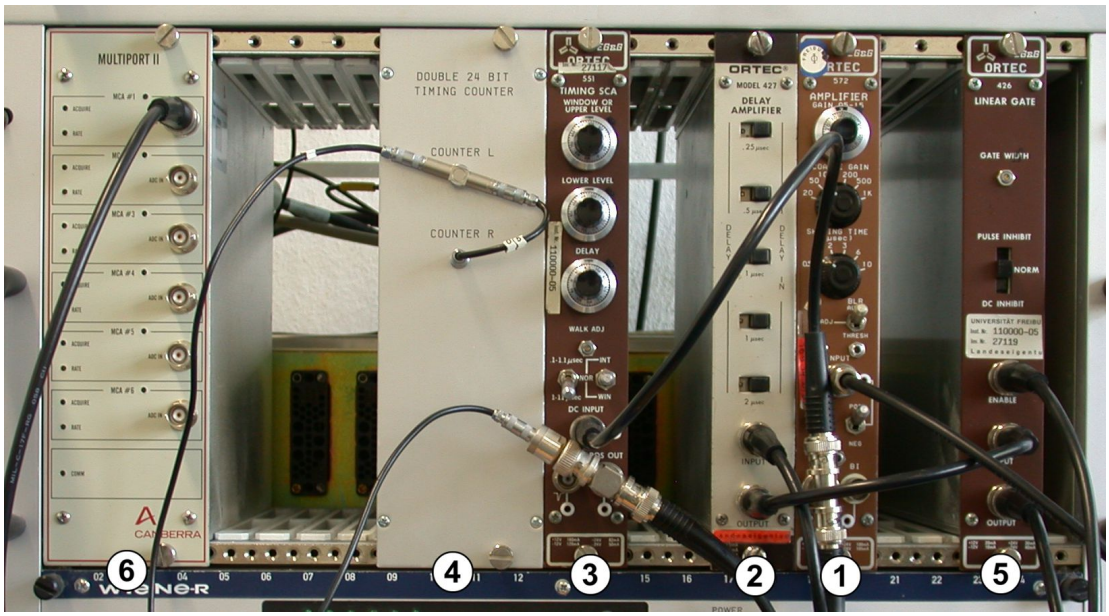


Figure 3.3: ① Amplifier ② Delay ③ Single channel analyser ④ Counter ⑤ Linear Gate ⑥ Multichannel analyser

