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Evidence for new isomers and band structures in ^{80}Rb

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Excited states in the doubly odd nucleus ^{80}Rb have mainly been studied via the ^{68}Zn(^{19}F,$\alpha 3n$) reaction at 72 MeV beam energy utilizing the NORDBALL detector system. The level scheme has been extended up to a (15$^+$) state at 4446 keV excitation energy. In the low-spin region seven new isomers with lifetimes in the nanosecond region have been found. In addition, a 6$^+$ isomer with a half-life of the order of μs has been identified at an excitation energy of 494.4 keV. For the level sequence built on this isomer positive parity is suggested and the states are ascribed to the intruder two-quasiparticle configuration ($\pi g_{9/2} \otimes \nu g_{9/2}$) and collective excitations.

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Recently, several new isomers and high-spin level sequences have been identified in the doubly odd nuclei ^{82,84}Rb [1,2]. In particular, in ^{82}Rb a 6$^+$ isomer has been observed at an excitation energy of 191.3 keV which is populated by a high-spin level sequence of positive parity. This sequence is ascribed to the two-quasiparticle (2-qp) intruder configuration ($\pi g_{9/2} \otimes \nu g_{9/2}$) in connection with collective excitations. The occurrence of such intruder excitations where both the unpaired proton and the unpaired neutron occupy the same single particle orbital is also expected in the adjacent doubly odd nucleus ^{80}Rb. Their investigation may provide more information about the shape driving properties of the $g_{9/2}$ orbitals.

So far, in the neutron deficient nucleus ^{80}Rb some low-

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spin states have been investigated via the radioactive decay of the ground state of ^{80}Sr [3]. In addition, states up to a tentative spin of $5\hbar$ have been studied in-beam via the ^{79}Br($\alpha, 3n$) reaction [4]. Delayed γ-ray emission with half-lives of 2.4(2) μs [5] or 1.60(2) μs [6] was also reported for this nucleus, but the placement of such an isomeric state in the level scheme was up to now open.

In the present study states in ^{80}Rb have been excited via the ^{68}Zn(^{19}F,$\alpha 3n$) reaction at 72 MeV. The fluorine beam was provided by the Tandem Accelerator at the Niels Bohr Institute in Risø, Denmark. The γ rays have been recorded with the NORDBALL detector system. Two coincidence measurements have been performed. In the first run the γ rays emitted from a thin (1 mg/cm^2) self-supporting ^{68}Zn foil (enrichment 99 %) were measured with 18 Compton-suppressed Ge detectors and 10 BaF$_2$ detectors as a multiplicity filter. This setup was combined with the HYSTRIX system [7] for the detection of charged particles. In the second measurement a thin ^{68}Zn layer of 1 mg/cm^2 was evaporated onto a 7.5 mg/cm^2 Bi backing. The γ rays were here recorded with 19 Compton-suppressed Ge detectors and one Compton-suppressed low-energy photon spectrometer (LEPS). These detectors were operated in coincidence with a multiplicity filter consisting of 39 BaF$_2$ detectors. In the second run a total number of 9×10^8 events have been stored on magnetic tape, of which about 8% constituted the (^{19}F,$\alpha 3n$)^{80}Rb reaction channel. It should be mentioned that the measurements were mainly performed in order to study 3-qp and 5-qp bands in the odd-mass nucleus ^{83}Sr, which was populated via the ^{68}Zn(^{19}F,$p3n$) reaction [8].

On the basis of the measured coincidence relations, e.g., prompt Ge(γ)-Ge(γ) coincidences, prompt and delayed LEPS(γ)-Ge(γ) coincidences as well as prompt alpha-Ge(γ)-Ge(γ) coincidences, the known [4] level scheme of ^{80}Rb could be considerably extended (see Fig. 1). The observation that the 159 keV peak is a close-lying doublet plays an important role in establishing the level scheme. The new level at 644.6 keV de-excites mainly via a 158.1 keV γ ray to the known state at 486.4 keV. This γ ray is clearly separated from the most intense 159.3 keV γ ray in the LEPS spectrum (see Fig. 2). It should be mentioned that the coincidence relation of the 159.3 keV peak with a γ ray at nearly the same energy can also be seen in the gated spectra shown in Ref. [4]. The observed decay pattern of the newly introduced levels at 644.6 and 884.5 keV confirm the previous [4] level scheme of ^{80}Rb except for the ordering of the 63.1 and 88.4 keV γ rays. They have now been reordered.

