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Collectivity of neutron-rich palladium isotopes and the valence proton symmetry

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Absolute transition probabilities for the first 2^+ states in ^{110,114}Pd were measured using the recoil distance Doppler shift technique following projectile Coulomb excitation at intermediate beam energy. This technique was applied for the first time to projectiles produced in a primary fragmentation reaction, which get Coulomb excited in a secondary reaction. The ^{110}Pd data was used to check the novel experimental technique as well as the data analysis procedure, which is based on the examination of γ-ray line shapes. Whereas the measured $B(E2)$ value for ^{110}Pd agrees very well with the literature, the value obtained for ^{114}Pd differs considerably. The new experimental data are compared to calculations in the framework of the Interacting Boson Model. The data are also used to test the novel concept of valence proton symmetry, which allows for extrapolation of nuclear properties to very neutron-rich nuclei.

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The present work explores the structure evolution of neutron-rich Pd isotopes. Nuclei in this region exhibit a large variety of shapes because here the transition from almost spherical Sn via vibrational Cd toward moderately deformed Pd and Ru is observed. In this region triaxiality and γ softness are features predicted to play an important role in shape evolution [1]. The neutron-rich Pd nuclei are of special interest because a prolate-to-oblate shape transition is expected from mean field calculations [2]. Along with the experimental investigations, a big effort was made to describe the properties of the Pd nuclei in the framework of various collective models (Refs. [3,4] and Refs. 11–15 in Ref. [5]), such as the Interacting Boson Model (IBM) [6]. Whereas the energy spectra of the neutron-rich palladium isotopes develop smoothly with the neutron number N, the measured $B(E2; 2_1^+ \rightarrow 0_1^+)$ values for ^{112,114}Pd [7,8] deviate from the prediction made by Kim *et al.* [4] or the Grodzins relation [9] (see Fig. 1).

For the investigation of very neutron-rich nuclei, secondary reactions such as Coulomb excitation or fragmentation often provide the only feasible experimental approach. For these reactions, it is important to establish Doppler shift methods, such as the Recoil Distance Doppler Shift (RDDS) technique, as tools for measuring absolute transition probabilities. The Doppler shift technique is largely model and reaction mechanism independent and thus can be used as a reliable probe of other methods or utilized in cases where other techniques cannot be applied. The technique was already successfully tested using a stable beam [10]. The purpose of the present work is to demonstrate that the technique can be successfully used for rare isotopes to measure lifetimes of excited 2^+ states populated in intermediate-energy projectile Coulomb excitation.

To measure the lifetime of the first excited states in ^{110,114}Pd, a dedicated plunger device was built at the IKP of University of Köln [11]. This device was mounted at the target position of the S800 spectrometer [12] in the center of the γ spectrometer SeGA [13] at the National Superconducting Cyclotron Laboratory (NSCL), Michigan State University (MSU). For the actual experiment, the SeGA detectors were mounted in two rings at forward and backward angles of 30° and 140° with respect to the beam axis. A 120 MeV/u primary beam of ^{124}Sn was delivered from the K500/K1200 coupled cyclotrons and directed on a ^{9}Be production target positioned at the object point of the A1900 fragment separator [14]. Via in-flight projectile fragmentation and by using a 553 μm Al wedge for energy loss separation at the dispersive plane, two cocktail beams, consisting among other components of ^{116}Ag, ^{112}Rh, and ^{114}Pd isotopes and ^{112}Ag, ^{108}Rh, and ^{110}Pd isotopes, respectively, were separated in the focal plane of the A1900 and sent to the S800 spectrometer. Particle identification after the plunger's target and the degrader foils was made on an event-by-event basis using the TOF measured via a diamond detector positioned in the object plane of the S800 and by a plastic scintillator in the focal plane of the S800. Energy loss signals of reacted Pd projectiles were measured with the ionization chamber of the S800 focal plane while scattering angle information was provided by two CRDC detectors [15]. The intensity of the ^{110}Pd and ^{114}Pd beams was 11 000 pps/pnA and 1 500 pps/pnA, respectively. The ^{114}Pd and ^{110}Pd projectiles impinging on the 100 μm ^{93}Nb plunger target at energies of ≈69 MeV/u and 66 MeV/u left the target at velocities of $v/c = 0.343$ and $v/c = 0.333$, respectively. After a defined flight distance the ^{114}Pd/^{110}Pd projectiles were slowed down to $v/c = 0.298/v/c = 0.273$ in a 500 μm thick carbon degrader. Data were taken for ^{110}Pd at four different target-degrader separations over the range of 0 to 10 mm and for ^{114}Pd at nine distances between 0 and 50 mm. The large separation of 50 mm was used to determine the fraction of

