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Magnetic moments of the 2^+ first excited states of even iron isotopes

J. M. Brennan, N. Benczer-Koller, M. Hass,* and H. T. King
Department of Physics, Rutgers University, New Brunswick, New Jersey 08903 †
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The large magnetic fields that act on fast-moving ions traversing thin magnetized Fe foils were utilized to remeasure the magnetic moments of the first excited 2^+ states of ^{54}Fe and ^{58}Fe. The technique reported here does not require an accurate knowledge of the nuclear lifetime and does not depend on the static magnetic field of Fe in Fe. Assuming $g(^{56}\mathrm{Fe},2^+) = 0.61 \pm 0.08$, we obtain $g = 1.68 \pm 0.38$ and $g = 0.46 \pm 0.10$ for the first 2^+ states of ^{54}Fe and ^{58}Fe, respectively. The present results agree well with previous measurements and support the existing models for the structure of these states.

[NUCLEAR REACTIONS $^{54,56,58}\mathrm{Fe}(^{32}\mathrm{S},{}^{32}\mathrm{S}')^{54,56,58}\mathrm{Fe}^*(2_1^+)$ $E = 72$ MeV, enriched targets; measured $W(\theta, H, \infty)$ in polarized iron. Deduced $g(^{54}\mathrm{Fe}, 2_1^+) = 1.68 \pm 0.38$, $g(^{58}\mathrm{Fe}, 2_1^+) = 0.43 \pm 0.10$.]

Large transient magnetic fields have recently been observed for various ions recoiling at high velocity through magnetized iron.[1,2] These fields provide a technique for measuring the magnetic dipole moments of very short-lived excited states which does not require accurate knowledge of the lifetimes of the states and which is independent of the static magnetic field of the host on the recoiling ions. This paper reports on a new measurement by this technique of the g factors of the first excited states of ^{54}Fe and ^{58}Fe. The results obtained are in good agreement with previous measurements and demonstrate the reliability of the technique.

A beam of 72 MeV, 7^+ ^{32}S ions from the Rutgers-Bell tandem Van de Graaff was used to excite the first 2^+ states in ^{54}Fe, ^{56}Fe, and ^{58}Fe. The energies and lifetimes of these states are given in Table I. The experimental apparatus has been described in detail in a previous publication.[1] The targets were prepared by melting the enriched isotope and rolling it to a nominal thickness of 2.6 mg/cm^2. A measurement of the magnetization of the targets showed this procedure to be superior to evaporation. The targets were backed with an evaporated 10 mg/cm^2 copper layer.

The initial velocity of the recoiling ^{54,56,58}Fe ions was approximately $0.05c$. The ions slowed down in the iron to $0.027c$ before entering the copper layer where they came to rest. The copper backing provided a perturbation-free environment (on a ps time scale), and thus the only perturbation experienced by the Fe ions was caused by the transient field acting on the moving ions inside the iron layer. The time over which this perturbation acts is given not by the lifetime of the excited state, but by the transit time through the iron. For this reason, the measured precession is independent of the lifetime of the state provided the lifetime is longer than the transit time (typically 0.3 ps). Precession due to the static magnetic field on the ion in iron, complicated by radiation damage effects, is also eliminated.

The angular correlation between the backscattered S beam and the decay γ radiation was measured to be

$$W(\theta) = 1 + (0.58 \pm 0.04)P_2(\cos\theta) - (1.18 \pm 0.05)P_4(\cos\theta)$$

for all three isotopes, in agreement with the pure $\Delta m = 0$, $2 \to 0$ correlation expected for the particular geometry involved. The precession measurements were carried out with the γ-ray detectors at $\pm 67.5°$ and $\pm 112.5°$, where the slope of the correlation is large. The magnetization of the iron layer was reversed periodically by an external magnetic field under computer control, and the coincidence γ-ray spectra were routed accordingly. Both real and random coincidences were stored for each detector; the random coincidences were subtracted in the analysis. Photopeak intensities were used to form double ratios, defined as

$$\rho_{ij} = \left(\frac{N(\theta_i)\uparrow}{N(\theta_i)\downarrow}\,\frac{N(\theta_j)\downarrow}{N(\theta_j)\uparrow}\right)^{1/2}, \quad i,j = 1,2,3,4,$$

where $\theta_{1(4)} = \pm 112.5°$, $\theta_{2(3)} = \pm 67.5°$. $N(\theta_i)\uparrow$ represents, for example, the peak sum for the ith detector with the magnetic field up.

