MÖSSBAUER EFFECT BY RECOIL IMPLANTATION THROUGH VACUUM*

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The Mössbauer effect was observed for Coulomb-excited ^{57}Fe recoils implanted through vacuum into various media. This method avoids radiation damage of the host medium by the beam. Where comparison data are available, the results at room temperature indicate that within the nuclear lifetime of 10^{-7} sec the recoils find a normal lattice site.

The Mössbauer effect has been observed for nuclear recoils implanted through vacuum into various media. The new method is best illustrated by the experimental arrangement shown in Fig. 1. The target nuclei are excited by a beam of charged particles from an accelerator. The forward momentum of the reaction propels them through vacuum and implants them in a catcher foil. The travel times are typically of the order of several nanoseconds. Thus, states with lifetimes longer than the travel time decay chiefly in the catcher foil. The Mössbauer effect of the emitted γ rays can be observed in the usual way by means of an absorber coupled to a velocity spectrometer. All radiations emitted earlier, and, in particular, background generated in the target and beam stopper itself, are effectively removed by the shield. Thus, it is possible to avoid the use of coincidence detection[1,2] or beam pulsing[3] to obtain a spectrum clean enough for a study of very low-energy gamma rays. This feature is important since the other techniques have serious inherent limitations on the maximum possible counting rate.

A Mössbauer implantation measurement was recently reported[4] with the target deposited directly on the catcher foil. In contrast to that technique the Mössbauer nuclei are now implanted in an environment free of heating and radiation damage caused by the beam of charged particles. In fact, the implantation medium can be maintained at any desired temperature and made of any desired material without requiring a change of target. In addition, by suitably defining the directions of emission of the recoils the nuclear polarization of the reaction could be studied. Since in this experiment the recoils leave the target in the forward direction, approximately 70% of these excited nuclei are deposited in the implantation medium. In addition, the geometrical arrangement avoids the contribution from excited recoils which do not leave the target (or are not deposited on the catcher foil) and the method does not suffer from line broadening due to resonance self-absorption in the target. Obviously, the technique is limited to nuclear states with appropriately long lifetimes.

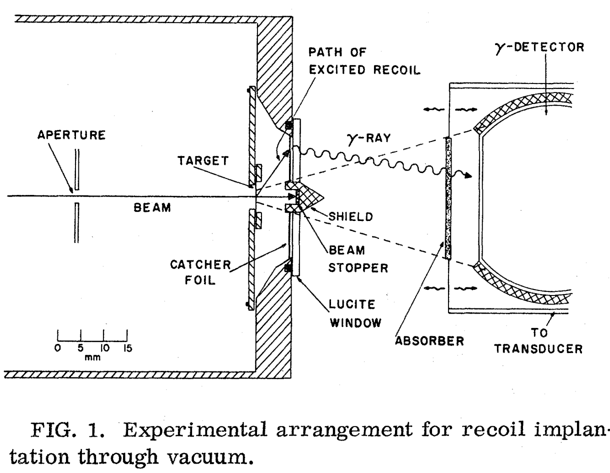

FIG. 1. Experimental arrangement for recoil implantation through vacuum.

The method has been successfully applied to ^{57}Fe implanted at room temperature in Cu, Al, Au, Fe, and $(Fe, Mg)_2SiO_4$ (olivine). The first three media are examples of "single line" environments in which the effect of implantation on isomer shift, linewidth, and recoil-free fraction was studied. The fourth medium, which is ferromagnetic, provided a measurement of the internal field after implantation. The last medium not only should produce a large quadrupole splitting[5] but is an insulator as well.

The excited ^{57}Fe recoils were produced by Coulomb excitation with ^{16}O ions from Stanford's High Voltage Engineering Corporation Model FN tandem. Metal targets of ^{57}Fe, 1.9 mg/cm^2 thick and enriched to 93%, were bombarded with an analyzed ^{16}O (5+) beam of energy 36 MeV and intensity approximately 100 nA. The beam was stopped in a Sn or Pd foil attached to the tantalum shield. The beam stopper should not be readily Coulomb excited nor produce x rays of undesirable energies since these can leak through the Ta shield or reach the detec-

