PHYSICAL REVIEW C **74**, 067301 (2006)

Lifetime measurement for the 2_1^+ state of ^{170}Hf

A. Costin,[1,2,3] T. Ahn,[1,2,3] B. Bochev,[1] K. Dusling,[1] T. C. Li,[1] N. Pietralla,[1,2,3] G. Rainovski,[1,4] and W. Rother[2]

[1]*Nuclear Structure Laboratory, SUNY at Stony Brook, Stony Brook, New York 11794-3800, USA*

[2]*Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany*

[3]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

[4]*Faculty of Physics, St. Kliment Ohridski University of Sofia, 1164 Sofia, Bulgaria*

(Received 9 August 2006; published 11 December 2006)

The lifetime of the $J^\pi = 2_1^+$ state of ^{170}Hf at 100.8 keV was measured. Excited states of ^{170}Hf were populated with the ^{158}Gd(^{16}O,4nγ) reaction at the TANDEM-LINAC facility of the State University of New York (SUNY) at Stony Brook. A lifetime of $\tau = 1.74 \pm 0.06$ ns was found using the delayed γ-radiofrequency coincidence method with respect to the pulsed LINAC beam. It corresponds to an $E2$ transition strength of 181 ± 6 W.u. to the $J^\pi = 0_1^+$ ground state. With its increased precision, by one order of magnitude with respect to previous literature, this value serves as a normalization parameter for collective models for this nucleus.

DOI: 10.1103/PhysRevC.74.067301 PACS number(s): 21.10.Tg, 27.70.+q

There has been a long-standing interest in the evolution of deformation of the nuclear ground state as a function of nucleon number. That interest was recently intensified when models such as the E(5) or X(5) solutions [1,2] of the Bohr Hamiltonian were proposed for predicting the characteristics of nuclei in those regions of the nuclear chart where nuclear ground states change their shape. The Confined Beta-Soft (CBS) rotor model [3] is a generalization of the X(5) solution of the Bohr Hamiltonian, describing nuclei between X(5) ($R_{4/2} = 2.90$) and the rigid rotor limit ($R_{4/2} = 3.33$). It has been observed [4] that the CBS model reproduces ground state band energies in well-deformed even-even nuclei to an accuracy of 1/1000, based on the concept of centrifugal stretching. However conclusions based on energies alone are not enough to validate the CBS model or any other model based on solutions of the Bohr Hamiltonian. Centrifugal stretching influences $B(E2)$ transition probabilities as well—the transitional quadrupole moment Q_t is expected to increase with increasing spin. This fact has already been observed in the ^{152}Sm nucleus [5], where Q_t increases by ≈11% from $J = 2$ to $J = 12$. However, the change in Q_t values in more rigidly deformed nuclei is predicted to be considerably smaller. Precise measurements of $E2$ transition rates are needed to judge whether nuclei agree better with the predictions of the CBS model or with those of the rigid rotor model. The change in Q_t is typically derived from absolute $B(E2)$ values along the ground state band relative to the Q_t value of the $2_1^+ \to 0_1^+$ transition. Because the changes $\delta Q_t(J)/Q_t(2_1^+) = [Q_t(J) - Q_t(2_1^+)]/Q_t(2_1^+)$ are expected to amount to 3%–10%, the precise knowledge of $Q_t(2_1^+)$ with an uncertainty $\lesssim$3% is a prerequisite of sensitive experimental tests of the relevant models.

^{170}Hf has an $R_{4/2}$ ratio of 3.19, which places it in the region well described by the CBS model. A previous measurement with the recoil distance Doppler shift (RDDS) method in singles mode determined a lifetime of $\tau(2_1^+) = 1.771 \pm 0.396$ ns [6]. A more precise determination of this lifetime and thus of the $B(E2; 2_1^+ \to 0_1^+)$ value is needed for a test of different models and for making more accurate model predictions for $E2$ strengths of higher-lying transitions. An improvement on the uncertainty by about one order of magnitude is desirable.

