Magnetic Moments of States in $^{110}$Sn.

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Abstract. The semi-magic Sn isotopes with $Z = 50$ are the subject of extensive experimental and theoretical studies. The measured $B(E2)$ values to the $2^+_1$ states for the neutron-deficient side of the isotope chain suggest enhanced collectivity when fewer particles are available if the proton shell is not broken. Magnetic moments which are sensitive to proton and neutron contributions to the wave functions of the states could provide critical and relevant information. Magnetic moments were previously measured only for the even stable and a few neutron-rich unstable Sn isotopes. A measurement of the $g$ factors of excited states in $^{110}$Sn using the transient field technique was performed at the 88-Inch Cyclotron at the LBNL in Berkeley. The $^{110}$Sn nuclei were produced via an $\alpha$-particle transfer to $^{106}$Cd.

The reduced transition probabilities, $B(E2; 0^+_g \rightarrow 2^+_1)$, to the first excited $2^+$ states in the Sn isotope chain on the neutron-deficient side exhibit a remarkable deviation from the shell model expectation. A recent compilation of the results can be found in Ref. [1]. In a simple shell-model picture the $B(E2)$ values are expected to have their maximum at midshell and fall off towards the closed shells in a parabolic shape. This picture holds for the upper half of the Sn isotope chain. But, on the neutron-deficient side of the chain the measured $B(E2)$ values are larger, indicating collectivity, as fewer and fewer particles are available in the pure neutron valence space. Unless, as strongly suggested by Bader et al. [2], “enhanced proton excitations across $Z = 50$” occur “as $N = Z$ is approached”.

The $B(E2)$ measurements of the neutron-deficient Sn isotopes are difficult and the results scatter across various experiments and have large errors. The Coulomb-excitation measurements suffer from low-intensity and often very high-energy beams. Many experiments therefore are relative measurements using “known” $B(E2)$’s obtained under “similar” conditions.

Magnetic moments of the unstable neutron-deficient Sn isotopes have not been previously measured. They, potentially, can provide valuable information on the proton-neutron contributions to the wave functions of the exited Sn states, given the well known large intrinsic $g$ factors with opposite signs for neutrons and protons.

Magnetic moments reported for the $2^+_1$ states in the stable even Sn isotopes [3-5] and the neutron-rich unstable, $^{126,128}$Sn isotopes [6,7] are shown in Figure 1. The trend is from positive values at $^{112}$Sn to negative values for the heavier neutron-rich isotopes, confirming the dominant role of neutrons. Most measurements used the transient field technique (TF) and some the recoil-in-vacuum method (RIV).

The measurements on unstable isotopes depend on the availability of pure isotopic beams. The light neutron-deficient isotopes can be produced by beam fragmentation. Beams of $^{124}$Xe at
hundreds of MeV/nucleon are smashed into a thick Be target. From the beam fragments the Sn isotopes of interest are selected. Because of their high velocities these isotopes are not suitable for \(g\)-factor measurements by either the TF or RIV methods. More suitable are the beams produced at REX-ISOLDE at CERN. Besides technical problems, like contaminant radioactivities in the beam, the low beam intensities of about \(10^{-6}\) p/s impose severe experimental limits.

In this TF experiment the \(^{110}\text{Sn} (T_{1/2} = 4.1\text{h})\) was produced by a transfer reaction of an \(\alpha\) particle from \(^{12}\text{C}\) to \(^{106}\text{Cd}\). An isotopically pure beam of \(^{106}\text{Cd}\) was accelerated to 410 MeV by the Berkeley 88-inch cyclotron. The traditional multilayer target consisted of 0.636 mg/cm\(^2\) C deposited on subsequent layers of Gd (8.34 mg/cm\(^2\)), Ta (1.1 mg/cm\(^2\)) and Cu (5.40 mg/cm\(^2\)). The \(\alpha\)-transfer reaction in inverse kinematics was successfully used in many TF experiments, see for example Ref.\cite{8} and references therein. The hallmark of this method is the accessibility of some radioactive nuclei produced in conditions suitable for a TF experiment; the nuclei should be excited, spin-aligned and forward-scattered with sufficient velocity to traverse the polarized ferromagnetic foil (Figure 2).