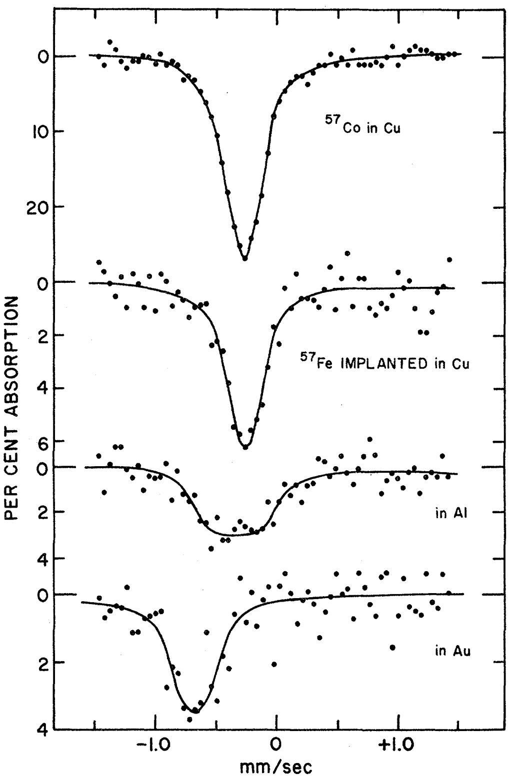

FIG. 2. Mössbauer spectra of excited ^{57}Fe recoils implanted in different metals, together with a reference spectrum for ^{57}Co diffused into Cu. The single-line absorber is enriched $Na_4Fe(CN)_6$. The ordinate is not corrected for background.

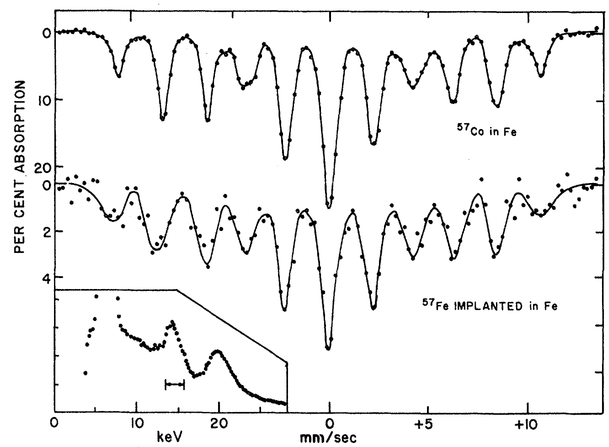

FIG. 3. Mössbauer spectra for excited ^{57}Fe recoils implanted in Fe metal and for ^{57}Co diffused into Fe metal. The absorber is an ^{57}Fe (91%) foil. The broadening of the outermost lines is due chiefly to the "cosθ effect." The insert shows the gamma-ray spectrum in the implantation measurement; the setting of the 14-keV channel is indicated.

tor by scattering. In all cases the catcher foils were nominally just thick enough to stop the recoils, since excessive thickness would unduly attenuate the 14-keV gamma rays. The counting rate in the 14-keV channel was typically 100 counts/sec. The Mössbauer resonance was analyzed using an electromechanical velocity spectrometer operating in the time mode.[6] The γ detector was a 2-in. diam xenon-filled proportional counter.

The velocity spectra obtained for implantation in Cu, Al, and Au are shown in Fig. 2. The absorber was 0.35 mg/cm^2 of ^{57}Fe in enriched $Na_4Fe(CN)_6 \cdot 10H_2O$ and gave a single line of width 0.36 mm/sec (full width at half-maximum). For comparison a spectrum obtained with a source of ^{57}Co diffused into Cu is also shown. Figure 3 shows the complete hyperfine spectrum for ^{57}Fe recoils implanted in Fe metal as observed with an Fe-metal absorber (1.9 mg/cm^2 of 91% ^{57}Fe) and the same spectrum for ^{57}Co diffused into Fe for comparison. The insert in Fig. 3 shows the γ-ray spectrum observed through the absorber in the implantation experiment. The signal-to-background ratio in the 14-keV channel is typically between 30 and 45%.

