Magnetism of an Excited Self-Conjugate Nucleus: Precise Measurement of the g Factor of the 2_1^+ State in ^{24}Mg

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A precise measurement of the g factor of the first-excited state in the self-conjugate ($N = Z$) nucleus ^{24}Mg is performed by a new time-differential recoil-in-vacuum method based on the hyperfine field of hydrogenlike ions. Theory predicts that the g factors of such states, in which protons and neutrons occupy the same orbits, should depart from 0.5 by a few percent due to configuration mixing and meson-exchange effects. The experimental result, $g = 0.538 \pm 0.013$, is in excellent agreement with recent shell-model calculations and shows a departure from 0.5 by almost 3 standard deviations, thus achieving, for the first time, the precision and accuracy needed to test theory. Proof of the new method opens the way for wide applications including measurements of the magnetism of excited states of exotic nuclei produced as radioactive beams.

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The g factor is an important observable in the study of the quantum mechanics of nuclear excitations, being sensitive to single-particle aspects of the wave function. Because alternative effective interactions in the shell-model approach can describe excitation energies equally well but predict significantly different configuration mixing in the wave functions and, hence, different g factors, measurements of nuclear magnetism play a critical role in building an accurate understanding of nuclear structure. The g factor g and magnetic moment μ are related by $\mu = gI$ where μ has the units of nuclear magnetons and the angular momentum I is in units of $\hbar$.

For many years, the g factors of the first-excited states of even-even nuclei with equal numbers of protons and neutrons ($N = Z$) were expected to depart little from $g = 0.5$ [1]. This behavior occurs for self-conjugate nuclei because protons and neutrons occupy the same orbits and the intrinsic-spin moments of the nucleons largely cancel, leaving the orbital motion of the protons to produce the nuclear magnetism. More recent shell-model calculations, however, predict departures from $g = 0.5$ by up to 10% for the first-excited 2^+ states in the $N = Z$ sd-shell nuclei from ^{20}Ne to ^{36}Ar [2]. These departures stem from three mechanisms. First, configuration mixing in the shell-model basis space does not fully quench the spin contributions to the nuclear moment. Second, the Coulomb interaction between protons leads to isospin mixing, which introduces isovector contributions to the nuclear moment. Third, within the nucleus, meson exchange and higher-order configuration mixing contributions modify the magnetic dipole operator from that of a free nucleon.

On the experimental side, the predicted departures from $g = 0.5$ have not previously been observed. The excited states in question are short lived, having lifetimes of a few picoseconds. Their g factors must be measured via the spin precession of the nucleus in an extremely strong magnetic field, of the order of 10 kT or more. Such fields can be produced at the nucleus only by hyperfine interactions. Experimental precision and accuracy for these measurements has been limited, in part, because the short nuclear lifetimes require the measurement of small differences in count rate. A more fundamental limitation, however, has stemmed from the use of ions with complex atomic configurations, for which the net strength of the hyperfine field is an uncertain superposition of many components.

This Letter reports a new measurement of the g factor of the first-excited state in the $N = Z$ nucleus ^{24}Mg (excitation energy $E_x = 1.369$ MeV, mean lifetime $\tau = 1.97$ ps [3]) based on hyperfine fields of hydrogenlike Mg ions. By the use of these well-defined hyperfine fields, together with efficient particle and γ-ray detection, the new measurement achieves the accuracy and precision needed to test the predicted departures from $g = 0.5$.

The experimental method is based on the observation of the precession of the nuclear moment as hydrogenlike ^{24}Mg ions fly through vacuum. As illustrated in Fig. 1, excited nuclei emerge from a target foil as ions carrying one electron. The nuclear spin $\boldsymbol{I}$ is aligned by the reaction whereas the atomic spin $\boldsymbol{J}$ is oriented randomly. The hyperfine interaction couples the atomic spin to the nuclear spin, and together they precess about the total $\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}$ with a frequency proportional to the nuclear g factor. Thus, the orientation of the nuclear spin is periodically reduced and restored during the flight through vacuum. As a consequence, the angular intensity pattern of the γ rays emitted by the nuclei varies periodically, in step with the orientation of the nuclear spin. In the traditional recoil-in-vacuum, or "plunger," technique [4], the ions travel a set distance through vacuum before being stopped in a thick stopper foil, which immediately quenches the hyperfine interaction and freezes the orientation of the nuclear spin. The nuclear precession frequency is determined by observing changes in the radiation pattern as the flight time is varied by changing the distance between the target and stopper foils.

