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MAGNETIC MOMENTS IN CALCIUM ISOTOPES VIA A SURFACE-INTERACTION EXPERIMENT(1).

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ABSTRACT

A rotation of the angular correlation of de-excitation γ-rays from ^{40}Ca and ^{44}Ca was observed in a tilted foil geometry. The signs and magnitudes of the magnetic moments of the 2_1^+ level of ^{44}Ca and of the 3_1^- level of ^{40}Ca were determined to be $g = -0.28 \pm 0.11$ and $g = +0.52 \pm 0.18$, respectively. This experiment provides further information regarding the polarization of deeply bound electronic configurations produced by a surface-interaction mechanism and demonstrates the feasibility of the present technique for measuring signs and magnitudes of magnetic moments of picosecond nuclear levels.

The magnetic moments of the 2_1^+ levels of even Ca isotopes have not been measured hitherto but it is evident that their values and signs can provide significant information regarding the shell-model structure of low-lying levels in this mass region. We report here the measurement of the magnetic moment of the 2_1^+ level of ^{44}Ca. The experiment utilizes the "tilted foil" hyperfine interaction i.e. the interaction between the nuclear level and a polarized electronic ensemble associated with high velocit ions emerging from a surface whose normal does not lie along the beam direction(2,3). The polarization of electronic configurations manifested in the emittance of circularly polarized light, has been extensively studied in the transmission (tilted-foil) geometry(4) and in the reflection (grazing angle) geometry(5). For deeply bound atomic levels such polarization can be observed via their hyperfine interaction with the nucleus. A rotation of the angular correlation of decay γ-rays from an excited nuclear level is a signature of a polarized electronic ensemble and provides a measure of the sign and magnitude of the magnetic moment of this level. The first two experiments utilizing this phenomenon were carried out for the 2_1^+ level of ^{18}O and 3_1^- level of ^{16}O confirming the negative and positive signs, respectively, of the magnetic moments of these levels(2,3). In the present experiment we have extended these measurements to the ^{44}Ca and ^{40}Ca isotopes. A better understanding of the phenomenology of the polarization in such geometries(5) makes it possible now to obtain the magnitude of $g(2_1^+)$ of ^{44}Ca by comparison to the known(6) $g(3_1^-)$ of ^{40}Ca. An independent measurement using the integral perturbation of an unpolarized electronic ensemble was also carried out for the 2_1^+ and 3_1^- levels of ^{44}Ca and ^{40}Ca, respectively.

An α beam from the tandem Van-de-Graaff accelerator at the Weizmann Institute was used to excite the 3_1^- and 2_1^+ levels of ^{40}Ca and ^{44}Ca via the (α,α') reaction on isotopically enriched targets. Backscattered α particles were detected in a 100 μm annular surface barrier detector. Decay γ-rays in coincidence with the inelastic α groups populating either the 3_1^- or the 2_1^+ levels were measured in four movable 12.5 cm x 12.5 cm NaI(Tℓ) counters. Random coincidences were monitored and consequently subtracted from each γ-spectrum. A narrow slit subtending 2° was placed in front of the particle detector, perpendicular to the plane of the γ counters, in order to sharpen the α-γ correlation and to prevent shadowing the particle counter by the target assembly in the tilted position(2). The targets consisted of ^{40}Ca or ^{44}Ca evaporated inside the experimental chamber on a 10 μg/cm^2 carbon foil. Measurements of the excitation function and of the angular correlation were carried out with the target at the same 70° angle to the beam direction subsequently used in the precession experiments. The target thickness at this position was measured by monitoring the positions and widths of the α energy peaks. An effective thickness of 240±40 μg/cm^2 was thus obtained, ensuring that the calcium ions did indeed recoil out of the target and thus experience the full hyperfine interaction in vacuum. The bombardment energies were chosen to maximize the yield and reduce interference from other levels, and were 16.17 MeV for ^{40}Ca and 13.10 MeV for ^{44}Ca. The recoil velocities of the ^{40}Ca and ^{44}Ca ions corresponding to these energies are very close and result in similar electronic environments for both isotopes.

