MÖSSBAUER RESONANCE-SCATTERING TECHNIQUES FOR EMISSION SPECTROSCOPY
ON GAMMA RADIATION FROM SHORT-LIVED RADIOACTIVE ISOTOPES

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ABSTRACT

Mössbauer experiments applying short-lived radioactive isotopes from the ISOLDE facility at CERN have been reported recently. To utilize fully the high activity (10-100 mCi), which is obtainable for some Mössbauer parent isotopes, a special counting technique is required.

The count rate limit of ordinary Mössbauer transmission technique can be overcome by resonance-scattering techniques. Resonance detectors of the parallel-plate avalanche counter type, detecting conversion electrons, are demonstrated to be a favourable solution for ^{119}Sn Mössbauer spectroscopy. The merits of such detectors compared with other scattering and with transmission techniques are discussed. An experimental set-up for on-line measurements at liquid-nitrogen temperature is described.

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1. INTRODUCTION

Mössbauer emission spectroscopy on γ radiation from radioactive isotopes implanted as probe atoms into solids is a well-established method for the study of hyperfine interactions and vibrational properties of impurity atoms in solids [see recent reviews^{1,2)}]. Such studies give valuable information about various properties of the impurity-host system, such as electronic and magnetic configurations or parameters of the lattice dynamics of the impurity atoms. Radioactive source isotopes are usually implanted rather than stable absorber isotopes, since emission spectroscopy is more sensitive by orders of magnitude than absorption spectroscopy. As Mössbauer cross-sections hardly exceed 10^{-18} cm², even highly sensitive absorption spectroscopy, utilizing re-emitted conversion electrons³⁾, demands about $\geq 10^{13}$ absorber atoms for favourable cases, whereas $\leq 10^{12}$ radioactive atoms are sufficient for reasonable emission spectra. In implantation studies the implanted doses have to be kept well below about 10^{13} atoms/cm² (for implantation energies of ~ 100 keV) to avoid impurity-impurity interaction effects or heavy damage to the implanted target. This condition can generally be fulfilled if radioactive isotopes are implanted. Emission spectroscopy is therefore well-suited for investigations of dilute impurities in solids, although complications in the interpretation of the spectra, owing to the nuclear decay, have to be considered.

The half-lives of radioactive isotopes implanted with off-line isotope separators range from about 10 hours to 1 year. The limits are due to handling times, on the one hand, and to beam intensity limitations, on the other. Thus source strengths of 10^{-6} – 10^{-3} Ci result for a typical implant of about 10^{12} radioactive atoms/cm². In many cases, however, owing to unavoidable beam contaminations with stable isotopes, e.g. by neighbour isotopes for radioactive isotopes produced by neutron capture reactions, the source strength will be lower by one to two orders of magnitude. This results in count rates of only 1 – 10^3 counts/s in a typical transmission experiment, for which branching ratios, internal conversion coefficients, and the solid angle of the detector have to be taken into account by at least a factor of 10^{-2} . Since absorption effects in transmission spectroscopy

hardly exceed 10%, a total of $\sim 10^8$ counts is needed for a spectrum exploiting the power of Mössbauer spectroscopy adequately. Thus measuring times of the order of days to years result per spectrum, and in many cases this may prevent systematic investigations. It has been demonstrated, however, that the measuring times may be reduced by about an order of magnitude in favourable cases, where resonance counting techniques can be applied that are based on the detection of conversion electrons re-emitted from the absorber⁴⁾.

More intense and cleaner beams of short-lived radioactive isotopes in particular (10^8 - 10^{10} ions/s) are available from on-line isotope separators, separating nuclear reaction products directly from a target. Source strengths of 10^{-3} - 10^{-1} Ci can be achieved for short-lived ($T_{1/2} \lesssim 1$ d) isotopes. Recently, first Mössbauer experiments utilizing the ISOLDE facility⁵⁾ have been reported⁶⁻⁹⁾. High source strength was obtained for samples implanted with radioactive ^{119}In ($T_{1/2} = 2.1$ min), which populates the 24 keV Mössbauer state of ^{119}Sn . The ^{119}In was produced by proton-induced fission in a uranium-carbide target bombarded with 600 MeV protons from the CERN Synchro-cyclotron. A mass-separated beam of 5×10^8 $^{119}\text{In}^+$ /s was obtained from the ISOLDE facility. In a few minutes, sources of 10 mCi could be collected. Such source strength is beyond the capabilities of conventional transmission techniques, which suffer from the count-rate limits of nuclear detectors with adequate energy resolution (10^4 - 10^5 counts/s for solid-state, gas-proportional or NaI-scintillation detectors). Thus a full exploitation of the obtainable source strengths may exceed the counting capabilities of transmission spectroscopy by more than an order of magnitude.

