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PRECESSION MEASUREMENTS OF THE 0.847-MeV LEVEL OF Fe^{56} IMPLANTED IN IRON AFTER A (p,p') REACTION*

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(Received 11 October 1967)

A number of magnetic moments of excited states have been measured recently using the high internal hyperfine fields acting on the excited nuclei embedded in polarized iron. All levels measured until now have been reached either by radioactive decay,[1] by resonance fluorescence,[2] or by Coulomb excitation with backscattered heavy ions.[3] In this Letter we report the first results of an integral precession by an internal magnetic field of a level which was populated by a nuclear reaction.

The nuclear reaction mechanism not only enables one to reach levels which may not be accessible by the above mentioned methods, but, as demonstrated in the present work, no anomalies in the hyperfine fields are observed. Such anomalies are seen in the high recoil implantation work[4,5] and complicate the extraction of magnetic moments from the measured precession angles.

The experiment was carried out on the 0.847-MeV ($\tau = 10.6$ psec) first excited state of Fe^{56}. Since the g value of this state is well known,[1,2] measurements on it are an excellent test of possible anomalies appearing after implantation; in particular, the "conical-field"[5] and the "transient-field"[4] models may be tested. The excellent agreement of the present results with those of Refs. 1 and 2 indicate that in this case neither type of anomaly is present. The technique is therefore applicable to short-lived states, and reliable magnetic moments may be deduced from the measured precession angles.

The first excited 2^+ level of Fe^{56} was excited by inelastic protons, and the precession of this level in the internal field in polarized iron was measured. The excited iron nuclei obtained have an average recoil energy of about 0.25 MeV, which is nearly a hundred times lower than the recoil energy of about 23 MeV obtained by Coulomb excitation of the same level with backscattered 33-MeV oxygen ions. The value of the internal field of iron in iron obtained from the present "low-recoil" measurement is $H_{int} = (-0.43 \pm 0.14) \times 10^6$ G, in full agreement with the "static" value, H_{int}(Fe-Fe)

$= -0.338 \times 10^6$ G,[6] and in clear disagreement with "high-recoil" Coulomb-excitation implantation results, $H_{\rm int}(\text{Fe-Fe}) = (-0.016 \pm 0.040) \times 10^6$ G.[4]

A natural-iron foil was bombarded with 7.8-MeV protons from the Massachusetts Institute of Technology Cyclotron. The first excited 2^+ level at 0.847 MeV ($\tau = 10.6$ psec) in Fe^{56} was strongly excited by the reaction $Fe^{56}(p, p')Fe^{56}$. The decay gamma rays were recorded by a 3-in.×3-in. NaI(Tl) detector and by a 7-cc (3.0-keV resolution) Ge(Li) detector. A weak line at the energy 0.811 ± 0.0015 MeV was seen with the Ge(Li) counter. This line and another line at the energy of 0.163 MeV were identified as transitions from levels in Co^{56}, which were excited by the reaction $Fe^{56}(p, n)Co^{56}$. These spurious peaks practically disappeared when a thin (0.005-in.) Mylar foil was inserted in front of the target [the Q value for the reaction $Fe^{56}(p, n)Co^{56}$ is -5.357 MeV].

The angular correlation of the 847-keV gamma radiation in coincidence with the inelastic protons backscattered from the first excited state into an annular ring counter was measured. The results of a short angular-correlation run, normalized to the number of elastically backscattered protons, indicated that the maximum relative slope of the angular correlation is $|W^{-1}dW/d\theta| \sim 0.8$.

The angular distribution (singles) of the 0.847-MeV gamma radiation was also measured using both Ge(Li) and NaI(Tl) counters. The data were normalized to the number of elastic protons recorded in a solid state detector placed at 90° to the beam and were corrected for the dead time of the multichannel analyzer. The angular distribution obtained with the NaI(Tl) counter is shown in Fig. 1. The solid line represents the best computer fit to the data, which is given by

$$W(\theta) = 1 + 0.188 P_2(\cos\theta) - 0.055 P_4(\cos\theta). \qquad \text{(a)}$$

This expression is quite similar to the distribution obtained by Gobbi, Pixley, and Sheldon,[7] who used 5.6-MeV protons to excite the first excited level in Fe^{56}.[8] A very similar distribution was obtained using the Ge(Li) counter. [The angular distribution of the weak $2^+ \to 3^+$ Co^{56} line, which was easily resolved in the Ge(Li) spectrum, turned out to be quite isotropic.]