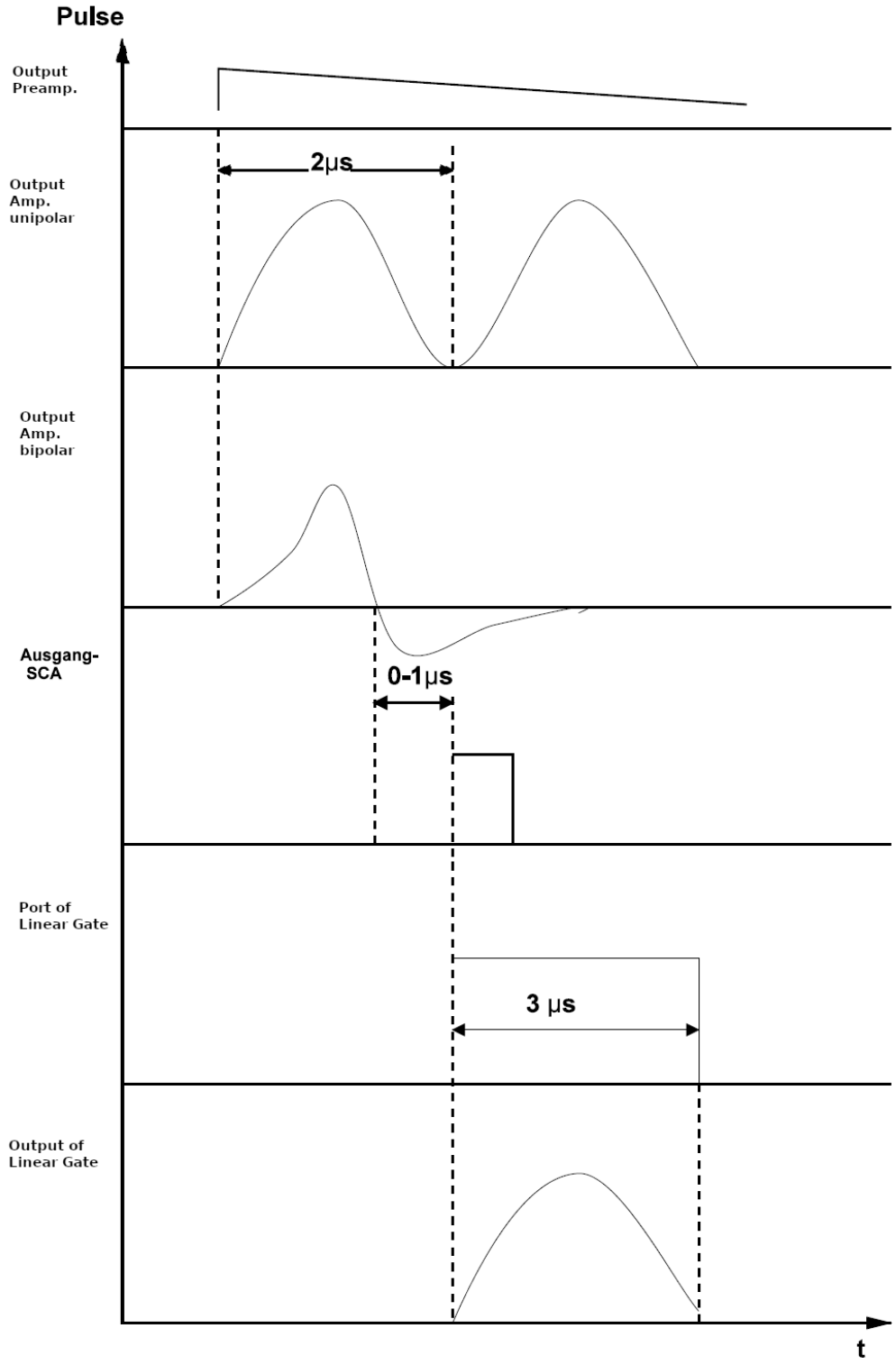


Figure 3.4: Schematic of the pulse shapes of the circuit.

4 Task and its Execution

1. Acquaint yourself with the experimental setup: how does the signal get transmitted, what is the timing? Document your observations.
2. Measure the K_α lines of different metals with the Americium source for calibration of the detector. The different metals are on a wheel in front of the source. Copper can be omitted.
3. Use the discriminator to apply a window on the 14.4 keV line in the iron spectrum. How should the window be chosen around the 14.4 keV peak? How is the window related to the natural line width?
4. Perform a series of measurements for the Compton background by gradually shielding the source with Aluminium sheets. The sledge should not be moved during this measurements. Choose sensible measurement times.
5. Take the spectra of the one and six line absorbers. When planing the measurement, take the expected statistical uncertainties into account.

Document your experimental procedure carefully and comprehensible!

Hints for the operation: The motor steering is done via the serial port of the PC with a LabVIEW programme. Your assistant will give you instructions.

5 Analysis

1. Perform the energy calibration.
2. Determine the Compton background:
   - The uncertainties of the background measurement should be much smaller that the uncertainty on the signal. If this is not the case: How could you solve the problem?
   - Fit the data and extrapolate to a thickness of zero. How can the functional form be explained?
   - Compare with the graph in appendix 4.
3. Determine the attenuation due to the Plexiglas window (Plexiglas: Polymethylmethacrylat, Density: $1.19\,\mathrm{g/cm^3}$, cf. appendix 5).
4. From the absorption spectra of stainless steel (S) and natural iron (N) determine
   a) the isomer shift (S, N)
   b) the effective absorber thickness (S):

      The following holds:

      $$T_\mathrm{A} = f_\mathrm{A} n_\mathrm{A} \beta \sigma_0 d_\mathrm{A}$$

      d_A: absorber thickness; n_A: number of iron atoms per $\mathrm{cm^3}$; β: fraction of ^{57}Fe in isotope mixture; σ_0: cross section; f_A: Debye-Waller factor of the absorber

      Necessary quantities: Stainless steel: $d_\mathrm{A} = 25\,\mu\mathrm{m}$, $f_\mathrm{A}(20\,^\circ\mathrm{C} = 0.8$, iron content (absorber): $70(5)\,\%$, $\beta = 0.022$. The number of iron atoms can be easily determined from literature values. The cross section can be calculated as stated in literature.

   c) the Debye-Waller factor f_Q of the source (S)

      The background has to be considered. f_Q can be determined with $f_\mathrm{A} = 0.8$ for stainless steel.

   d) the lifetime of the 14.4 keV state in ^{57}Fe (S):

      For the determination of the relative line broadening due to the 'thick' absorber the knowledge of the effective source thickness T_Q is also necessary. The source thickness d_Q is not given by the manufacturer but it can be estimated to be $\mathcal{O}(100\,\text{Å})$. With this T_Q can be estimated. Why does $T_\mathrm{Q} = T_\mathrm{A} = 0$ hold for $\Gamma_\mathrm{a}/\Gamma = 2.0$?

