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Sign of the g factor of the 4_1^+ state in ^{68}Zn

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In two recent papers a *negative* g factor was reported for the 4_1^+ state in ^{68}Zn. The negative sign is unexpected. It is not consistent with the systematics of g factors in the neighboring Zn and Ge isotopes and could not be explained by shell-model calculations even when significant contributions of the $0g_{9/2}$ neutrons were included. Therefore, an independent g factor measurement was performed, using ^{68}Zn projectiles which were accelerated to a higher energy in order to obtain a higher yield for the 4_1^+ state. The new measurement yielded a positive g factor, $g(4_1^+) = +0.6(3)$, which agrees with the results of full *fp* spherical shell model calculations, as well as with Z/A, the collective model prediction.

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The measured signs and magnitudes of the magnetic moments of nuclear states provide information sensitive to the respective neutron and proton contributions to the wave functions of these states. In two recent publications [1,2] a negative g factor was reported for the 4_1^+ state in ^{68}Zn. This negative sign is surprising because it disagrees with the systematics of $g(4_1^+)$ factors in this region. According to Refs. [1,2] the sign and magnitude of this g factor indicate and require strong contributions from neutron excitation into the $g_{9/2}$ orbital. However, detailed shell-model calculations presented in those two papers could not reproduce a negative value, even when significant contributions of the $0g_{9/2}$ neutrons were included.

Substantial deviations of a measured moment from the results of shell-model calculations and from systematics of the data for neighboring nuclei raise questions about our understanding of the underlying nuclear structure and call for additional experimental work to clarify the situation.

The g-factor measurements of short-lived and weakly excited states, using the transient field method, are especially difficult and present major experimental challenges. In the first such experiment [1] to measure the $g(^{68}\text{Zn},4_1^+)$ NaI detectors were used. The γ-ray line corresponding to the $4_1^+ \to 2_1^+$ transition sits on top of a substantial Doppler shifted Compton background (including the Compton edge) from the $3_1^- \to 2_1^+$ transition; furthermore, it is not resolved from the $2_3^+ \to 2_1^+$ transition. This makes it difficult (see Fig. 3 in Ref. [1]) to subtract unambiguously the background under the $4_1^+ \to 2_1^+$ transition. That experiment yielded a precession of $\Delta\theta = -11(5)$ mrad, consistent (in the notation of [1] Eq. (1), which uses a sign convention opposite to the standard convention in the field of hyperfine interactions [3]) with a negative g factor for the 4_1^+ state. Since this negative value was unexpected, this result stimulated a follow-up experiment by the same group. The second measurement [2] again utilized the transient field technique but used high resolution Ge detectors. The data had low statistics, yielding a precession angle of $\Delta\theta = -6(8)$ mrad which, however, does not exclude a negative sign for the g factor.

This paper reports on a remeasurement of the g factors of the $2_1^+, 2_2^+, 4_1^+$, and 3_1^- states (Fig. 1) of ^{68}Zn, with special emphasis on the sign of the 4_1^+ g factor. The transient field technique was used on projectiles excited in an inverse kinematic condition. The current experiment is essentially a repeat of the experiment of Ref. [2] except for the larger γ detectors (Clover type) and the higher beam energy, which results in a higher excitation cross section for the 4_1^+ state.

A beam of isotopically pure ^{68}Zn was accelerated to energies of 180 and 200 MeV at the ESTU Tandem of the Wright Nuclear Structure Laboratory at Yale University. The target consisted of a 0.42 mg/cm^2 carbon layer deposited on 3.24 mg/cm^2 gadolinium evaporated onto a 1.4 mg/cm^2 tantalum foil backed by 3.5 mg/cm^2 copper. A 5 μg/cm^2 titanium flashing was added between the carbon and gadolinium to ensure good adherence of the carbon. The magnetization of the target was measured as a function of the temperature in the range between 25 K and 150 K in an AC magnetometer [4]. It was found to be M = 0.1726 T, approximately constant from 60 K to 120 K. An additional copper foil of 11.2 mg/cm^2 was placed behind the target to stop the beam.

