detector and the total probability that a neutron entering the phosphor will make at least one collision with hydrogen is

$$\epsilon=\frac{p_1 f_1}{1-p_2 f_2}+\frac{p_1 f_3 p_2^* f_1^*}{(1-p_2 f_2)(1-p_2^* f_2^*)},$$

where the following notation is used: L=length of plastic phosphor; n_H and n_C=respective densities of hydrogen and carbon atoms in detector; σ_H and σ_C=respective neutron elastic scattering cross section in hydrogen carbon; σ_{Ci}=neutron inelastic cross section in carbon; $\sigma_t=(n_H/n_C)\sigma_H+\sigma_C+\sigma_{Ci}$, $f_1=(n_H/n_C)\sigma_H/\sigma_t$, $f_2=\sigma_C/\sigma_t$, $f_3=\sigma_{Ci}/\sigma_t$; $p_1=1-\exp(-n_C\sigma_t L)$; p_2 is defined and approximated as in reference 6; p_2^*, f_1^*, and f_2^*=respective values of p_2, f_1, and f_2 at an energy $(E-T)$; E is the energy of incoming neutrons, and T is the threshold for inelastic scattering of neutrons by the carbon. This formula is derived in essentially the same way as the formula in the Appendix of reference 6.

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Nuclear Zeeman Effect in Sn^{119}†

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Ferromagnetic alloys of manganese and tin have been used to obtain large internal magnetic fields at the tin nuclei. The resultant Zeeman splittings of the two low levels of Sn^{119} have been measured by observing the hyperfine spectra in the resonant absorption of the 24-kev radiation of Sn^{119}. In Mn_4Sn an internal field of roughly 40 koe was found. In this field the splitting of the ground state was observed but that of the excited state was unresolved. In Mn_2Sn an internal field of about 190 koe was produced. In this field additional structure was obtained which was attributed to the splitting of the excited state. The measured splitting gives a value of (0.78±0.08) nm for the magnetic moment of the excited state.

THE Mössbauer absorption and scattering by the 24-kev level of Sn^{119} has been studied in some detail by several investigators.[1,2] With nonferromagnetic sources and absorbers, no magnetic splitting of the nuclear levels has been reported. In this communication we describe a series of measurements on ferromagnetic alloys of tin in which we have observed the nuclear Zeeman effect in the resonant absorption in Sn^{119}.

The source of radiation was metallic tin containing Sn^{119m}. This radioactive tin had been prepared three years earlier by a six-month irradiation of natural tin metal in the Argonne research reactor. After irradiation the active tin was heated to 1000°C to drive off the contaminant Sb^{125} which has a 2-yr half-life and produces a 27-kev x ray. Sources having a strength of roughly 100 μC were prepared by rolling the active metal into foils approximately 1 mil thick and using circular pieces of this foil $\frac{1}{2}$ in. in diameter. A source was held rigidly by clamping it against a solid backing with a thin beryllium disk. In most of the work the radiation from the source was filtered by a 2-mil palladium foil in order to reduce greatly the 25-kev x ray from tin. The radiation was detected by means of a sodium iodide crystal, 40 mil thick and 2 in. in diameter. Velocity spectra were obtained by moving the source back and forth by means of the lead screw of a lathe, as in our previous work on the Fe^{57} nucleus.[3] In all the observations both source and absorber were kept at about 80°K by mounting them in vacuum on the bottoms of metal cans containing liquid nitrogen. The 24-kev radiation passed through 2-mil Mylar windows in the walls of the vacuum chambers. The absorber was mounted rigidly by clamping it between two thin pieces of beryllium.

At the top of Fig. 1 is shown the absorption spectrum obtained with a pure tin absorber (a 2-mil metal foil of natural tin). With this absorber only a single resonant line, symmetric about zero velocity, is observed. The width of this line is approximately three times the width which can be attributed to the natural width of the nuclear level. The cause of this broadening has not been investigated in detail.

The first alloy studied was Mn_4Sn (or possibly $Mn_{11}Sn_3$) which was reported[4,5] to be ferromagnetic

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[5] H. H. Potter, Phil. Mag. **12**, 261 (1931).

