g-FACTORS OF THE FIRST EXCITED 2^+ STATES OF THE STABLE, EVEN-EVEN Mo ISOTOPES

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The low-energy structure of the even-even $_{42}$Mo isotopes undergoes a change from spherical at the neutron-closed shell nucleus ^{92}Mo$_{50}$ to rotational-like at ^{104}Mo$_{62}$, for which $E(2_1^+) = 192$ keV and $E(2_1^+)/E(4_1^+) = 2.91$. In addition, the excited 0^+ state observed at an energy near the 2_1^+ state in both ^{98}Mo and ^{100}Mo is a signature of shape-coexistence. Toward the proton drip line, the $E(2_1^+)$ values drop dramatically from 1510 keV in ^{92}Mo to 444 keV in the self-conjugate nucleus ^{84}Mo. To learn more about the single-particle structures underlying the emerging low-energy collective properties of the even-even Mo isotopes in the transition region between $A = 90$ and $A = 100$, we have measured the g factors of the first 2^+ states of the stable, even-even isotopes ^{92,94,96,98,100}Mo.

Some information on the g factors of 2_1^+ states in the even-even Mo isotopes is available in the literature. The average g factor for the first 2^+ states in ^{98,100}Mo was deduced to be 0.34(18) [1] from early ion implantation perturbed angular correlation measurements. This was a 'thick-foil' measurement in which the Mo nuclei experienced both static and transient fields. The transient field was not well characterized at the time, so the result must be taken as tentative. The individual g factors for the 2_1^+ states in the stable, even-even isotopes of Mo were measured in an early transient field study at Chalk River [2, 3]. This transient field measurement employed a sequence of targets of isotopically enriched Mo ~0.7 mg/cm^2 thick, followed by 3.6 - 4.0 mg/cm^2 thick annealed Fe foils with Cu backings. A 130 MeV ^{40}Ca beam was used to Coulomb excite the Mo target nuclei. The g factors, deduced from consecutive measurements, had errors in the range 14 - 17%; these errors include statistical uncertainties and systematic uncertainties in the transient field calibration, the recoil energy loss, and the slope of the angular correlation. As systematic errors can occur through the consecutive use of a sequence of different targets, a new set of simultaneous measurements is required.

The transient field technique [4] was used to determine the g factors of the first excited states of the stable, even-even Mo isotopes, ^{92,94,96,98,100}Mo. A beam of 100 MeV ^{32}S^{8+} from the 14UD Pelletron accelerator at Australian National University, having an average current of 30 enA, was made incident upon a multilayered target consisting of 0.757 mg/cm^2 ^{nat}Mo, 2.57 mg/cm^2 ^{nat}Fe, and a 7.6 mg/cm^2 Cu backing foil. The ^{32}S beam entered the Mo side of the target, Coulomb exciting Mo nuclei. The resulting Mo γ rays were detected using four high purity Ge detectors placed at $\theta_\gamma = \pm 65°$ and $\theta_\gamma = \pm 115°$ relative to the incident beam direction. The $+65°$ and $-65°$ detectors were placed 7.3 cm and 6.7 cm, respectively, from the target position, to match their solid-angles, while the two backward detectors were each placed 8.7 cm from this location. Particle-γ-ray correlations were measured by detecting the Mo γ rays in coincidence with backscattered ^{32}S ions which entered an annular Si detector covering an angular range from $150°$ to $167°$, again relative to the incident beam direction.

The Fe layer of the target was polarized by an external field of ≈ 0.08 T, the direction of which was reversed automatically, approximately every 20 min, to minimize possible systematic errors. After leaving the ferromagnetic foil, the Mo nuclei were stopped in the Cu backing where they experience no further magnetic perturbations. The Fe foil magnetization was measured with the Rutgers magnetometer [5] to be consistent with the full saturation value of $M = 0.171$ T at 300 K for $B_{\rm ext} = 0.08$ T.

The precession angle of the Mo nuclei due to the interaction of their magnetic moments with the transient hyperfine field in the Fe foil is

$$\Delta\theta = g\phi \tag{1}$$

where g is the nuclear g factor and ϕ is the integral strength of the transient field.

Unperturbed particle-γ-ray angular correlations for the $2^+ \to 0^+$ transitions in each Mo nucleus were calculated using a version of the Winther-de Boer Coulomb exitation code [6]. These calculations considered the finite angular coverage of the particle detector, the beam energy loss in the target, and feeding from populated higher-excited states. Relevant matrix elements for the Coulomb excitation calculations were taken from Ref. [7]. To confirm the angular correlation calculations, the unperturbed particle-γ-ray angular correlations were also measured for the two forward detectors.