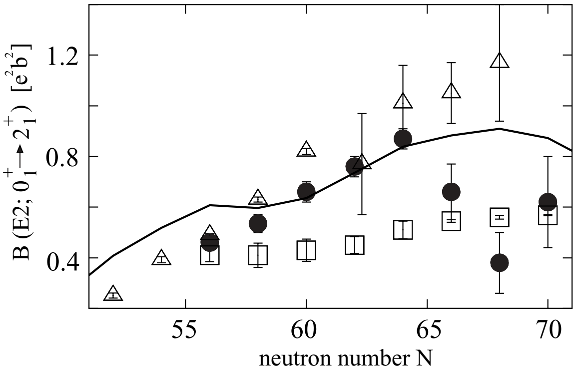

FIG. 1. Systematics of $B(E2, 0^+_1 \rightarrow 2^+_1)$ values in Pd (dots), Cd (squares), and Ru (triangles) nuclei. The $B(E2, 0^+_1 \rightarrow 2^+_1)$ values for ^{112,114}Pd are taken from Ref. [7], others are taken from [20]. Also given are the Grodzins estimates for Pd as a solid curve.

Coulomb excitation occurring in the degrader, which must be subtracted from all the spectra for the further lifetime analysis.

To analyze the data, the procedure developed for the lifetime determination in a similar RDDS experiment [16] using a single neutron knockout reaction at intermediate beam energies was adopted. This procedure was modified to meet the special requirements of the present measurements. The calculations treat the process of γ radiation emission from excited nuclei relativistically. The change of the detection angle with respect to the velocity of the nucleus and the locus of the γ-ray emission were taken into account. Attention was also paid to the decays occurring behind the degrader for relatively long lifetimes. In this way, the total line shape, consisting of the peaks generated by emissions in flight (fully shifted and degraded) and of the contributions from emissions while slowing down in the target or degrader, can be calculated as a function of the lifetime τ and a factor that normalizes the simulation to the data. A fitting procedure leads to the determination of these quantities for each target-to-degrader distance. For selected distances Fig. 2 shows an excellent agreement between the data for the first excited 2^+_1 state in ^{114}Pd and results of the simultaneous fit of the line shapes at forward and backward angles. A strong forward-backward asymmetry of peak intensities was observed for two reasons: First, in ^{114}Pd the fast component appears in the spectra taken at backward angle at the low energy part where the detector efficiency drops very steeply; second, because the target is moved upstream toward the backward detectors, the effective observation angle for the γ transitions becomes closer to 90° and consequently the fast component of the transition of interest is less well separated from the degraded component. Therefore, for the specific conditions of this experiment, the backward spectra are less sensitive for the final lifetime determination. Nevertheless, they were used in the simultaneous fitting process and the results prove that the spectra are at least consistent with the calculated line shapes.

With the new procedure, the lifetimes of the first 2^+ states in ^{110}Pd and ^{114}Pd have been determined. For the 2^+_1 lifetime in ^{110}Pd, which is quite well known, a value of $\tau = 67(8)$ ps was obtained that coincides with the average value from the literature. This gives us confidence that the new procedure works properly. In contrast, the lifetime of the 2^+_1 level in ^{114}Pd, determined to be $\tau = 118(20)$ ps, is more than two times smaller than the previously known result [7,8]. One has to consider that the lifetime value given in Ref. [8] has been determined in a very challenging experiment and consequently might be less reliable than that of ^{110}Pd.