TABLE I. Energies and lifetimes of the first 2^+ states of even Fe isotopes.

Isotope	J^π	E^* (MeV)	Lifetime (ps)
^{54}Fe	2^+	1.41	1.4
^{56}Fe	2^+	0.85	10
^{58}Fe	2^+	0.81	11.7

TABLE II. Summary of the experimental results for the various targets used. The first two rows correspond to a S beam of 64 MeV (see text) and were reported previously (Ref. 1). $\Delta\theta$ is the measured shift.

Isotope	Effective iron layer thickness (mg/cm^2)	ρ_{14}	ρ_{23}	ρ_{13}	ρ_{24}	$\Delta\theta$ (mrad)
^{56}Fe	2.27	0.947(13)	1.051(13)	1.006(13)	0.991(13)	-9.2 ± 1.6
^{56}Fe	1.30	0.976(11)	1.040(11)	1.010(11)	0.986(11)	-5.6 ± 1.3
^{56}Fe	2.27	0.950(14)	1.048(14)	0.987(14)	1.001(14)	-8.7 ± 1.7
^{54}Fe	2.15	0.914(34)	1.155(34)	1.048(34)	1.013(34)	-21.4 ± 4.1
^{58}Fe	2.00	0.964(8)	1.034(8)	0.985(8)	1.009(8)	-6.2 ± 1.0

The symmetric-angle ratios ρ_{14} and ρ_{23} reflect the angular precession. The average double ratio $\rho=(\rho_{23}/\rho_{14})^{1/2}$ is free of systematic error and is related to the observed angular shift $\Delta\theta$ by

$$\Delta\theta=\frac{1}{S}\frac{\rho-1}{\rho+1}\,;\quad S=\frac{1}{W(\theta)}\frac{dW(\theta)}{d\theta}\bigg|_{\theta=67.5^\circ}.$$

The double ratios ρ_{13} and ρ_{24} should show no effect, and serve as a consistency check of the data. Table II lists the effective thickness of the iron layer, the measured value of ρ_{ij}, and the angular shifts determined for each target. The iron thicknesses reflect the average distance traversed by the recoiling ion originating in the front layer of the target.[1]

The net precession experienced by an ion in traversing the iron layer is given by

$$\Delta\theta=-\int_0^T g\frac{\mu_n}{\hbar}B[v(t)]\,dt\,,$$

where $B(v)$ is the strength of the transient field at ion velocity v, and T is the transit time through the iron. Previous results[1,2] suggest that this field can be described by the phenomenological expression

$$B=\mathcal{A}Z(v/v_0)^{\mathcal{P}}\,,$$

where Z is the charge of the moving ion, v_0 is the Bohr velocity $(e^2/\hbar)$, and $\mathcal{A}$ and $\mathcal{P}$ are free parameters. All existing data[1,2,9] are consistent with $\mathcal{P}=1.0$, for which the angular precession becomes

$$\Delta\theta=-g\frac{\mu_n}{\hbar}\frac{\mathcal{A}Z}{v_0}\int v\,dt=-g\frac{\mu_n}{\hbar}\frac{\mathcal{A}Z}{v_0}L\,,$$

where L is the thickness of the iron layer. Therefore the net precession depends linearly on L and is independent of both the initial ion velocity and the dE/dx of the ion in iron. The dependence on Z and the value of the parameter $\mathcal{A}$ do not play a role in the analysis.

