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Magnetic moments of the 2_1^+ levels in even Sn isotopes

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The g factors of the 2_1^+ states of even Sn nuclei have been measured using the dynamic magnetic field which acts on fast ions traversing thin magnetized iron foils. The results obtained are $g = +0.37 \pm 0.13$, $g \gtrsim 0$, $g = -0.16 \pm 0.10$, $g = +0.02 \pm 0.09$, $g = -0.14 \pm 0.07$, $g = -0.07 \pm 0.11$, and $g = -0.15 \pm 0.10$ for $^{112-124}$Sn, respectively. The shell-model structure of the Sn isotopes is discussed.

NUCLEAR REACTIONS $^{112-124}\text{Sn}(^{35}\text{Cl}, ^{35}\text{Cl}')\, ^{112-124}\text{Sn}^*(2_1^+)$ $E = 108$ MeV, enriched targets: measured $W(\theta, H, \infty)$; fast ions in thin polarized iron. Deduced magnetic moments of the 2_1^+ levels in $^{112-124}$Sn.

INTRODUCTION

Experimental and theoretical investigations of the nuclear structure of the Sn isotopes which have a closed $Z = 50$ proton shell have been the subject of much interest during the last several years.[1,2] Nuclear properties such as level schemes, lifetimes, spectroscopic factors, and electromagnetic moments and transitions have been measured and the results interpreted in the framework of several theoretical models. The 2_1^+ levels of the even Sn isotopes exhibit a remarkable similarity in their energies and $B(E2)$ values, agreeing well with the predictions of the generalized seniority scheme.[3] The magnetic moments of these levels, however, have not been measured and it is clear that such measurements can contribute to the understanding of their structure. Due to the single-particle nature of the magnetic moment operator, the sign and the magnitude of the magnetic moment are sensitive to the configurations that contribute to the wave function of an individual level. In the particular case of the Sn isotopes they can give information on small admixtures of proton excitations from the closed $Z = 50$ shell.

The present experiment was undertaken to measure the magnetic moments of the 2_1^+ levels in the even Sn isotopes using the dynamic magnetic field which acts on fast ions traversing a ferromagnetic foil. Due to the very short lifetimes of these levels ($\tau \sim 0.5-1$ ps), measurement of their g factors relies on the dynamic (transient) magnetic field technique at high velocities[4,5] and, in particular, on the thin-foil method[6-8] which has been developed in the last few years. The experimental procedure will be presented and the results for the g factors of the 2_1^+ levels of $^{112-124}$Sn will be discussed and compared to g factors of neighboring nuclei and to the shell-model picture in this mass region.

EXPERIMENTAL PROCEDURE AND RESULTS

The experiment utilizes the large dynamic magnetic field which acts on high-velocity ions traversing *thin* magnetized iron foils. This technique has been described in detail in several recent publications and has been employed in measuring magnetic moments in Fe, Ni, Pd, Cd, and Ba isotopes.[7-10] By using sufficiently thin foils, one can assure that the transit time through the magnetized material is short compared to the lifetime of the level, thus assuring that the evaluation of the g factors from the measured angular precession will be essentially independent of the lifetime.

A beam of the 108 MeV ^{35}Cl from the Pelletron accelerator at the Weizmann Institute was used to Coulomb excite the 2_1^+ levels in even $^{112-124}$Sn isotopes. Decay γ rays were detected in six 12.5 × 12.5 cm NaI(Tl) crystals in coincidence with backscattered ^{35}Cl ions detected in an annular surface-barrier particle detector. Random coincidences were recorded and subtracted to obtain the final γ spectra. The targets were prepared by evaporating a 400–500 μg/cm^2 layer of the particular enriched isotope on an ~1.5 mg/cm^2 iron foil backed with a 10 mg/cm^2 copper layer. A layer of 100 μg/cm^2 of natural Cd was evaporated on top of the Sn layer. Decay γ rays from the 2_1^+ levels of the Cd isotopes were well separated from the higher energy γ rays from the Sn isotopes.[11]