As already mentioned, the Pd isotopes belong to a transitional region between vibrational and rotational nuclei. They have been experimentally investigated up to the neutron-rich ^{120}Pd [17–19]. A systematic study of the excitation energies in the even palladium isotopes $^{106-118}$Pd is presented in Ref. [5] and shows a smooth development from a vibrational-like toward a rotational-like structure when approaching midshell. A maximum value of the energy ratio $E4^+_1/E2^+_1 = 2.6$ is obtained for ^{114}Pd positioned with $N = 68$ close to midshell between $N = 50$ and $N = 82$. This is a typical value for a γ-soft rotor or a nucleus that can be described with the dynamical symmetry O(6) of the IBM. Additionally, the low-lying excitation spectra of these nuclei show features of a γ-soft rotor or of a O(6)-like nucleus. No indication of any deviation from the general trend of evolution toward

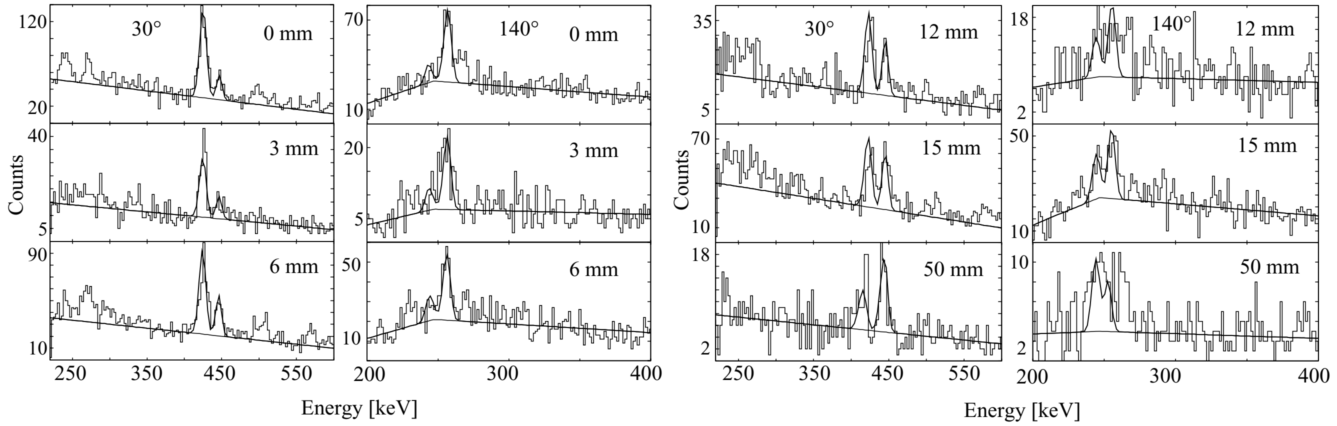

FIG. 2. Simultaneous fit of spectra at forward and backward angles in ^{114}Pd. Shown are the data and fits for the SeGA rings at 30°/140°. The corresponding target-degrader separations are indicated. The Doppler corrections account for the detector segmentation but not for the angular position of the detector in the array.

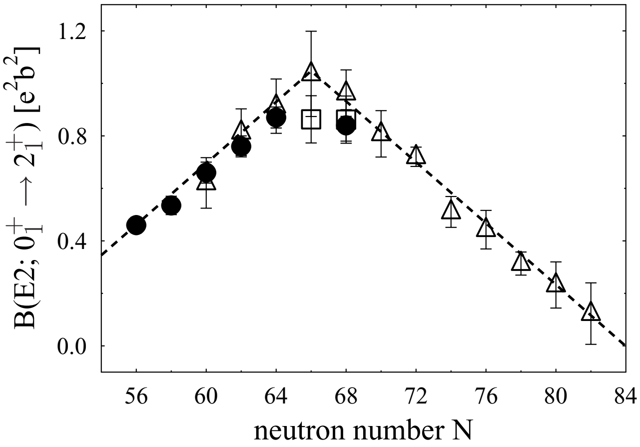

FIG. 3. $B(E2, 0_1^+ \rightarrow 2_1^+)$ values of Pd isotopes (dots) compared with scaled values of the corresponding Xe VPS partners (open triangles) using the scaling factor $S = (Z_{\mathrm{Pd}}/Z_{\mathrm{Xe}})^2 * (A_{\mathrm{Pd}}/A_{\mathrm{Xe}})$. Open squares correspond to values for ^{112,114}Pd taken from Ref. [22]. In addition, the scaled $B(E2)$ values according to relation (1) are given as a dashed line. See also text.

a moderate triaxial deformation around midshell can be observed based on the available energy-level information, in contrast to what was indicated by the $B(E2; 0^+ \rightarrow 2^+)$ values reported in Refs. [7,8].

