Measurement of the ^{96}Ru $g(4_1^+)$ factor and its nuclear structure interpretation

D. A. Torres,* G. J. Kumbartzki, Y. Y. Sharon, L. Zamick, B. Manning, and N. Benczer-Koller
Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903, USA

K.-H. Speidel
Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany

T. Ahn, V. Anagnostatou,† M. Elvers,‡ P. Goddard,† A. Heinz, G. Ilie,§ D. Radeck,‡ D. Savran,‖ and V. Werner
Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA

G. Gürdal
DePaul University, Chicago, Illinois 60604, USA

M. J. Taylor
School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom

P. Maier-Komor
Physik-Department, Technische Universität München, D-85748 Garching, Germany

M. Hjorth-Jensen
Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway

S. J. Q. Robinson
Department of Physics, Millsaps College, Jackson, Mississippi 39210, USA
(Received 16 December 2011; published 30 January 2012)

Background: The experimental study of $g(I > 2)$ factors of nuclear states can provide information about the evolution of collectivity in certain regions of the nuclear chart, and assist in obtaining a microscopic description of the nuclear wave functions. The measurements and explanations of $g(I > 2)$ factors are still a challenge for experiments and theory.
Purpose: Measurement of the $g(2_1^+)$ and $g(4_1^+)$ factors, the latter for the first time, in the $^{96}_{44}$Ru nucleus. Comparison of the experimental results with calculations using the shell model and collective models.
Methods: The experiments made use of the transient field technique, using a Coulomb-excitation reaction in inverse kinematics. Large scale shell model calculations were performed; comparisons with previous theoretical predictions, using the tidal-wave model and the hydrodynamical model, were carried out.
Results: The values of $g(2_1^+) = +0.46(2)$ and $g(4_1^+) = +0.58(8)$ were experimentally obtained. While the $g(2_1^+)$ value agrees with the hydrodynamical model prediction of $g = Z/A = +0.46$, the $g(4_1^+)$ is in agreement with the shell model predictions. The trend of the experimental g factors, as a function of nuclear spin, is not reproduced by the theoretical models discussed.
Conclusions: Measurements of $g(2_1^+)$ and $g(4_1^+)$ in ^{96}Ru were performed. Further theoretical efforts are necessary to explain the trend of the g factors as a function of nuclear spin for the ^{96}Ru nucleus. Future measurements of $g(4_1^+)$ should reduce the uncertainty of the result.

DOI: 10.1103/PhysRevC.85.017305 PACS number(s): 21.10.Ky, 25.70.Hi, 27.60.+j

The study of the nuclear-spin dependence of the g factors, for a given nucleus, can reveal particular features of the structure functions such as, for example, the interplay between single-particle configurations and collective excitations [1]. Traditionally, the study of magnetic moments of the 2_1^+ states of even-even nuclei, along an isotopic chain, allows the microscopic study of the structure of the nuclear wave functions of the relevant isotopes. A recent work, by Chamoli *et al.* [2], applied the tidal-wave model [3] to describe the experimental $g(2_1^+)$, and most of the $g(4_1^+)$, factors for all the stable isotopes of Mo, Ru, Pd, and Cd. Their calculated g-factor trends are in overall agreement with their experimental

*Present address: Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia; datorresg@unal.edu.co
†Also at: Department of Physics, University of Surrey, Guildford, UK.
‡Also at: Institut für Kernphysik, Universität Köln, Germany.
§Present address: National Institute for Physics and Nuclear Engineering, Bucharest, Romania.
‖Also at: Institut für Kernphysik, Technische Universität Darmstadt, Germany; Present address: ExtreMe Matter Institute EMMI and Research Division, GSI, Germany.

results, and the deviations from the collective $g = Z/A$ values are well accounted for. Notwithstanding, a complete comparison with their results needs additional experimental $g(4_1^+)$ values for several isotopes. Such information is pivotal to test, for example, the tidal-wave model prediction of $g(4^+) < 0.5g(2^+)$ in the $A \sim 100$ region [2]. It should be noted that for $I > 2$, the experiments are challenging and the data are scarce. The ^{96}Ru nucleus, with two neutrons beyond the $N = 50$, has the highest $E(2_1^+)$ excitation energy and smallest $B(E2; 2_1^+ \to 0_1^+)$ value of all the even-A Ru isotopes with $N > 50$, thus, being the least collective [4]. Yet, the ^{96}Ru literature value, $g(2_1^+) = +0.46(2)$, agrees well with the collective $Z/A = +0.46$ prediction [4]. Hence, measuring the ^{96}Ru $g(4_1^+)$ value would help to clarify the structure of this nucleus. These details would also elucidate the gradual transition from single-particle to collective behavior as N increases beyond $N = 50$ in the even-A Ru isotopes.