The next step in the experiment was the measurement of the angular precession due to tilting the target at an angle of $\psi = \pm 70^\circ$ to the beam direction. The experimental arrangement was essentially similar to that described earlier(2,3) and is shown in fig. 1. The γ-counters were placed at angles where the logarithmic derivatives $\frac{1}{W}\frac{dW}{d\theta}$ are large. The precession of the angular correlation for ^{40}Ca ions recoiling into a solid silver backing was also measured to serve as a check against various systematic errors; for recoil-into-solid, there should be no effect due to target tilting since the ions stop inside the backing and do not experience the surface-interaction. The results of the precession experiments are given in Table 1.

We define the double ratios $\rho_{ij} = \left(\frac{W_i^R}{W_i^L}\cdot\frac{W_j^L}{W_j^R}\right)^{1/2}$ where W_i^R, for example, is the number of counts in detector i=1-4 with the target tilted in the "right" direction (see fig. 1). The precession angle $\Delta\phi$ is given by

$$\Delta\phi = \left(\frac{1}{W}\,\frac{dW}{d\theta}\right)^{-1}\cdot\frac{1-\rho}{1+\rho} \quad \text{where } \rho = (\rho_{14}\cdot\rho_{32})^{1/2}.$$

The absence of a measurable precession in the ^{40}Ca recoil-into-silver experiment and the values of the cross-ratios ρ_{13} and ρ_{42} in all experiments demonstrate the quality of the measurements and the lack of significant systematic errors. The respective signs of $\Delta\phi$ for ^{40}Ca and ^{44}Ca directly yield $g(^{40}\mathrm{Ca},3_1^-)>0$(7) and $g(^{44}\mathrm{Ca},2_1^+)<0$. The determination of the relative signs is model independent and the determination of the individual signs depends only on the well established sense of polarization in a tilted-foil geometry.

In order to deduce the magnitude of the magnetic moment, one has to utilize information regarding the electronic configurations and polarization of Ca ions recoiling into vacuum at about $v/c \approx 0.01$ (with charge states 3^+-6^+). The intermediate ionization model has been successfully used for various ions and in particular for Ca ions at a close recoil velocity$^{(6)}$. For the present experiment we use a slight modification of this model and assume that Ca ions with charge 10-n ($4 \leq n \leq 7$) populate only M shell configurations of the type $3s^2p^{n-2}$, $3s^1 3p^{n-1}$. The hyperfine magnetic fields at the nucleus are taken from Ref. 6 and the perturbation of the angular correlation is calculated for each allowed LSJ term. Various modifications of the intermediate ionization model have been tried with no significant change in the results presented below.

It can be shown that the perturbed angular distribution (for a single LSJ term) is given by:

$$W_p(\theta) = \sum_k A_k (G_k \; P_k(\theta) + H_k \; P_k^1(\theta)) \qquad (1)$$

where A_k are the unperturbed correlation coefficients and P_k and P_k^1 are the Legendre and associated Legendre polynominals. G_k is the well known integral perturbation-attenuation coefficient:

$$G_k = \frac{1}{2J+1} \cdot \sum_{FF'} (2F+1) \cdot (2F'+1) \cdot \begin{Bmatrix} F & F' & k \\ I & I & J \end{Bmatrix}^2 \cdot \frac{1}{1+(\omega_{FF'}\tau)^2} . \qquad (2)$$

I and J are the angular momenta of the nucleus and the electrons, $\bar{F} = \bar{I} + \bar{J}$, $\omega_{FF'} = \frac{F(F+1) - F'(F'+1)}{2} \cdot \tilde{\omega}$, $\tilde{\omega} = -\frac{g\mu_N}{\hbar} \cdot H(o) \cdot a(USJ)$, $a(LSJ)$ is a geometrical coupling factor, $H(o)$ is the field at the nucleus and τ is the mean life of the nuclear level. H_k is the coefficient reflecting the presence of atomic polarization and its time integral form is given by

$$H_k = \frac{3p \cdot \cos(J,L)}{k(k+1) \; \tilde{\omega}\tau \sqrt{J(J+1)}} \cdot (1-G_k) \qquad (3)$$