From the present work it can be concluded that the expected large deformation still exists for this neutron-rich nucleus and that the collectivity is not reduced as implicated by the results of Refs. [7,8]. From the $B(E2; 0^+ \rightarrow 2^+) = 51(9)$ W.u. determined in this work a quadrupole deformation $\beta = 0.24(1)$ is deduced. In Fig. 3 the $B(E2; 0^+ \rightarrow 2^+)$ values of this work are compared to those of neighboring Pd nuclei. They fit nicely into a smoothly developing systematics as a function of neutron number. In consequence there is no reason for assuming a special physical effect that may cause a reduced deformation like, e.g., the modification of the single particle energies due to large isospin values, as has been considered for lighter nuclei [21]. This is further supported by a measurement performed at the JYFL, Jyväskylä, using fast timing techniques. Mach *et al.* reported lifetimes for ^{112}Pd and ^{114}Pd in an annual laboratory report of the JYFL from 2003 [22]. The latter perfectly agrees with our result, while the former is in conflict with the one given in Ref. [7]. This finding is consistent with systematic IBM calculations performed by Kim *et al.* [4] for the palladium isotopes with $A = 102$–116. We have extended these calculations up to ^{118}Pd because recently new experimental data became available [17,18]. In Fig. 4 we show as examples low-spin spectra of ^{110,114,118}Pd compared to those calculated within IBM using the parameters of Ref. [4]. The theoretical $B(E2)$ values were determined using the effective charge values $e_\pi = 12e$ fm^2 and $e_\nu = 10e$ fm^2 for every nucleus. The obtained agreement of the calculated values and the experimental results including the $B(E2)$ values is rather good and it can be concluded that the structure of the neutron-rich Pd nuclei is described well by this collective model.

Because the actual interest in nuclear structure physics concentrates on very neutron-rich nuclei, it is appropriate to develop methods for extrapolating nuclear observables like the energy spectrum and absolute transition rates toward this extreme. This was done, e.g., in Ref. [4]. Parameters used in their IBM-2 calculations of a chain of Pd isotopes up to ^{116}Pd were extrapolated to heavier Pd isotopes to predict excitation energies and $B(E2)$ values for very neutron-rich Pd isotopes up to ^{126}Pd. The resulting nuclear structure predictions indicate a transition from a γ-soft rotor to a vibrator for these isotopes.

We want to use an alternative approach to determine the expectations for the nuclear structure of Pd isotopes at large isospin values that is based on a concept, called valence proton symmetry (VPS), which can be considered as a special case of the valence correlation scheme (VCS) introduced in Ref. [23]. Nuclei $({}^{A_x}_{Z_x}X_{N_x})$ and $({}^{A_y}_{Z_y}Y_{N_y})$ can be considered as valence-proton symmetric if $N_x = N_y$, $Z_x < Z_m < Z_y$, and $|Z_m - Z_x| = |Z_m - Z_y| = N_\pi$, where Z_m is the magic proton