Since the g factors of the 2_1^+ levels of the Cd isotopes have been measured previously using this technique, the presence of the Cd lines served as an on-line calibration for determining the absolute value of the strength of the dynamic field. The angular correlations for the Cd line and for the Sn line were measured for each target separately. The angular correlation for the Cd decay γ rays was found to be

$$W(\theta)_{\mathrm{Cd}}=1+0.52(2)P_2(\cos\theta)-1.11(3)P_4(\cos\theta)\,.$$

The angular correlations for all Sn isotopes were found to agree with one another giving the average value

$$W(\theta)_{\mathrm{Sn}}=1+0.66(1)P_2(\cos\theta)-1.26(6)P_4(\cos\theta)\,.$$

These correlations are consistent with Coulomb excitation calculations, after taking into account the finite detector geometry. The precession measurements to determine the angular rotation, which in turn determines the sign and magnitude of the g factor, were carried out in a similar manner to that described previously.[6-8] Six NaI(Tl) crystals were placed at angles of ±67.5°, ±112.5°, and ±22.5° to the beam direction where the slope of the angular correlation allows large sensitivity to small rotations. Photo peak intensities were used to form double ratios for the Cd and Sn lines for each target. The double ratios are defined as

$$\rho_{ij}=\left(\frac{W(\theta_i^{\uparrow})}{W(\theta_i^{\downarrow})}\cdot\frac{W(\theta_j^{\downarrow})}{W(\theta_j^{\uparrow})}\right)^{1/2},$$

where $W(\theta_i^{\uparrow})$ represents, for example, the peak sum for the ith detector with the magnetic field up and $\theta_j=-\theta_i$. The three double ratios for $\theta_i=+67.5°$, $+112.5°$, and $+22.5°$ were used to obtain angular precession angles $\Delta\phi_{ij}$ using the expression

$$\Delta\phi_{ij}=\frac{1}{S}\,\frac{1-\rho_{ij}}{1+\rho_{ij}}\,.$$

$S=(1/W)dWd\theta$ is the logarithmic derivative of the angular correlation with values of −3.15, +3.15, and +2.46 for the Sn lines at $\theta=+67.5°$, +112.5°, and 22.5°, respectively, and −2.63, +2.63, and + 2.35 for the Cd lines at the same angles. The symmetric angle ratios $\rho_{\theta,\theta-\pi}$ which should show no effect are indeed measured to be consistent with unity. The magnetization of the iron foils was reversed periodically by a computer controlled, external magnetic field of 600 G; magnetometer measurements proved this field to be sufficient to magnetize the iron foils to saturation. A beam-bending correction of $\Delta\phi_{\mathrm{bb}}=0.3\pm0.3$ mrad was subtracted from all angular precession values. This correction was calculated from the measured profile of the external field and is consistent with a precession measurement of the Cd line using an iron-free target. The three values of the precession angle $\Delta\phi_{ij}$ were averaged to obtain the final precession angle $\Delta\phi$ (after beam-bending correction). The value of $\Delta\phi$ for each isotope together with the corresponding values of the Cd precession are shown in Table I. Also shown are the lifetime, the transit time T through the iron, and the iron thickness for each isotope. The experimental $\Delta\phi$ for ^{114}Sn has to be corrected for the

TABLE I. Summary of experimental conditions and results. The angular precession $\Delta\phi$ (after beam-bending subtraction) is given for each Sn isotope together with the corresponding $\Delta\phi$ for the Cd line and the deduced g factor. The values for the g factors were obtained using the linear-velocity parametrization of the dynamic field and include a small correction due to the short lifetimes (see text). The average g factor for the Cd is taken to be $g=+0.30\pm0.02$ (Refs. 9, 10). Also shown are the energy of the 2_1^+ level, its lifetime, the iron thickness, and the flight time through the iron for each isotope. Due to the low purity (30%) of the ^{114}Sn, the experimental $\Delta\phi$ implies only $g(^{114}\mathrm{Sn},2_1^+)\gtrsim 0$. The average velocity of the Sn in the iron is $v/c\simeq0.035$.