All pertinent results are summarized in Table I. Within the stated accuracies the hyperfine parameters and recoil-free fractions for recoil-implanted ^{57}Fe do not differ from the values observed for ^{57}Fe produced by ^{57}Co diffused into similar media. One may conclude that in Cu, Au, and Fe (for Al the comparison is incomplete), the recoil nucleus reaches a normal lattice site within a time of 10^{-7} sec at a temperature of 300°K. The centroids of the resonance lines for ^{57}Co diffused in Cu and ^{57}Fe implanted in Cu can be compared directly and they agree within 2×10^{-2} mm/sec. If attributed entirely to a thermal shift, this limit indicates that the local temperature of the implanted ion is within 30° of room temperature after 10^{-7} sec.

In a run with 100 mg/cm^2 of $(Fe, Mg)_2SiO_4$ as a catcher, no effect larger than 0.5% was observed. If the recoil-free fraction in olivine at room temperature is taken to be 0.7, one may conclude that no more than 20% of the implanted Fe atoms find an Fe or Mg site or, alternatively, that the recoil-free fraction for these atoms is less than 0.1 due to an elevated local temperature.

Table I. Parameters measured at 300°K for ^{57}Fe implantation (RI) and for diffused ^{57}Co sources (D).

Host	Method	Dip (%) Exp.	Corr.	Width[a] (mm/sec)	Shift versus Fe (mm/sec)	$\frac{1}{2}e^2qQ$ (mm/sec)	H_{int} (kOe)
Cu	RI	6.1 ± 0.5	21 ± 5	0.37 ± 0.02	-0.23 ± 0.01	≤ 0.03	...
	D	27.2 ± 0.3	30 ± 3	0.36 ± 0.01	-0.23 ± 0.005	0	...
Al	RI	2.6 ± 0.2	8.5 ± 2	0.8 ± 0.1	-0.31 ± 0.02	≤ 0.45	...
	D	...	...	...	-0.23[b]	...	...
Au	RI	3.9 ± 0.3	20 ± 5	0.48 ± 0.05	-0.63 ± 0.01	≤ 0.1	...
	D	...	24.5[c]	0.43[c]	-0.62[c]	≤ 0.05	...
Fe	RI	7.1 ± 0.4[d]	27 ± 5[d]	0.6 ± 0.05[e]	0.00 ± 0.02	≤ 0.1	336 ± 8
	D	26.0 ± 0.3[d]	29 ± 2[d]	0.6 ± 0.03[e]	0.00 ± 0.005	0	333 ± 3[f]

[a]Full width at half-maximum.
[b]For a 50-50 Fe-Al alloy from K. Ôno, Y. Ischikawa, and A. Ito, J. Phys. Soc. Japan 17, 1747 (1962).
[c]Calculated from relative values versus Cu from W. A. Steyert and R. D. Taylor, Phys. Rev. 134, A716 (1964).
[d]For the central line.
[e]Large value due to thick absorber.
[f]From R. S. Preston, S. S. Hanna, and J. Heberle, Phys. Rev. 128, 2207 (1962).

These observations have shown that it is possible to study ion implantation with the Mössbauer effect under varied and controlled conditions. The method can obviously be extended to various solid-state problems, to the measurement of polarization in nuclear reactions, and to other Mössbauer nuclei which cannot be studied with radioactive sources or with standard implantation techniques in which background radiations prove troublesome.

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OBSERVATION OF THE LONG-RANGE CORRELATION EFFECT IN THE RAYLEIGH LINEWIDTH NEAR THE CRITICAL POINT OF Xe†

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This Letter reports the observation of deviations from the Landau-Placzek theory[1] of Rayleigh scattering of light in xenon near the critical point by means of optical homodyne spectroscopy.[2,3] In the basic theory of inelastic scattering of light by fluctuations in a fluid, Landau and Placzek predicted that the observed quasielastic Rayleigh line should have a linewidth dependence

$$\Delta\omega_{1/2} = \chi_0 |\vec{K}|^2, \quad (1)$$

where χ_0 is the thermal diffusivity of the medium. The wave vector $\vec{K}$ of the Kth Fourier component of entropy fluctuation is related to the incident light wave in the medium $\vec{k}$, by $|\vec{K}| = 2|\vec{k}|\sin\frac{1}{2}\theta$, with θ the scattering angle. Previously, preliminary quasielastic-scattering experiments conducted near critical points[3-7] have indicated reasonable agreement with the Landau-Placzek theory. However, Fixman[8] and Felderhof[9] noted that the presence of long-range correlations near the critical point will