It is the aim of this paper to point out some advantages of the application of scattering techniques under conditions as characterized above. For the special case of ^{119}Sn , resonance detectors of the parallel-plate avalanche counter type, detecting re-emitted conversion electrons from an absorber, are shown to be a favourable solution in the extreme cases of both low- and high-activity sources for the 24 keV Mössbauer transition of ^{119}Sn . Examples of spectra from samples ion-implanted with different radioactive source isotopes are presented. An

ultra-high vacuum chamber designed for on-line Mössbauer experiments on samples implanted at liquid-nitrogen temperature is described briefly.

2. THE CONCEPT OF RESONANCE DETECTORS

A sketch of Mössbauer-transmission and scattering experiments is shown in fig. 1. Doppler-shifted γ radiation is emitted from a source moving with a velocity v . A certain fraction of this radiation is absorbed resonantly in an absorber. The transmitted radiation is detected in a γ detector. Since the resonance absorption probability and thus the count rate in the detector depend on the relative velocity between the source and the absorber, a transmission spectrum is recorded, as illustrated in the figure, by measuring the count rate at different velocities. For ideal source and absorber materials (with unbroadened emission and absorption lines) the lines in the transmission spectrum have approximately Lorentzian shapes for not too thick absorbers. The width of the spectral lines depends on the absorber thickness¹⁰):

$$\Gamma_{\text{exp}} = 2\Gamma_0(1 + 0.14 T) \text{ for } T \leq 5, \quad (1)$$

where Γ_0 is the natural width given by the lifetime of the state, and the effective absorber thickness for Mössbauer γ radiation is defined as $T = n\sigma_0 f_a$. Here n is the number of Mössbauer isotopes per cm^2 , f_a is the Debye-Waller factor of the absorber material, and

$$\sigma_0 = \frac{1}{2} \frac{2I_e + 1}{2I_g + 1} \frac{1}{1 + \alpha} \frac{\lambda^2}{\pi} \quad (2)$$

is the resonance cross-section (I_e , I_g being the spins of the excited and the ground state of the nucleus, respectively, α the internal conversion coefficient, and λ the wavelength of the γ radiation). If one considers high-resolution Mössbauer spectroscopy only by demanding a line broadening of less than 10%, the absorber thickness is limited to $T \lesssim 0.7$. Consequently, the absorption effect

$$|\epsilon_t| = [N(0) - N(\infty)]/N(\infty) \approx \frac{1}{2} f_s T \quad (3)$$

[$N(\infty)$ and $N(0)$ are the count rates far off and at resonance, respectively] hardly exceeds $\sim 10\%$. This is due to a finite Debye-Waller factor of the source

($f_s \lesssim 0.7$) and to background contributions from non-resonant γ radiation emitted from the source or scattered into the detector, which reduce the absorption effect measured in a transmission experiment.

Alternatively to transmission experiments, scattering experiments may be performed. In the decay of the excited Mössbauer nucleus in the absorber, γ radiation (γ') or conversion electrons (e^-) are emitted. These radiations or the X-rays emitted subsequently to internal conversion transitions can be detected to measure a scattering spectrum as illustrated in fig. 1. In contrast to a transmission spectrum, the effect-to-background ratio, ϵ_s , may become large ($\epsilon_s \gg 1$) in a scattering geometry. However, this presumable advantage is restricted by losses in the count rate due to comparably small solid angles of the detector, and -- for γ scattering -- by large conversion coefficients α or -- for the detection of conversion electrons or X-rays -- by low ranges of these radiations in the absorber material and low α . For conventional experimental arrangements as sketched in fig. 1, the γ -scattering technique is superior to transmission techniques with respect to measuring times needed for a given spectral accuracy in cases of high-energy (~ 100 keV) γ transitions with low Debye-Waller factors and internal conversion coefficients ($f_s, \alpha \ll 1$)¹¹⁾. For low-energy γ transitions (~ 10 keV), which usually have large internal conversion coefficients ($\alpha \gtrsim 1$), resonance detectors of different types, detecting conversion electrons or X-rays, have been developed¹²⁻¹⁴⁾. It is common to these detectors that the resonance absorber is incorporated as an integral part into the detector, to maximize the solid angle for the detection of the scattered radiation. For some favourable Mössbauer cases, including the important isotopes ^{57}Fe and ^{119}Sn , such detectors have considerable advantages with respect to counting efficiency over transmission techniques. Besides, interesting applications in high-resolution Mössbauer spectroscopy, time-differential spectroscopy, or surface investigations have been demonstrated (see, for example ref. 4). This paper is concentrated on a discussion of advantages of the application of fast resonance detectors in Mössbauer emission spectroscopy on implanted radioactive isotopes. The resonance detector