Here, we report the first use of a new time-differential recoil-in-vacuum (TDRIV) method. Proposed by Stuchbery, Mantica and Wilson [5] as a method suited for radioactive beams, its novel feature is to replace the thick stopper foil by a thinner foil that simply resets the electron configuration. For radioactive beams, this change allows projectile-excitation experiments in which the radioactive beam ion is

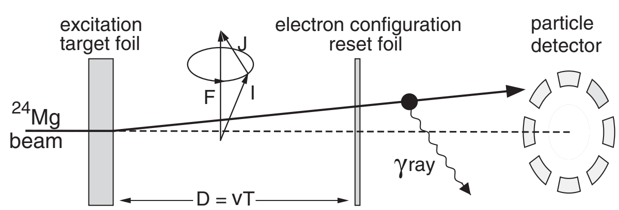

FIG. 1. Sketch of experiment. The "stopper" of the traditional plunger technique is replaced by a thin foil that resets the electron configuration of H-like ions. The particle detector, with segmentation around the beam axis, is located downstream of the γ-ray detectors.

detected at forward angles out of the view of the γ-ray detectors. In the present application to ^{24}Mg, the method enables experiments on high-velocity ions ($v/c \sim 0.1$) for which the optimal charge-state distribution of about 50% H-like can be achieved. The previous measurement [6], by the conventional TDRIV method following the ^{12}C(^{16}O, $\alpha\gamma$)^{24}Mg reaction, achieved a Mg recoil velocity of only $v/c \sim 0.056$ so that the H-like fraction was around 15%; most Mg ions carried three or four electrons.

A beam of ^{24}Mg at an energy of 120 MeV (5 MeV/nucleon) from the ALTO accelerator facility at IPN Orsay was excited in glancing collisions on a stretched foil of ^{93}Nb, 2.4 mg/cm^2 thick. Excited projectiles emerged from this target with ~93 MeV, corresponding to a velocity of $v/c = 0.0915(5)$. This velocity and its uncertainty were determined from experimental Doppler shifts and by evaluation of the reaction kinematics, taking into account the energy loss of the beam in the target. A 1.7 mg/cm^2 thick ^{197}Au foil served as the movable, stretched "reset" foil.

The experimental setup was comprised of the ORGAM hyperpure germanium (HPGe) detector array surrounding the Orsay plunger [7], on which the stretched foils were mounted, and an eightfold segmented plastic scintillation detector, located inside the beam line, 61 mm downstream from the target. Each segment had an azimuthal opening of $\Delta\phi_p = 30°$ and a polar opening angle from $\theta_p = 33°$ to $\theta_p = 38°$. The flight time of the excited ions T is related to the target-reset foil separation D by $T = D/\langle v\cos\theta_{\mathrm{p}}\rangle$, where $\langle v\cos\theta_{\mathrm{p}}\rangle$ represents an average over the angular acceptance of the particle detector.

ORGAM was populated with 13 HPGe detectors at the polar angles $\theta = 46.5°$, 72.1°, 85.8°, 94.2°, 108.0°, 133.6°, and 157.6°, relative to the beam axis. Gamma-ray detection angles near 90° were favored as these show the strongest anisotropy around the ϕ direction.

Data were taken in event-by-event mode, recording the arrival time and amplitude of the detected radiation from each particle and γ detector. Twenty-four target-reset foil distances from (near) the touching point of the foils to about 100 μm separation were measured. The beam intensity was about 0.3 pnA, and the running time was approximately 2 h for each distance.

Coincidence events corresponding to a γ-ray detection in the ORGAM array and a beam-particle detection in the plastic scintillator were sorted from the event data. Random coincidences were subtracted. An example of a resultant γ-ray spectrum is shown in Fig. 2. The intensity of the peak corresponding to the $2^+ \to 0^+$ transition of ^{24}Mg was determined for all particle-γ combinations.

