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# Measurement of the magnetic moment of the 4.49-MeV ($5^-$) state of $^{40}Ca$

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The $g$ factor of the 4.49-MeV ($5^-$) state of $^{40}Ca$ has been measured in a time integral, external magnetic field, perturbed angular correlation experiment. A value of $g = 0.54 \pm 0.10$ was obtained. The angular rotation of the $p'$-$\gamma$ correlation for the 4.49-MeV ($5^-$) state was also measured for calcium nuclei implanted into a polarized iron foil. This measurement yields an average hyperfine magnetic field on calcium in iron which differs by a factor of 2 from the hyperfine field result obtained for $^{42}Ca$ (3.19-MeV, $6^+$ state) implanted in iron. The discrepancy in observed fields indicates a multiplicity of lattice sites for this system. The theoretical estimate of the $5^-$ state $g$ factor is in agreement with the experimental value.

[NUCLEAR MOMENTS $^{40}Ca(p, p'\gamma)$; measured $\mu(5^-$, 4.49-MeV level) and $H_{hyp}$ at Ca(Fe).]

## I. INTRODUCTION

The properties of the low-lying negative parity states of $^{40}Ca$ have long been a subject of experimental and theoretical interest. In addition to excitation energies, experimental information on these states includes spectroscopic factors for stripping reactions[1] and electromagnetic transition rates (see Ref. 2 and references contained therein). Each of these properties is sensitive to particular components of the wave functions. For example, stripping reactions which clearly pick out majority components indicate a relatively simple ($d_{3/2}^{-1}, f_{7/2}$) structure for the $5^-$ state. On the other hand, inclusion of small admixtures of deformed state components seems indicated to achieve a consistent description of radiative decay strengths.[3,4] Although the magnetic dipole moments of these states are not expected to be sensitive to details of the description which has evolved, a satisfactory description must, at minimum, correctly predict the experimentally observed moments.

The relatively short mean lifetime of the 4.49-MeV ($5^-$) state ($\tau = 392 \pm 12$ ps)[3] dictated the use of the time integral perturbed angular correlation technique which is abundantly described in the literature (for example, see Refs. 5, 6). The technique depends upon the perturbation of the angular correlation of decay $\gamma$ rays due to the $\vec{\mu} \cdot \vec{H}$ interaction; the correlation precesses at a rate $\omega = -(\mu_N/\hbar)gH$ for a mean time $\tau$ and thus rotates through an angle $\Delta\theta = \omega\tau$ (for $\omega\tau \ll 1$). In the absence of complicating effects, a knowledge of $H$ and $\tau$ combined with a measurement of $\Delta\theta$ yields a value for $g$. In the present case, the $5^-$ state $g$ factor was measured in an externally applied 12 kG field. An implantation perturbed angular correlation (IMPAC) experiment, initially undertaken to determine $g$, ultimately yielded a value for the average magnetic hyperfine field on calcium implanted into iron.

## II. EXPERIMENTAL TECHNIQUE

In both the external field and IMPAC experiments, the $5^-$ state was excited by inelastic proton scattering at an incident energy of 7.68 MeV. Backscattered protons were detected in an annular surface barrier detector at a mean angle of 170°; $\gamma$ rays in coincidence with protons were detected in a 7.62-cm diam by 7.62-cm long NaI(Tl) detector at a distance of 25 cm. Standard electronic circuitry was used to establish time coincidence, particle and $\gamma$-ray energy conditions, and to gate and route various particle, $\gamma$-ray, and time spectra into memory subgroups of a Sigma-2 computer. The direction of magnetic field was periodically reversed under computer control as determined by the yield of the appropriate backscattered particle group; spectra were separately stored for each field direction and counting rates of interest were continually monitored by scalers.