considered here is of the parallel-plate avalanche counter type, the construction and operation of which has been described previously⁴). The counter (see fig. 2) consists of two (or more) parallel electrodes fabricated of material with low atomic number. One or several electrodes are covered with thin layers of highly enriched ($\geq 90\%$) absorber material of low line width (e.g. $\text{Ca}^{119}\text{SnO}_3$ for the case of ^{119}Sn). The electrode system is mounted in a gas-filled (acetone vapour at ~ 40 Torr) chamber with a thin entrance window for the Mössbauer γ radiation. Conversion electrons emitted from the absorber material are detected in the gap between the electrodes by a gas amplification mechanism. Such counters for the 24 keV γ radiation of ^{119}Sn are characterized by an effect-to-background ratio $\epsilon_s \geq 20$ for a fictive ^{119m}Sn single-line source with $f_s = 1$, an effective absorber thickness of $T \approx 1$, a relative solid angle for the detection of the conversion electrons of $\Omega \approx 0.4$ (normalized to 4π), and a detection efficiency for conversion electrons in the active volume close to 1. Large effect-to-background ratios are achieved by suppressing all interactions (mainly photoabsorption) of incoming γ radiation other than Mössbauer resonance absorption as much as possible. This leads to the choice of material of low atomic number for the absorber layer and the detector construction. The absorber layers have to be thinner than the range of the conversion electrons in the absorber material, which limits the effective thickness of a single layer to $T \leq 1$. The counting gas and its pressure can be selected to optimize the efficiency for the detection of low-energy electrons, while at the same time the efficiency for the detection of the incoming γ -rays is kept sufficiently low. Such counters have a typical over-all efficiency for recoil-free emitted γ radiation of

$$D_s = \frac{1}{2} \Omega T \alpha / (\alpha + 1) \leq 0.1$$

for the case of ^{119}Sn ($\alpha = 5.2$) with a single absorber layer. Similar parameters may be reached for a number of other Mössbauer transitions (^{57}Fe , ^{151}Eu , ^{161}Dy , or ^{169}Tm). The counters are rather versatile, since their mechanical construction can be adjusted to many needs. For example, because of their low weight, they can easily be moved with conventional Mössbauer drive systems. This is advantageous

for on-line experiments, since it allows for a simple design of the implantation chamber (see section 5).

An outstanding quality of parallel-plate avalanche counters is their time resolution. The internal time resolution with highly polished electrodes is better than $\text{FWHM} = 1 \text{ ns}$, independent of the energy of the electrons¹⁵⁾. With absorber layers on the electrode surfaces a time resolution of $\text{FWHM} \approx 5 \text{ ns}$ has been achieved for the case of ^{119}Sn ¹⁶⁾. Since no pulse-height analysis of the detector pulses is needed, with fast electronic equipment count rates of 10^5 - 10^6 counts/s can be utilized with such counters.

In the following, relevant properties of resonance detectors for emission spectroscopy will be discussed and compared with conventional transmission techniques in particular. Most aspects of these considerations apply equally well to any other scattering technique.

