nances. Because of the complexity of the spectrum, no definite assignment can be made to these peaks at this time.

Finally, we note that an interesting characteristic of the trapped-electron method as applied to the study of states in the ionization continuum is the unusually high visibility of negative-ion resonances as compared to autoionizing states. In the studies of both He [6] and Ne only one peak in the trapped-electron spectrum corresponds unambiguously to the energy of an autoionizing level. The absence of any peaks at the energies of other known levels leads to the suggestion that all the visible structure in the trapped-electron spectra of He and Ne may be due to interference effects of negative-ion states, and that excitation to autoionizing states leads to an undetectably small change in the large number of slow electrons from direct ionization. Should this suggestion prove to be true, it becomes imperative that energy scales be calibrated by direct methods such as used in the present study as opposed to indirect calibrations performed by comparing peaks in the trapped-electron spectrum to known autoionizing levels in the target species. One must also adopt a more cautious attitude in the interpretation of trapped-electron spectra in the energy region of negative-ion resonances.

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PRESERVATION OF ALIGNMENT OF RECOILING NUCLEI AND DETECTION WITH THE MÖSSBAUER EFFECT*

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The nuclear alignment following Coulomb excitation was detected by observing directly the sublevel populations with the quadrupole Mössbauer effect. The alignment was preserved in flight from the target to a single crystal of Zn by frequent collisions with gas molecules. The hyperfine magnetic field acting on the recoil nuclei in flight was determined by observing the residual alignment for different gas pressures.

The sublevel populations of an excited nuclear level resulting from a nuclear reaction have been observed directly with the Mössbauer effect. The 14-keV level of ^{57}Fe was Coulomb excited by ^{16}O and ^{35}Cl projectiles from the Stanford Model FN tandem accelerator. The ^{57}Fe recoils emitted from the target at angles between 10° and 25° to the beam axis were allowed to implant into a single crystal of Zn in the apparatus shown in Fig. 1. For recoils ejected at 0° the projection of the spin of the recoil nucleus along the beam direction is a constant of the motion, and only the $m = \pm\frac{1}{2}$ sublevels of higher states are excited. For direct excitation of the $\frac{3}{2}^-$, 14-keV level of ^{57}Fe only $m = \pm\frac{1}{2}$ sublevels would be populated. However, most of the excitation proceeds through excited states which decay to the 14-keV level and produce a small dealignment.[1,2] The expected population ratio of the $m = \pm\frac{1}{2}$ and $m = \pm\frac{3}{2}$ sublevels is dependent on the projectile energy but typically is 4:1 for the conditions used. This large alignment can be preserved in flight by either decoupling the nuclear spin I from the atomic angular momentum J by application of a large magnetic field,[3] or by introducing a gas into the transit region so that the frequent collisions of the recoiling ion preserve the nuclear alignment.[4]

The aligned nuclei enter the single crystal of

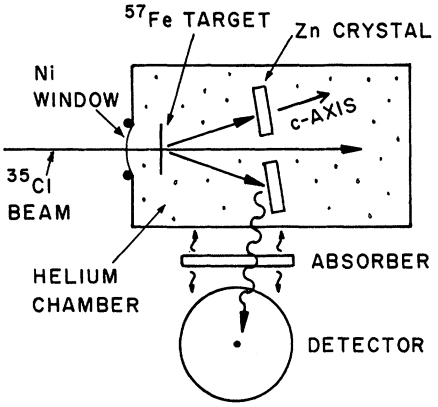

FIG. 1. Apparatus for detecting nuclear alignment with the Mössbauer effect. The Zn single crystal is tilted slightly to reduce absorption in the crystal.

Zn and are slowed down and stopped in about 10^{-12} sec. The stopped nuclei experience an electric field gradient along the c axis of the single crystal, which splits the $\frac{3}{2}^-$, 14-keV level into its two components with $m = \pm\frac{1}{2}$ and $m = \pm\frac{3}{2}$. The radiations from these two separate components will have separate angular distributions about the c axis of the Zn single crystal. At a given angle the line intensities were determined by analysis with a single-line Mössbauer absorber. The upper spectrum in Fig. 2(a) was taken with vacuum in the transit region, and the ratio of intensities of the two lines is consistent with no alignment of the implanted ^{57}Fe recoils and an average angle of observation of 120° between the c axis of the crystal and the Mössbauer detector. In the lower spectrum, the geometry was unchanged but He gas was admitted into the target chamber. The increased intensity of the lower velocity line reflects directly the increased population of the $m = \pm\frac{1}{2}$ sublevels.