The prompt coincidence spectra of the 561.2 and 707.5 keV γ rays show weak peaks at 150.2 as well as at 164.0, 226.3 and 390.0 keV. These γ rays de-excite the levels at 644.6 and 884.5 keV, respectively, to a new state at 494.4 keV. The absence of prompt coincidences between these γ rays and lower-lying γ rays at 63.1, 78.0, 83.9, 88.4, 159.3, and 175.6 keV is interpreted as arising from a rather long half-life of the 494.4 keV state. To this state a lifetime in the range of μs, so far suggested for an unknown level in ^{80}Rb, has now been assigned.

The electronic set up of the second coincidence measurement was designed in such a way that in addition to the γ-ray energy and the BaF$_2$ ball multiplicity the time information of each Ge detector and of the LEP spectrometer with respect to the BaF$_2$ ball was written on magnetic tape. Each Ge or LEPS event was used to start an individual time to amplitude converter and the BaF$_2$ ball signal was taken as a common stop. Therefore, additional proof for the existence of this μs isomer has been obtained from sorting the data with respect to time delays between Ge- and LEPS events. During this sorting only such events have been stored in the matrix where the time difference of two γ rays were at least 70 ns. Two examples of delayed coincidence spectra obtained by setting gates in this matrix are shown in Fig. 3. In the spectrum of events belonging to the gate at 175.6 keV several transitions feeding this γ ray could be identified, in particular, the most intense γ rays at 156.8 and 164.0 keV. On the other hand, in the spectrum of events belonging to the gate at 156.8 keV, most of the low-lying γ rays assigned previously to ^{80}Rb that obviously follow the 156.8 keV transition can be seen. Since in this spectrum both the

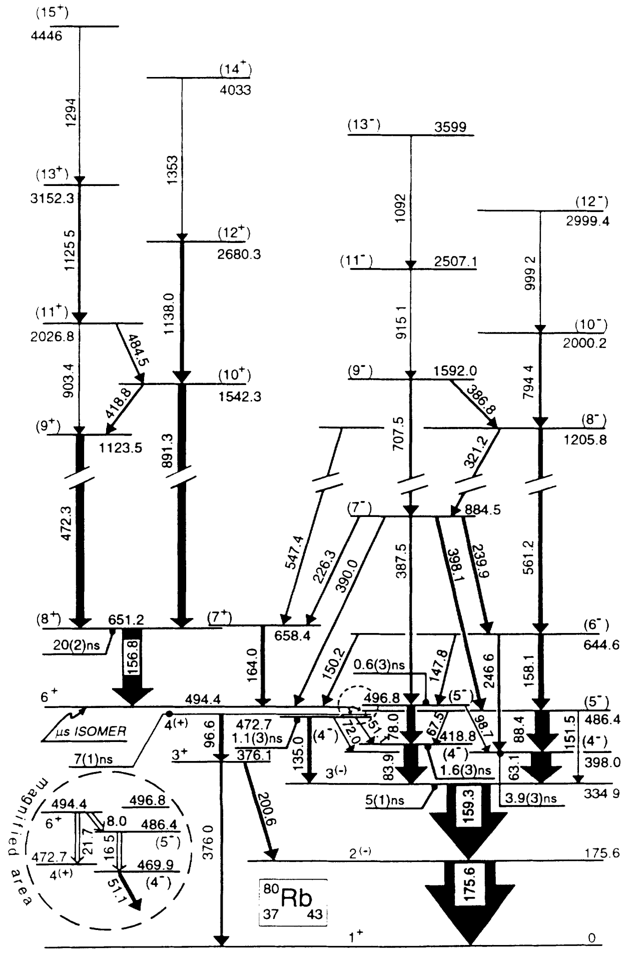

FIG. 1. Partial level scheme of ^{80}Rb obtained in the present study. The lifetimes of the new isomers are indicated. Above 900 keV the energy scale has been compressed by a factor of 4.