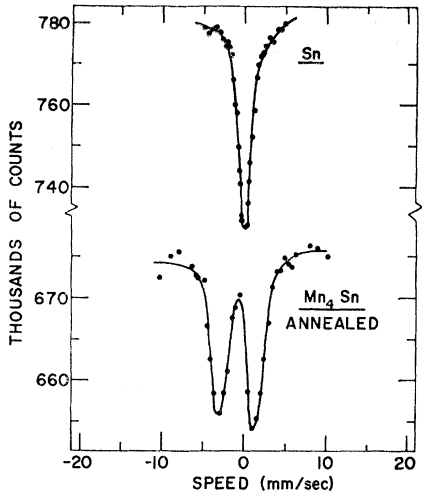

FIG. 1. Resonant absorption spectra of the 24-kev radiation from Sn^{119m}. Top: pure tin absorber in the form of a 2-mil metal foil of natural tin. Bottom: annealed Mn_4Sn absorber 67 mg/cm² thick.

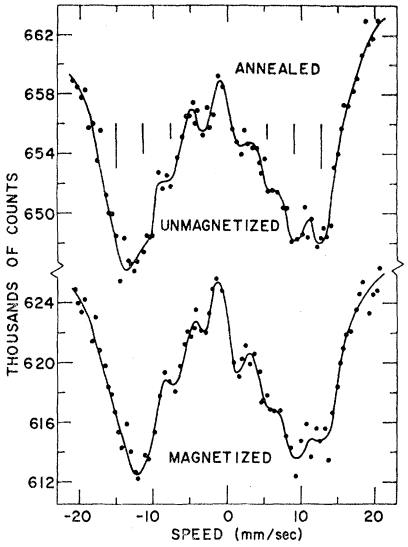

FIG. 3. Resonant absorption of the 24-kev radiation from Sn^{119m}. Top: annealed Mn_2Sn absorber 80 mg/cm² thick. Bottom: same absorber immersed in a magnetic field of about 600 oe.

with a transition temperature of about 150°C. Samples were prepared by mixing manganese and natural tin in the (atomic) ratio four to one and arc-melting the mixture in a helium-argon atmosphere. X-ray examination showed only one crystal structure in these samples. Furthermore, the material was magnetic at room temperature. This alloy and others used in this investigation were so brittle that it was not possible to roll them into thin films for use as absorbers. Instead, the samples were ground to a fine powder with a mortar and pestle. The powder was then suspended in acetone and allowed to settle uniformly on a beryllium disk. With these ferromagnetic samples, it was invariably found that the structure observed in the absorption spectrum became considerably sharper if the absorbers were annealed. Accordingly, each powder sample, mounted on beryllium, was annealed in vacuum for 8 hr at 450°C. After annealing the layer of powder was sometimes "sealed on" by spraying it with Krylon.

The velocity spectrum obtained with an annealed Mn_4Sn absorber, 67 mg/cm² thick, is shown at the bottom of Fig. 1. The single line observed with pure tin has been split magnetically into two prominent lines. The asymmetrical location of these lines (at about +1.5 and −3.0 mm/sec) is undoubtedly due, in part at least, to the difference in composition between the source and the absorber. The spins and parities of the ground state and first excited level of Sn^{119} are $\frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively, so that for $M1$ radiation the basic hyperfine pattern consists of six lines. Two possible cases are illustrated in Fig. 2. Since the radiation emitted by the nonmagnetic source is unsplit (monoenergetic), the structure observed with Mn_4Sn should contain the six lines of Fig. 2. We conclude that each of the two lines in the Mn_4Sn spectrum is an unresolved triplet, so that the splitting in the excited state of Sn^{119} is smaller than in the ground state, as is the case in Fig. 2. This result is in agreement with the work of the Saclay group[6] who observed the splitting in an external magnetic field of 20 koe. With this interpretation, the splitting observed in the Mn_4Sn spectrum is approximately equal to the ground-state splitting. Since the magnetic moment of the ground state is −1.041 nm,[7]

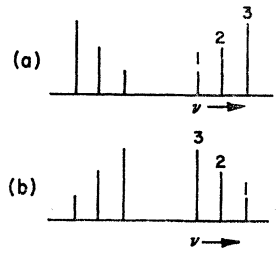

FIG. 2. Hyperfine spectrum emitted (or absorbed) by Sn^{119} in magnetic field (for $M1$ radiation). Top: $3\mu_g = -4\mu_{ex}$. Bottom: $\mu_g = +2\mu_{ex}$. The numbers give the relative intensities of the lines.

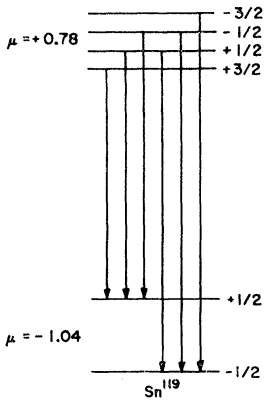

FIG. 4. Energy level diagram of Sn^{119} in a magnetic field. The magnetic dipole transitions are shown.