The purpose of the experiment is to measure the lifetime τ of the 2_1^+ state in ^{170}Hf. Low spin states of ^{170}Hf were populated using the ^{158}Gd(^{16}O,4nγ)^{170}Hf fusion evaporation reaction at the TANDEM-LINAC facility of the State University of New York (SUNY) at Stony Brook. An 80-MeV pulsed ^{16}O beam bombarded a 4.5 mg/cm^2 thick ^{158}Gd target with a 4 mg/cm^2 thick ^{232}Th backing. The pulsed ^{16}O beam with a frequency of 150.4 MHz and a width of about 1.5 ns allows us to measure sub-nanosecond lifetimes [7]. The detection system consisted of two high purity Ge (HPGe) coaxial detectors and two low energy photon spectrometer (LEPS) detectors mounted in the Stony Brook cube array [8]. The pulses from the Ge detectors provided the start signals for delayed γ-radiofrequency (rf) coincidences [9]. Signals synchronized to the LINAC rf were used to stop the time-to-amplitude converter. Smaller values for the time difference $\Delta t_{\text{start-stop}}$ between the start and stop signals correspond to γ rays that arrive later at the detector with respect to a prompt γ ray of the same energy. The γ-ray energies as well as their corresponding time differences $\Delta t_{\text{start-stop}}$ were recorded and sorted off-line into γ-time matrices. The total number of events collected during the experiment was approximately 10^7 at an average count rate of 2.5 kHz/detector. Sample γ-ray and time spectra are presented in Figs. 1 and 2, respectively.

We use the generalized centroid shift method [9] for data analysis [7]. An experimental improvement with respect to the data analysis described in Ref. [7] resides in the fact that to construct the zero-time curve we used only x rays coming from electron capture in the atomic shells of the ^{232}Th backing. The lifetimes of the atomic states that produce these x rays are known to be of the order of femtoseconds. Both the ^{158}Gd target and the ^{232}Th backing were foils clamped tightly together by a frame. The zero-time curve was fitted with a linear function as seen in Fig. 3. It clearly shows the time delay of the 100.8-keV $2_1^+ \to 0_1^+$ transition in ^{170}Hf. The observed shift from the zero-time curve amounts to 31.3(10) channels for the example given

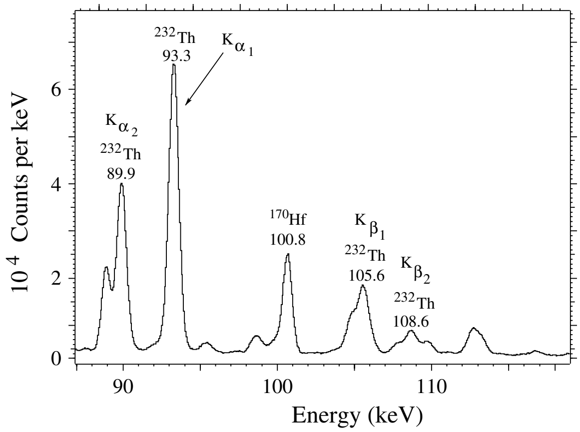

FIG. 1. Part of the γ-ray spectrum obtained in the experiment. The x-ray transitions of interest in ^{232}Th and the delayed 100.8-keV $2_1^+ \rightarrow 0_1^+$ transition in ^{170}Hf are labeled.

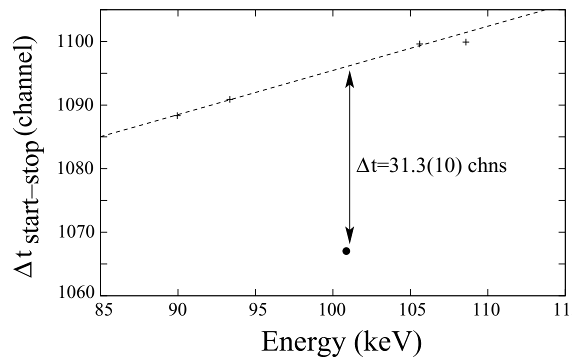

FIG. 3. Centroid diagram obtained in the ^{158}Gd(^{16}O,4nγ)^{170}Hf fusion-evaporation reaction for one of the Ge detectors. Crosses represent the centroids of the time distributions of the prompt x-ray transitions. The solid circle represents the data point for the $2_1^+ \rightarrow 0_1^+$ transition in ^{170}Hf. The radii of the symbols correspond to the statistical errors.

in Fig. 3. The quoted uncertainty includes statistical errors and the uncertainty of our linear fit for the zero-time curve over the short energy interval of interest from 90 to 110 keV. An additional uncertainty is related to the distance between the target and the ^{232}Th backing assumed to be below 0.1 mm, resulting in an uncertainty of 0.03 ns in the time centroids for the ^{232}Th x rays used for establishing the zero-time curve. The quoted total error also includes this uncertainty.