where $\cos(\bar{J},\bar{L}) = \frac{1}{2} \cdot \frac{J(J+1) + L(L+1) - S(S+1)}{\sqrt{J(J+1) \; L(L+1)}} \quad (J,L \neq 0)$

and $p = \frac{\langle L_x \rangle}{\sqrt{L(L+1)}}$ $(L \neq 0)$ is the polarization fraction. G_k and H_k have to be averaged over all LSJ terms. The polarization fraction p may be regarded as an average polarization of the electronic ensemble. However, recent experiments and theoretical considerations indicate that p is approximately constant for all electronic terms at a given velocity and tilt-angle$^{(5)}$. It should be noted that in the limit $\tilde{\omega}\tau \to 0$ one obtains $H_k \xrightarrow[\tilde{\omega}\tau \to 0]{} p \cdot \cos(J,L) \cdot \tilde{\omega}\tau \sqrt{J(J+1)}$, independent of I and k and resembling a classical precession. In this approximation the perturbed angular distribution (eq.1) reduces to

$$W_p(\theta) = W_o(\theta) \cdot \left(1 - \frac{1}{W_o} \frac{dW_o}{d\theta} \Delta\phi\right)$$

where

$$W_o(\theta) = \sum_k A_k P_k(\theta) \quad \text{and} \quad \Delta\phi = H_k^{(8)}.$$

However, for $\tilde{\omega}\tau \geq 1$ (as in the case for ^{40}Ca), this approximation no longer holds and one has to use the full formalism of eqs. 1-3.

The results of calculations for the 3_1^- and 2_1^+ levels of ^{40}Ca and ^{44}Ca using the electronic model and eqs. 1-3 are presented in fig. 2. For ^{40}Ca one can use the value for the g-factor of $g=0.55 \pm 0.11$ (see below) and the mean life $\tau = 68 \pm 3$ ps$^{(9)}$ to obtain $g\tau(^{40}\mathrm{Ca}, 3_1^-) = 37.4 \pm 7.7$ ps. The fraction p can now be treated as a free parameter and can be deduced from $\Delta\phi$ to be $p = \frac{\langle L_x \rangle}{\sqrt{L(L+1)}} = 0.077 \pm 0.018$. This value of p in turn leads to $|g\tau|(^{44}\mathrm{Ca}, 2_1^+) = 1.6 \pm 1.0$ and with $\tau = 4.2 \pm 0.3$ ps$^{(9)}$ we obtain $g(^{44}\mathrm{Ca}, 2_1^+) = -0.38 \pm 0.23$. The error includes the statistical errors in the ^{40}Ca and ^{44}Ca precession measurements as well as the uncertainties in the magnetic moment of the 3^- level. As mentioned above, the procedure adopted here is quite insensitive to the particulars of the electronic model employed.

An additional experiment was carried out to determine $|g|(^{44}Ca, 2_1^+)$. The ratio R of counts at $\theta=45^\circ$ to counts at $\theta=90^\circ$ was separately measured for recoil-into-silver and recoil-into-vacuum. This ratio is sensitive to the magnitude of the hyperfine interaction and therefore determines the magnetic moment (assuming the above electronic model). We obtain R=14.60±1.03 and R=13.06±0.78 for the two cases, respectively, yielding $|g|=0.25\pm0.12$. This result is independent of the precession measurement and is in agreement with it. Averaging the two results for ^{44}Ca we obtain $g(^{44}Ca,\ 2_1^+)=-0.28\pm0.11$. Taking the data for the unperturbed and perturbed correlation for ^{40}Ca (table 1) we obtain $|g|(^{40}Ca,\ 3_1^-) = 0.52\pm0.18$, in good agreement with the value g=0.56±0.13 of Ref. 6. The value g=0.55±0.11 used above for the *determination* of $g(^{44}Ca,\ 2_1^+)$ is the average of these two results.