[6] J. L. Picou, J. Quidort, R. Barloutaud, and E. Cotton (to be published).

[7] W. G. Proctor, Phys. Rev. **79**, 35 (1950).

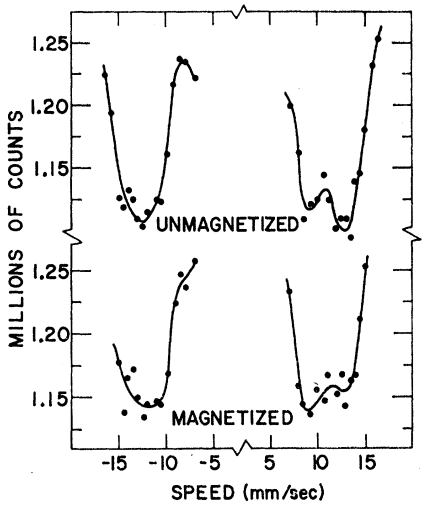

FIG. 5. Resonant absorption of the 24-kev radiation from Sn^{119m} in the range of 5–18 mm/sec. Top: Mn_2Sn absorber, unmagnetized. Bottom: same absorber, magnetized.

the measured splitting gives a value of roughly 40 koe for the internal field at the tin nucleus in Mn_4Sn.

In the hope of obtaining an internal field large enough to resolve the splitting of the excited state, the alloy Mn_2Sn was investigated. This alloy was reputed to show enhanced magnetic properties below 0°C.[5] Absorbers were prepared from the appropriate mixture of manganese and tin in the manner described above. The spectrum observed with an absorber 80 mg/cm² thick is shown at the top of Fig. 3. The lines at about +1.5 and −3.0 mm/sec are attributed to the presence of Mn_4Sn in the sample. The intensity of these lines was found to vary in different batches of alloy, while the other structure in the spectrum retained its main features. Although this latter structure which is attributed to Mn_2Sn is incompletely resolved, one can easily distinguish six lines with spacings and intensities in qualitative agreement with the pattern in Fig. 2(a). There is some evidence for some nonuniformity of the splitting within each triplet, which would indicate a displacement of the magnetic sublevels by quadrupole interaction.

The energy level diagram shown in Fig. 4 is based on this interpretation of the spectrum from Mn_2Sn. (The possible quadrupole displacement of the lines is not included.) The hyperfine lines in Fig. 2(a) correspond to this level diagram. The splitting in the ground state is $2\mu_g H_n = (16.0 \pm 1.0)$ mm/sec in velocity units. The magnetic moments in the ground and first excited states are designated by μ_g and μ_{ex}, respectively, and the internal field at the nucleus by H_n. With $\mu_g = -1.041$ nm, we obtain $H_n = (192 \pm 12)$ koe. In the excited state the splitting is (4.0 ± 0.2) mm/sec. Hence, $\mu_{ex} = (0.78 \pm 0.08)$ nm. We note that μ_{ex} is positive since μ_g is negative.[7] The value of +0.78 nm is in good agreement with the prediction of the shell model. A pure $d_{\frac{3}{2}}$ level would give a value of +1.15 nm (Schmidt limit). Empirically, $d_{\frac{3}{2}}$ levels have values of the magnetic moment which cluster around +0.8 nm.

The spectrum at the bottom of Fig. 3 was obtained with the same sample of Mn_2Sn but it was placed in an external field of about 600 oe. This was done in an attempt to magnetize the sample to saturation so as to align the internal fields at the nuclei. In an aligned field the intensities of the lines in Fig. 2 change from 3:2:1 to 3:4:1, i.e., the central line in the triplet is enhanced. The absorber was mounted between the pole pieces of two small permanent magnets arranged in a parallel mounting. The whole assembly was then cooled to the temperature of liquid nitrogen. The spectrum in Fig. 3 is not entirely conclusive but is consistent with the expected enhancement of the central line. A second spectrum, obtained in order to improve the statistics, is shown in Fig. 5. At positive velocities the enhancement in the central line is well established; at negative velocities the two lines are not well resolved in agreement with the earlier observation in Fig. 3.

Note added in proof. In recent work both alloys have been studied above their transition temperatures. In the case of Mn_4Sn only a single absorption line is observed at a temperature of 165°C. With Mn_2Sn ($T_c = -10$°C) a poorly resolved doublet (separation≈1 mm/sec) remains at 20°C. These observations greatly strengthen the assumption that the structure observed at low temperature in both alloys is predominantly magnetic in character.

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