In this Brief Report, experiments were carried out using Coulomb excitation in inverse kinematics, with beam energies of 350 MeV and 343 MeV, in order to measure the g factors of the 2_1^+ and 4_1^+ states of ^{96}Ru ($Z = 44$). The results were interpreted on the basis of shell-model (SM) calculations, and recent results from tidal-wave model calculations [2]. In addition, the lifetime of the 2_1^+ state has been redetermined using the Doppler-shift attenuation method (DSAM).

The experiments used for the present report have been described in detail in Ref. [5] and will be briefly summarized below. Excited states of ^{96}Ru were populated using the reaction ^{12}C(^{96}Ru,^{12}C)^{96}Ru*. An isotopically pure beam of ^{96}Ru, with intensities of ∼1 pnA, was accelerated to energies of 350 MeV and 343 MeV. At the ESTU tandem accelerator of the Wright Nuclear Structure Laboratory (WNSL) at Yale University. The experiment utilized a multilayered target of 0.61 mg/cm^2 of carbon, deposited on 6.42 mg/cm^2 of gadolinium, which in turn was deposited on a 1.0 mg/cm^2 tantalum foil, backed by 5.6 mg/cm^2 of copper. The beam energies were chosen to reach, in the middle of the carbon layer, values close to the Coulomb barrier for ^{96}Ru on C (about 333 MeV). To distinguish the Coulomb-excited events from other possible reaction channels (α transfer or fusion evaporation, for example) the scattered carbon ions were detected in a passivated, implanted, planar silicon (PIPS) Canberra particle detector. The PIPS was positioned at 0° with respect to the beam direction, subtending an angle of ±26°.

De-excitation γ rays of ^{96}Ru were detected in four clover HP-Ge detectors, placed symmetrically to the beam direction at angles $\theta = \pm 67^\circ, \pm 113^\circ$ around the center of the target. The HP-Ge detectors were placed at a distance of about 130 mm from the target. Figure 1 presents the γ-ray projection of the events in coincidence with the carbon particles. The initial and final velocities of the ^{96}Ru ions entering and leaving the gadolinium foil are presented in Table I.

The nuclear spins of the ^{96}Ru excited states precess in the transient magnetic hyperfine field (TF), which acts while the ions are traversing the gadolinium layer. The ions were subsequently stopped in the hyperfine-interaction-free copper backing. The beam itself was stopped by an additional 11.2 mg/cm^2 copper foil placed downstream from the target. The orientation of the TF was controlled by the direction of the magnetic field inside the gadolinium layer, polarized by an external magnetic field, $B_{\rm ext} = 0.07$ Tesla, applied alternately up (↑) and down (↓) with respect to the γ-ray detection plane. The field direction was changed every 136 s. The magnetization M of the target was found to be $M = 0.1795$ Tesla at temperatures between 50 and 100 K. Such a magnetization was measured offline, before the experiment, using an AC magnetometer [6].