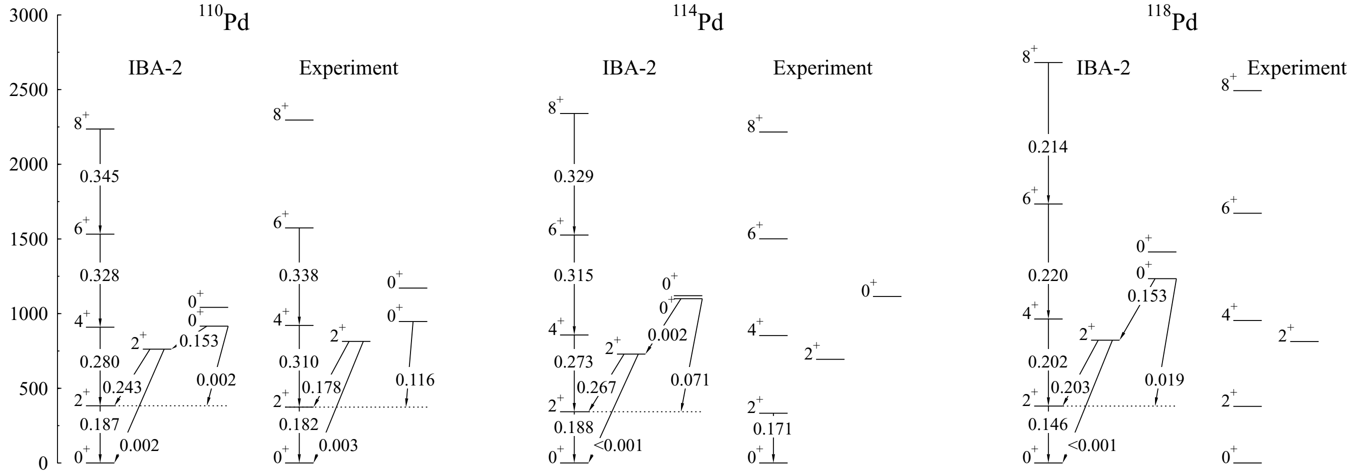

FIG. 4. Spectra and $B(E2)$ values of ^{110,114,118}Pd compared to IBM calculations. Numbers given at the arrows are $B(E2)$ values in units of e^2b^2.

number closest to Z_x and Z_y and N_π is the valence proton number. Proton symmetric nuclei form pairs of nuclei (valence proton symmetry pairs, VPS pairs) where each partner is supposed to have the same nuclear structure, exhibited, in an ideal case, by identical excitation spectra and transition probabilities. In real nuclei this symmetry is broken to some extent and differences are expected, but the gross features of the nuclear structure should be preserved. According to this definition the nuclei ${}^{52+N}_{50+2}\mathrm{Te}_N$ and ${}^{48+N}_{50-2}\mathrm{Cd}_N$ with identical neutron numbers N are VPS pairs with $N_\pi = 2$. For $N_\pi = 4$ and $N_\pi = 6$ one gets the pairs $({}^{54+N}_{50+4}\mathrm{Xe}_N/{}^{46+N}_{50-4}\mathrm{Pd}_N)$ and $({}^{56+N}_{50+6}\mathrm{Ba}_N/{}^{44+N}_{50-6}\mathrm{Ru}_N)$, respectively.

The similarity of the nuclear structure of valence proton symmetric nuclei can be understood, for example, in the framework of the IBM because both nuclei have the same number of active bosons. Because the Pd and Xe nuclei with identical neutron numbers N form VPS pairs, the same deformation or collectivity is expected for these nuclei, exhibited by similar energies of the low-lying excited states and similar $B(E2)$ transition strengths. Already in Ref. [5] a striking similarity between the nuclei ^{116}Pd and ^{124}Xe was pointed out. The similarity of the experimental data for the Xe and Pd isotopes with identical neutron numbers reveals the equivalence of the valence space in these nuclei. Some differences remain, mainly due to the mass and charge differences that break the VPS to some extent. For the $B(E2)$ values the effect of symmetry breaking can be compensated by applying the scaling factors $S(N, Z_m) = ((Z_m - N_\pi)/(Z_m + N_\pi))^2 * (N + Z_m - N_\pi)/(N + Z_m + N_\pi)$. In case of $N_\pi = 4$ we can write this factor as $S(N, 50) = (Z_{\mathrm{Pd}}/Z_{\mathrm{Xe}})^2 * (A_{\mathrm{Pd}}/A_{\mathrm{Xe}}) = (46/54)^2 * (46 + N)/(54 + N)$, where N is the neutron number. Using these scaling factors for the $B(E2)$ values in the Xe isotopes, the agreement of the experimental values of the two isotopic chains Pd and Xe becomes evident, as shown in Fig. 3. In this figure the scaled $B(E2)$ values of Xe isotopes are compared with $B(E2)$ values of Pd isotopes. For the VPS pairs (^{114}Xe/^{106}Pd), (^{116}Xe/^{108}Pd), (^{118}Xe/^{110}Pd), and (^{122}Xe/^{114}Pd), the experimental values agree within the errors. Only for (^{120}Xe/^{112}Pd) do the values deviate a bit more, but are still very close. In Fig. 3 we also give as dashed lines the $B(E2)$ values determined by the relation

$$B(E2, 0_1^+ \rightarrow 2_1^+) = 0.0215 N_\pi \cdot N_\nu e^2 b^2 + 0.17 e^2 b^2, \quad (1)$$