The beam projectiles which are Coulomb excited in the carbon layer are stopped in the copper backing of the target. The scattered carbon ions, as well as light particles from reactions were detected in a PIPS Canberra particle detector positioned 26 mm downstream of the target and subtending an angle of $\pm 20^\circ$. The γ rays were detected in four HPGe Clover detectors mounted outside of the vacuum chamber, at

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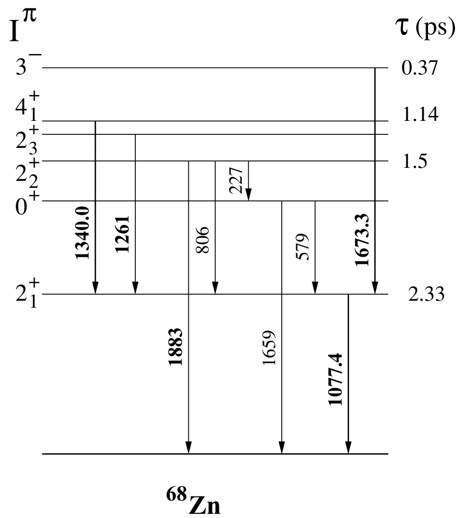

FIG. 1. Energy level diagram of the low-lying levels and transitions in ^{68}Zn.

129 mm from the target. All particles and γ rays were recorded as singles in a PIXIE-4 system from XIA [5]. From the trigger times for each singles event, particle-γ coincidence spectra were constructed offline.

Figure 2 shows a ^{12}C-γ coincidence spectrum obtained for a beam of 200 MeV. Compton scattered γ-rays were added back to the spectra of each individual detector segment. The particle-γ coincidence condition ensures that only Coulomb excitation in the carbon layer is considered. The energies and velocities of the probe ions entering and exiting the gadolinium foil are summarized in Table I.

Two quantities are required to determine a g factor: the spin alignment of the state, determined from an angular distribution measurement, and the spin precession, determined from a measurement of the rotation of this angular distribution.

Particle-γ angular correlations, $W(\theta)$, were determined for each state from an anisotropy measurement in which

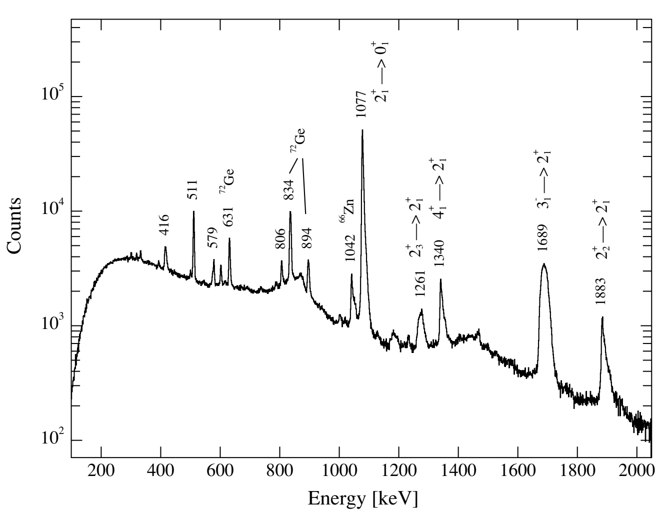

FIG. 2. A random subtracted ^{12}C-γ-coincidence spectrum for one segment of a Clover detector at 66°.

TABLE I. Summary of beam energies, angular momenta and parity of each excited state, and kinematics of the recoiling ion. The $\langle E\rangle_{\rm in}$ and $\langle E\rangle_{\rm out}$, and $\langle v/v_0\rangle_{\rm in}$ and $\langle v/v_0\rangle_{\rm out}$, are, respectively, the average energies and velocities of the excited ^{68}Zn ions as they enter into and exit from the gadolinium layer; $v_0 = e^2/\hbar$ is the Bohr velocity. $\Delta\theta_{\rm calc}$ is the expected precession for the target and kinematic conditions of this experiment for $g = 1$ using the Rutgers parametrization [6].