In the presence of vacuum deorientation, the time-dependent particle-γ angular correlation takes the form (see e.g., Ref. [8] and references therein)

$$W(\theta_p, \theta_\gamma, \Delta\phi, t) = \sum_{kq} a_{kq}(\theta_p) G_k(t) D^{k*}_{q0}(\Delta\phi, \theta_\gamma, 0), \quad (1)$$

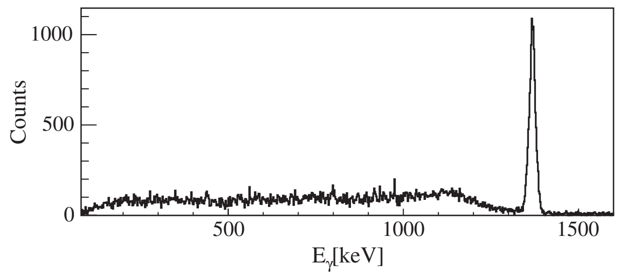

FIG. 2. Random-subtracted γ-ray spectrum collected at 80 μm plunger separation, showing the ^{24}Mg $2^+ \to 0^+$ 1368-keV photopeak. Data for all γ-ray detectors in coincidence with one particle detector segment are shown.

where θ_p and θ_γ are the polar detection angles for particles and γ rays, respectively; $\Delta\phi = \phi_\gamma - \phi_p$ is the difference between the corresponding azimuthal detection angles. $a_{kq}(\theta_p) = B_{kq}(\theta_p) Q_k F_k$, where $B_{kq}(\theta_p)$ is the statistical tensor, which defines the spin orientation of the initial state. F_k represents the F coefficient for the γ-ray transition, and Q_k is the attenuation factor for the finite size of the γ-ray detector. $D^{k*}_{q0}(\Delta\phi, \theta_\gamma, 0)$ is the Wigner-D matrix. For $E2$ excitation, $k = 0, 2, 4$ and $-k \le q \le k$. The attenuation coefficients $G_k(t)$ specify the time-dependent vacuum deorientation effect. For H-like $J = 1/2$ configurations, the $G_k(t)$ are cosine functions with a frequency determined by the nuclear g factor.

We refer to ions that decay between the target and the reset foil as "fast" and those that decay after the reset foil as "slow." The TDRIV method does not require that the γ-rays emitted from the fast and slow ions be separated in the observed energy spectrum. Decays of slow ions beyond the reset foil oscillate as $G_k(T)\bar{G}_k(\infty)$, where T is the flight time and $\bar{G}_k(\infty)$ is the average integral attenuation coefficient for slow ions that decay beyond the reset foil [5]. The fast component, however, is an average over decays taking place between the target and reset foils, so a range of precessions angles contribute and the oscillations are washed out [5]. Because the fast and slow components of the γ-ray line are not resolved, the net angular correlation shows damped oscillations, with the rate of damping determined by the nuclear lifetime.

With eightfold segmentation of the particle detector and 13 detectors in ORGAM, there are 104 individual particle-γ combinations. To analyze the data, the 104 time-dependent angular correlations were evaluated based on Eq. (1) and ordered according to the amplitude of the oscillations and whether the γ-ray intensity should initially increase, $W^\uparrow(T)$, or decrease, $W^\downarrow(T)$, with time. Forty-nine particle-γ combinations increase in magnitude initially. The remaining 55 particle-γ combinations initially decrease. Ratios of the coincidence γ-ray intensity corresponding to $W^\uparrow/W^\downarrow$ were formed in order, beginning with the pairing of the case showing strongest increase with the case of strongest decrease. These ratios were then formed into a geometric average

$$R(T) = \left(\prod_{i=1}^{n} \frac{W_i^\uparrow(T)}{W_i^\downarrow(T)}\right)^{1/n} \quad (2)$$

where n is the number of $W_i^\uparrow/W_i^\downarrow$ ratios included. The experimental geometric averages $R(T)$ largely factor out the detection efficiency for both γ-rays and particles.