Figure 1 shows the electromagnet and chamber used in the external field measurement. Tapered pole tips resulted in a field of ($12.0 \pm 0.05$) kG in the 6-mm diam gap. The target consisted of 1 mg/cm$^2$ of self-supporting natural calcium. Energy windows were electronically set on the 4.49-MeV ($5^-$) and 3.91-MeV ($2^+$) particle groups so as to ensure that only events associated with excited calcium nuclei which stopped in the target were accepted. Correlations were measured simultaneously for the $5^-$ and $2^+$ states; the latter correlation served to monitor the effects of beam bending in the external magnetic field.

The IMPAC measurements were carried out with targets consisting of 30 $\mu g/cm^2$ of natural calcium evaporated onto a 300 $\mu g/cm^2$ iron foil. The targets were placed in a 1 kG external magnetic field such that the magnetic domains in the iron were aligned in a direction perpendicular to the beam axis and reaction plane. $\gamma$-ray spectra were simultaneously accumulated for the $5^-$ state and the 0.847-MeV ($2^+$) state of $^{56}Fe$ which served as a monitor of experimental conditions. As in the case of the external field measurement, the external polarizing field was periodically reversed. An IMPAC measurement of the $g$ factor of the 3.74-MeV ($3^-$) state was attempted at a bombarding energy of 9.27 MeV. The short lifetime of the state $\tau_m = 59 \pm 5$ ps,[2] precluded an external field measurement and severely limited the accuracy of the IMPAC measurement.

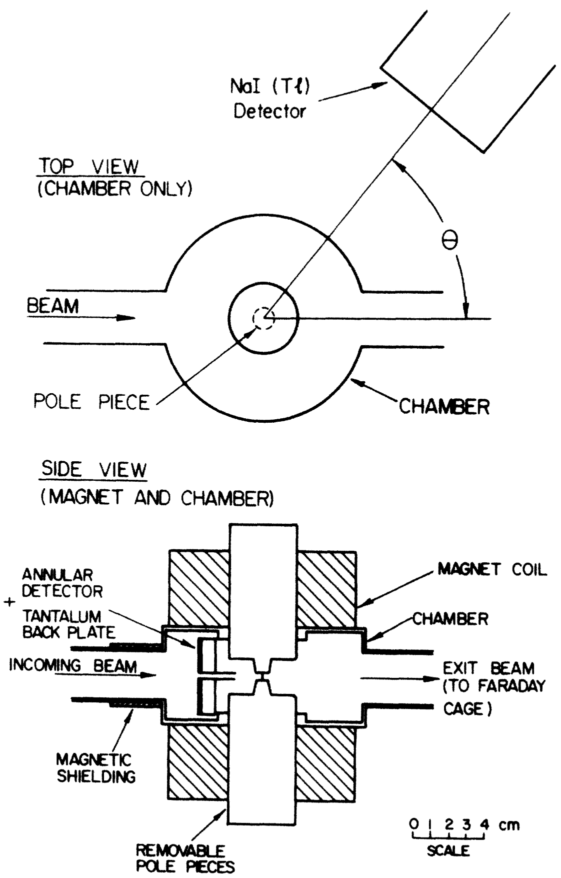


FIG. 1. Electromagnet and chamber used in the external field measurements.

## III. RESULTS AND ANALYSIS

### A. External field measurement

Coincidence $\gamma$-ray spectra were accumulated for two field directions, "up" and "down," and at supplementary angles $\theta$ and $\pi - \theta$ in order to establish the $p'$-$\gamma$ angular correlations. Longer runs at optimum slope angles of 55 and 125° established the angular shift with adequate precision. Analysis of the data must take into account the deflection of the incident and scattered proton beam in the fringing field of the magnet. The field displaced the incident beam from its zero field position by approximately 0.5 mm and consequently changed both the solid angle subtended by the $\gamma$-ray detector and its angle with respect to the beam axis. These effects were observed in both the $5^-$ and the $2^+$ state correlations and agreed in magnitude with calculations based on the measured magnetic field profile. In practice, the correlations of Fig. 2 were obtained for both the $5^- \to 3^-$ and subsequent $3^- \to 0^+$ transitions by summing field up and down data at supplementary angles thus, to an excellent approximation, cancelling these systematic effects. Such averages, shown on Fig. 2, combined with the slope of the correlations at the particular angle, yield angular shifts of $\Delta\theta = (35 \pm 3.5)$ mrad and $(35.5 \pm 1.5)$ mrad for the