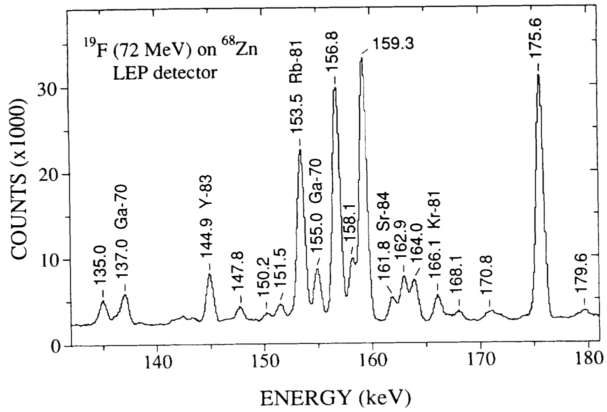

FIG. 2. Part of the prompt LEPS γ-ray spectrum obtained from the projection of the energy(LEPS)-energy(Ge) matrix where the time difference of coincident γ rays is less than 70 ns. It should be mentioned that the 156.8 keV γ ray is a very close-lying doublet. In addition to the ^{80}Rb line there is a second component which belongs very probably to ^{84}Y.

88.4 and the 96.6 keV lines have been observed but the 96.6 keV transition is not in prompt coincidence with the 158.1 keV γ ray, two separated isomeric decay branches are proposed as shown in the magnified insert of Fig. 1. Therefore, the isomeric decay is connected with two unobserved γ rays at 8.0 and 21.7 keV populating the levels at 486.4 and 472.7 keV, respectively. From the observed de-excitation paths and from systematic considerations spin and parity of 6^+ are tentatively suggested for this μs isomer. The 16.5 keV γ ray also shown in the insert of Fig. 1 has been introduced in order to explain the observed prompt coincidences between the 51.1, 72.0, and 135.0 keV γ rays and the 158.1 and 561.2 keV lines.

Our spin and parity assignments to the μs isomer are supported by earlier suggestions given on the basis of the measured magnetic moment [5, 6]. In both papers the time differential perturbed angular distribution method has been used and a g factor of $g = +0.56(1)$ has been determined. Therefore, a spin of $6\hbar$ has been proposed in Ref. [5] whereas in Ref. [6] spin and parity of 6^+ or 7^- are suggested. The measured g factor can be well reproduced by predictions of the additivity rule for the 2-qp configuration ($\pi g_{9/2} \otimes \nu g_{9/2}$) which is in this case independent on the spin of the state and gives $g_{\text{cal}} = +0.564(2)$. This value has been calculated using the single particle g factors [9] for $g_{9/2}$ protons derived from the $\frac{9}{2}^+$ state in ^{85}Rb, $g = +1.344(2)$, and for $g_{9/2}$ neutrons taken from the $\frac{9}{2}^+$ state in ^{83}Kr, $g =- 0.216(1)$. Our interpretation of the 6^+ isomer in ^{80}Rb is similar to those of the isomeric 6^+ state in ^{90}Nb [10] where the g factor has been measured to be $g = +0.620(4)$.

The ns lifetimes of several levels have been deduced from the background-corrected time distributions of the de-exciting γ rays recorded with the LEP spectrometer in the second coincidence run by means of the centroid shift method and/or by slope fitting. For this purpose the measured LEPS events have been sorted in an energy-time matrix of size 4096×1024 and subsequently analyzed by setting gates on peaks and appropriate background intervals. The lifetimes found are given in the level scheme (Fig. 1) and some results are shown in Figs. 4 and 5. In the case of the 159.3 and 175.6 keV γ rays the slope-fitting method has also been applied since the fast timing of the LEPS results in a time resolution of FWHM = 6.85 ns for the 155.0 keV line originating from the reaction ^{68}Zn(^{19}F,4αn)^{70}Ga (see Fig. 4). In both methods the delayed feedings of the 159.3 and 175.6 keV lines by the 63.1 and 83.9 keV γ rays have been taken into account and the results obtained are in fair agreement. The average value of $\tau = 5(1)$ ns is assigned to the $3^{(-)}$ level at 334.9 keV. The centroid position versus the γ-ray energy is shown in Fig. 5 for some additional lines.