      In addition to the direct computation of the relative line broadening nowadays one also can estimate the line broadening due to the absorber. This is done by fitting the received distribution to a convolution of a Lorentzian and a Gaussian (a so called Voigt function). The width is only determined by the Lorentzian part of the fit. Conduct such a fit and compare the results. Make sure that you take enough data to be able to get a good fit.

   e) the magnetic field strength at the nucleus and the magnetic moment of the 14.4 keV state (N)

f) if you are in a group with two weeks of time, determine f_Q, γ (resp. τ), also for the six line absorber (N):

T_A has to be determined for each line separately. Natural iron (not Fe_2O_3!): $d_A = 25\,\mu m$, $f_A(20\,°C = 0.8$, iron content: $98(2)\,\%$, $\beta = 0.022$.

Think about the uncertainty on the velocity of the sledge. Due to this uncertainty one gets a broadening of the Lorentz peak. (Functional form: Gaussian/Lorentzian/Voigt?)

All results have to be compared with the manufacturer data (if possible). If you write small scripts/programmes for the analysis their source code listenings have to be attached to the written report.

Appendix

1 Specifications of the Radioactive Source

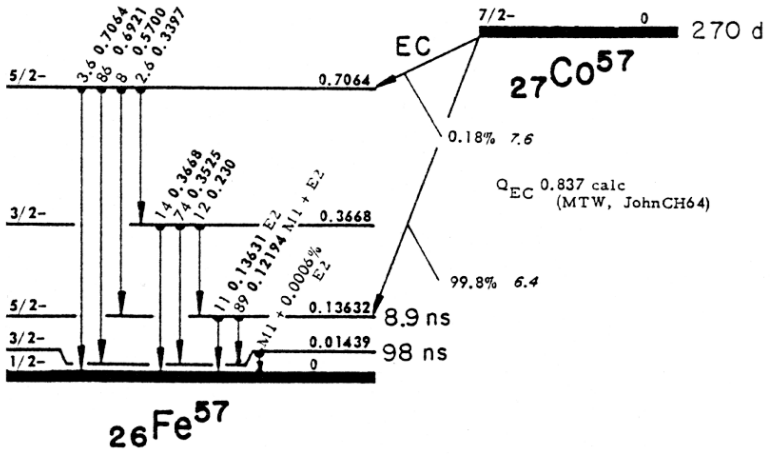


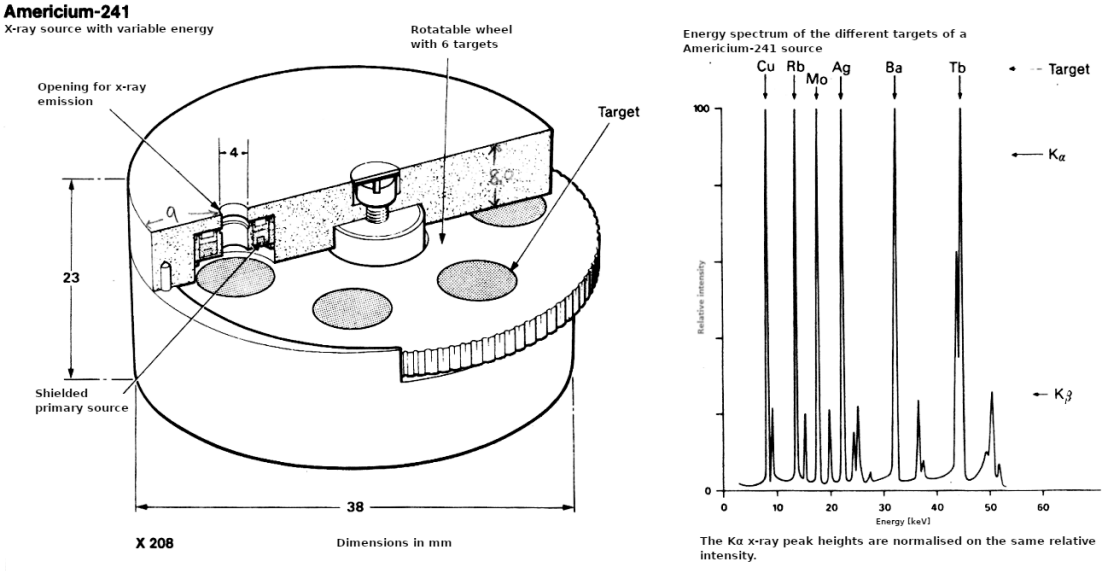
Figure 1: Decay of ^{57}Co

2 Specifications of the Fluorescence Source

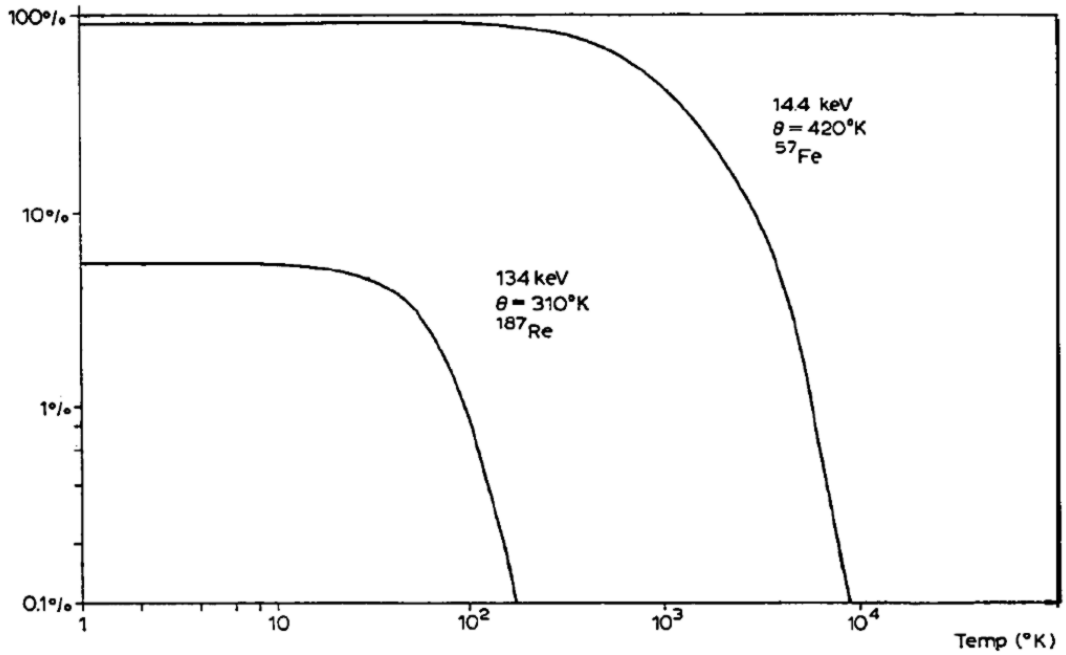
The variable x-ray source is suitable for use as calibration source for x-ray and gamma spectrograph. In addition it can be used for the demonstration of the x-ray fluorescent effect. The source/target unit consists of a ^{241}Am primary source and six inactive x-ray fluorescent targets on a stainless steel wheel mount. The primary source ($10^{+2.5}_{-0}$mCi) contains a ^{241}Am ceramic which is shielded by tungsten to the backside and is tightly embedded into the welded stainless steel frame. The targets are placed on a rotatable wheel and can be placed in front of the source in such a way that the characteristic x-rays of the target are emitted through the frame opening (diameter: 4 mm).

Table 1: X-ray emission: Different targets of the Americium source. The x-ray emission is collimated and has a maximum emission angle of ~ 0.5 steradian.

Target	Energy [keV]		Yield
	K_α	K_β	$[\gamma s^{-1}\,sr^{-1}]$
Cu	8.04	8.91	2.5×10^3
Rb	13.37	14.97	8.8×10^3
Mo	17.44	19.63	2.43×10^4
Ag	22.10	24.99	3.85×10^4
Ba	32.06	36.55	4.65×10^4
Tb	44.23	50.65	7.6×10^4