![Multilayer target](image)

**Figure 2.** Multilayer target. The excited and spin aligned probe ions \(^{110}\text{Sn}\) and \(^{106}\text{Cd}\), which are created in the first layer, traverse the Gd, where their spins precess in the dynamic magnetic TF. The target is designed to stop the probe ions in the Cu layer, a field-free environment. The nuclei deexcite in the Cu layer without further spin rotation.
In the $\alpha$-transfer reaction $^{12}$C($^{106}$Cd,$^{8}$Be)$^{110}$Sn the residual $^{8}$Be nuclei break up into two $\alpha$ particles moving forward in the beam direction. This reaction competes with the Coulomb excitation of the projectiles, which is usually used to measure magnetic moments. This simultaneous measurement of $g$ factors provides an ideal check of the TF experiment. The $\alpha$-pickup has its maximum yield near the Coulomb barrier of the projectile and $^{12}$C which can be considered a three $\alpha$-cluster nucleus. Compared to Coulomb excitation of the beam projectiles, the $\alpha$-transfer reaction has a much lower yield, comes with a reduced spin alignment and the population of higher states in the nuclei of interest making feeding corrections possibly necessary.

Typical particle and $\gamma$ spectra are shown in Figure 3. A description of the detector arrangement and data acquisition can be found in Ref. [8]. Requiring a particle-$\gamma$ coincidence provides not only cleaner spectra but also selects an ensemble of aligned nuclei which decay with a characteristic angular distribution for each state of interest. The spin rotation in the transient magnetic field causes a rotation of the angular correlation pattern. This rotation is measured as a rate change in the stationary $\gamma$ detectors when the polarizing field at the target is reversed. The precession effect $\epsilon = (\rho - 1)/(\rho + 1)$ is calculated from quadruple ratios involving four detectors, with the same quadrant angle $\theta_{\gamma}$:

$$\rho = \sqrt{\rho_{1,4}/\rho_{2,3}} , \text{ where } \rho_{ij} = \sqrt{(N_{i}^{\uparrow}N_{j}^{\downarrow})/(N_{i}^{\downarrow}N_{j}^{\uparrow})} . \tag{1}$$

$N_{i}^\uparrow$ and $N_{i}^\downarrow$ are the integrated $\gamma$-peak rates for the two magnetic field directions. The polarizing field of 0.07 T at the target was reversed every 150 s. This field should not be confused with the transient hyperfine field which is $10^5$ times stronger. The logarithmic slope, $S(\theta_{\gamma}) = \frac{1}{W(\theta_{\gamma})} \int_{0}^{\theta_{\gamma}} \frac{dW(\theta)}{d\theta} d\theta$, of the angular correlation is needed to transform the rate change at

**Figure 3.** Particle and gated $\gamma$ spectra. Panel A: Coincident particle spectrum with areas indicating the detection of the two $\alpha$ particles hitting the detector simultaneously and the carbon recoils. Panel B: Gated on the carbon peak showing only $\gamma$ transitions in $^{106}$Cd for a clover detector at 60°. Panel C: $^{110}$Sn spectrum obtained by gating on the 2$\alpha$ particle peak in a detector at 120°. The prominent line shapes in some $\gamma$ lines are due to decay in flight and can be used to determine the lifetimes of the states by the Doppler Shift Attenuation Method.
the detector positions into the rotation angle $\Delta \theta = \epsilon/S(\theta_\gamma)$. The particle-\(\gamma\) angular correlation, using the usual notation,

$$W(\theta) = 1 + A^{2P}_{2}Q_{2}P_{2}(\cos \theta) + A^{4P}_{4}Q_{4}P_{4}(\cos \theta)$$

(2)

has been determined from anisotropy ratios obtained from the same precession data in the individual clover segments. The \(g\) factor follows from equation (3)

$$g = \frac{\Delta \theta}{\mu S} \cdot \int_{t_{in}}^{t_{out}} B_{TF}(v(t), Z) \cdot e^{-t/\tau} dt$$

(3)

with \(B_{TF}\) the transient field acting between \(t_{in}\) and \(t_{out}\), the time spent in the ferromagnetic layer.

