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Nuclear magnetic moment of ^{59}Fe†

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The nuclear magnetic moment of ^{59}Fe has been determined to be $|\mu| = (0.29 \pm 0.03)\mu_N$ based on measurement of the anisotropies of the γ radiation emitted following the decay of ^{59}Fe oriented at low temperatures in Fe.

[NUCLEAR MOMENTS ^{59}Fe [from Fe(n,γ)]; measured $\gamma(\theta)$ from polarized nuclei; ^{59}Fe—deduced nuclear magnetic moment μ.]

Two recent publications[1,2] have indicated conflicting results for the magnetic moment of ^{59}Fe measured in nuclear orientation experiments. Tschanz and Sapp[1] oriented ^{59}Fe in crystals of rare-earth double nitrates, obtaining $|\mu| = (1.1 \pm 0.2)\mu_N$. Daly *et al.*[2] oriented ^{59}Fe in Fe, obtaining $|\mu| < 0.9\mu_N$. In order to resolve this conflict regarding the ^{59}Fe and further investigate the properties of the radiations emitted by ^{59}Fe, we have observed the angular distribution of γ radiation from the decay of oriented ^{59}Fe. As was done by Daly *et al.*, we have chosen to orient ^{59}Fe in Fe, but at temperatures down to 2.8 mK rather than 10 mK. In addition, the 192-keV γ ray in the ^{59}Fe decay was used to determine the magnetic moment. This γ ray is of low intensity, but has a large asymmetry. In analyzing the γ-ray angular distribution, we assume the distribution to be of the form,

$$W(\theta) = 1 + Q_2 B_2 U_2 A_2 P_2(\cos\theta) . \tag{1}$$

A description of the nuclear orientation formalism is given in the preceding paper. The P_4 term in the angular distribution vanishes owing to the $\frac{3}{2}$ spin of the initial state. For convenience we will let $a_2 = Q_2 B_2 U_2 A_2$ in the discussion following.

The ^{59}Fe decay scheme is illustrated in Fig. 1. In previous nuclear orientation work, the 1099- and 1292-keV γ rays were observed. Although the 1099-keV transition is established as pure-$E2$ radiation from previous work,[3,4] a possible small $M3$ admisture cannot be excluded for the 1292-keV transition.[5] The β decays to the 1099- and 1292-keV levels can be mixtures of Fermi and Gamow-Teller type decays. The β-γ circular polarization correlations ($\beta\gamma_{\mathrm{cp}}$) for the two decays have been measured previously.[6,7] The analysis of the $\beta\gamma_{\mathrm{cp}}$ results cannot be done unambiguously in terms of both the Fermi to Gamow-Teller ratio $y = C_V M_F / C_A M_{\mathrm{GT}}$ and the $M3/E2$ mixing ratio δ. Assuming $\delta = 0$, the $\beta\gamma_{\mathrm{cp}}$ data indicate that for the two β's of interest (see Fig. 1), $y(\beta_2) = -0.04 \pm 0.05$ and $y(\beta_3) = -0.15 \pm 0.04$. The deorientation parameter, U_2, for a $\frac{3}{2} \to \frac{3}{2}$ decay varies from 0.200 for a Gamow-Teller transition to 1.000 for a Fermi transition; thus, for $\delta = 0$, the $\beta\gamma_{\mathrm{cp}}$ results indicate $U_2 \approx 0.2$. Also, for a vanishing $M3/E2$ mixing ratio, $A_2 = -0.143$ for both the 1099- and 1292-keV transition. Thus $U_2 A_2 \approx -0.03$, and since $(B_2)_{\max} = 1$ and $Q_2 \lesssim 1$, it follows that $(-a_2)_{\max} = 0.03$. Tschanz and Sapp,[1] however, observed values of $(-a_2)$ as large as 0.14, while the values of Daly *et al.*[2] were $-a_2 < 0.01$. Assuming the γ rays to be pure $E2$, it follows that the β decays are essentially pure Gamow-Teller, and the results of Tschanz and Sapp then require an intermediate state reorientation resulting in an enhancement of the anisotropy by at least a factor of 5. Although, in principle, such enhancements may exist, the short half-lives of the intermediate states (see Fig. 1) compared with typical relaxation times (the order of seconds) make such effects extremely unlikely [to obtain $a_2 \approx -0.14$ ($\approx A_2$) requires complete alignment of the intermediate level].

γ-γ angular correlation results[5,8,9] for the 192-1099-keV cascade yield (using emission matrix elements for the mixing ratio[10]) $\delta(192) = +0.22 \pm 0.02$, assuming pure $E2$ for the 1099-keV transition. This yields $A_2(192) = -0.707 \pm 0.023$, and thus the anisotropy of the 192-keV transition yields a measure of B_2 5 times more sensitive than that of the 1099- and 1292-keV transitions. (Although the branching intensity of the 192-keV transition is significantly less than that of the 1292-keV transition, the increased detector efficiency for the former γ-ray relative to the latter compensates for most of the deficiency.)