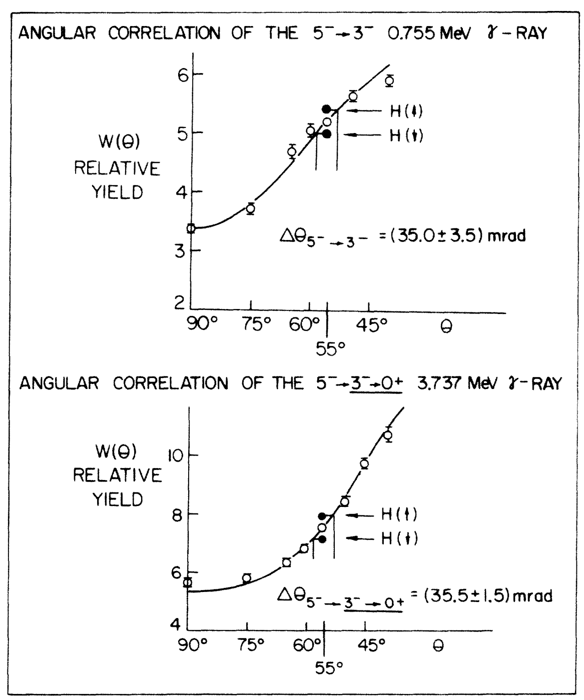


FIG. 2. External magnetic field angular correlations of the $\gamma$ rays emitted in the decay of the 4.49-MeV ($5^-$) state.

$5^- \rightarrow 3^-$ (0.755-MeV) and the $5^- \rightarrow 3^- \rightarrow 0^+$ (3.74-MeV) $\gamma$-ray correlations, respectively. The latter angular shift obviously includes precessions due to both the $5^-$ and $3^-$ states. The shift contributed by the precession of the $3^-$ state $(2.8 \pm 2.6)$ mrad was obtained from the analysis of the results described in Sec. III B.

A more significant fringing field effect causes an actual rotation of the axis of quantization by an amount determined by the trajectories of both incoming and backscattered particles. The observed rotation angle of $\theta_B = (20.0 \pm 1.8)$ mrad for the $2^+$ state correlation is due entirely to this beam bending effect. Particle trajectory calculations yield $\theta_B = 21$ mrad for both the $2^+$ and $5^-$ state correlations.

The angular shifts due to Larmor precession only, become $\Delta\theta = 14.0 \pm 3.5$ mrad and $11.7 \pm 3.0$ mrad for the 0.755- and 3.74-MeV $\gamma$-ray correlations, respectively. These data result in an average $g$ factor for the $5^-$ state of $g_{5^-} = 0.56 \pm 0.10$.

### B. Impac measurements

Figure 3 shows the low energy region of a typical $\gamma$-ray spectrum obtained in the IMPAC measurement of the $5^-$ state magnetic moment. The 0.847-MeV $\gamma$ ray from the decay of the first excited state of $^{56}Fe$ arises from the cascade feeding of this level from a high-lying state in $^{56}Fe$ which was, in turn, excited by inelastically scattered

