Magnetic Moment of the 26.8-keV State of ^{129}I Measured with the Aid of Superconducting Magnets*

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The magnetic moment of the 26.8-keV state in ^{129}I has been determined from the Zeeman effect of the 26.8-keV gamma line in an external field. The line was observed in a Mössbauer spectrometer with a vibrating ^{66}Zn ^{129}Te source cooled by liquid nitrogen. A K^{129}I absorber was mounted in a 50-kG superconducting magnet immersed in liquid helium. The absorption spectrum of the $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ transition consists of twelve Zeeman components when observed in the direction of the magnetic field. These components could not be resolved because their spacings are less than a linewidth. The shape of this unresolved spectrum, however, depends sensitively on the ratio of the magnetic moment of the excited state to that of the ground state. Analysis of such spectra by curve-fitting techniques yields $+2.84\pm0.05$ nm for the magnetic dipole moment of the 26.8-keV state.

IN this paper we report a measurement of the magnetic moment of the first excited state in ^{129}I by use of the Mössbauer effect. In addition to its obvious interest as a confirmation of a recent theoretical prediction,[1] this moment is important for the study of ferromagnetism in tellurium compounds such as Cr_2Te_3, and also because the ^{129}Te $\rightarrow$ ^{129}I decay is one of the few cases that are suitable for the Morita experiment[2] on nonconservation of parity in beta decay.

The Mössbauer effect has made it possible to observe the Zeeman effect in gamma-ray transitions. In some ferromagnetic materials (metallic ^{57}Fe and $Mn_2{}^{119}Sn$, for instance), the internal magnetic field is strong enough to produce a well-resolved hyperfine spectrum. There are, however, many cases in which the Zeeman structure cannot be resolved because the width of the components is larger than their spacing. The interpretation of such spectra observed in ferromagnetic compounds often becomes difficult, since it involves a least-squares adjustment in which the observed spectrum is fitted by a calculated spectrum characterized by some or all of the following parameters: (1) the Zeeman splitting $\mu_{gd}H/I_{gd}$ of the ground state, (2) the Zeeman splitting $\mu_{exc}H/I_{exc}$ of the excited state, (3) and (4) the quadrupole interactions in the ground state and excited state, (5) the isomer shift, (6) the width of a single component, and (7) the total intensity, i.e., the sum of the intensities of all the components. (The relative intensities of the individual components are usually known.)

As was first demonstrated by Heberle, Hanna, and Schulhof,[3] the absorption line of metallic ^{119}Sn can be split completely in an external field produced by a superconducting magnet. Even when the Zeeman spectrum is not resolved, the analysis of a spectrum obtained with a superconducting magnet is made simpler because the number of adjustable parameters is reduced. First, the isomer shift and the linewidth can be determined from a measurement at zero field. Next, it is usually possible to choose compounds with cubic lattices so that the quadrupole interactions vanish. After an external field of known strength is applied, the only remaining variable parameters are the Zeeman splitting of the excited state and the total intensity. (The magnetic moment μ_{gd} of the ground state, and therefore $\mu_{gd}H/I_{gd}$, is usually known.) Furthermore, it is natural to observe the photons in the direction of the field produced by the superconducting magnet, so that the $\Delta m=0$ components do not occur in the spectrum.

The method outlined above has been applied to a determination of the magnetic dipole moment of the 26.8-keV $\frac{5}{2}^+$ state of ^{129}I. The 70-min ^{129}Te activity was induced by irradiation of cubic ^{66}Zn ^{128}Te in a flux of 2×10^{13} neutrons cm^{-2} sec^{-1} in the Argonne research reactor. The ground state of ^{129}Te decays by beta emission, mainly to the 26.8-keV state in ^{129}I. Cubic K^{129}I absorbers were used in order to obtain single-line spectra at zero field. The sources, cooled by liquid nitrogen in a simple cryostat, are vibrated sinusoidally by a loudspeaker (Fig. 1); the cryostat and velocity drive are the same as in previous experiments.[4,5] The 26.8-keV gamma rays pass through a superconducting magnet[6] in which a K^{129}I absorber is mounted. Two different magnets have been used: one ($M7$) has a field of 54 kOe at 22 A, the other ($M8$) produces a field of 48 kOe at a current of 21 A. The gamma rays are detected by a $2\times\frac{1}{8}$ in. NaI crystal. The absorption spectra were recorded in the usual way[4] in the first subgroup of a 400-channel analyzer. Normalizing counts from a nonresonant part of the gamma spectrum were accumulated in the other subgroup. The velocity scale

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[1] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[2] M. Morita, Phys. Rev. **122**, 1525 (1961).
[3] J. Heberle, M. Schulhof, and S. S. Hanna, Rev. Mod. Phys. **36**, 407 (1964).
[4] H. deWaard, G. DePasquali, and D. Hafemeister, Phys. Letters **5**, 217 (1963).
[5] D. W. Hafemeister, G. DePasquali, and H. deWaard, Phys. Rev. **135**, B1089 (1964).
[6] J. Heberle, Rev. Mod. Phys. **36**, 408 (1964).