If one compares the counting rates and the value of $W^{-1}dW/d\theta$ at the angles of maximum slope for the singles (about 100 counts/sec and $W^{-1}dW/d\theta = -0.32$) and coincidence (about 4 counts/sec and $|W^{-1}dW/d\theta| \sim 0.8$) runs, one may see the advantage of performing the precession measurements by counting the single gammas, rather than requiring coincidences with the inelastic protons. Singles precession measurements were therefore performed, using the Ge(Li) as well as the NaI(Tl) counters. The geometry for these measurements was identical to that in which the angular distributions were taken. The gamma counters were set at an angle of 60° to the beam, where $W^{-1}dw/d\theta$ equals -0.32. An external field of about 300 G was used to polarize the iron. This magnetic field was flipped alternately "up" and "down," and the counting rates under the 0.847-MeV line in both field directions [$N(\uparrow)$ and $N(\downarrow)$] were recorded. The precession angle ($\omega\tau$) was deduced from the ratio $[N(\uparrow) - N(\downarrow)]/[N(\uparrow) + N(\downarrow)]$.

Because of the small anisotropy of the $2^+ \to 0^+$ angular distribution, only a very small difference of about 0.5 % between the counting rates with field "up" and "down" is expected, and an accurate normalization is necessary. A built-in normalization independent of variations in beam intensity (dead time) and of slight "wandering" of the beam spot was obtained by exciting a "nonprecessing" level simultaneously with the iron line. The iron target was clamped

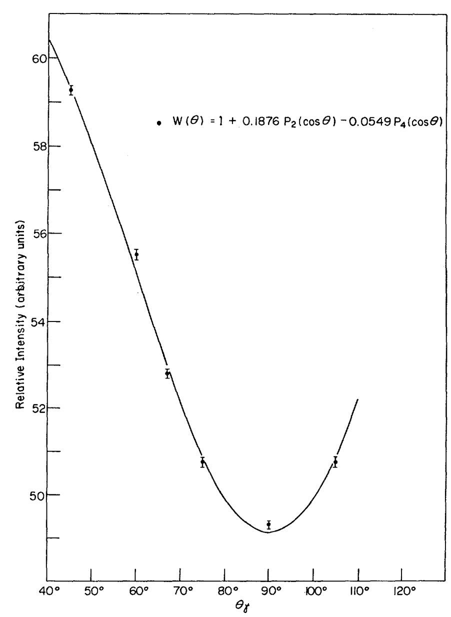

FIG. 1. Angular distribution of the 0.847-MeV gamma rays produced by 7.8-MeV protons incident on a natural iron target.

between two Mylar foils 0.005 in. thick. These foils had a two-fold purpose: (a) The 4.438-MeV, very short-lived ($\tau = 5.1\times10^{-14}$ sec), 2^+ state in C^{12} was strongly excited by the (p,p') reaction and served as a "nonprecessing" normalization. (b) The energy of the protons was reduced by the Mylar before hitting the iron, and the 0.811-MeV line could no longer be seen.

Three different sets of precession measurements were performed. In the first set of runs, a 7-cc Ge(Li) detector was used to detect the gamma rays, whereas in the second and third sets a 3-in.×3-in. NaI(Tl) detector was used. The polarizing magnetic field was switched in the first two sets every three minutes. In the third set the field was flipped approximately every 12 sec in order to eliminate any possible difference in normalization or in background between the spectra with field "up" and "down."

The proper routing of the multichannel analyzer was carefully checked by interchanging quadrants in which the spectra with field "up" and "down" were stored.

Typical counting rates for the three sets are the following: The number of counts under the 0.847-MeV peak was about 1.7×10^4, 1×10^6, and 3×10^5 for representative points in sets 1, 2, and 3, respectively. (The background under the peaks varied between 30 and 40 % for the various runs.) The number of counts under the carbon peak, which served for normalization, was typically 3.4×10^4 (second escape peak plus part of Comptons) for the Ge(Li) spectra, and about 1×10^6 and 2.5×10^6 (photopeak plus first and second escape peaks) for the NaI(Tl) spectra.

The precession angles calculated for the various runs are given in Fig. 2. The errors indicated are statistical errors only.

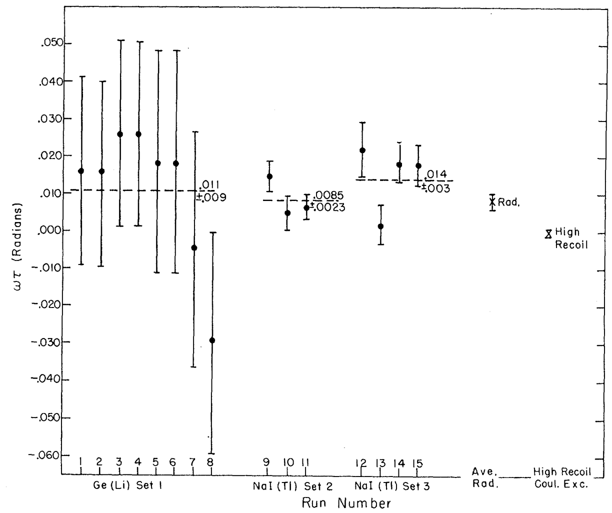

FIG. 2. Summary of three sets of precession measurements of the first excited 2^+ state in Fe^{56}. The averages of $\omega\tau$ for any one of the sets is given in the figure. The results for $\omega\tau$ obtained from radioactivity (Refs. 1 and 2) and high-recoil Coulomb excitation (Ref. 4) measurements are also shown.