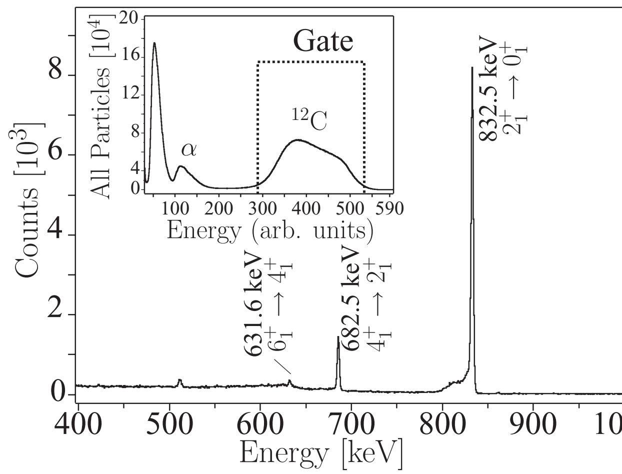

FIG. 1. The ^{96}Ru γ-ray spectrum, from clover 1 at a backward angle of $\theta = 113^\circ$, in coincidence with scattered carbon particles. The gate on the carbon particles is shown in the upper-left corner of the spectrum. The γ spectrum is dominated by the $2_1^+ \to 0_1^+$ and $4_1^+ \to 2_1^+$ transitions.

The g factor for each state is calculated using the formula

$$\Delta\theta = -g \cdot \frac{\mu_N}{\hbar} \cdot \int_{t_{\rm in}}^{t_{\rm out}} B_{TF}(v(t), Z) \cdot e^{-t/\tau} dt. \quad (1)$$

Here μ_N is the nuclear magneton ($e\hbar/2M_pc$), $t_{\rm in}$ ($t_{\rm out}$) is the mean entrance (exit) time of the ions into (from) the ferromagnetic gadolinium layer, τ is the mean lifetime of the state being considered, and B_{TF} is the calculated transient field using the Rutgers parametrization [7]. The precession angle $\Delta\theta = \epsilon/S(\theta_\gamma)$ [8] of a given state is obtained from the ratio of the γ-ray photopeak intensities. The precession effect, $\epsilon = (\rho - 1)/(\rho + 1)$, is calculated from quadruple ratios involving the four HP-Ge clover detectors:

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

where $N_i^\uparrow$ ($N_i^\downarrow$) is the γ-ray peak intensity measured at clover i when the external magnetic field, B$_{\rm ext}$, is up (down). $S(\theta_\gamma)$ is the logarithmic slope of the particle-γ ray angular correlation

TABLE I. Mean velocities and transit time, T, of ^{96}Ru in the gadolinium layer. The velocities are given in units of the Bohr velocity, $v_0 = e^2/\hbar$.

$E_{\rm beam}$ [MeV]	$\langle v_{\rm in}/v_0 \rangle$	$\langle v_{\rm out}/v_0 \rangle$	$\langle v/v_0 \rangle$	T [fs]
350	9.0	4.8	6.8	412.0
343	8.9	4.7	6.7	521.0

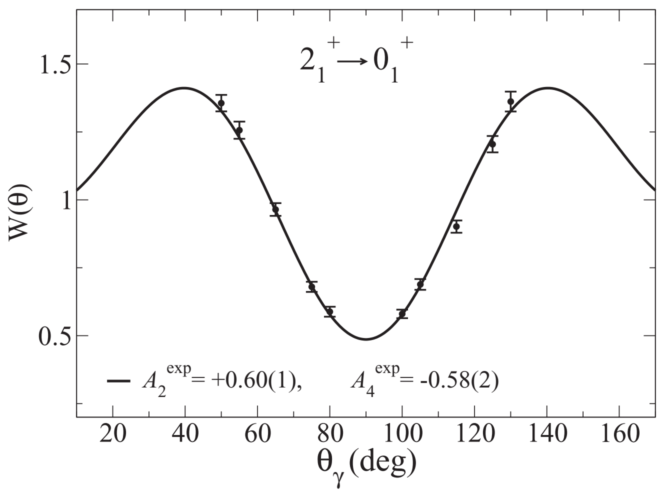

FIG. 2. The experimental γ-ray angular correlation for the $2_1^+ \rightarrow 0_1^+$ transition in ^{96}Ru. The solid line is a fit of the angular correlation function to the data; the resulting A_k^{exp} coefficients are shown in the lower part of the figure.

function, $W(\theta)$, evaluated at the angle θ_γ in the rest frame of the γ-ray emitting nuclei,

$$S(\theta_\gamma) = \frac{1}{W(\theta_\gamma)} \cdot \left.\frac{dW(\theta)}{d\theta}\right|_{\theta=\theta_\gamma}, \tag{3}$$

where the angle θ is measured with respect to the beam axis. The calculation of the logarithmic slope for the $2_1^+ \rightarrow 0_1^+$ γ-ray transition, $S(67^\circ)$ in Eq. (3), was made using the anisotropy-ratio technique [9], which uses the ratios of the values of the angular correlation at two sets of angles. In this experiment, the anisotropy ratio is measured for two sets of angles. The set (130°, 100°) was utilized for the backward clovers 1 and 4, while the set (80°, 50°) was used for the forward clovers 2 and 3. This procedure has the advantage of being independent of the run time and the efficiency of the detectors [8].