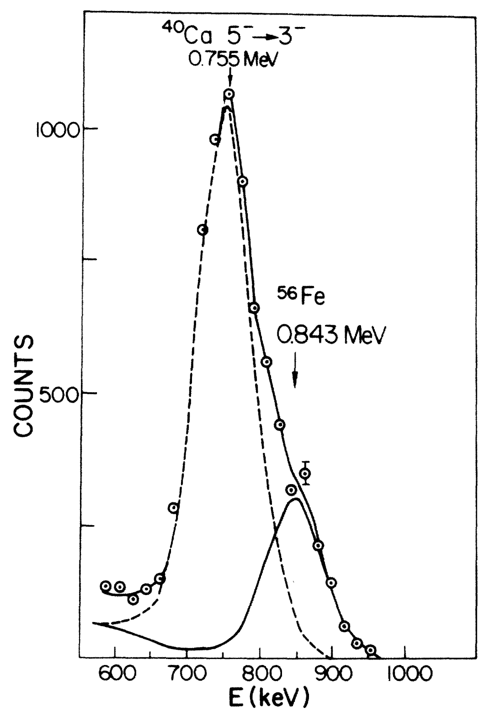


FIG. 3. Low energy region of a typical $\gamma$-ray spectrum obtained with a Ca(Fe) target.

protons included in the particle window. A Ge(Li) detector coincidence spectrum showed no other contaminant $\gamma$ rays in this energy region. The $p'$-$\gamma$ correlation for the $5^- \rightarrow 3^-$, 0.755-MeV $\gamma$ ray shown in Fig. 4 was established by adding data taken at supplementary angles and both field directions. The solid curve, a least squares fit to the data, is entirely compatible with a $5^- \rightarrow 3^-$, $p'$-$\gamma$ correlation. The angular shift is $\Delta\theta = (-48.5 \pm 9.0)$ mrad. Figure 4 also shows the correlation and slope angle data for the direct excitation of the 3.74-MeV ($3^-$) state. The experimentally observed angular shift is $\Delta\theta = (-5.1 \pm 2.2)$ mrad. This shift includes an angular shift $\theta_B$ due to beam bending and a shift $\phi$ caused by rotation in a transient magnetic field, and can be written as:

$$\Delta\theta = g\left(\frac{\mu_N H_{\rm int}}{\hbar} + \frac{\phi}{g}\right) + \theta_B .$$

The beam bending angular shift $\theta_B$ was calculated to be 0.93 and 0.21 mrad, respectively, for

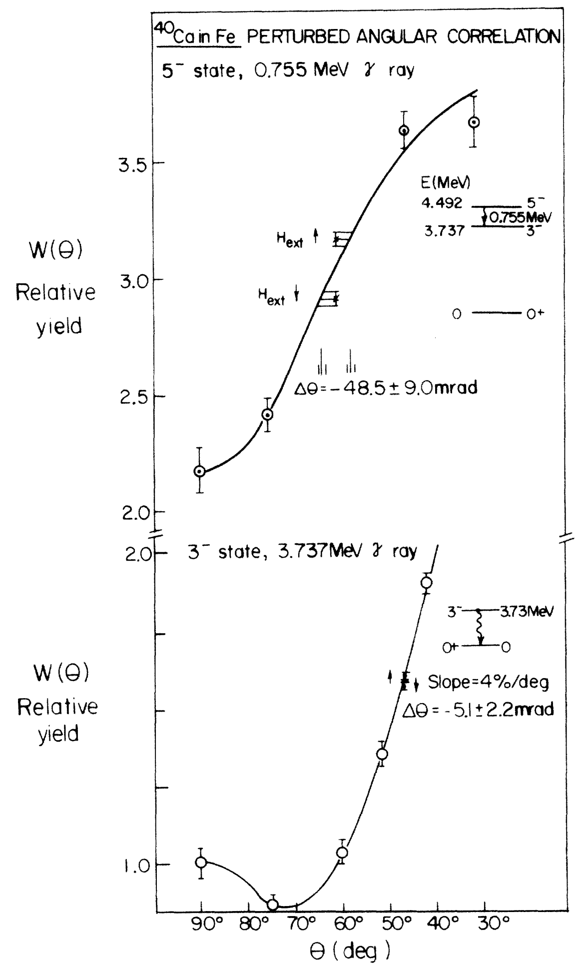


FIG. 4. $\gamma$-ray angular correlations obtained in the IMPAC measurement on the 4.49-MeV ($5^-$) and 3.734-MeV ($3^-$) states.