The assignment of the 156.8 keV γ ray to feed the 6^+ isomer in ^{80}Rb is confirmed on the basis of α-Ge(γ)-Ge(γ) coincidences measured with the HYSTRIX set up. The 156.8 keV γ ray is found to be in coincidence with one α particle, but not with protons. Furthermore, the

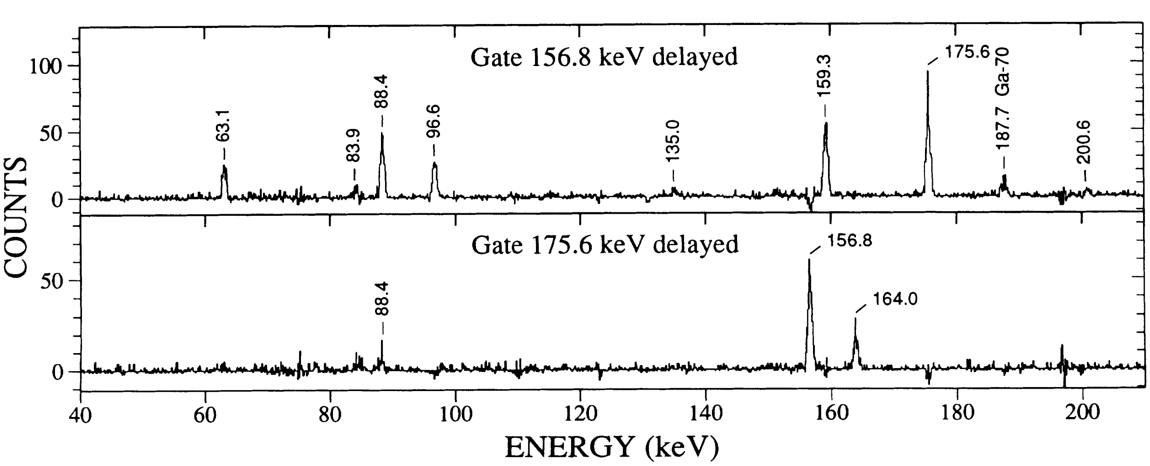

FIG. 3. Examples of background-corrected coincidence spectra obtained by setting gates on the Ge detector projection of the delayed energy(LEPS)-energy(Ge) matrix. In this matrix only such coincidence events have been stored off-line where the time difference lies within the time interval $70 \leq t_{\text{DIF}} < 250$ ns.

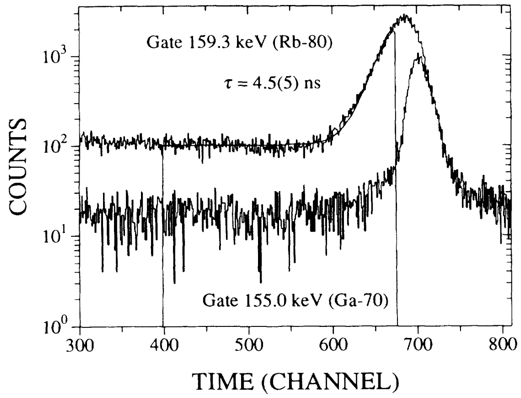

FIG. 4. Background-corrected time distribution of the 159.3 keV γ ray assigned to ^{80}Rb. For the sake of comparison the time distribution of the 155.0 keV γ ray of ^{70}Ga is also shown which is considered as a prompt transition. The lifetime given for the 159.3 keV γ ray is obtained by slope fitting within the interval shown. In this fit the delayed feedings by the 63.1 and 83.9 keV transitions have been taken into account.

excitation function of the 156.8 keV γ ray deduced from its intensity measured at 62, 72, and 81 MeV beam energies in coincidence with α particles is quite similar to those of the most intense γ rays of 159.3 and 175.6 keV assigned earlier [4] to ^{80}Rb. In spite of the low statistics the 156.8 keV gate of the prompt α-Ge(γ)-Ge(γ) coincidence matrix reveals γ rays at energies of 418.8, 472.3, 484.5, and 891.3 keV which are also assigned to ^{80}Rb. These γ rays are involved in a high-spin level sequence (see Fig. 1). It should be mentioned that additional coincidences of the 156.8 keV γ ray as found in the total Ge(γ)-Ge(γ) matrix (e.g., γ rays at 512.1 and 914.1 keV) do not belong to ^{80}Rb but very probably to the ^{68}Zn(^{19}F,3n)^{84}Y reaction channel.