scaled with the S factors defined above. N_π and N_ν are the valence proton and neutron numbers, respectively. Relation (1) was found to describe the experimental values in the $A = 130$ mass region very well [24] and especially those of the Xe isotopes with $N_\pi = 4$. The fact that the scaled relation (1) also describes the $B(E2, 0_1^+ \rightarrow 2_1^+)$ values of the Pd isotopes further supports the VPS concept. For the Xe nuclei with $62 < N < 90$, a lot of experimental data are available to determine the nuclear structures; thus these can be used to predict structure properties of the corresponding Pd VPS partners. In this way rather concrete predictions can be made for very neutron-rich Pd isotopes. More details and applications of the VPS concept will be given in an upcoming publication [25]. The comparison of the $B(E2, 0_1^+ \rightarrow 2_1^+)$ values of Pd and Xe isotopes as shown in Fig. 3 further indicates that the $B(E2, 0_1^+ \rightarrow 2_1^+)$ value of ^{114}Pd determined in this work fits very well into the expected systematics for palladium nuclei in this mass range.

In summary, the lifetimes of the first 2^+ states in ^{110,114}Pd were measured using the recoil distance Doppler shift technique following projectile Coulomb excitation at intermediate beam energies. This technique was applied for the first time for projectiles produced in a primary fragmentation reaction. The method used for data analysis is based on the investigation of the observed γ-ray line shapes. The absolute transition probability for excitation to the first 2^+ state in ^{110}Pd coincides with the earlier results published for this isotope. This makes us confident in the reliability of both the experimental technique and the data analysis and demonstrates that Doppler-shift methods can be applied in radioactive beam experiments in a reliable way. Additionally, the measured $B(E2)$ value for ^{114}Pd differs considerably from the value published earlier and adopted in NDS and confirms the result reported by H. Mach *et al.* [22] in a JYFL annual report. The new $B(E2)$ value of the present work fits nicely into the systematic trends deduced from the lighter Pd isotopes. This trend is in agreement with the predictions of the IBM. The novel experimental results obtained in this work positively verify the concept of valence proton symmetry, which allows for the extrapolation of nuclear properties to very neutron-rich nuclei.

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[1] J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. **A617**, 282 (1997).

[2] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).

[3] J. Stachel, P. Van Isacker, and K. Heyde, Phys. Rev. C **25**, 650 (1982).

[4] K.-H. Kim *et al.*, Nucl. Phys. **A604**, 163 (1996).

[5] Youbao Wang *et al.*, Phys. Rev. C **63**, 024309 (2001).

[6] F. Iachello and A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, 1987).

[7] G. Mamane *et al.*, Nucl. Phys. **A454**, 213 (1986).

[8] J. Blachot, Nucl. Data Sheets **97**, 593 (2002).

[9] L. Grodzins, Phys. Lett. **2**, 88 (1962).

[10] A. Chester *et al.*, Nucl. Instrum. Methods Phys. Res. A **562**, 230 (2006).

[11] A. Dewald *et al.*, GSI Sci. Rep. **2005**, 38 (2006).

[12] D. Bazin *et al.*, Nucl. Instrum. Methods B **204**, 629 (2003).

[13] W. F. Mueller *et al.*, Nucl. Instrum. Methods A **466**, 492 (2001).

[14] D. J. Morrissey *et al.*, Nucl. Instrum. Methods B **204**, 90 (2003).

[15] J. Yurkon *et al.*, Nucl. Instrum. Methods A **422**, 291 (1999).

[16] K. Starosta *et al.*, Phys. Rev. Lett. **99**, 042503 (2007).

[17] A. Jokinen *et al.*, Eur. Phys. J. A **9**, 9 (2000).

[18] X. Q. Zhang *et al.*, Phys. Rev. C **63**, 027302 (2001).
[19] M. A. Stoyer *et al.*, Nucl. Phys. **A787**, 455c (2007).
[20] S. Raman, C. W. Nestor, Jr., and P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
[21] T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001).
[22] H. Mach *et al.*, JYFL Annual Report 2003.
[23] R. F. Casten and N. V. Zamfir, Phys. Rev. Lett. **70**, 402 (1993).
[24] A. Dewald *et al.*, XIV International School on Nuclear Physics, Neutron Physics, and Nuclear Energy BgNS TRANSACTION, edited by Prof. Dr. DSc Natalia Janeva, Science and Technology Journal, special issue, Sept. 2002.
[25] A. Dewald (to be published).