The time calibration was accomplished by means of shifting the ^{16}O beam bunches in time relative to the oscillator signal of the LINAC by multiples of two rf periods (2×6.6489 ns). This beam-skipping procedure yields an accurate result, with an uncertainty in the determination of the slope of the time calibration line smaller than 0.2 ps/channel.

The deviation from the zero-time curve measured for the time centroid of the $2_1^+ \rightarrow 0_1^+$ transition reveals a time delay $\Delta t = 1.86(6)$ ns with respect to the prompt x rays. This value was obtained from an average of the observed centroid

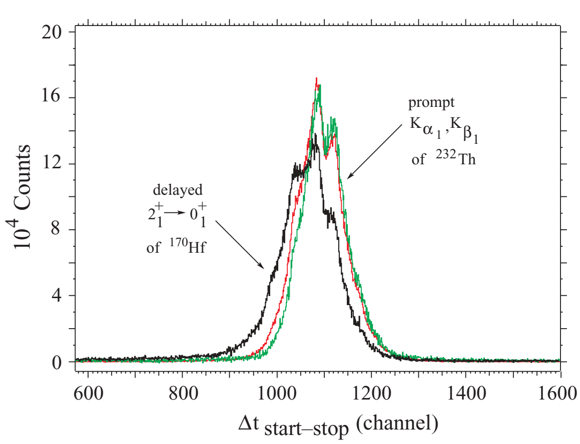

FIG. 2. (Color online) Time difference histograms corresponding to the delayed 100.8-keV $2_1^+ \rightarrow 0_1^+$ transition in ^{170}Hf (black) and to the prompt 93.3-keV (online red) and 105.6-keV (online green) x-ray transitions in ^{232}Th. The histograms were normalized with respect to the one with maximum integral. Their shape is related to the time structure of the beam bunches.

shifts. At this point one must take into account the effective population time of the level of interest from the levels above it. For the 2_1^+ level, considering all known level lifetimes [10], $\Delta t_{\mathrm{pop}} = 0.12(1)$ ns. After correcting for this effect we obtain the 2_1^+ state lifetime

$$\tau = 1.74 \pm 0.06 \text{ ns}. \tag{1}$$

The corresponding $B(E2; 2_1^+ \rightarrow 0_1^+)$ transition probability is calculated using

$$\frac{\hbar}{\tau} = (1+\alpha) c_{E2} E_\gamma^5 B(E2; 2_1^+ \rightarrow 0_1^+), \tag{2}$$

where α is the electron conversion coefficient. For our case $\alpha = 3.47$, as calculated from the adopted E_γ and pure $E2$ multipolarity. Then $B(E2; 2_1^+ \rightarrow 0_1^+) = 181 \pm 6$ W.u.

The data point from this work is compared to the literature values for the 2_1^+ state of other even-even Hf isotopes in Fig. 4. Data on $E2$ transition strengths are available for all nuclei from ^{164}Hf to ^{180}Hf [11]. The 2_1^+ state's excitation energy decreases smoothly to a minimum value at the neutron midshell nucleus ^{176}Hf. The $B(E2)$ value almost doubles going from ^{164}Hf, $R_{4/2} = 2.79$, to ^{166}Hf, $R_{4/2} = 2.97$. This, together with the significant drop in $E(2_1^+)$, is interpreted as an increase in $E2$ collectivity of the ground state due to the crossing from the vibrator region, $2.2 < R_{4/2} < 2.9$, to the rotor region, $2.9 < R_{4/2} < 3.33$. From ^{168}Hf on, an almost constant $E2$ transition strength is observed. Our new value for ^{170}Hf is close to the maximum values found in ^{174,176}Hf at neutron midshell. For ^{174}Hf, the data compilation by Raman, Nestor, and Tikkanen [11] reports $B(E2; 2_1^+ \rightarrow 0_1^+)$ values of 182(12) W.u. [12] and 185(12) W.u. [13] from Coulomb excitation conflicting with $B(E2; 2_1^+ \rightarrow 0_1^+)$ values of 158(11) W.u. [14] and 154(9) W.u. [15] from delayed coincidence measurements. Because both pairs have been confirmed independently but cannot be right simultaneously, we chose to plot the weighted average of each pair. Because Coulomb excitation is the more direct method for measurements of $B(E2)$ values one might be inclined to favor the higher-lying data point over the lower