$E_{\rm beam}$ MeV	I^{π}	$\langle E\rangle_{\rm in}$ MeV	$\langle E\rangle_{\rm out}$ MeV	$\langle \frac{v}{v_0}\rangle_{\rm in}$	$\langle \frac{v}{v_0}\rangle_{\rm out}$	$\Delta\theta_{\rm calc}(g=1)$ mrad
180	2_1^+	80.9	32.7	6.93	4.40	23.7
200	2_1^+	91.5	40.6	7.36	4.91	22.9
200	2_2^+	92.0	41.0	7.38	4.93	21.7
200	4_1^+	92.3	41.2	7.40	4.94	20.7
200	3_1^-	92.5	41.4	7.41	4.95	14.9

each of the four Clover detectors was alternately placed at two angles: $\theta_1 = 50°$, close to a maximum, or $\theta_2 = 80°$, near a minimum of the angular correlation (see Ref. [7] for more details). The experimental $A_2^{\rm exp}$ and $A_4^{\rm exp}$ coefficients, as well as the logarithmic slopes of the angular correlations, $S(\theta_\gamma) = \frac{1}{W(\theta_\gamma)} \cdot \frac{dW(\theta_\gamma)}{d\theta}$, were derived for each transition from the measured anisotropy ratios R as described in Ref. [7].

For the precession measurements the target was mounted on the tip of a closed-cycle refrigerator and kept at a temperature of about 60 K. An external field of $B_{\rm ext} = 0.07$ T was applied alternately up (↑) or down (↓) with respect to the γ-ray detection plane; the field direction was changed every 136 sec. The four Clover detectors, 1 to 4, were placed at angles of $+114°$, $+66°$, $-66°$, and $-114°$, respectively, with respect to the beam axis, where the logarithmic slope of the angular distribution is optimal.

The precession angle $\Delta\theta = \epsilon/S$ was determined from the ratios of the peak intensities N↑ and N↓, which were extracted from the spectra for each individual detector [8]. The precession effect $\epsilon = (\rho - 1)/(\rho + 1)$ was then determined from quadruple ratios involving the four detectors:

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

In order to obtain a negative $g(4_1^+)$ the precessions for the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions should have opposite signs. In Fig. 3 the effect ratios, ϵ, are shown separately for the different runs during the experiment. The runs are arbitrarily split from each other, and the ϵ's are displayed from left to right for successive runs. Also shown for each run, denoted by triangles, are effects $\epsilon_c = (\rho_c - 1)/(\rho_c + 1)$ calculated from so-called "cross ratios" $\rho_c = \sqrt{\rho_{1,3}/\rho_{2,4}}$. These are obtained from the same data for detectors grouped into pairs, which should always yield a zero effect. The points on the extreme right site of the graph are the weighted averages of all runs. It is seen that the two triangles which represent the weighted averages of the cross ratios indeed have zero values. The top