The intensity ratios of the $4_1^+ \rightarrow 2_1^+$ γ-ray transition are affected by background (Fig. 1). Thus, the $S(67^\circ)$ value for this transition is difficult to determine from the anisotropy ratios. Therefore, the slope for the $4_1^+ \rightarrow 2_1^+$ transition was determined by calculating the angular correlation function,

$$\begin{aligned} W(\theta) = 1 &+ Q_2 \cdot G_2 \cdot A_2 \cdot P_2(\cos\theta) \\ &+ Q_4 \cdot G_4 \cdot A_4 \cdot P_4(\cos\theta). \end{aligned} \tag{4}$$

In Eq. (4), the Q_k's are the geometrical attenuation coefficients, while the G_k coefficients also take into account the attenuation of the angular correlation obtained at beam energies near the Coulomb barrier. The G_k coefficients were estimated with a fit to the experimental angular correlation of the $2_1^+ \rightarrow 0_1^+$ γ-ray transition (Fig. 2).

The lineshape exhibited by the $2_1^+ \rightarrow 0_1^+$ γ-ray transition (Fig. 1) allows the determination of the lifetime of the 2_1^+ state using the DSAM. To avoid corrections, due to feeding from the 4_1^+ state, the data were taken from measurements at beam energies of 230 MeV and 280 MeV [4]. Both measurements, using different targets, provide consistently the same result: $\tau = 4.5(2)$ ps. This value is slightly larger than the value of $\tau = 4.24(9)$ ps presented in the Nuclear Data Sheets [10].

Table II presents the main results from this work. A value of $g(2_1^+) = +0.46(2)$ was obtained, after corrections for feeding from the 4_1^+ state [11], in agreement with the recent results of Taylor *et al.* [4] and Chamoli *et al.* [2]. The g factor of the 4_1^+ state was determined to be $g(4_1^+) = +0.58(8)$.

The present results are discussed within the framework of various theoretical models. Shell-model calculations were performed as part of the present investigation and their results are summarized in Fig. 3 and Table III. These calculations made use of the set of programs CENS [14]. The $V_{\text{low-}K}$ effective interaction was constructed based on the CD-Bonn nucleon-nucleon interaction [14]. The inert core was ^{88}Sr and the shell-model space involved the $(1p_{1/2}, 0g_{9/2})$ orbitals for protons and $(1d_{5/2}, 2s_{1/2}, 1d_{3/2}, 0g_{7/2}, 0h_{11/2})$ orbitals for neutrons. Effective charges of $\epsilon_\nu = 1.0e$ and $\epsilon_\pi = 1.7e$ were used, while the effective nucleon g factors were taken to be $g_\pi^l = 1$, $g_\nu^l = 0$, $g_\pi^s = 3.18$, $g_\nu^s = -2.18$ (Ref. [13]). These SM calculations agree with experimental excitation energies and $B(E2)$ values, as shown in Table III, but the evolution of the predicted g-factor trend with the spin is not well accounted for (Fig. 3).

Previous SM calculations, using the same inert core and almost the same valence space, have been carried out by Halse [12] and Holt *et al.* [13]. Their predicted g factors are presented in Fig. 3. In Halse's work, the interaction was built using a set of effective operators incorporating a comparison of calculated and measured quantities, excluding the $0h_{11/2}$ orbital, and using the code OXBASH [15]. Halse predicted a decrease of the g factors with spin [$g(2_1^+) = +0.66$, $g(4_1^+) = +0.55$, and $g(6_1^+) = +0.36$], in disagreement with the experimental data. This decrease was also calculated in this work (Fig. 3).