Sensitivity is lost if $W^\uparrow/W^\downarrow$ ratios showing small amplitude oscillations are averaged with ratios showing large amplitude oscillations. The data set was therefore analyzed by forming geometric ratios in three groups, two of which are shown in Fig. 3. The $n = 14$ combinations showing the largest amplitude oscillations are labeled "strong," while the $n = 17$ ratios showing a moderate amplitude are labeled "intermediate." A further $n = 18$ pairs show a small amplitude. Because of the symmetry of the particle- and γ-detector arrays, certain particle-γ detector combinations should show the same angular correlation at all times. Ratios of such combinations should show a null effect. An example is shown in Fig. 3, labeled "null."

The g factor was determined from fits to the experimental data, as shown in Fig. 3. Fitting was performed using a computer code [9] that models the experimental conditions in detail based on Coulomb-excitation calculations, the formulas in Ref. [5], and Eq. (1) and then assembles $R(T)$ ratios in the same way that the experimental data are combined. The fitting procedures were broadly similar to those of Horstman *et al.* [6], the main difference being that the H-like K-shell hyperfine field is dominant in our measurement. Its value, $B_{1s}(0) = 29.09$ kT, was evaluated

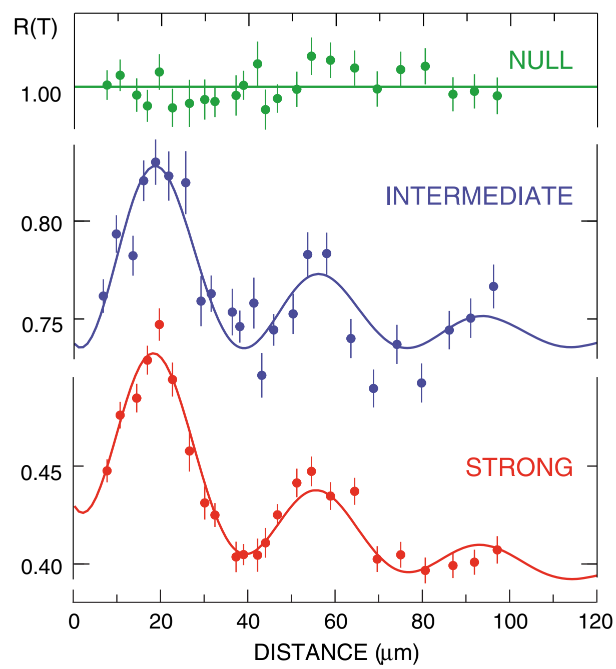

FIG. 3 (color online). $R(T)$ ratio data, Eq. (2), and fits based on detailed modeling of the experiment [9]. The distance is the separation of target and reset foils (22.4 μm = 1 ps flight time). The frequency of the oscillation determines the g factor.

with the General Relativistic Atomic Structure Package, GRASP2K [10]. Relativistic effects are of order 1%; the uncertainty in $B_{1s}(0)$ is negligible, which underpins the accuracy of the experimental g factor.

Results of the fits to the $R(T)$ data having strong, intermediate, and weak amplitude oscillations were $g = 0.538(13)$, 0.539(24), and 0.54(3), respectively, where the uncertainties are statistical only. The weighted average is $g = 0.538(11)$ (statistical error).

Systematic errors were evaluated as (i) $\delta g = \pm 0.0045$ from an uncertainty of ± 1.5 mm in the distance from the target to particle-detector face, (ii) $\delta g = \pm 0.0040$ from uncertainty in lifetime, $\tau = 1.97(5)$ ps [3], (iii) $\delta g = \pm 0.0035$ from the uncertainty in v/c, and (iv) $\delta g = \pm 0.0010$ from uncertainties in the distribution of hyperfine fields. The experimental g factor is therefore $g = 0.538 \pm 0.011(\text{statistical}) \pm 0.007(\text{systematic})$ or $g = 0.538(13)$, in reasonable agreement with, but more precise than, the previous measurement, $g = 0.51(2)$ [6]. The improvement stems in part from better statistical precision; however, systematic errors are also reduced. Uncertainty in the distribution of hyperfine fields has a small influence on the present measurement but was an important source of uncertainty in the previous measurement.