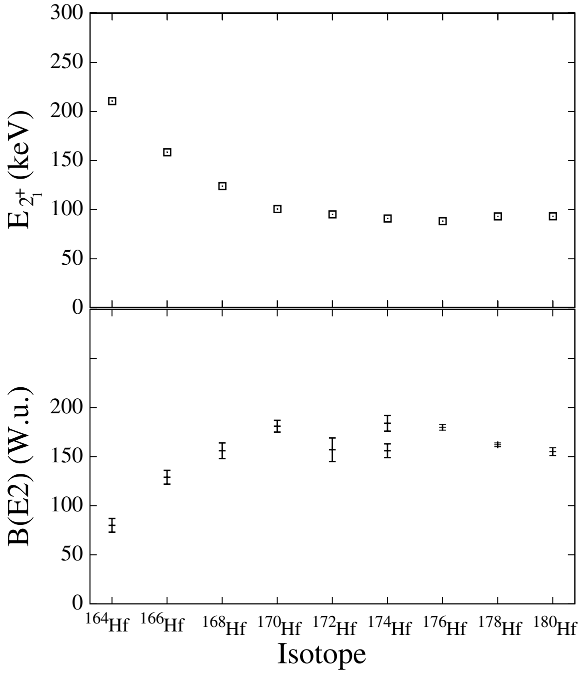

FIG. 4. $2_1^+ \to 0_1^+$ transition energies (top) and corresponding $B(E2; 2_1^+ \to 0_1^+)$ values (bottom) across the Hf isotopic chain. Two conflicting values of $B(E2)$ are plotted for ^{174}Hf corresponding to Coulomb excitation (top value) and delayed coincidence (bottom value) measurements. Data on Hf isotopes other than ^{170}Hf were taken from Ref. [11].

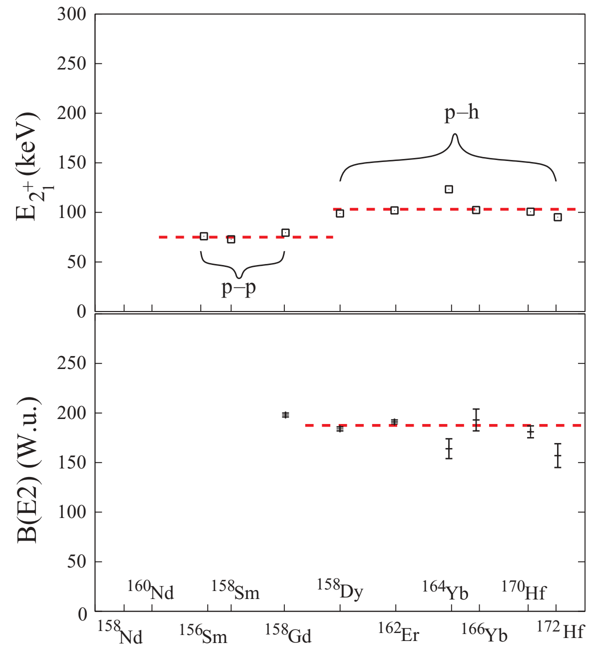

FIG. 5. (Color online) $2_1^+ \to 0_1^+$ transition energies (top) and corresponding $B(E2; 2_1^+ \to 0_1^+)$ values (bottom) for nuclei with a P parameter of 6.2 ± 0.3 and situated in the p-p ($Z = 50$–66, $N = 82$–104) and p-h ($Z = 68$–82, $N = 82$–104) regions. Data other than the $B(E2; 2_1^+ \to 0_1^+)$ value of ^{170}Hf are taken from Ref. [11]. No $2_1^+ \to 0_1^+$ transition energies or $B(E2; 2_1^+ \to 0_1^+)$ values for ^{158,160}Nd are known. The $B(E2; 2_1^+ \to 0_1^+)$ values for ^{156,158}Sm are also unknown.

one. The isotope ^{172}Hf, for which the $B(E2; 2_1^+ \to 0_1^+)$ value has the largest experimental uncertainty, does not seem to follow the smooth trend of data from neighboring isotopes, although the $E(2_1^+)$ energy does. The data point relied entirely on delayed coincidence data from the 1960s [16]. Coulomb excitation of ^{172}Hf has not been done because the nuclide is radioactive. New measurements with higher accuracy would be needed for checking whether an interesting structural effect causes this anomaly or whether the error bars have been underestimated on the data point. Except for the delayed coincidence data on ^{172,174}Hf, the entire data set of even-even Hf isotopes ($Z = 72$) shows the smooth variation expected for fully collective structures with maximum collectivity near neutron midshell.