The alignment deduced from the data in Fig. 2(a) is 81% of the predicted alignment. As we expect some loss of alignment in flight for the He pressure used, we conclude there is very little dealignment associated with the slowing-down process and subsequent interactions in the crystal. In particular, the Fe nucleus does not experience any electric field gradient perpendicular to the c axis which is as strong as that along the c axis and lasts for more than $\approx 10^{-9}$ sec. Also the relaxation time of the nuclear spins is long compared with the 150-nsec lifetime of the 14-keV level.

By studying the preservation of the alignment in flight between the target and the catcher, information about the hyperfine interactions of

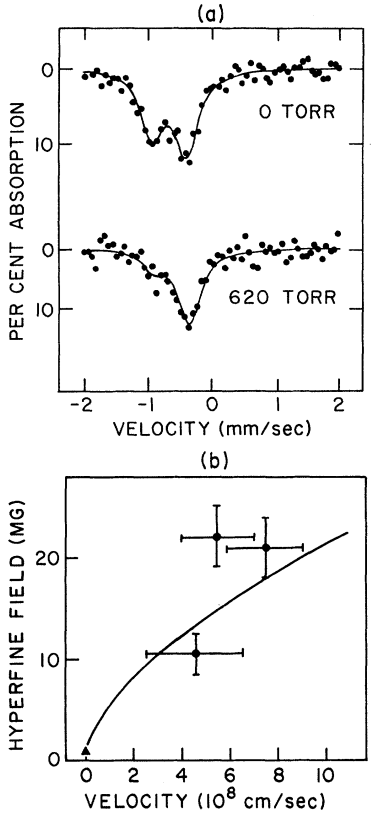

FIG. 2. (a) Mössbauer spectra for ^{57}Fe nuclei implanted in Zn for two different pressures of He gas. (b) Velocity dependence of the hyperfine field. The triangle, plotted at zero velocity, is from Ref. 6 and the smooth curve is the empirical relation $H = 0.4Z(100v/c)^{0.8}$ MG given by Ref. 7.

highly stripped free atoms can be obtained. In an earlier experiment[5] a magnetic field of 5 kG was applied along the beam direction in the transit region. The alignment observed[5] was 41% of the alignment predicted, indicating that the decoupling of the nuclear spin from the electron angular momentum was not complete. We can make an estimate of the effective field acting on the Fe nucleus while in flight since the precession frequency of the electronic angular momentum J about the external field B must be about equal to the precession frequency of the nuclear angular momentum about J. Hence,

$$H_{\mathrm{eff}} \approx (\mu_e/\mu_n) H_{\mathrm{ext}} \approx 10^7 \text{ G}.$$

More accurate measurements of this field were made by allowing the ions to recoil into He gas at different pressures. For a rapidly fluctuating magnetic field induced by the frequent collisions, the alignment will be given as a function of time

Table I. Summary of alignment data.

Run number	Recoil velocity (10^8 cm/sec)	Travel time (nsec)	He pressure (Torr)	Holding field (kG)	Alignment (% of maximum)
1	4.5 ± 2[a]	13	0	0	9 ± 7
			100	0	16 ± 7
			360	0	58 ± 13
			680	0	64 ± 13
2	4.5 ± 2[a]	2.5	0	0	0 ± 7
			0	5	41 ± 9
3	7 ± 1.5[b]	2.5	0	0	6 ± 8
			240	0	23 ± 10
			370	0	35 ± 11
			500	0	55 ± 14
			600	0	81 ± 11
4	5.5 ± 1.5[c]	3	240	0	27 ± 8
			370	0	29 ± 11

[a] 25-MeV ^{16}O beam.
[b] 40-MeV ^{35}Cl beam.
[c] 40-MeV ^{35}Cl beam with 0.6-mg/cm^2 Ni foil used to degrade recoil velocity.

by

$$A(t) = A(0)e^{-2\omega^2 t\tau_c}, \quad (1)$$

where ω is the Larmor precession frequency in the effective hyperfine field, and τ_c, the correlation time, is given by

$$1/\tau_c = \pi v N(r_{\mathrm{Fe}} + r_{\mathrm{He}})^2,$$

where v is the velocity of the recoiling ion, N is the number of He atoms per unit volume, and r_{Fe} and r_{He} are the radii of the Fe ion and the He atom, respectively. We used $r_{\mathrm{Fe}} = 0.88$ Å and $r_{\mathrm{He}} = 0.81$ Å. In our case, we observe the alignment remaining after the travel time T. Since the interaction acts only during this time, we observe that $A(T) = A(0)\exp(-2\omega^2 T\tau_c)$.