3. THE STATISTICAL ACCURACY IN TRANSMISSION AND SCATTERING GEOMETRY

For a convenient comparison of the resonance counter with transmission techniques in respect to the statistical accuracy that is obtained in a given measuring time interval, the following simplifying assumptions may be made: the effect-to-background ratio is large for the scattering experiment ($\epsilon_s \gg 1$) and small for the transmission experiment ($|\epsilon_t| \ll 1$). A single-line source emits Mössbauer γ radiation only, which is absorbed by the same single-line absorber in both cases. The solid angle relevant for the absorption of the γ radiation is the same in both cases. The transmitted radiation is detected with high efficiency ($D_t \sim 1$). Finally, the statistical accuracy of a complete Mössbauer spectrum is evaluated by the statistical accuracy of the quantity $m = N(0) - N(\infty)$ only. Then the relative statistical error of the Mössbauer effect m can be approximated by

$$(\delta m_t)^2 = 2/\epsilon_t^2 N_t(\infty) \quad (5)$$

for the transmission experiment and by

$$(\delta m_s)^2 = 1/N_s(0) \quad (6)$$

for the scattering experiment. The count rate at resonance, $N_s(0)$, is related to the count rate off resonance in the transmission experiment $N_t(\infty)$, by

$$N_s(0) = \frac{1}{2} f_s T \Omega N_t(\infty) \cdot \alpha / (\alpha + 1) . \quad (7)$$

The ratio of the squares of the two relative errors is then calculated to be

$$\left(\frac{\delta m_t}{\delta m_s} \right)^2 = \frac{f_s T \Omega \alpha}{\epsilon_t^2 (\alpha + 1)} = \frac{4 \Omega \alpha}{f_s T (\alpha + 1)} . \quad (8)$$

Thus the criterion for a better statistical accuracy in the e^- scattering than in the transmission experiment, $\delta m_t / \delta m_s > 1$, requires the construction of an e^- detector with

$$\Omega > \frac{f_s T (\alpha + 1)}{4 \alpha} . \quad (9)$$

For the case of ^{119}Sn , even for extreme values of $f_s = 1$, $T = 1$, this condition, $\Omega > 0.3$, can be fulfilled. Analogously, for a γ -scattering experiment the condition would be

$$\Omega > \frac{f_s T (\alpha + 1)}{4} \quad (10)$$

which cannot be achieved generally for ^{119}Sn , since this means $\Omega \geq 1.5$ for $f_s = 1$, $T = 1$. The same condition reads for the detection of scattered X-rays:

$$\Omega > \frac{f_s T (\alpha + 1)}{4 \alpha \omega} , \quad (11)$$

where ω is the fluorescence yield of the detected X-rays. However, for the case of ^{119}Sn , where no K_X -rays are emitted ($E_{BK} = 29.2$ keV), the low energy of L_X -rays ($E_{LX} = 2$ keV) makes X-ray scattering experiments impractical. It should be noted that the construction of resonance detectors with large solid angles for the detection of γ - or X-rays is hampered by the difficulty of keeping the efficiency for γ radiation emitted directly from the source sufficiently low, which is indispensable for a large effect-to-background ratio. On the other hand, since extremely large effect-to-background ratios can be obtained in conventional scattering geometries (where the detector is shielded from the source radiation) by applying high-resolution solid-state detectors, the disadvantage of a small solid

angle may be compensated for special experimental requirements. This is, as mentioned before, the case for low Debye-Waller factors of the source [see eqs. (9), (10) and (11)], but also, for example, in cases where overload of the detector is limiting the data accumulation speed in a transmission geometry.

The absorption effect in a transmission experiment is given by

$$\epsilon_t \approx -\frac{1}{2} f_s T \quad (12)$$

for the ideal case; however, as mentioned before, a reduction factor should be applied to account for background contributions. For a realistic comparison of the conversion electron resonance detector with a transmission experiment in the case of ^{119}Sn (displayed graphically in fig. 3), a reduction factor of 0.7 has been assumed for the transmission effect. This seems reasonable, since most nuclear detectors cannot discriminate between the 24 keV γ radiation and 25 keV X-rays, emitted with about equal intensity from the $^{119\text{m}}\text{Sn}$ source for example. By critical absorption with intensity losses of $\sim 10\%$ for the γ -radiation the X-ray intensity is reduced to $\sim 50\%$. In the graph, eq. (6) is assumed to be valid to $\epsilon_s \approx 1$, which is justified since $N_s(\infty)$ is rather well determined in a usual Mössbauer spectrum due to long measuring times off resonance. For $\epsilon_s \ll 1$, the accuracy in the scattering experiment has been approximated by eq. (5). Figure 3 shows the dependence of the ratio of the squares of the relative errors in the transmission and the scattering experiments [eq. (8)] on the Debye-Waller factor of the source f_s for a number of absorber thickness parameters T . The hatched area is the experimentally interesting area as given by a realistic range for the Debye-Waller factor of the source, $f_s = 0.05-0.8$, and reasonable absorber thicknesses that avoid substantial line broadening, $0.3 \leq T \leq 1$. Since the measuring times to reach a given accuracy increase with the square of the relative errors, the advantage in measuring time of the ^{119}Sn resonance detector over a transmission experiment can be read directly from the graph. The measuring time is shortened for all experimental conditions ($\delta m_t / \delta m_s > 1$) and this advantage is particularly great (more than an order of magnitude) for high-resolution spectroscopy on sources with relatively low Debye-Waller factors. As will be evident later, this is precisely the area of interest for studies on implanted impurity atoms in solids.