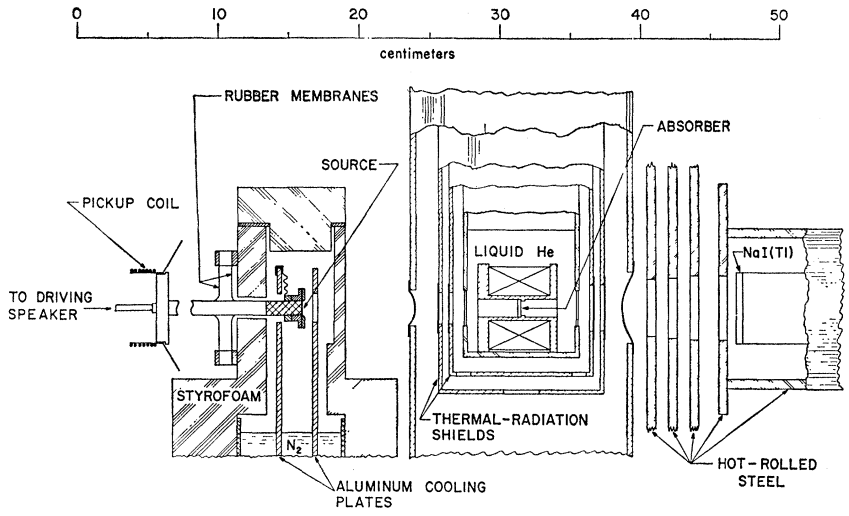

FIG. 1. Apparatus. The steel plates shield the photomultiplier from the stray field of the superconducting magnet.

was calibrated by means of the six-line spectrum[7] of metallic iron.

With a thick absorber (11.6 mg/cm^2 of $K^{129}I$), a linewidth of 1.4 mm/sec was observed in the absence of a magnetic field. At 54 kOe the spectrum shows considerable broadening, and two closely spaced minima are discernible near the center. The high-field spectrum was fitted to a 12-line spectrum calculated for the $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ magnetic-dipole transition in a longitudinal field. Fixed parameters in this calculation are: (1) The relative intensities of the components, proportional to the squares of the appropriate Clebsch-Gordan coefficients, (2) the Zeeman splitting of the ground state, namely, $2\mu_{gd}H_{ext}c/(7E_\gamma)=1.44$ mm/sec, computed from the known values of H_{ext} and of the magnetic moment[8] $\mu_{gd}=+2.617$ nm, and (3) a linewidth of 1.4 mm/sec obtained from the measurement at zero field. All components are assumed to have Lorentzian shapes of the same width. The only variable parameters in the curve fitting are the total intensity, the ratio ζ of the Zeeman splitting of the excited state to that of the ground state, the center of gravity of the spectrum, and the counting rate off resonance.

A possible objection to our curve-fitting procedure is that the calculated spectrum was obtained by linear addition of the components. This is rigorous only for very thin absorbers, for which nonlinear absorption effects are negligible. Since the linewidth measured at zero field is 40% larger than that obtained with a thinner absorber [Fig. 2(a)], it is not safe to assume that nonlinear absorption effects may be neglected. However, a calculation of the spectrum in which nonlinear effects are taken into account would be extremely complicated and has not been attempted. Instead, the reliability of the magnetic moment derived by our procedure was checked in two ways. Firstly, the curve