The \(g\)-factor results of the initial data analysis are shown in Table 1. For \(^{110}\)Sn only coincident \(\gamma\) spectra were used when both \(\alpha\) particles were recorded in the particle detector. The \(g\) factor of the long-lived \(6^+_1\) state was previously measured to a high precision [9], \(g = +0.012(3)\). The lifetime of the \(4^+_1\) state is unknown but judging from the lineshape of the transition, its lifetime is long enough not to affect the TF measurement. Both states feed into the \(2^+_1\) state contributing to the stopped component in the line shape. Therefore, to avoid the feeding corrections only the tail of the 1212 keV line was used in the precession analysis of the \(2^+_1\) state.

### Table 1. Preliminary results from the \(\alpha\)-transfer reaction measured simultaneously with the Coulomb excitation of \(^{106}\)Cd.

| Nucleus | \(E_x\) (keV) | \(I^\pi\) | Transition | \(\tau\) (ps) | \(|S(67^\circ)|\) | \(g\) |
|---------|--------------|---------|------------|-------------|----------------|-----|
| \(^{110}\)Sn | 1212.0 | \(2^+_1\) | \(2^+_1 \rightarrow 0^+_1\) | 0.69(6) | 0.411(55) | +0.31(11) |
| | 2197.0 | \(4^+_1\) | \(4^+_1 \rightarrow 2^+_1\) | > 4.0 | 0.463(55) | +0.07(23) |
| | 2477.7 | \(6^+_1\) | \(6^+_1 \rightarrow 4^+_1\) | 8.1(4) \(\times 10^3\) | 0.549(126) | +0.05(22) |
| \(^{106}\)Cd | 632.7 | \(2^+_1\) | \(2^+_1 \rightarrow 0^+_1\) | 10.5(12) | 1.76(3) | +0.407(17) |
| | 1493.8 | \(4^+_1\) | \(4^+_1 \rightarrow 2^+_1\) | 1.26(15) | 0.663(24) | +0.24(5) |

Figure 4. Precession effect of the \(2^+_1\) state in \(^{106}\)Cd and average total particle rate versus run number. In this experiment the observed effect is negative. A lower beam correlates with a larger effect.
The observed $g^{(110}\text{Sn};\Delta J = 1) = +0.31(11)$ is in line with empirical single-particle $g$ factors calculated for neutrons as discussed in Ref. [4]. A break-up of the $Z = 50$ shell would result in a large positive $g$ factor, $g > 1$.

The published $g^{(106}\text{Cd};\Delta J = 0) = 0.393(31)$ value in Ref. [10] was reproduced in a measurement at 400 MeV and used as "monitor" of the target magnetization throughout the run period. As a byproduct the $g$ factor of the $4^+_1$ state in $^{106}\text{Cd}$ was measured for the first time.

The temperature of the target spot varies with the beam load and that can affect the magnetization and ultimately the strength of the magnetic field parametrized as

$$B_{TF} = 96.7MZ^{1.1}(v/v_0)^{0.45}$$

where $M$ is the magnetization of the ferromagnetic layer.

In Figure 4 the influence of beam heating on the precession effect $\epsilon$ is demonstrated. Shown is the correlation of the beam intensity (average particle rate) and the observed precession effect for each run. When the particle rate exceeded 15000 p/s the measured effect was zero. Even at particle rates below 10000 p/s the deduced magnetization from the known $g$ factor of $^{106}\text{Cd}$ was reduced from the offline-measured value of $M = 0.1800$ T. This example clearly shows the importance of controlling the beam load at the target. The magnetization derived from the $^{106}\text{Cd}$ data was applied in the $g$ factor calculation for the $^{110}\text{Sn}$.

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