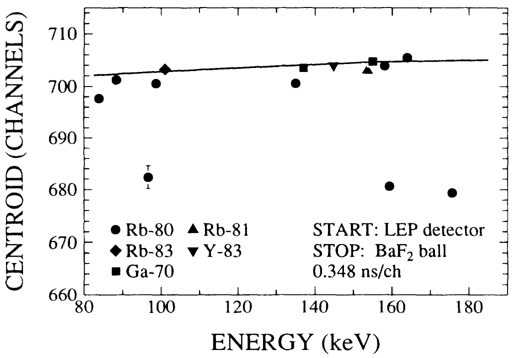

FIG. 5. Center of gravity of the background-corrected time distributions recorded with the LEP spectrometer versus the γ-ray energy. The smooth curve connects the fastest transitions and is used as a reference. Using this reference the known [11] lifetime of $\tau = 0.30(14)$ ns for the 153.5 keV transition in ^{81}Rb can be well reproduced. Here the data points for the 159.3 and 175.6 keV γ rays are not yet corrected for their delayed feedings. When not shown the statistical error of the data point is less or equal to the size of the symbol.

Moreover, additional measurements have been performed at the Rossendorf cyclotron using the ^{76}Se(^{7}Li,3n)^{80}Rb and ^{77}Se(^{7}Li,4n)^{80}Rb reactions at $E(^7\mathrm{Li}) = 35$ MeV. Here prompt and delayed singles γ-ray spectra have been recorded with respect to the radio frequency of the cyclotron and the lowest members of the high-spin level sequence, the 156.8, 472.3, and 891.3 keV γ rays, could unambiguously be observed. Furthermore, an inspection of the singles spectra given in connection with the ^{79}Br(α, 3n) reaction (see Fig. 1 of Ref. [4]) reveals an unidentified peak at 156.5 keV. All these arguments support our assignment of the 156.8 keV γ ray to ^{80}Rb.

Directional correlation of oriented nuclei (DCO) matrices were sorted from the events of the first coincidence run under the conditions that the coincident events are recorded by detectors placed in the rings at 37/143 and 79/101 degrees with respect to the beam axis and with an angle between the detector planes of ϕ=36°. For the 156.8 keV transition an experimental DCO ratio of $R_{\mathrm{DCO}} = I_\gamma$(156.8 at 37/143° gated with 891.3 at 79/101°)/I_γ(156.8 at 79/101° gated with 891.3 at 37/143°) = 1.17(21) is deduced. This value supports a $\Delta I = 2$ assignment and, therefore, spin and parity (8^+) are proposed for the level at 651.2 keV.

For the 156.8 keV composite peak an effective lifetime of $\tau = 20(2)$ ns has been determined by slope fitting. The experimental time distribution does not show any indication for two decay components, as might be expected from the fact that this γ ray belongs with roughly equal intensity to two different nuclei, ^{80}Rb and (probably) ^{84}Y. The only hint is that in the delayed coincidence spectra of the 156.8 keV line the 891.3 keV transition of ^{80}Rb is much weaker than the 914.1 keV transition of (probably) ^{84}Y, compared to equal intensity in the prompt spectra, suggesting a longer lifetime for the ^{84}Y component. The lifetime of 20(2) ns gives a reduced $E2$ transition probability of $B(E2) = 18(2)$ Weisskopf units (W.u.) for the 156.8 keV line of ^{80}Rb.

The (8^+) state at 651.2 keV is populated by a high-spin level sequence which could be identified up to a (15^+) state at 4446 keV. The properties of this level se-

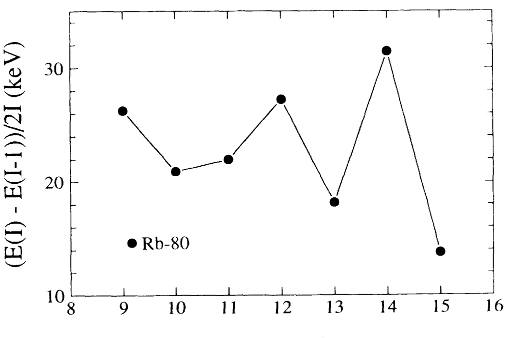

FIG. 6. Moment of inertia (= $\hbar^2/2\Theta$) as a function of spin for the positive-parity band built on the 8^+ level at 651.2 keV. The signature inversion at spin I = 11 $\hbar$ can clearly be seen as a reversal of phase in the alternating staggering.