	$E(2_1^+)$ (MeV)	$\tau(2_1^+)$ (ps)	d(Fe) mg/cm^2	T (ps)	$\Delta\phi$ (mrad)	g
^{112}Sn	1.26	0.50	1.2	0.17	−4.7 ± 1.7	+0.37 ± 0.13
Cd					−5.0 ± 1.6	
^{114}Sn	1.30	0.40	1.5	0.13	−0.6 ± 1.7 [a]	(+0.04 ± 0.07) [a] $g\gtrsim0$
Cd					−5.1 ± 1.0	
^{116}Sn	1.29	0.52	1.5	0.22	+2.4 ± 1.5	−0.16 ± 0.10
Cd					−6.1 ± 0.6	
^{118}Sn	1.23	0.67	1.5	0.22	−0.4 ± 1.7	+0.02 ± 0.10
Cd					−6.8 ± 0.6	
^{120}Sn	1.17	0.91	1.6	0.24	+2.4 ± 1.3	−0.14 ± 0.07
Cd					−8.8 ± 1	
^{122}Sn	1.14	1.1	1.7	0.27	+1.3 ± 2.0	−0.07 ± 0.11
Cd					−8.0 ± 1	
^{124}Sn	1.13	1.4	1.5	0.23	+2.6 ± 1.9	−0.15 ± 0.10
Cd					−5.8 ± 1	

[a] Low-purity target; the quoted result has to be corrected for the isotopic abundance.

low enrichment (30%) of the target. Since the other isotopes have negative g factors, we can conclude from the result only that $g(^{114}\mathrm{Sn}, 2_1^+) \gtrsim 0$. The last column of Table I gives the deduced values of the g factors of the Sn isotopes. In the evaluation of these g factors a small correction was applied to account for the transit times not being infinitely short compared to the lifetimes. This correction is not larger than ~15% and can be estimated to an accuracy of about 20%; consequently this uncertainty does not contribute significantly to the error in the g factors. The advantages of the thin-foil technique are well demonstrated here since use of thicker foils would demand much better knowledge of the lifetime and stopping powers and would produce less reliable results, even for relative values of the magnetic moments.

The scale for deducing the absolute values of the g factors was determined by the precession of the Cd γ rays. The average g factor[9,10] for a natural Cd target is $g = +0.3 \pm 0.02$ and the lifetimes of all 2_1^+ levels in Cd isotopes are essentially infinite compared to the transit time. The values of $\Delta\phi$ for the Cd line for all Sn targets are in agreement with one another. The resulting average value is in excellent agreement with the linear-velocity parametrization of the dynamic field:

$$B(Z, v) = aZ\frac{v}{v_0}\mu_N N_P , \qquad (1)$$

where v_0 is the Bohr velocity, $\mu_N N_P = 1752$ G for saturated iron, and a is a parameter determined by previous results to be $a = 70 \pm 5$ for this mass and velocity region.[10] The Sn results were obtained using this parametrization. It is important to note that although other parametrizations may fit the overall dynamic field data as well as the expression in Eq. (1), all such parametrizations would produce very similar results for the g factors of the Sn isotopes due to the very close Z and v of the recoiling Cd and Sn nuclei.[10] Any error arising from a choice of the parametrization and its parameters would be much smaller than the statistical error.

DISCUSSION

The final results for the g factors of the 2_1^+ levels of even Sn isotopes are presented in Fig. 1 together with the energies of the low-lying levels in the neighboring odd-neutron isotopes. The individual g factors have not been determined to a high accuracy due to the low excitation and very short lifetimes of the 2_1^+ levels. Nevertheless, an overall trend from negative g factors for the heavy isotopes to positive g factor for the lighter isotopes is rather well pronounced. This trend does not depend on the absolute calibration of the dynamic field and the relative values are well determined.