The ^{59}Fe activity has been prepared *in situ* by

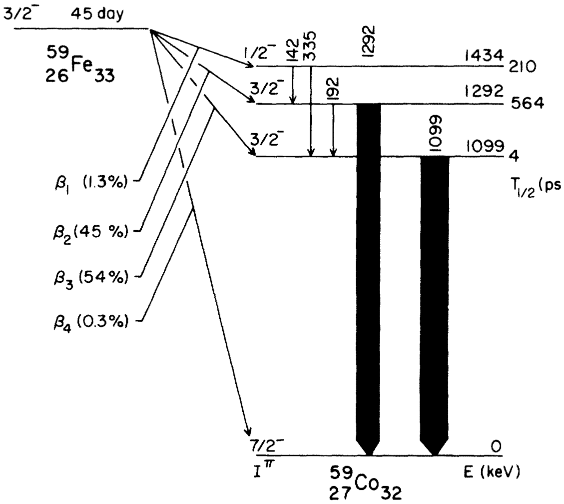

FIG. 1. The decay scheme of ^{59}Fe.

TABLE I. γ-ray anisotropies following the decay of oriented ^{59}Fe ($2.8\,\mathrm{mK} \le T \le 3.8$ mK).

E (keV)	$B_2U_2A_2$ (units of 10^{-4})
142	33 (157)
192	−277 (23)
335	391 (600)
1099	−43 (13)
1292	−79 (16)

irradiating 99.99% pure Fe metal foils (thickness 76 μm) with thermal neutrons in the Los Alamos Omega West reactor to obtain an activity of 3 μCi of ^{59}Fe. After irradiation, the foils were annealed in H_2 at 900°C for one hour. The samples were soldered with 99.999% pure indium to the cold-finger of a cerium magnesium nitrate demagnetization stage coupled to a ^{3}He-^{4}He dilution refrigerator.[11] The sample temperature was monitored using a ^{125}Sb *Ni* γ-ray anisotropy thermometer. A description of the apparatus and thermometry techniques is given in the preceding paper.[12]

Although the ^{59}Fe γ rays are expected to show small (or vanishing) anisotropies, the ^{125}Sb 428-keV anisotropy is large. Our experience in nuclear orientation experiments suggests that the live-time correction associated with the analog-to-digital converter introduces uncertainties in the measurement of small anisotropies when large anistropies are also present. For this reason we have placed a ^{60}Co source outside the cryostat in the vicinity of the detectors. The ^{60}Co γ rays provide an isotropic reference with which the small anisotropies of the 1099- and 1292-keV γ rays can be compared.

The measured γ-ray anisotropies are summarized in Table I. The results shown have been averaged over the temperature range 2.8–3.8 mK. Possible systematic uncertainties in these anisotropies were eliminated by comparison with the (vanishing) γ-ray anisotropies of the external ^{60}Co source, deduced to be $W(0°) = 1 - (0.0003 \pm 0.0011)$.

The ^{59}Fe orientation parameter can be determined from the 192-, 1099-, and 1292-keV anisotropies, which yield $B_2(192) = 0.180 \pm 0.031$, $B_2(1099) = 0.140 \pm 0.042$, and $B_2(1292) = 0.255 \pm 0.052$. The average value for the relative hyperfine splitting determined from these values is $\Delta/T = 0.663 \pm 0.034$. Taking an average temperature $T = 3.5 \pm 0.3$ mK and using a hyperfine field[13] $H = (-33.7 + H_{\mathrm{applied}})T$, we obtain

$$|\mu| = (0.29 \pm 0.03)\mu_N \ .$$

Although we have analyzed our data assuming the 1292-keV transition to be pure $E2$, the angular correlation data[5] suggest the possibility of a $M3/E2$ mixture with $\delta = -0.033 \pm 0.030$. This value of δ corresponds to $A_2(1292) = -0.173 \pm 0.029$, and we would expect the possibility of a 20% larger (negative) anisotropy for the 1292-keV transition compared to the 1099-keV transition. Our data are consistent with this expectation.

The anisotropies of the 142- and 335-keV angular distributions are vanishingly small, in agreement with the spin assignment of $\frac{1}{2}$ for the 1434-keV level.

The ^{59}Fe ground-state configuration can be represented by $(\pi f_{7/2})^6(\nu p_{3/2})^3(\nu f_{5/2})^2$ or perhaps $(\pi f_{7/2})^6(\nu p_{3/2})^1(\nu f_{5/2})^4$. The 14.4-keV $\frac{3}{2}^-$ level of ^{57}Fe has a similar configuration with two fewer neutrons and a magnetic moment of $\mu = -0.155\mu_N$.[14] The ^{59}Fe moment may also be compared with the moments of the $N = 33$ isotones, ^{61}Ni ($\mu = -0.750\mu_N$) and ^{63}Zn($\mu = -0.282\mu_N$).[14] Each of these differs considerably from the Schmidt value of $-1.9\mu_N$ for a $p_{3/2}$ neutron, indicating the importance of the more complex configurations in the nuclear structure of these states. Moreover, the variations in μ observed for the three $N = 33$ isotones indicate the influence of the proton configuration (the largest negative moment is that of the semi-magic ^{61}Ni).

A calculation of the magnetic moment of this level using the configuration mixing model of Noya, Arima, and Horie[15] gives $\mu = -0.29\mu_N$, a value in fortuitously excellent agreement with our measurement. The principal reductions of the moment below the Schmidt value come from the following admixtures (in order of decreasing size): $2p_{1/2} \leftrightarrow 2p_{3/2}$ and $1f_{5/2} \leftrightarrow 1f_{7/2}$ for neutrons, and $1f_{5/2} \leftrightarrow 1f_{7/2}$ for protons.

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