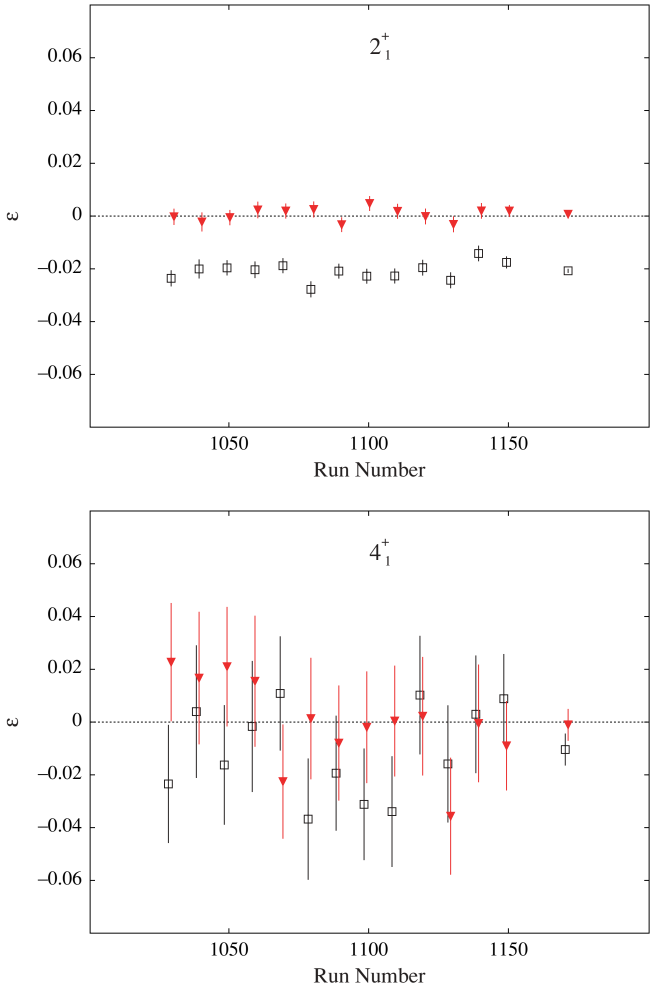

FIG. 3. (Color online) Precession effects for the 2_1^+ and 4_1^+ states in ^{68}Zn for arbitrarily split runs. The squares are the effect ratios, ϵ, the triangles are "cross ratios" of the same data for detector pairs which should have no net precession.

of Fig. 3 shows the good overall quality of the experiment. A comparison of the upper and lower parts of Fig. 3 indicates that the two ϵ's, for the 2_1^+ and the 4_1^+ states, have the same sign. Since the slopes, S, for both transitions have the same sign, it follows that the g factors have the *same* positive sign.

Finally, the g factors for each state were extracted from the corresponding measured precession angles, $\Delta\theta$, using

$$\Delta\theta = -g \cdot \frac{\mu_N}{\hbar} \cdot \int_{t_{\rm in}}^{t_{\rm out}} B_{\rm TF}(v(t), Z) \cdot e^{-t/\tau} dt. \qquad (2)$$

Here $B_{\rm TF}$, the transient field, is a function of both the velocity v and the atomic number Z of the projectile ion, τ is the mean lifetime of the state being considered, and $t_{\rm in}$ and $t_{\rm out}$ are the mean entrance and exit times of the ions into and out of the ferromagnetic gadolinium layer. The value of $B_{\rm TF}$ was derived from the Rutgers parametrization [6]. In general, in the velocity regime of this experiment, the Bonn [1] and Rutgers parametrizations are in good agreement, and any difference between them leads only to a small change in the absolute value of g, but not in its sign. The calculated precessions, $\Delta\theta_{\rm calc}(g = 1)$, are listed in Table I.

The results of the measurements of the current experiment are presented in Table II together with the weighted averages of the g values from Refs. [1,2]. The accuracy of the $g(2_1^+)$ measured at 180 MeV is limited due to a short runtime. The data for the $2_1^+ \rightarrow 0_1^+$ transition were corrected for the feeding from higher excited states. At 200 MeV, even though good statistical accuracy was obtained for the $2_1^+ \rightarrow 0_1^+$ transition, substantial feeding corrections contribute to the large error.

There is excellent overall agreement between the results of the present work and those of [1,2] with the sole exception of the sign and magnitude of $g(4_1^+)$.

The last column in Table II refers to the results of calculations that were carried out using the computer code ANTOINE [9] and the GXPF1A interaction [10] in the full *fp* shell model space. The GXPF1A interaction provided the best agreement with the experimental data. These results suggest that the observed g factors in ^{68}Zn can be explained without including the $g_{9/2}$ orbital in the shell model space. However, due to the large errors in $g(4_1^+)$ one cannot rule out some $g_{9/2}$ admixture.

In an effort to calculate a negative $g(4_1^+)$ the authors of Refs. [2,11] have included the $g_{9/2}$ orbital in their shell model calculations. Their latest results, labeled SM-4 in Ref. [11], yield $g(4_1^+) = +0.003$. In addition, this calculation fails badly in its prediction for the 2_1^+ state, yielding $g(2_1^+) = +0.148$.

The negative sign measured in Refs. [1,2] for the $g(4_1^+, {}^{68}\text{Zn})$ raised the question of whether there was a similar negative sign for the $g(4^+)$ in the isotone ^{70}Ge [12].