The first-excited state of ^{24}Mg is an isospin $T = 0$ state in a nuclide with $N = Z$. As such, it is useful to write the magnetic moment in terms of the isoscalar and isovector matrix elements

$$\mu = gI = g_{\ell_0}\langle \ell_0 \rangle + g_{\ell_1}\langle \ell_1 \rangle + g_{s_0}\langle s_0 \rangle + g_{s_1}\langle s_1 \rangle, \quad (3)$$

where ℓ and s represent the orbital and spin operators, and the subscripts 0 and 1 represent isoscalar and isovector, respectively. $I = \langle \ell_0 \rangle + \langle s_0 \rangle$. The free-nucleon values for the g factors are $g_{\ell_0} = (g_{\ell p} + g_{\ell n})/2 = 0.5$, $g_{\ell_1} = (g_{\ell p} - g_{\ell n})/2 = 0.5$, $g_{s_0} = (g_{sp} + g_{sn})/2 = 0.880$, and $g_{s_1} = (g_{sp} - g_{sn})/2 = 4.706$. (See Refs. [11–13] for further details.)

We first consider the sd shell-model space with isospin conserving Hamiltonians for which the isovector terms are zero: $\langle \ell_1 \rangle = \langle s_1 \rangle = 0$. Thus, if $\langle s_0 \rangle = 0$, $g(2^+) = g_{\ell_0} = 0.5$ for the bare $M1$ operator. However, the sd shell model gives small but nonzero values for $\langle s_0 \rangle$ [1]. For the ^{24}Mg case, $\langle s_0 \rangle = 0.069$ is obtained with the universal sd-shell interaction USDB. The USDA and USDB interactions with 30 and 56 parameters, respectively, update the universal sd-shell Hamiltonian USD to include additional data on neutron-rich nuclei [14]. USDB gives a slightly better rms deviation; however, there is little difference in the wave functions of stable nuclides. The following discussion is based on USDB, making reference to USD and USDA to give an indication of the theoretical uncertainty in the effective Hamiltonian. As will become evident below, this uncertainty affects the g factor at the level of ± 0.001. Taking USDB wave functions and bare nucleon values for g_{ℓ_0} and g_{s_0} gives $g(2^+) = 0.513$, which falls short of our experimental result.

Next we evaluate the effect of isospin mixing. In ^{24}Mg, the dominant contribution comes from mixing with the lowest $T = 1$, $I^\pi = 2^+$ state at $E_x \sim 10$ MeV. The isovector matrix elements were evaluated with the isospin non-conserving Hamiltonian of Ormand and Brown [15], obtaining $\langle \ell_1 \rangle = 0.020$ and $\langle s_1 \rangle = 0.0012$. Thus, with the addition of isospin mixing, $g(2^+) = 0.521$, which still falls short of the experimental value at the level of 1 standard deviation. The results with the USDA and USD interactions are 0.522 and 0.520, respectively.

It is well known that there are corrections to all of the matrix elements in Eq. (3) from mesonic exchange currents and higher-order configuration mixing. These corrections have been evaluated for the $d_{5/2}$ orbit at $A = 17$ by Towner and Khanna [11] and Arima *et al.* [12]. Because the magnetic moment of the predominantly $T = 0$ first-excited state in ^{24}Mg is dominated by the isoscalar orbital term, it is most sensitive to the corrections to g_{ℓ_0}, denoted δg_{ℓ_0}. The contribution to this correction coming from higher-order configuration mixing is $\delta g_{\ell_0} = 0.010$ according to Ref. [11] and $\delta g_{\ell_0} = 0.011$ according to Ref. [12], but there is disagreement for the mesonic-exchange contribution with Ref. [11] giving essentially zero and Ref. [12] giving $\delta g_{\ell_0} = 0.013$ (see Table 7.2 in Ref. [12]). Nevertheless, the resulting values of $g(2^+) = 0.531$ and 0.544, evaluated with the USDB Hamiltonian plus isospin nonconserving contributions and δg_{ℓ_0} corrections from Refs. [11,12], respectively, are both within the range of the experimental uncertainty.

An alternative approach is to determine the $M1$ operator empirically by performing a global fit to a wide range of data [2,13]. Our experimental g factor is shown in Fig. 4 along with previous results for $N = Z$ nuclei in the sd shell and NUSHELLX [16] calculations in the sd model space with the USDA and USDB interactions and the corresponding empirical $M1$ operators [2]. As is evident from Fig. 4, the new measurement is in very good agreement with these calculations; USDB gives $g(2^+) = 0.544(17)$. An uncertainty of about ± 0.017 in these theoretical g factors comes mainly from the δg_ℓ terms in the empirical $M1$ operator.