The alignment measured at different pressures of He gas and at different recoil velocities is shown in Table I. For each range of recoil velocities, the effective magnetic field acting on the recoil nuclei was calculated from Eq. (1). These fields are shown in Fig. 2(b) along with the neutral atomic-beam measurement.[6]

The velocity dependence of the effective field is in agreement with either a linear relationship or the $v^{0.6}$ behavior suggested by previous experiments,[7] and the fields are smaller than those in heavier elements moving at the same velocity. However, these fields are still sufficiently large to produce measurable perturbations of the angular distributions of states with $\tau \approx 10^{-11}$ sec.

The measurement of magnetic moments of states with lifetimes in the 10^{-11}-sec range by means of these large internal fields is now in progress in this laboratory. An experiment is also underway to utilize the measured electric field gradient in a Zn crystal to determine the quadrupole moment of an excited nuclear state.

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SUBSTANTIAL NUCLEAR ORDERING IN SOLID He^3†

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Evidence for a substantial nuclear ordering in solid bcc He^3 at melting pressure has been inferred from solid entropies s_S deduced from measurements of the slope of the melting curve for a liquid-solid mixture cooled by adiabatic compression. At 3.4 mK we find experimentally that $s_S/R = 0.83 \ln 2$. It is likely that much lower temperatures and solid entropies are obtained during parts of the experiments. The possibility for bulk nuclear polarization is also discussed.

It is possible to convert an ordered Fermi liquid to a solid with ordered nuclear spins.[1] More specifically, highly ordered liquid He^3 may be produced readily at temperatures of 10 to 20 mK, a temperature region easily attained by dilution refrigeration, since liquid He^3 is a Fermi liquid with an effective Fermi temperature much greater than 20 mK. Isentropic conversion of liquid to solid should then produce a highly nuclear-spin-ordered solid. Quantitatively, the ordering of the solid may be measured by its entropy. In this work we determined the solid entropy by measuring the slope dP/dT of the melting curve and using the Clausius-Clapeyron equation

$$\frac{dP}{dT} = -\left(\frac{s_S - s_L}{v_L - v_S}\right), \tag{1}$$

where s_S, v_S and s_L, v_L are the molar entropy and volume on the melting curve for the solid and liquid phases, respectively. Alternatively, nuclear ordering could be observed by forming the solid in a strong magnetic field and measuring the bulk nuclear magnetic moment. This has not been done in the present experiments, but work along these lines is in progress.

At temperatures below a few tenths of a kelvin the entropy of solid He^3 results from disorder in the nuclear-spin system. In zero external field, the spins may be described by an effective spin Hamiltonian[2]

$$\mathcal{H} = -J\sum_{ij} \vec{I}_i \cdot \vec{I}_j, \tag{2}$$

where J is a parameter, and the sum is usually assumed to be over nearest neighbors. Using data of Anderson, Reese, and Wheatley[3] we showed[4,5] that $J < 0$, in agreement with recent measurements by Pipes and Fairbank[6]; Kirk, Osgood, and Garber[7]; and Sites, Osheroff, Richardson, and Lee.[8] Hence in zero external field, antiferromagnetic nuclear ordering is to be expected at low enough temperatures.

In recent work we demonstrated[4] that it is possible to cool a two-phase mixture of liquid and solid He^3 mechanically to temperatures below 3 mK. However, we did not determine the resultant nuclear ordering. In some preliminary work we measured the nuclear-spin diffusion coefficient D in a solid formed by adiabatic compression. We found that, at the lowest temperatures, D had decreased to about $\frac{2}{3}$ of its temperature-independent value at higher temperatures.[9] This result indicated that something interesting was happening in the nuclear-spin system. However, we interrupted the diffusion measurements in favor of the melting-curve measurements since these have the double advantage of yielding a direct measurement of solid entropy and of being much less sensitive to thermal disequilibrium in the solid nuclear-spin system.