Another aspect of the difference between a transmission and a scattering spectrum that is worth mentioning concerns the question of the resolution of a weak line alongside a strong line. This situation is sketched in fig. 1 with approximately realistic accuracy ratios between the two spectra. It can easily be shown that the ratio of the relative errors for a second weak line to that of the strong line 1 is given by

$$\frac{\delta m_{t_2}}{\delta m_{s_2}} = \sqrt{\frac{I_1}{I_2}} \frac{\delta m_{t_1}}{\delta m_{s_1}}, \quad (13)$$

where I_1 and I_2 are the intensities of lines 1 and 2, respectively. Thus if the relative accuracy for line 1 is the same in a scattering and a transmission experiment, the accuracy for line 2 is better in the scattering than the transmission experiment by a factor of $\sim \sqrt{I_1/I_2}$, as long as $\epsilon_s \gtrsim 1$. This advantage is of practical importance in all cases where complex spectra, containing several lines of different intensity, have to be analysed.

4. PERFORMANCE OF ^{119}Sn RESONANCE DETECTORS IN MEASUREMENTS ON IMPLANTED RADIOACTIVE ISOTOPEs

As shown in fig. 4, the 24 keV Mössbauer state of ^{119}Sn is populated in the decay of ^{119}Sb and ^{119}In . Whereas the lifetime of the ^{119}Sb isotope is sufficiently long to allow for off-line isotope separation, the short lifetime of ^{119}In necessitates on-line separation techniques. The third alternative for a direct population of the ^{119}Sn Mössbauer state (not shown in fig. 4), a $^{119\text{m}}\text{Sn}$ source ($T_{1/2} = 250$ d), is the preponderantly used source. This activity, produced by the $^{118}\text{Sn}(n,\gamma)^{119\text{m}}\text{Sn}$ reaction, is commercially available. The specific activity of the $^{119\text{m}}\text{Sn}$ is limited to a few hundred mCi per g ^{118}Sn , owing to a relatively low cross-section. The activity of an implanted source of isotope-separated $^{119\text{m}}\text{Sn}$ is furthermore affected by a larger cross-section of the (n,γ) reaction to the ^{119}Sn ground state. Thus for implants maintaining the dose criterion of $\leq 10^{13}$ atoms/cm² as given in section 1, source strengths of ≤ 10 nCi are obtained. Acceptable Mössbauer spectra from such samples with extreme low activity can be recorded in measuring times of the order of weeks with a resonance detector, since

the background count rates, which critically reduce the effect-to-background ratio for weak sources, are sufficiently low, $\sim 10^{-2}/s$ ^{17,18}). For practical purposes, however, a source strength of ≥ 100 nCi has to be considered as a lower limit for samples accessible to systematic Mössbauer studies. This limit applies to all three parent activities.

An example of a spectrum measured within 23 h for ^{119}Sb implanted into InP is shown in fig. 5 ¹⁹). The ^{119}Sb was obtained as a decay product from $^{119\text{m}}\text{Te}$ produced by the $^{116}\text{Sn}(\alpha, n)^{119\text{m}}\text{Te}$ reaction ²⁰). The spectrum has been analysed assuming two independent lines of Lorentzian shape to be present as indicated in the figure. Obviously, the statistical accuracy of the spectrum is just sufficient to establish the presence of a second line (line 2), which has $\leq 10\%$ of the intensity of line 1. From the considerations in the previous section, it is evident that no spectrum with sufficient accuracy to distinguish the two lines could have been measured by transmission techniques within the lifetime of the source ($T_{1/2} = 38$ h).