quence, such as transition energies, branching ratios, and the moment of inertia, are very similar to high-spin level sequences found in ^{82,84}Rb [1, 2]. Especially, a signature inversion has been found at spin $I = 11\hbar$ as shown in Fig. 6. This feature has already been identified before in the positive-parity bands of ^{74,76}Br [12, 13] and interpreted in the framework of a two-noninteracting-quasiparticle plus rotor model [14] assuming the intrinsic state to be of $(\pi g_{9/2} \otimes \nu g_{9/2})$ parentage. The model predicts a signature inversion at spin $I = 9\hbar$, the highest spin based on the intrinsic motion of two $g_{9/2}$ particles. States below this spin are mainly built up on a realignment of the particle angular momenta and collective rotation whereas for the states above $9\hbar$ collective motion of a system with two fully aligned quasiparticles is involved. This situation seems obviously also to be valid for the band observed in ^{80}Rb. Therefore, an interpretation in terms of the intruder 2-qp configuration $(\pi g_{9/2} \otimes \nu g_{9/2})$ in connection with collective excitations is proposed. It should be pointed out that the signature inversion as observed in rotational spectra based on high-j configuration bands can also be consistent with an axially symmetric shape, as shown for odd-odd nuclei in the mass 160 region [15].

In summary, a new level scheme of ^{80}Rb has been established which shows as a striking feature a high-spin level sequence of positive parity. The experimental properties of this band are very similar to known bands in adjacent odd-odd nuclei of the mass region around $A \sim 80$. The signature splitting and inversion at $I = 11\hbar$ can qualitatively be understood in the framework of a 2-qp plus rotor model using the intruder $g_{9/2}$ orbitals for both unpaired particles.

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[1] J. Döring, L. Funke, W. Wagner, and G. Winter, Z. Phys. A **339**, 425 (1991).
[2] J. Döring, G. Winter, L. Funke, L. Käubler, and W. Wagner, Z. Phys. A **338**, 457 (1991).
[3] R. Broda, A.Z. Hrynkiewicz, J. Styczeń, and W. Waluś, Nucl. Phys. **A216**, 493 (1973).
[4] M. Behar, A. Filevich, G. Garcia Bermúdez, and M.A.J. Mariscotti, Nucl. Phys. **A287**, 255 (1977).
[5] H. Haas, H. Grawe, R. Keitel, M. Menningen, and W.-D. Zeitz, Prog. Report HMI-Berlin **294**, 56 (1978); M. Menningen, H. Grawe, H. Haas, W.-D. Zeitz, and R. Keitel, Prog. Report HMI-Berlin **318**, 80 (1979).
[6] R.S. Raghavan, P. Raghavan, W. Semmler, and M. Senba, Rutgers University Progress Report, 63 (1979).
[7] F. Lidén, Nucl. Instrum. Methods **A288**, 455 (1990).
[8] J. Döring, L. Funke, G. Winter, F. Lidén, B. Cederwall, A. Johnson, R. Wyss, J. Nyberg, and G. Sletten, in *Proceedings of the International Conference on High Spin Physics and Gamma-Soft Nuclei*, Pittsburgh, PA, 1990, edited by J.X. Saladin, R.A. Sorensen, and C.M. Vincent (World Scientific, Singapore, 1991), p. 381.
[9] P. Raghavan, At. Data Nucl. Data Tables, **42**, 189 (1989).
[10] R.E. Holland, F.J. Lynch, R.J. Mitchell, T.V. Ragland, and R.P. Scharenberg, Phys. Lett. **58B**, 43 (1975).
[11] J. Panqueva, H.P. Hellmeister, L. Lühmann, K.P. Lieb, F.J. Bergmeister, P. von Brentano, and R. Richter, Nucl. Phys. **A376**, 367 (1982).
[12] J. Döring, G. Winter, L. Funke, P. Kemnitz, and E. Will, Z. Phys. A **305**, 365 (1982).
[13] J.W. Holcomb, T.D. Johnson, P.C. Womble, P.D. Cottle, S.L. Tabor, F.E. Durham, and S.G. Buccino, Phys. Rev. C **43**, 470 (1991) and references cited therein.
[14] A.J. Kreiner and M.A.J. Mariscotti, Phys. Rev. Lett. **43**, 1150 (1979).
[15] I. Hamamoto, Phys. Lett. B **235**, 221 (1990).