Table III summarizes the results of this work. The indicated net precessions are obtained by

TABLE III. Final results of the present experiment. In column 5, IMPAC stands for ion implantation perturbed angular correlation and IPAC for integral perturbed angular correlation. $\Delta\theta_{net}$ for ^{56}Fe is the average of all ^{56}Fe measurements (Table II) as described in the text. $\Delta\theta_{net}$ were obtained by subtracting the beam-bending shift of (-1 ± 1) mrad from the measured $\Delta\theta$ (Table II) and scaling the ^{54}Fe and ^{58}Fe results to an effective target thickness of 2.27 mg/cm^2. g adopted (column 6) corresponds to the weighted average of the present and previous values for ^{54}Fe and ^{58}Fe and to a weighted average of previous results for ^{56}Fe.

Isotope	$\Delta\theta_{net}$ (mrad)	g Present work	g Previous work	Method	g Adopted
			0.60 ± 0.10	IMPAC [a]	
^{56}Fe	-7.9 ± 1.4		0.65 ± 0.10	IPAC [b]	0.61 ± 0.08
			0.60 ± 0.13	IPAC [c]	
^{54}Fe	-21.6 ± 4.3	1.68 ± 0.38	1.43 ± 0.28	IMPAC [d]	1.52 ± 0.22
^{58}Fe	-5.9 ± 1.6	0.46 ± 0.13	0.43 ± 0.10	IPAC [e]	0.44 ± 0.08

[a] Reference 3.
[b] Reference 4.
[c] Reference 5.
[d] Reference 6.
[e] References 7 and 8.

scaling the measured $\Delta\theta$'s to equal target thickness and subtracting a contribution of (-1 ± 1) mrad for the beam bending, measured using a nonmagnetic iron target. The values of the net precession are directly proportional to the g factor of the corresponding states. No correction has been applied for the small difference in recoil velocities of the Fe isotopes as the angular shift is independent of the initial ion velocity if the magnetic field $B(v)$ is proportional to v. The agreement of results for ^{56}Fe at 64 and 72 MeV (rows one and three of Table II) is consistent with this hypothesis. A different velocity dependence of B would not change the reported results by any significant amount.

The values of the g factors reported here for ^{54}Fe and ^{58}Fe are deduced from the net angular shifts assuming the value of $g = 0.61 \pm 0.08$ for the g factor of ^{56}Fe. This value was obtained by taking the weighted average of the results of various experiments indicated in column 4 of Table III. The errors assigned to the ^{54}Fe and ^{58}Fe g factors include the error in the g factor of ^{56}Fe in addition to the statistical errors in the net angular shifts.

The g factors obtained by the present high-velocity transient field experiment are in good agreement with previous results (Table III). For ^{54}Fe, the present result of $g = 1.68 \pm 0.38$ agrees with the value of $g = 1.43 \pm 0.28$ obtained by Hubler, Kugel, and Murnick[6] from a transient field experiment at lower velocity in which the ions stopped in the iron foil. The ^{54}Fe (2_1^+) result is consistent with a shell-model configuration of two proton $f_{7/2}$ holes. The previous result for ^{58}Fe, $g = 0.54 \pm 0.17$, was obtained by Singh *et al.*[7] from an integral precession measurement using the static field of Fe in Fe. Since that time a new and more accurate measurement of the lifetime of this state has been reported,[8] resulting in a change in the value of the g factor to 0.43 ± 0.10. The present measurement agrees well with this result and with the expected Z/A value for this state.

The agreement between the present measurements and previous results demonstrates the reliability of the technique reported here for magnetic moment measurements in this region of the Periodic Table. Additional experimental data on the Z and velocity dependence of transient fields at high velocity are currently being obtained.[9] Knowledge of the systematic behavior of these large fields would provide a general and very powerful method for the measurement of magnetic moments of states with lifetimes in the ps region.

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