TABLE II. Experimental precession effect ϵ, slope of the angular correlation $S(\theta)$, precession effect $\Delta\theta$ calculated for $g = 1$, and g values for the 2_1^+ and 4_1^+ states in ^{96}Ru.

I_i^π	γ ray [keV]	τ [ps][a]	E_{beam} [MeV]	ϵ	$S(67^\circ)$	$\Delta\theta$ [mrad]	$\Delta\theta(g=1)$	$g(I_i^\pi)$
2_1^+	832.4	4.24(9)	343	−0.054(1)	−1.80(3)	29.6(10)	64.6	+0.46(3)
			350	−0.048(1)	−1.63(3)	29.5(8)	64.2	+0.45(3)
4_1^+	685.3	9.9(7)	343	−0.028(5)	−0.67(6)	41.8(83)	67.6	+0.62(12)
			350	−0.024(5)	−0.66(6)	36.4(83)	67.0	+0.54(12)
								$g(2_1^+) = +0.46(2)$
							Weighted mean	
								$g(4_1^+) = +0.58(8)$

[a]From Ref. [10].

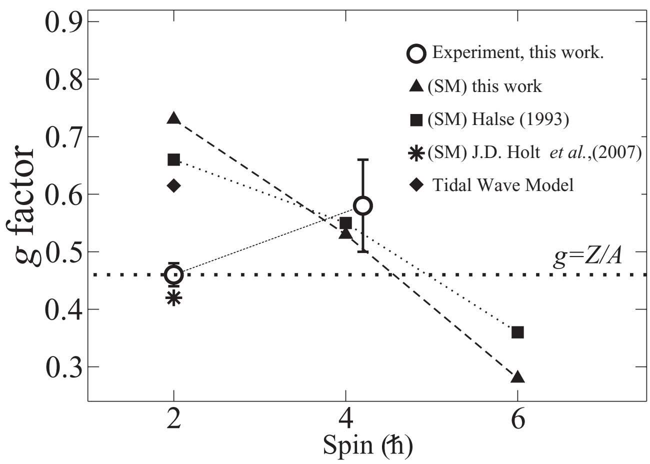

FIG. 3. Comparison between experimental and theoretical g factors as a function of the nuclear spin in ^{96}Ru. Circles: Experimental results from this work. Triangles: SM calculations from this work. Squares: SM calculations by Halse [12]. Asterisk: SM calculations from Holt *et al.*, [13]. Diamond: tidal-wave model from [2]. The horizontal line corresponds to the collective model prediction $g = Z/A = +0.46$.

The calculations made by Holt *et al.* successfully describe the g factor of the 2_1^+ state in ^{96}Ru. These authors used a $V_{\text{low-}K}$ interaction which included effects of core polarization to second order [13]. The resulting value of $g(2_1^+) = +0.42$ only slightly underpredicts the experimental results (Fig. 3). The present experimental value, $g(2_1^+) = +0.46(2)$, agrees with the systematics for the $N = 52$ isotonic chain shown in Ref. [13]. In that paper the evolution of 2_1^+ and 2_2^+ g factors is discussed and a description of the $B(E2)$'s, $B(M1)$'s and magnetic moments is presented. The trend of the g factors is a nearly linear rise of $g(2_1^+)$ from $^{92}_{40}$Zr toward the $Z = 50$ shell closure. Unfortunately, only 2^+ states were discussed in [13] and a g factor for the 4_1^+ state in ^{96}Ru was not reported.

The tidal-wave model (TWM) predicts $g(2_1^+) = +0.615$ [2]. This approach suggests a slight deformation for the ground and the 2_1^+ states. No g factor was reported for the 4_1^+state, but that calculation predicts a limit of $g(4_1^+) < 0.5g(2_1^+)$. This result also disagree with the general trend observed in the experimental $g(2_1^+)$ and $g(4_1^+)$ values.

TABLE III. Comparison between the results of the large-scale shell model calculations (SM) and the experimental (exp) $B(E2)$ values and g factors for the lowest excited state energies and transitions under study in ^{96}Ru.