TABLE I. Experimental and theoretical determinations of the $g$ factors of the 3.737-MeV ($3^-$) and 4.492-MeV ($5^-$) states of $^{40}$Ca.

| $E$ (MeV) | $J^{\pi}$ | $\tau$ (psec) | $g_{exp}$ | $g_{theory}$ $d_{3/2}^{-1}f_{7/2}$ | RPA + def. |
|---|---|---|---|---|---|
| 3.737 | $3^-$ | 59 ± 5 | 0.83 ± 0.76 | 0.554 | 0.486 |
| 4.492 | $5^-$ | 392 ± 12 | 0.56 ± 0.10 | 0.515 | 0.512 |

the $5^-$ and $3^-$ states data. The transient field is a velocity dependent interaction arising from the scattering of polarized electrons by the nucleus recoiling in the magnetic target backing. The transient field model of Lindhard and Winther,[7] yields estimated shifts $\phi = (5.6 \pm 2.8)g$ mrad and $(6.5 \pm 3.2)g$ mrad, respectively, for the $5^-$ and $3^-$ states. The errors assigned represent the limits of success of the model in explaining a range of observed transient fields.[8]

A value $H_{int} = (-45 \pm 14)$ kG is obtained from the data on the $5^-$ decay and $g_{5^-}$ determined in the external field measurements on the 0.755-MeV $5^- \to 3^-$ transition. These results can now be combined with the shifts observed for the $3^-$ state to yield $g_{3^-} = 0.83 \pm 0.76$.

## IV. DISCUSSION

Table I summarizes the experiments and resulting $g$ factors. In the case of the $3^-$ state, the observed precession is small and of the same magnitude as the correction factors due to transient fields, thus precluding a precision determination of $g_{3^-}$.

The hyperfine magnetic field on calcium in iron has been measured by Marmor, Cochavi, and Fossan[9] who utilized the 3.19-MeV ($6^+$, $\tau_m = 7.7$ ns) state of $^{42}$Ca in a time differential perturbed angular correlation experiment. Their results combined with the $6^+$ state $g$ factor of Nomura *et al.*,[10] $g(6^+) = -0.5 \pm 0.03$, yield a value $H_{int} = (-84 \pm 8)$ kG. [*Note added in proof:* New measurements by S. K. Bhattacherjee *et al.*, reported at the International Conference on Hyperfine Interactions Studied in Nuclear Reactions and Decay, Uppsala, June 1974, yield $g(6^+) = -0.415 \pm 0.015$ and $H_{int} = (-100 \pm 7)$ kG.] The IMPAC measurements of the present experiment yield an average hyperfine field $H_{int} = (-45 \pm 14)$ kG and indicate that not all implanted nuclei experience the same hyperfine field. Indeed, MacDonald, Boie, and Hensler[11] have investigated the lattice sites of implanted calcium atoms in an iron single crystal using particle induced $K$ x rays as a function of beam-crystal orientation. These experiments show a substitutional fraction of $0.50 \pm 0.10$ for calcium in iron with the remaining fraction being in undetermined sites. A plausible but not unique interpretation of the present data is that one of the lattice sites has an associated hyperfine field of $-100$ kG and the other a field of magnitude $\lesssim 20$ kG. Such an hypothesis leads to an "effective field" in the IMPAC experiment of approximately $-50$ kG and leads to compatibility of the internal and external field data.

The simplest theoretical calculation of the $5^-$ state $g$ factor assumes a $(d_{3/2}^{-1}, f_{7/2})$ configuration for both neutrons and protons and gives $g_{5^-} = 0.52$. The more realistic wave functions of Goode,[4] which include random phase approximation and deformed state components, give $g_{5^-} = 0.51$. These calculations are in agreement with the measured $g$ factor, although, as a result of the lack of specificity, such comparisons are not a severe test of minority wave function components.

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