The variation of collectivity seen in the Hf isotopes corresponds to the variation in P factor defined [17] as the average valence proton-neutron interaction, $P = N_p N_n/(N_p + N_n)$. Here N_p (N_n) is the number of proton (neutron) particles or holes outside the nearest shell closure. The P factor is closely correlated to the evolution of nuclear collectivity [17]. Along the Hf isotopic chain the P factor varies from 5.0 (^{164}Hf) to 6.9 (^{176}Hf). It is interesting to compare the data on the Hf chain to those from nuclei that have the same P factor. Our data point on ^{170}Hf corresponds to $P \simeq 6.2$. Figure 5 shows all available data on $E(2_1^+)$ (top) and $B(E2; 2_1^+ \to 0_1^+)$ (bottom) for even-even nuclei in the rare earth region with $5.9 < P < 6.5$ and valence neutron particles. It is interesting to note that the data points for $E(2_1^+)$—with two exceptions discussed below—fall on two constant lines: one line for nuclei with valence proton holes and another one for nuclei with valence proton particles. The 2_1^+ energies in nuclei with valence proton and neutron particles are lower than those in nuclei with valence neutron particles and proton holes. This indicates higher collectivity in particle-particle nuclei as compared to those in the particle-hole region. Valence proton-neutron interaction in nuclei with identical character (particle-particle or hole-hole) stronger than the interaction in nuclei with the opposite character (particle-hole) has recently been found to lead to earlier formation of collectivity [18]. This is consistent with the jump in $E(2_1^+)$ values seen at the top of Fig. 5. Unfortunately, $B(E2)$ values are not available for ^{158,160}Nd and ^{156,158}Sm to confirm this finding for nuclei with $P = 6.2 \pm 0.3$ for quadrupole transition strengths too. Only one data point, the $B(E2; 2_1^+ \to 0_1^+)$ value of ^{158}Gd, is known to date in the p-p region. The data on the ^{164}Yb and ^{172}Hf nuclei deviate from the constant behavior of their neighbors. ^{164}Yb is less collective [higher $E(2_1^+)$, lower $B(E2; 2_1^+ \to 0_1^+)$] than other nuclei with the same P. Although the P factor for ^{164}Yb agrees within 5% with the ones of its neighbors, its valence nucleon product $N_p N_n$ deviates by 10% ($N_p N_n = 144$) compared with that of ^{170}Hf ($N_p N_n = 160$). The valence product $N_p N_n$ is known to be an alternative parameter for the evolution of collectivity [19]. It can be used to differentiate the behavior of nuclei with equal P factors. The low value of $N_p N_n$ for ^{164}Yb is consistent with observations. Out of all the other nuclei in Fig. 5, only ^{156}Sm (-10%), ^{160}Nd, and ^{172}Hf

(+12.5%) have deviations of the N_pN_n product by more than 5% from that of ^{170}Hf. We already pointed out the case of ^{172}Hf. We further note the lower energy of its 2_1^+ state compared to other p-h nuclei in Fig. 5 and its higher N_pN_n product. We expected, therefore, a $B(E2)$ value slightly higher than those found for the other p-h nuclei in Fig. 5. This is not the case. However, the questionable reliability of the literature $B(E2)$ value for ^{172}Hf is discussed above.

Centrifugal stretching is one of the CBS rotor model predictions. A consequence of it is the increase in the transitional quadrupole moment Q_t along the ground state band. The change in Q_t with spin decreases when considering more rigidly deformed nuclei; thus, the precision in lifetime measurements must increase in order to see this effect. Figure 6 shows the predictions of the rigid rotor model and CBS model with the $E2$ operator $T(E2) \propto \beta + \chi\beta^2$ (normalized to the experimental $B(E2; 2_1^+ \to 0_1^+)$ value) and the experimental Q_t values. Apparently, a precision of the order of the new data point is needed in all values for concluding on the centrifugal stretching of the ^{170}Hf nucleus.