State		$E_x(I_i^\pi)$ [keV]		$B(E2: I_i^\pi \to I_f^\pi)$[W.u.]		$g(I_i^\pi)$	
I_i^π	I_f^π	exp	SM[a]	exp	SM[a]	exp[a]	SM[a]
2_1^+	0_1^+	832.6	896.5	17.3(8)[a]	16.7	+0.46(2)	+0.73
4_1^+	2_1^+	1518.1	1563.5	20.8(1.5)[b]	20.5	+0.58(8)	+0.53
2_2^+		1931.1	2069.5				+0.69
0_2^+		2148.8	1791.6				
6_1^+	4_1^+	2149.7	2134.5	20.7(6.9)[b]	16.2		+0.28

[a]Values from this work.
[b]Values calculated using lifetimes from Ref. [10]. 1 Weisskopf unit [W.u.] = $2.62 \times 10^{-3} e^2\text{b}^2$.

In summary, the $g(4_1^+)$ of ^{96}Ru was measured for the first time. The experiments employed the projectile excitation of ^{96}Ru and the transient field technique. Values of $g(2_1^+) = +0.46(2)$ and $g(4_1^+) = +0.58(8)$ were obtained. While the $g(2_1^+)$ value is well accounted for by the hydrodynamical model, the $g(4_1^+)$ seems to agree more with the shell model predictions. The general experimental trend shows an increase of the g factor with the nuclear spin, while the trend predicted by SM calculations shows the opposite tendency, namely, a decrease of the g factor with the nuclear spin. This discrepancy should be studied further.

The authors are indebted to the staff of the Wright Nuclear Structure Laboratory for their assistance during the experiment. The work was supported in part by the US National Science Foundation and the US Department of Energy under Grant No. DE-FG02-91ER-40609. Y.Y.S. would like to acknowledge a Stockton College Research and Professional Development Grant. D.A.T would like to thank Fernando Cristancho for stimulating discussions, and the Universidad Nacional de Colombia and the Centro Internacional de Física for hosting him as a guest researcher. K.H.S acknowledges support by the DFG under SP 190/16-1. D.R. and D.S. acknowledge support by the DAAD.

[1] 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).

[2] S. K. Chamoli, A. E. Stuchbery, S. Frauendorf, J. Sun, Y. Gu, R. F. Leslie, P. T. Moore, A. Wakhle, M. C. East, T. Kibédi *et al.*, Phys. Rev. C **83**, 054318 (2011).

[3] S. Frauendorf, Y. Gu, and J. Sun, [http://arxiv.org/abs/0709.0254].

[4] M. J. Taylor, G. Gürdal, G. Kumbartzki, N. Benczer-Koller, A. E. Stuchbery, Y. Y. Sharon, M. A. Bentley, Z. Berant, R. J. Casperson, R. F. Casten *et al.*, Phys. Rev. C **83**, 044315 (2011).

[5] D. A. Torres, G. J. Kumbartzki, Y. Y. Sharon, L. Zamick, B. Manning, N. Benczer-Koller, G. Gürdal, K.-H. Speidel, M. Hjorth-Jensen, P. Maier-Komor *et al.*, Phys. Rev. C **84**, 044327 (2011).

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

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

[8] N. Benczer-Koller and G. J. Kumbartzki, J. Phys. G: Nucl. Part. Phys. **34**, R321 (2007).

[9] 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).
[10] D. Abriola and A. Sonzogni, Nucl. Data Sheets **109**, 2501 (2008).
[11] D. Ballon, Y. Niv, S. Vajda, N. Benczer-Koller, L. Zamick, and G. A. Leander, Phys. Rev. C **33**, 1461 (1986).
[12] P. Halse, J. Phys. G: Nucl. Part. Phys. **19**, 1859 (1993).
[13] J. D. Holt, N. Pietralla, J. W. Holt, T. T. S. Kuo, and G. Rainovski, Phys. Rev. C **76**, 034325 (2007).
[14] M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rep. **261**, 125 (1995).
[15] A. Etchegoyen, W. Rae, and N. Godwin, OSBAXH-MSU, The Oxford-Buenos Aires-Michigan State University shell model code (MSU version by B. A. Brown).