The measured precession angles are presented in Table 1. To extract the g factors for the 2_1^+ states from the measured precession angles, knowledge of the integral strength of the transient field for Mo ions traversing magnetized Fe is needed. The field calibration adopted for Mo in Fe was of the form

$$B(Z, v) = a\ Z\ (v/v_0)^p, \tag{2}$$

with $p = 0.41$ [8] and $a = 23.65 \pm 1.01$ T extracted from experimental field strengths for Pd and Rh in Fe measured under very similar conditions. The adopted ϕ values are listed in Table 1, along with the deduced $g(2_1^+)$ values for ^{92,94,96,98,100}Mo. The finite lifetimes of each of the 2_1^+ states, which were taken from the compilation of Raman *et al.* [9], were included in the evaluation of ϕ.

Table 1: Integral transient field strengths and absolute g factors for the 2_1^+ states in ^{92,94,96,98,100}Mo.

Isotope	J_i^π	τ (ps) [a]	$\Delta\theta$ (mrad)	ϕ	g [b]
^{92}Mo	2_1^+	0.537 ± 0.033	-29 ± 12	-22.66 ± 1.09	$1.28 \pm 0.53 \pm 0.53$
^{94}Mo	2_1^+	4.00 ± 0.08	-8.9 ± 2.4	-32.45 ± 1.39	$0.274 \pm 0.074 \pm 0.075$
^{96}Mo	2_1^+	5.27 ± 0.10	-13.8 ± 1.1	-32.92 ± 1.41	$0.419 \pm 0.033 \pm 0.038$
^{98}Mo	2_1^+	5.04 ± 0.09	-15.7 ± 1.2	-32.86 ± 1.40	$0.478 \pm 0.037 \pm 0.042$
^{100}Mo	2_1^+	17.89 ± 0.35	-17.5 ± 1.2	-33.99 ± 1.45	$0.515 \pm 0.035 \pm 0.042$

[a] Lifetimes taken from Ref. [9].
[b] The first error, from the statistical error in the measured precession alone, represents the error in the relative g factors; the second, which includes the uncertainty in the field calibration, represents the error in the absolute g factors.

On the whole, the present g factors for the first excited 2^+ states of the stable, even-even Mo isotopes compare favorably with the earlier results of Hausser *et al.* [2, 3], re-evaluated using the transient field calibration adopted here for Mo in Fe. However, the present results reveal a steady increase in the $g(2_1^+)$ values with increasing neutron number in the range $A = 94 - 100$ that is not apparent from the older measurements. In particular, the previous g factor for ^{100}Mo appears to be smaller than the present value. Given that this state is relatively long lived and that the exit velocity in the Chalk River measurement was rather low, there is a chance that a smaller precession was observed because a fraction of the ^{100}Mo ions stopped in the Fe foil (rather than the Cu backing) where they experience the static hyperfine field which, for Mo in Fe, is $-25.6(5)$ T [10]. On the other hand, this effect on its own is unlikely to fully account for the difference in the measured g factors and the two measurements almost agree within the assigned errors. For the following discussion we therefore adopt g factors that are the average of the present and (re-evaluated) previous work. These values are shown in the final column of Table 2.

Table 2: Adopted g factors for the 2_1^+ states of even-even Mo isotopes.

Isotope	$E(2_1^+)$ (keV)	g factor				
		Ref. [2, 3]			present	adopted
		$\Delta\theta$ (mrad)	ϕ [a]	Re-evaluated		
^{92}Mo	1509	-32.7 ± 2.0	-28.63 ± 1.22	$+1.14 \pm 0.14$	$+1.28 \pm 0.53$	$+1.15 \pm 0.14$
^{94}Mo	871	-14.1 ± 1.5	-43.35 ± 1.85	$+0.325 \pm 0.053$	$+0.274 \pm 0.075$	$+0.308 \pm 0.043$
^{96}Mo	778	-15.4 ± 1.4	-44.21 ± 1.89	$+0.348 \pm 0.052$	$+0.419 \pm 0.038$	$+0.394 \pm 0.031$
^{98}Mo	787	-22.2 ± 1.7	-44.87 ± 1.92	$+0.495 \pm 0.067$	$+0.478 \pm 0.042$	$+0.483 \pm 0.036$
^{100}Mo	536	-21.2 ± 1.4	-52.53 ± 2.24	$+0.404 \pm 0.052$	$+0.515 \pm 0.042$	$+0.471 \pm 0.033$
^{102}Mo	297					$+0.42 \pm 0.07$ [b]
^{104}Mo	192					$+0.19^{+0.12}_{-0.11}$ [b]

[a] ϕ evaluated with transient field parametrized by Eq. 2 with $a = 23.65 \pm 1.01$ T and $p = 0.41$.
[b] Ref. [11].

The Migdal-corrected geometrical model [12], successful in mapping the trends in $g(2_1^+)$ values of collective nuclei in the rare-earth region [13], was found to reproduce well the adopted $g(2_1^+)$ values for the even-even Mo isotopes with $A \geq 94$ (see Fig. 1).