In summary, the lifetime of the 2_1^+ state of ^{170}Hf at 100.8 keV was measured to be $\tau = 1.74 \pm 0.06$ ns. This level decays by an $E2$ transition to the 0_1^+ ground state with a transition strength of $B(E2; 2_1^+ \to 0_1^+) = 181 \pm 6$ W.u. This $E2$ transition rate follows the expected trend of known $B(E2)$ values in isotopic nuclei and empirically confirms the correlation between deformation and the filling of major shells. The small error (≈3%) makes this value sufficiently precise to serve as a normalization parameter for meaningful tests of relevant models.

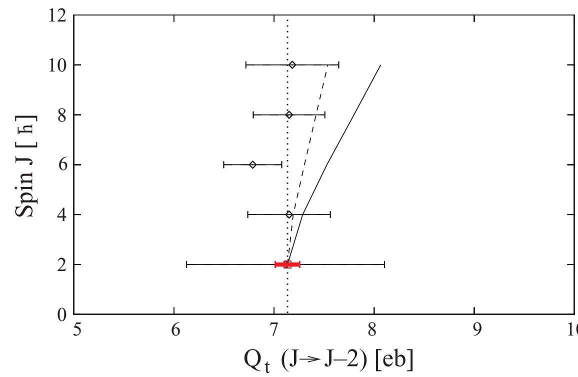

FIG. 6. (Color online) Theoretical and experimental transition quadrupole moments, Q_t, as a function of spin, J, in ^{170}Hf. The dotted line represents the rigid rotor prediction and the solid curve is the CBS rotor model prediction with the $E2$ operator in the lowest order in the quadrupole deformation parameter, β ($\chi = 0$). Q_t values including a second-order correction ($\chi = -0.535$ [3]) in the $E2$ operator are represented by the dashed curve. Our experimental $Q_t(2_1^+ \to 0_1^+)$ (online red) is superimposed on the previously known experimental value.

Help from the NSL staff, in particular from R. Lefferts, A. Lipski, and B. Gutschow for providing excellent beams and technical support, is gratefully acknowledged. We thank A. Dewald and P. von Brentano for discussions. This work was supported by the U.S. National Science Foundation under Grant PHY-0245018 and by the U.S. DOE under Grant DE-FG02-04ER41334.

[1] F. Iachello, Phys. Rev. Lett. **85**, 3580 (2000).
[2] F. Iachello, Phys. Rev. Lett. **87**, 052502 (2001).
[3] N. Pietralla and O. M. Gorbachenko, Phys. Rev. C **70**, 011304(R) (2004).
[4] K. Dusling and N. Pietralla, Phys. Rev. C **72**, 011303(R) (2005).
[5] N. V. Zamfir *et al.*, Phys. Rev. C **60**, 054312 (1999).
[6] B. Bochev, S. Iliev, R. Kalpakchieva, S. A. Karamian, T. Kutsarova, E. Nadjakov, and Ts. Venkova, Nucl. Phys. **A282**, 159 (1977).
[7] A. Costin, N. Pietralla, T. Koike, C. Vaman, T. Ahn, and G. Rainovski, Phys. Rev. C **72**, 054305 (2005).
[8] R. M. Wirowski, dissertation, University of Cologne, 1993.
[9] W. Andrejtscheff, M. Senba, N. Tsoupas, and Z. Z. Ding, Nucl. Instrum. Methods **204**, 123 (1982).
[10] National Nuclear Data Center, Brookhaven National Laboratory, http://www.nndc.bnl.gov/ (2006).
[11] S. Raman, C. W. Nestor Jr., and P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
[12] J. Bjerregaard, B. Elbek, O. Hansen, and P. Salling, Nucl. Phys. **44**, 280 (1963).
[13] H. Ejiri and G. B. Hagemann, Nucl. Phys. **A161**, 449 (1971).
[14] H. Abou-Leila, N. N. Perrin, and J. Valentin, Arkiv Fysik **29**, 53 (1965).
[15] A. Charvet, Do Huu Phuoc, R. Duffait, A. Emsallem, and R. Chery, J. Phys. (Paris) **32**, 359 (1971).
[16] H. Abou-Leila, Ann. Phys. (Paris) **2**, 181 (1967).
[17] R. F. Casten, D. S. Brenner, and P. E. Haustein, Phys. Rev. Lett. **58**, 658 (1987).
[18] R. B. Cakirli and R. F. Casten, Phys. Rev. Lett. **96**, 132501 (2006).
[19] R. F. Casten, Nucl. Phys. **A443**, 1 (1985).