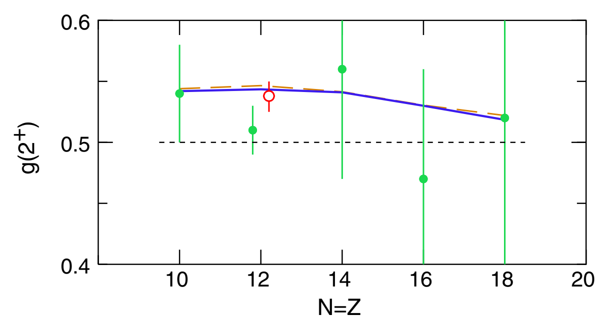

FIG. 4 (color online). Present result (open red circle) and previous results (filled green circles) [6,17–19] compared to shell-model calculations with USDA (dashed brown line) and USDB (solid blue line) calculations.

Thus, shell-model calculations consistently predict that the g factor of the first-excited state in the $N = Z$ nucleus ^{24}Mg is increased from $g = 0.5$, and our experiment confirms these predictions for the first time.

We have validated a new method for measuring the g factors of excited nuclear states with lifetimes in the picosecond regime. Measurements on stable isotopes like ^{24}Mg can reach new levels of precision and test nuclear model calculations in ways that were not previously possible. Moreover, as the method was designed for applications to radioactive beams, the present work prepares the way for a future measurement on the neutron-rich nucleus ^{32}Mg in the "island of inversion" [20].

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[1] B. A. Brown, J. Phys. G **8**, 679 (1982).
[2] W. A. Richter, S. Mkhize, and B. A. Brown, Phys. Rev. C **78**, 064302 (2008).
[3] S. Raman, C. W. Nestor, Jr., and P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
[4] G. Goldring, in *Heavy Ion Collisions*, edited by R. Bock (North Holland, Amsterdam, 1982), Vol. 3, p. 483.
[5] A. E. Stuchbery, P. F. Mantica, and A. N. Wilson, Phys. Rev. C **71**, 047302 (2005).
[6] R. E. Horstman, J. L. Eberhardt, H. A. Doubt, C. M. E. Otten, and G. Van Middelkoop, Nucl. Phys. **A248**, 291 (1975).
[7] J. Ljungvall *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **679**, 61 (2012).
[8] A. E. Stuchbery, Nucl. Phys. **A723**, 69 (2003).
[9] A. E. Stuchbery, computer code TDRIV_MODEL (unpublished).
[10] P. Jönsson, G. Gaigalas, J. Bieron, C. Froese Fisher, and I. P. Grant, Comput. Phys. Commun. **184**, 2197 (2013).
[11] I. S. Towner and F. C. Khanna, Nucl. Phys. **A399**, 334 (1983); I. S. Towner, Phys. Rep. **155**, 263 (1987).
[12] A. Arima, K. Shimizu, W. Bentz, and H. Hyuga, Adv. Nucl. Phys. **18**, 1 (1987).
[13] B. A. Brown and B. H. Wildenthal, Nucl. Phys. **A474**, 290 (1987).
[14] B. A. Brown and W. A. Richter, Phys. Rev. C **74**, 034315 (2006).
[15] W. E. Ormand and B. A. Brown, Nucl. Phys. **A491**, 1 (1989).
[16] B. A. Brown and W. D. M. Rae, Nucl. Data Sheets **120**, 115 (2014).
[17] J. L. Eberhardt, R. E. Horstman, H. A. Doubt, and G. van Middelkoop, Nucl. Phys. **A244**, 1 (1975).
[18] P. C. Zalm, A. Holthuizen, J. A. G. De Raedt, and G. Van Middelkoop, Nucl. Phys. **A315**, 133 (1979).
[19] K.-H. Speidel, S. Schielke, J. Leske, J. Gerber, P. Maier-Komor, S. J. Q. Robinson, Y. Y. Sharon, and L. Zamick, Phys. Lett. B **632**, 207 (2006).
[20] E. K. Warburton, J. A. Becker, and B. A. Brown, Phys. Rev. C **41**, 1147 (1990).