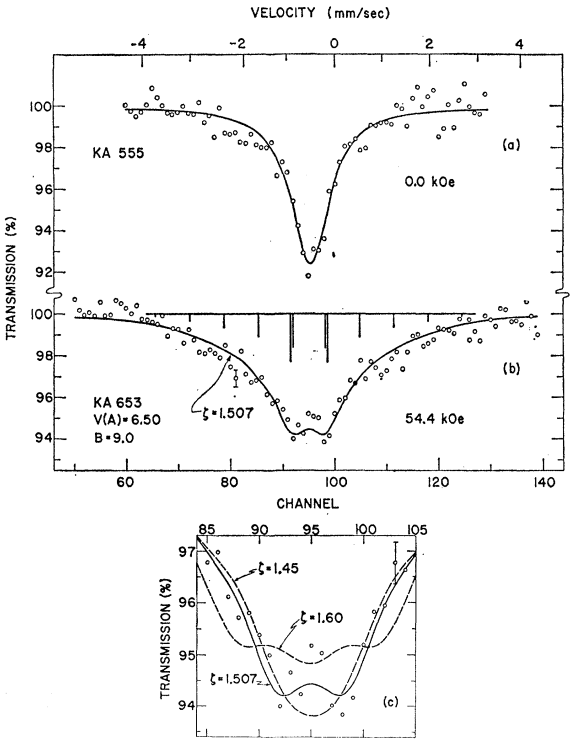

FIG. 2. Typical velocity spectra of the thin absorber (4.6 mg/cm^2 of $K^{129}I$): (a) In zero magnetic field. The solid curve has been obtained by adjusting the width for a best fit. (b) In a field of 54.4 kOe. The solid curve represents the best-fitting calculated spectrum, in which each component has the width obtained from curve (a). The twelve vertical lines indicate the positions and intensities of the twelve Zeeman components. (c) Central part of the Zeeman spectrum. The experimental points and the solid curve are taken from Fig. 2(b). The broken curves labeled $\zeta=1.45$ and 1.60 represent best fits (to the entire spectrum) with the value of μ_{exc} fixed at 2.71 nm and 2.99 nm, respectively.

[7] R. S. Preston, S. S. Hanna, and J. Heberle, Phys. Rev. 128, 2207 (1962).

[8] All values of nuclear magnetic moments were taken from the compilation of I. Lindgren, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964).

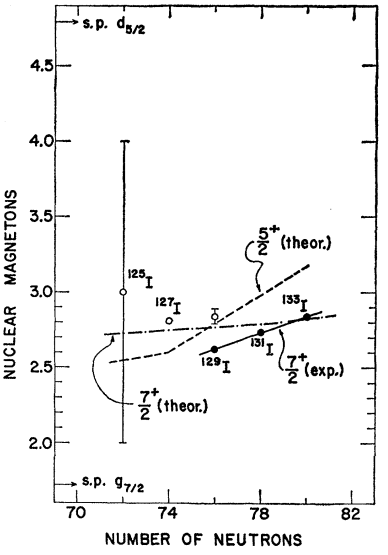

FIG. 3. Experimental and theoretical values of the iodine magnetic moments for $I=\frac{5}{2}$ and $\frac{7}{2}$. The arrows represent the single-particle estimates.

fitting was repeated for three different values of the linewidth. Secondly, spectra were measured with a thinner absorber (Fig. 2) and the same curve-fitting procedure was repeated, again for several different choices of the linewidth. The extreme values of the magnetic moment of the 26.8-keV state thus obtained differ by only 4.5%. The standard deviation of μ (26.8 keV) obtained with the thicker absorber is $+1.1\%$; with the thin absorber it is $\pm 1.3\%$. Taking into account these errors, we obtain μ (26.8 keV) $=+2.84\pm 0.05$ nm. The accuracy claimed here is supported by Fig. 2(c) which shows the calculated spectra for several different values of ζ, the ground-state splitting being kept constant. It is clear that the shape of the spectrum depends sensitively on the ratio of the magnetic moments.

In Fig. 3 are shown the magnetic moments of ^{129}I and of several other even-N iodine nuclei together with the moments computed by Kisslinger and Sorensen.[1] We note that our measurement is in good agreement with the theoretical value. Furthermore, we note that the measured moments of the $\frac{7}{2}^+$ states vary linearly with the neutron number. It is a fact[5] that the quadrupole moments of these $\frac{7}{2}^+$ states exhibit a similar linear trend, as do the quadrupole moments of the $\frac{5}{2}^+$ states. The question whether also the magnetic moments of the $\frac{5}{2}^+$ states obey such a linear relation awaits a more accurate determination of the magnetic moment of ^{125}I.

The magnetic moment of the 26.8-keV state of ^{129}I also provides an important parameter in the analysis of the Mössbauer spectra that can be obtained[5] with ferromagnetic compounds of ^{129}Te. These spectra are important in connection with the Morita experiment[2] on nonconservation of parity in beta decay. At present ^{129}Te is one of the few activities that are suitable for this experiment, in which beta particles emitted by a magnetized source must be detected in coincidence with a Mössbauer line.

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