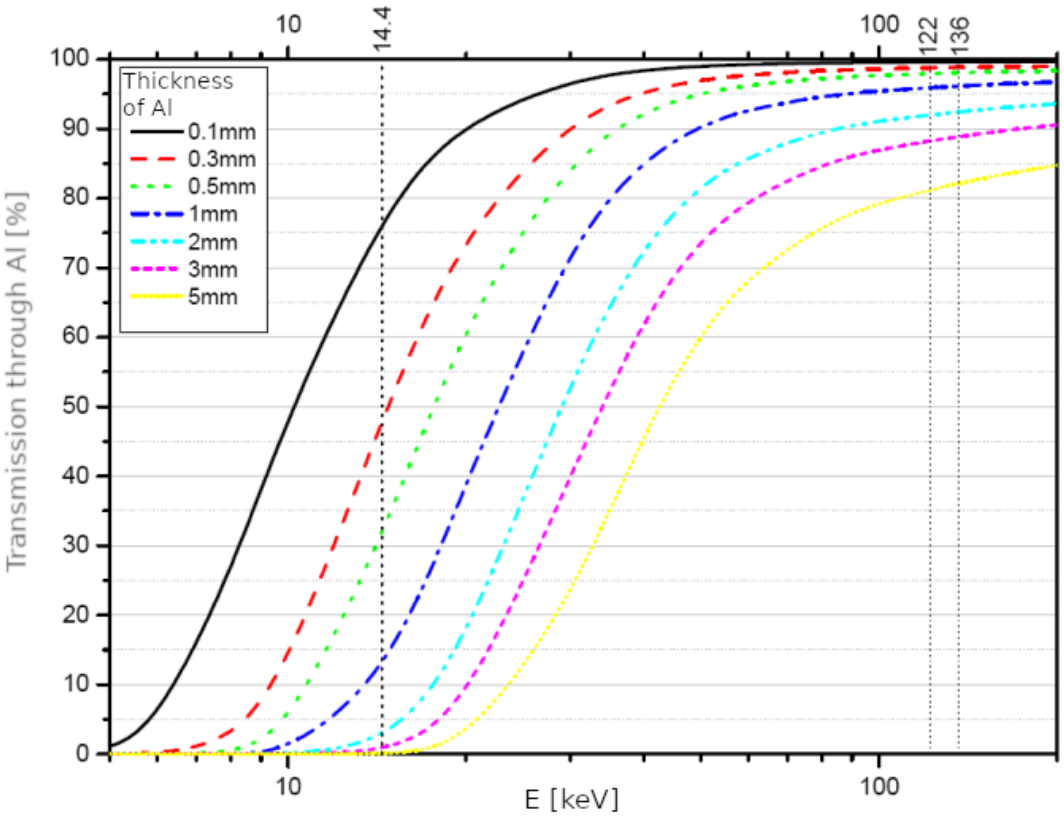


3 Debye-Waller-Factor



Fractions of recoil-free nuclear transitions (Debye-Waller factors) in ^{57}Fe and ^{187}Re, shown as functions of the temperature.

4 Transmission of Photons



5 Mass Attenuation Coefficient of Plexiglas

Table 2: Plexiglas: Mass attenuation coefficient μ/ρ and mass-energy attenuation coefficient μ_{en}/ρ as function of the photon energy [8].

Energy [MeV]	μ/ρ [cm^2/g]	μ_{en}/ρ [cm^2/g]
1.0×10^3	2.794×10^3	2.788×10^3
1.5×10^3	9.153×10^2	9.131×10^2
2.0×10^3	4.037×10^2	4.024×10^2
3.0×10^3	1.236×10^2	1.228×10^2
4.0×10^3	5.247×10^1	5.181×10^1
5.0×10^3	2.681×10^1	2.627×10^1
6.0×10^3	1.545×10^1	1.498×10^1
8.0×10^3	6.494	6.114
1.0×10^2	3.357	3.026
1.5×10^2	1.101	8.324×10^1
2.0×10^2	5.714×10^1	3.328×10^1
3.0×10^2	3.032×10^1	9.645×10^2
4.0×10^2	2.350×10^1	4.599×10^2
5.0×10^2	2.074×10^1	3.067×10^2
6.0×10^2	1.924×10^1	2.530×10^2
8.0×10^2	1.751×10^1	2.302×10^2
1.0×10^1	1.641×10^1	2.368×10^2
1.5×10^1	1.456×10^1	2.657×10^2
2.0×10^1	1.328×10^1	2.872×10^2
3.0×10^1	1.152×10^1	3.099×10^2
4.0×10^1	1.031×10^1	3.185×10^2
5.0×10^1	9.410×10^2	3.206×10^2
6.0×10^1	8.701×10^2	3.191×10^2
8.0×10^1	7.641×10^2	3.116×10^2
1.00	6.870×10^2	3.015×10^2
1.25	6.143×10^2	2.882×10^2
1.50	5.591×10^2	2.755×10^2
2.00	4.796×10^2	2.533×10^2
3.00	3.844×10^2	2.210×10^2
4.00	3.286×10^2	1.995×10^2
5.00	2.919×10^2	1.843×10^2
6.00	2.659×10^2	1.731×10^2
8.00	2.317×10^2	1.579×10^2
1.0×10^1	2.105×10^2	1.482×10^2
1.5×10^1	1.820×10^2	1.348×10^2

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