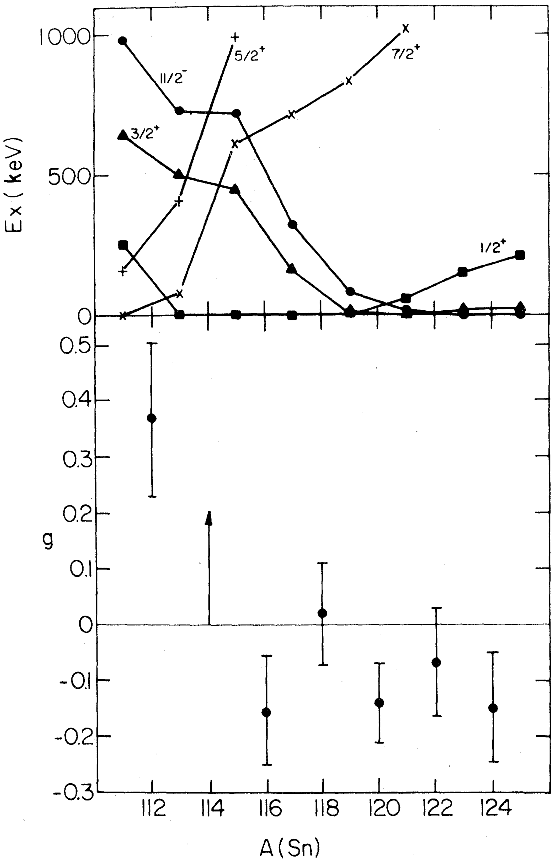

FIG. 1. Deduced g factors for the 2_1^+ levels of even Sn isotopes. Also shown are the low-energy levels of the odd isotopes, representing the energies of the various single-particle neutron configurations in this shell. The trend from negative to positive g factors is apparent.

The energy levels of the odd isotopes shown in Fig. 1 represent the various single-particle neutron configurations that occur in this mass region. These levels correspond to the $1g_{7/2}$, $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$ subshell neutron configurations that one usually includes in nuclear structure calculations of Sn isotopes.[1] It is possible to draw qualitative conclusions from the present results without going into detailed and complicated calculations. Only a few of the possible neutron configurations have a negative g factor and for heavy nuclei these negative g factors are small due to the decreasing weight of the neutron spin in the particular j of a configuration. Negative magnetic moments, especially of levels like the 2_1^+, are indeed rare and are generally expected only in quite pure shell-model configurations of neutrons in stretched angular momentum states.[12] From Fig. 1 one may expect that the configurations within the neutron space that contribute to the 2_1^+ wave functions of the heavy $^{120-124}$Sn isotopes are the $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$. From experimental data on the odd isotopes,[13] the effective g factors of these configurations are $g(h_{11/2}) \simeq -0.25$, $g(d_{5/2}) \simeq +0.3$, and $g(s_{1/2}) \simeq -2.0$; from these we get also that $g([d_{3/2}s_{1/2}]2^+) \simeq -0.3$. The negative g factors for $^{120-124}$Sn indicate the importance of configurations like $(h_{11/2})^n$ and $(d_{3/2}s_{1/2})$ in the wave function of the 2_1^+ levels. It is also possible to estimate the proton admixture in the wave functions of these levels. Since a proton component will have a large and positive g factor, it is possible to conclude that the strength of a proton admixture has to be small ($\lesssim 0.2$). For the lighter Sn isotopes, with the positive g factor for ^{112}Sn of $\sim +0.3$, one can see the importance of the $g_{7/2}$ neutron configuration (with its positive g factor) which comes down in energy to become the ground-state configuration of ^{111}Sn. It is also possible that proton admixtures are more important for the lighter isotopes. This trend indicates the sensitivity of the magnetic moments to the occupation parameters of neutrons in the various possible subshells, compared to the level energies and $B(E2)$ values that remain rather constant. The static quadrupole moments have also been measured[2] and although the errors are large, no systematic trend similar to the present results can be observed.

It is clear that the above qualitative remarks should serve only as guide lines to detailed theoretical investigations. Calculations within the quasiparticle BCS model[14] are, in general, sensitive to the occupation parameters of the various single-particle configuration and indeed are in qualitative agreement with the experimental results. In particular, the trend from negative to positive g factors is predicted. More recent BCS calculations by Allaart[15] also reproduce this general trend. It is hoped that more theoretical efforts to understand the quantitative aspects of the present results will be initiated.

It is interesting to note the marked difference between the present results and the g factors of the 2_1^+ levels in the neighboring Pd ($Z = 46$), Cd($Z = 48$), and Te($Z = 52$) isotopes.[9,10] The g factors of the 2_1^+ levels in these nuclei all have values around $g \simeq +0.3$, indicating their collective vibrational nature—compared to the transition from negative to positive g factors and the shell-model structure of the closed $Z = 50$ shell Sn nuclei.

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