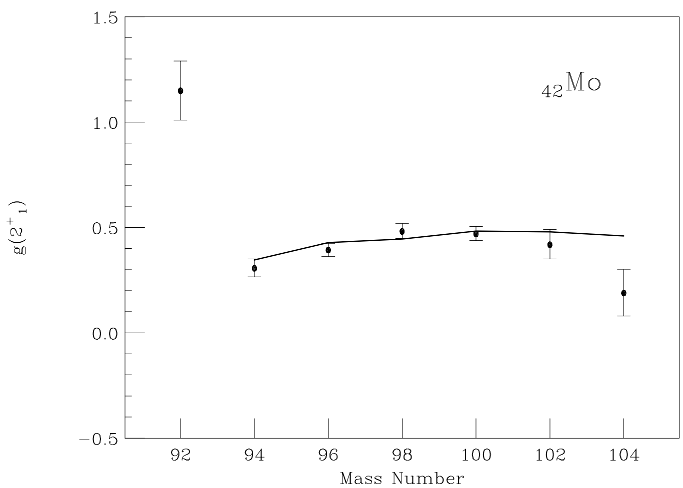

Figure 1: Adopted $g(2_1^+)$ values (filled cirlces) for the even-even Mo isotopes compared with g factors predicted from the hydrodymanical model with pairing corrections in the Migdal approximation. The pairing gaps required were calculated using the Woods-Saxon potential. Deformations were taken from the intrinsic quadrupole moments calculated by Möller and Nix [14].

Near the $N = 50$ shell closure, the results of shell model calculations using a very restricted basis outside a ^{90}Zr core track well the moments of the nearly pure $\pi(1g_{9/2})^2_{8+}$ configurations in ^{92,94}Mo. This simple calculation, however, underpredicts the g factors of low-spin states in ^{94,95,96}Mo. The extension of the shell model calculations to include more valence orbitals better reproduces the experimental $g(2_1^+)$ values near $N = 50$. The shell model results are compared to the experimental g factors in Fig. 2. Although the 2_1^+ magnetic moments are nearer to Z/A than predicted from the shell model, the collective contributions are not dominant near $N = 50$, supporting a picture in which the valence proton and neutron spaces are weakly coupled. However, as one adds neutrons beyond $N = 56$, the $\nu 1g_{7/2}$ - $\pi 1g_{9/2}$ neutron-proton interaction becomes significant. Khasa *et al.* [15] predicted that the $\pi 2p_{1/2}$ orbital is completely empty except for ^{92}Mo and ^{90}Zr, and that for $^{100-106}$Mo the valence protons are equally distributed between the $2d_{5/2}$ and $1g_{9/2}$ orbitals. Interacting Boson Model IBM-2 calculations with configuration mixing support such a picture, where the ground state of ^{98}Mo is a mixed two proton particle and four proton particle - two proton hole configuration and the ground state of ^{100}Mo is predominately of four proton particle - two proton hole character [16].

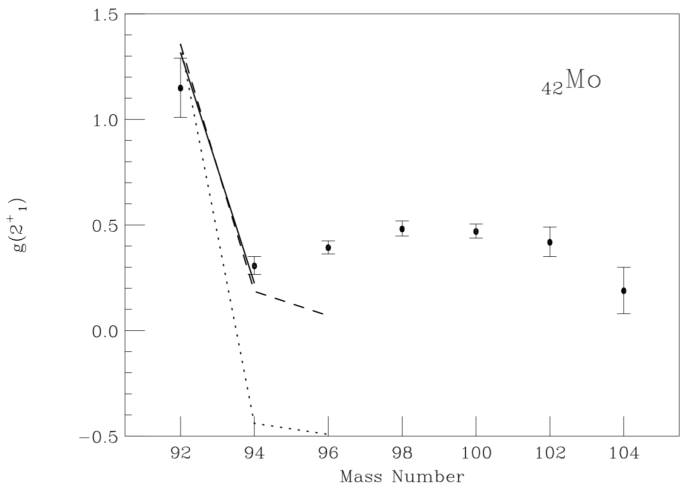

Figure 2: Adopted $g(2^+_1)$ values (filled cirlces) for the even-even Mo isotopes compared with g factors predicted from shell model calculations using a ^{90}Zr core with valence orbitals $\pi 1g_{9/2}$ and $\nu 2d_{3/2}$ (dotted line), a ^{88}Sr core with valence orbitals $\pi(2p_{1/2}, 1g_{9/2})$ and $\nu(2d_{5/2}, 3s_{1/2})$ (dashed line), and a more extended space which includes $\pi(1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 1g_{9/2})$ and $\nu(1g_{9/2}, 2p_{1/2}, 2d_{5/2}, 3s_{1/2}, 2d_{3/2}, 1g_{7/2})$ (solid line).

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