Negative g-factors of nuclear 2^+ levels are rare and can, in fact, be expected only in quite pure shell model configurations of neutrons in streched angular momentum states ($p_{3/2}$, $d_{5/2}$, $f_{7/2}$, etc.); even small admixtures will in general, increase appreciably the algebraic value of the g-factor. In the calcium nuclei beyond ^{40}Ca, $f_{7/2}$ neutrons are predominant, and the negative value of $g(^{44}Ca,\ 2_1^+)$ indicates that the $(f_{7/2})^4$ configuration is quite pure in this case.

It is interesting to compare the measured value of $g(^{44}Ca,\ 2_1^+)$ to other g-factors of low-lying levels in Ca isotopes beyond ^{40}Ca. The g-factors of the $7/2^-$ ground-states of ^{41}Ca and ^{43}Ca were measured to be g = -0.456 and g = -0.380$^{(10)}$. The g-factor of the 6_1^+ level of ^{42}Ca was measured to be g = -0.415±0.015$^{(10)}$. Our result agrees with the general trend (c.f. fig.3) of negative g-factors of monotonously decreasing magnitude indicating enhanced importance of small admixtures of configurations other than $f_{7/2}$ for the low-lying levels in the heavier Ca isotopes.

The polarization fraction determined above of p=0.08 is quite appreciable and suggests that polarization effects for deeply bound electronic configurations can be comparable to the effect observed in atomic tilted-foil experiments for outer configurations. The present results, together with the previous experiments for ^{16}O and ^{18}O demonstrate the usefulness of the present technique for measuring signs and magnitudes of magnetic moments of picosecond nuclear levels.

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TABLE I

	θ	$\frac{1}{W}\frac{dW}{d\theta}$	ρ_{14}	ρ_{32}	ρ_{13}	ρ_{24}	ρ	$\Delta\phi$ (mrad.)
^{44}Ca (into vacuum)	68°	-3.53(5)	1.020(12)	1.020(15)	0.984(13)	0.986(15)	1.020(9)	+2.8±1.3
^{40}Ca (into vacuum)	52.5°	-2.06(13)	0.956(12)	0.974(12)	0.985(12)	1.004(12)	.965(8)	-8.6±1.9
^{40}Ca (into silver)	52.5°	-4.60(20)	1.006(18)	0.992(18)	1.007(18)	1.007(18)	.999(13)	-0.1±1.3

Table 1

Summary of the experimental results. θ is the angle of the NaI(Tℓ) counters in the precession measurements. ρ and $\Delta\phi$ are defined in the text.

FIGURE CAPTIONS

Fig. 1: Schematic view of the experimental arrangement. The target is shown in the "right" position. The normal $\hat{n}$ is at $\psi = 70^{\circ}$ to the beam direction and the electronic polarization is in the direction of the +x-axis.

Fig. 2; The absolute value of the angular precession $\Delta\phi$ calculated by using the electronic model described in the text and eqs. 1-3 with a polarization fraction of $p = 0.077$.

Fig. 3: g-factors of levels in Ca isotopes beyond ^{40}Ca. The ^{44}Ca result is from the present experiment; the other results are from Ref. 10.

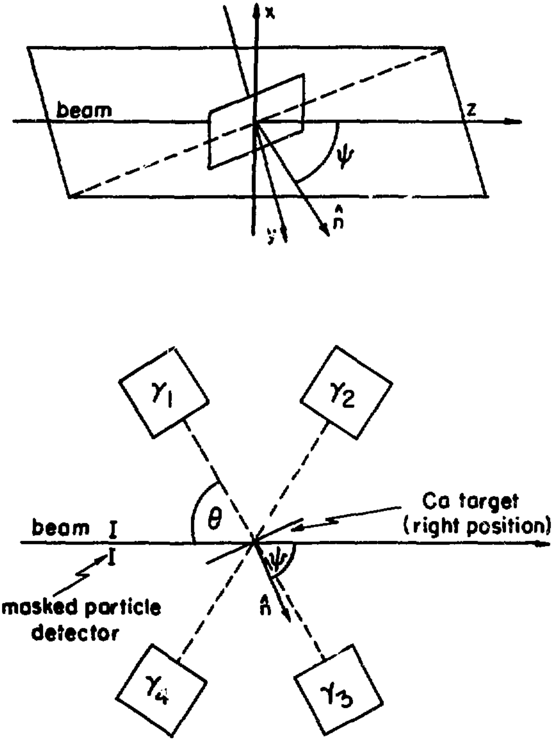
x
beam
z
ψ
n̂
y
γ1
γ2
θ
Ca target
(right position)
beam
I
I
masked particle
detector
ψ
n̂
γ4
γ3