Figure 6 shows a spectrum from ^{119}In implanted into GaAs. The spectrum has been accumulated in 2×4 min shortly after two implantations (≤ 1 min). Each data point in the figure has been measured in a total channel opening time of < 2 s. The count rate at resonance, $N_s(0)$, corresponding to a count rate of $N_t(\infty) > 10^5$ for an equivalent transmission experiment, exceeds the counting capabilities of ordinary nuclear detectors. This means that the total advantage in measuring time by applying a resonance detector amounts to about two orders of magnitude. Thus the special counting technique is vital for this experiment, since the available measuring time is limited by the short half-life of the ^{119}In isotope ($T_{1/2} = 2.1$ min).

5. THE ULTRA-HIGH VACUUM CHAMBER FOR ON-LINE MÖSSBAUER EXPERIMENTS AT ISOLDE

A schematic sectional view of the stainless steel chamber used for on-line Mössbauer spectroscopy is displayed in fig. 7. The chamber is pumped by an ion pump (not shown) placed underneath the chamber. This pump was chosen to avoid

line broadening from vibrations. The chamber is coupled to the beam line by a narrow tube (1) ($\varnothing$ 6 mm, length 300 mm) to disconnect the two vacua from each other. A soft bellows (not shown) between this tube and the beam tube suppresses the transmission of vibrations from the beam line to the chamber. Prior to an experiment, the chamber is aligned optically to the beam axis by looking up into the beam direction through the view port opposite to the beam entrance port (1). When the beam enters through port (1), it may be stopped in a movable Faraday cup (2) to monitor the transmission of the beam into the chamber. The Faraday cup can be drawn upwards through a linear-motion feed-through, so that the ion beam hits the target (3). Fourteen target crystals (three of them are shown) are mounted on a liquid-nitrogen cooled copper disc (4). This target holder is connected rigidly to a liquid-nitrogen reservoir on top of it, inside the chamber. The reservoir is filled from the outside through a rotatable, double-walled feed-through, which is pumped differentially. A liquid-nitrogen cooled heat shield surrounds the target holder (marked with dashed lines in fig. 7). After an implantation, the target holder may be rotated into a position where the implanted target is in front of a lamp (5), which consists of a halogen bulb and a gold-coated mirror. The light from this lamp heats the surface of the implanted crystal to a desired annealing temperature (≤ 600 °C) and, owing to relatively good thermal contact, afterwards the sample is cooled to liquid-nitrogen temperature rapidly again (≤ 1 min). Finally, the implanted crystal is rotated into the measuring position in front of a resonance detector (6). The Mössbauer γ radiation can leave the chamber through thin windows (Al, Be). The resonance counter (6) is moved on an electromechanical Mössbauer drive system (not shown). In subsequent experiments, a new target is implanted simultaneously in a measuring period. Thus the incoming ion beam is utilized continuously, except for target handling and annealing times (≤ 2 min).

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Figure captions

- Fig. 1 : Schematic illustration of a scattering and a transmission Mössbauer experiment.
- Fig. 2 : Mechanical construction of a parallel-plate resonance detector.
- Fig. 3 : Figure of merit of a ^{119}Sn resonance detector, $(\delta m_t / \delta m_s)^2$, versus the Debye-Waller factor of the source, f_s , for effective absorber thicknesses of $0.3 < T < 1$.
- Fig. 4 : Decay scheme of ^{119}In and ^{119}Sb .
- Fig. 5 : ^{119}Sn Mössbauer spectrum from ^{119}Sb implanted into InP (from ref. 19). The spectrum was measured within 23 h at 77 K ($f_s \approx 0.7$); the source had a strength of $\sim 5 \mu\text{Ci}$.
- Fig. 6 : ^{119}Sn Mössbauer spectrum from ^{119}In implanted into GaAs (from ref. 6). The spectrum was recorded in 8 min; the source strength was $\sim 10 \text{ mCi}$.
- Fig. 7 : Schematic sectional view of the implantation chamber for on-line Mössbauer experiments at ISOLDE. 1 - beam entrance port, 2 - movable Faraday cup, 3 - target crystal, 4 - liquid-nitrogen cooled target holder, 5 - lamp for annealing experiments, 6 - resonance detector.

Fig. 1

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Fig. 5

Fig. 6

Fig. 7