The results of the precession measurements are compared in Table I with $\omega\tau$ values obtained by other techniques. The values of $H_{\rm int}$ given in the fourth column of Table I were calculated by use of the relationship

$$H_{\rm int}(\text{recoil}) = \frac{\omega\tau(\text{recoil})}{\omega\tau(\text{static})} H_{\rm int}(\text{static}), \qquad \text{(b)}$$

where $H_{\rm int}(\text{static}) = -0.339\times10^6$ G.[6]

The value of the internal field after the low-recoil-reaction excitation agrees very well with the known "static" value of the field. No anomaly is observed, indicating that, at least

Table I. Summary of internal fields and precession angles of the first excited state of Fe^{56} in iron as determined by various methods.

Method		$\omega\tau$	$(\omega\tau)_{\rm av}$	$H_{\rm int}$(Fe-Fe) (10^6 G)
Present	Set 1 Ge(Li)	0.011 ± 0.009	0.0106 ± 0.0021[a]	−0.43 ± 0.14
experiment	Set 2 NaI(Tl)	0.0085 ± 0.0023		
	Set 3 NaI(Tl)	0.014 ± 0.003		
Radioactivity	γ-γ precession[b]	0.0079 ± 0.0037	0.0083 ± 0.0020	−0.339
	Resonance fluorescence[c]	0.0085 ± 0.0024		
High-recoil Coulomb excitation[d]		0.0004 ± 0.0010	0.0004 ± 0.0010	−0.016 ± 0.040

[a]The error in $(\omega\tau)_{\rm av}$ includes a 10% uncertainty in the slope of the angular distribution.
[b]Ref. 1.
[c]Ref. 2
[d]Ref. 4.

in the Fe-Fe case, the anomaly in the field happens during the first part of the recoil when the excited nuclei still move very fast, and does not originate in the final stopping process or in misalignment of the internal fields at the site of the stopped nucleus.[5] The present result seems to support the transient-field theory proposed in Ref. 4. In this theory, the anomalous hyperfine field is induced by polarized $3d$ electrons which are picked up from the polarized iron by the fast ($v > 10^8$ cm/sec) recoiling ions. At the recoil velocities of the present experiment ($V_{av} \sim 0.9 \times 10^8$ cm/sec) no such pickup seems to occur, and no anomalous field can be observed.

The extension of the technique of perturbed-angular-correlation implantation described here makes many new levels which cannot be reached by radioactive chains, resonance fluorescence, or by Coulomb excitation accessible to precession measurements. The fact that no anomaly in the internal field has been seen removes the difficulties in extracting magnetic moments from precession angles measured by high-recoil Coulomb excitation. There is, therefore, hope that many other g factors of "new" levels will be measured utilizing the technique described here.[9]

*This work is supported in part through funds provided by the U. S. Atomic Energy Commission under Contract No. AT(30-1)-2098.

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MEASUREMENT OF POLARIZATION IN $\pi^- p \to \pi^0 n$ AND $\pi^- p \to \eta n$*

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(Received 13 November 1967)

We report here measurements carried out at the Argonne zero-gradient synchrotron (ZGS) of the polarization in the charge-exchange reaction $\pi^- p \to \pi^0 n$ at momenta between 2.0 and 5.0 GeV/c, and in the reaction $\pi^- p \to \eta^0 n$ at momenta between 3.2 and 5.0 GeV/c. The reaction $\pi^- p \to \pi^0 n$ provides a critical test of some dynamical models of strong interactions. A Regge-pole model involving the exchange of a single 1^{-+} trajectory (the ρ) has been successful in fitting the differential cross-section data from 4 to 18 GeV/c.[1] This simple one-trajectory model clearly implies a polarization of zero.

Recent measurements performed at CERN[2] at 5.9 and 11.2 GeV/c have revealed a significant nonzero polarization which has stimulated various explanations.[3] The measurements at 5.9 GeV/c give a polarization of 16 ± 3.5 % when averaged over a momentum-transfer interval from 0.04 to 0.24 [GeV/c]^2.

Our measurements were made at 2.07, 2.50, 2.72, 3.20, 3.46, and 5.00 GeV/c, a region in which direct-channel resonances are known to exist. In this region a simple Regge-pole model leads to a prediction of nonzero polarization when combined with the known resonances in the direct channel.[4,5] Our data at 5.00 GeV/c give a polarization of 9 ± 6 % when averaged over a momentum transfer interval from 0.047 to 0.465 [GeV/c]^2. The 5.00-GeV/c result reported here, while consistent with the value at 5.9 GeV/c, is also consistent with zero polarization. The lower momentum measurements reveal appreciable nonzero polarization in good agreement with a simple interference model.[6]

For each momentum, measurements were