Figure 1

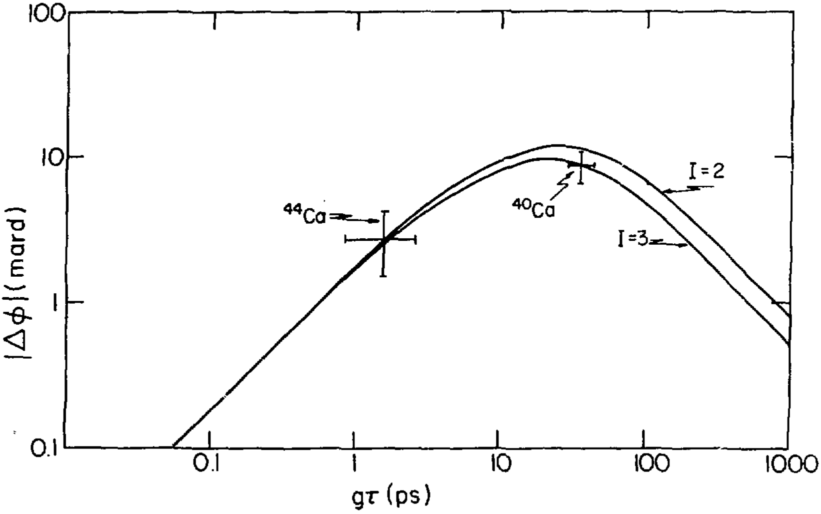
100
10
1
0.1
$|\Delta\phi|$ (mard)
^{44}Ca
^{40}Ca
I = 2
I = 3
0.1
1
10
100
1000
$g\tau$ (ps)

Figure 2

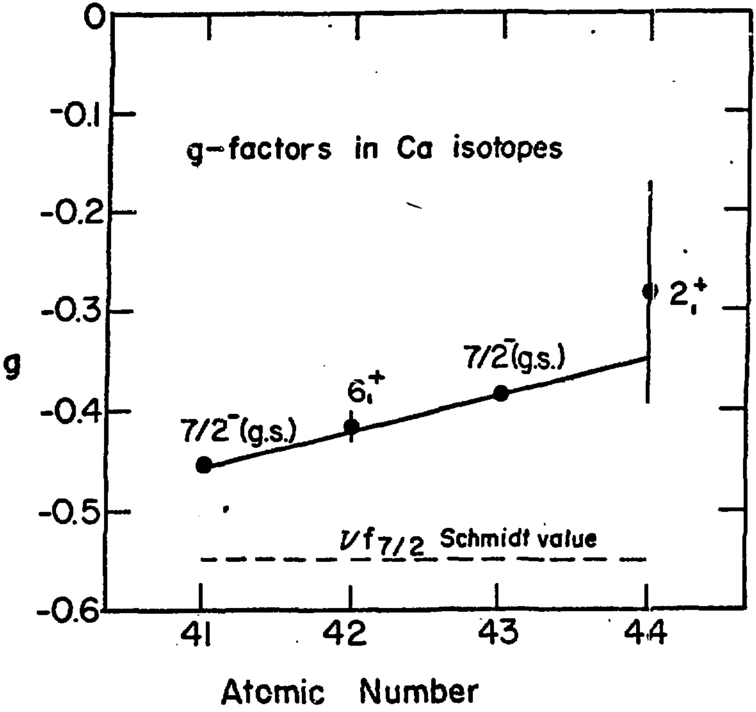
g-factors in Ca isotopes
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
g
7/2⁻(g.s.)
6₁⁺
7/2⁻(g.s.)
2₁⁺
νf7/2 Schmidt value
41
42
43
44
Atomic Number

Figure 3