TABLE II. Level energy E_x, spin and parity, mean life, logarithmic slopes $S(\theta_\gamma)$ of the angular correlations, measured precession angles $\Delta\theta$, experimental g factors and theoretical predictions.

E_x	I^π	τ(ps) Ref. [1]	Transition	$\|S(66°)\|$	$\Delta\theta$(mrad)	g		
						this work	Refs. [1,2]	theory
1077.4	2_1^+	2.33(3)	$2_1^+ \rightarrow 0_1^+$	2.21(2)	−12.5(13)	+0.53(6)[a]	+0.48(3)	+0.58
				2.01(7)	−12.4(14)	+0.54(6)[b]		
1883.1	2_2^+	1.5(1)	$2_2^+ \rightarrow 0_1^+$	1.11(10)	−11.8(55)	+0.6(3)	+0.50(11)	+0.88
2417.4	4_1^+	1.14(6)	$4_1^+ \rightarrow 2_1^+$	0.86(8)	−12.1(70)	+0.6(3)	−0.37(17)	+0.65
2750.4	3_1^-	0.37(1)	$3_1^- \rightarrow 2_1^+$	0.35(3)	−4.9(61)	+0.3(4)	+0.4(3)	

[a] $E_{\rm beam} = 180$ MeV.
[b] $E_{\rm beam} = 200$ MeV.

Preliminary data obtained at Yale earlier did not support that suggestion [13]. A new subsequent recent measurement yielded unambiguously a positive sign for the g factor of the 4_1^+ state in ^{70}Ge [14].

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[1] J. Leske, K.-H. Speidel, S. Schielke, O. Kenn, D. Hohn, J. Gerber, and P. Maier-Komor, Phys. Rev. C **71**, 034303 (2005).

[2] J. Leske, K.-H. Speidel, S. Schielke, J. Gerber, P. Maier-Komor, T. Engeland, and M. Hjorth-Jensen, Phys. Rev. C **72**, 044301 (2005).

[3] R. Borchers, J. Bronson, D. Murnick, and L. Grodzins, Phys. Rev. Lett. **17**, 1099 (1966).

[4] A. Piqué, J. M. Brennan, R. Darling, R. Tanczyn, D. Ballon, and N. Benczer-Koller, Nucl. Instrum. Methods Phys. Res. A **279**, 579 (1989).

[5] X-Ray Instrumentation Associates: http://www.xia.com/.

[6] N. K. B. Shu, D. Melnik, J. M. Brennan, W. Semmler, and N. Benczer-Koller, Phys. Rev. C **21**, 1828 (1980).

[7] T. J. Mertzimekis, N. Benczer-Koller, J. Holden, G. Jakob, G. Kumbartzki, K.-H. Speidel, R. Ernst, A. Macchiavelli, M. McMahan, L. Phair *et al.*, Phys. Rev. C **64**, 024314 (2001).

[8] J. Holden, N. Benczer-Koller, G. Jakob, G. Kumbartzki, T. J. Mertzimekis, K.-H. Speidel, C. W. Beausang, R. Krücken, A. Macchiavelli, M. McMahan *et al.*, Phys. Rev. C **63**, 024315 (2001).

[9] E. Caurier, computer code ANTOINE, IReS, Strasbourg (1989–2004).

[10] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C **69**, 034335 (2004).

[11] J. Leske, K.-H. Speidel, S. Schielke, J. Gerber, P. Maier-Komor, T. Engeland, and M. Hjorth-Jensen, Phys. Rev. C **73**, 064305 (2006).

[12] J. Leske, K.-H. Speidel, S. Schielke, J. Gerber, P. Maier-Komor, S. J. Q. Robinson, A. Escuderos, Y. Y. Sharon, and L. Zamick, Phys. Rev. C **74**, 024315 (2006).

[13] P. Boutachkov, G. Kumbartzki, N. Benczer-Koller, S. Robinson, A. Escuderos, E. Stefanova, Y. Sharon, L. Zamick, E. McCutchan, V. Werner *et al.*, Bull. Am. Phys. Soc. **51**, 36 (2006).

[14] P. Boutachkov *et al.*, to be submitted to Phys. Rev. C.