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Decay out of the highly deformed bands in the odd Nd isotopes: The ^{137}Nd nucleus

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The decay of the highly deformed (HD) band in the nucleus ^{137}Nd has been studied with the GASP array using the reactions ^{110}Pd+^{30}Si and ^{123}Sb+^{19}F. Four decay paths linking the HD band to the normal-deformed states have been established, which fix $I^{\pi}=29/2^{+}$ for the lowest state of the HD band lying at $E_x=4885$ keV. The sudden disappearance, at the low spin side, of the HD bands in the ^{133,135,137}Nd isotopes can be explained by total Routhian surface calculations through a change of the nuclear shape which is microscopically related to the transfer of the valence neutron from a $N=6$ to a $N=4$ Nilsson orbital.

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In the Nd nuclei with neutron number ranging from $N=73$ to 77 super-deformed or highly-deformed (HD) rotational bands were reported some time ago [1], which have been interpreted as being built on a second minimum in the nuclear potential energy surface. The experimental fact that the population of these bands in the odd Nd isotopes is much larger than usual [1,2] offers a good opportunity to search here for the connection of the HD structures with the normal-deformed (ND) states. Indeed, the decay out of the HD bands has been recently studied in great detail in the two nuclei ^{133}Nd [3] and ^{135}Nd [4] exploiting the improved sensitivity of the new generation of large γ-ray detector arrays. The spin and the parity of the band levels could be determined for the first time, thus allowing a detailed comparison with theoretical calculations. The $i_{13/2}$ neutron character of the bands has been firmly established and the rather different decay-out behavior in the two nuclei could also be understood. In ^{133}Nd the decay out of the HD band has been explained, in a quantitative way, in terms of an accidental mixing of highly-deformed and normal-deformed states [3]. Within this approach it is also clear why the band in ^{133}Nd ends at spin $17/2^{+}$. In ^{135}Nd, where the HD band ends at spin $25/2^{+}$ and no mixing with ND levels has been observed, the low spin "termination" of the band has been related to the disappearance, at low rotational frequency, of the second minimum in the nuclear potential energy surface [4]. It is worth noting that total Routhian surface (TRS) calculations for the nuclei of this mass region (which have been in existence for several years) [5,6] predict both the presence of a second minimum associated with the occupation of the $i_{13/2}$ neutron orbital and also its disappearance at low rotational frequencies. However, the validity of such calculations could not be tested in a quantitative way since precise data on the decay out of the bands was missing.

In order to understand which of the two different decay-out mechanisms observed in the ^{133}Nd and ^{135}Nd nuclei is characteristic for the $A=130$ mass region, new experimental data on the decay out of the HD bands was clearly needed. In this spirit we have extended our investigation to the next heavier odd Nd isotope where a HD band is known [1], namely to ^{137}Nd. From lifetime measurements using the Doppler shift attenuation method [7] a quadrupole moment $Q=4.0$ eb for the HD band of ^{137}Nd has been measured. Under the assumption of an axially symmetric shape, a deformation parameter $\beta_2=0.22$ has been derived which is the smallest among the known HD bands in the $A=130$ mass region. The experimental quadrupole moment is equally well explained by TRS calculations either through a triaxial minimum ($\beta_2=0.27$, $\gamma\sim 10°-20°$) based on the $i_{13/2}$ orbital or a prolate minimum ($\beta_2=0.20$) based on the less deformation driving $h_{9/2}$ orbital [7]. It is therefore essential to experimentally determine the parity of the HD band in order to discriminate between the two different possibilities.

We have populated the ^{137}Nd nucleus via the ^{110}Pd(^{30}Si,3n) and the ^{123}Sb(^{19}F,5n) reactions at beam energies of 125 and 97 MeV, respectively. The GASP array with 40 Compton-suppressed Ge detectors and the 80 element BGO ball has been used for a standard coincidence measurement, where only triple- or higher-fold events have been collected. Two different experiments have been performed using the ^{30}Si beam, one with a stack of thin ^{110}Pd foils (2×0.5 mg/cm^2) and one with a gold-backed ^{110}Pd target (1.5 mg/cm^2 of ^{110}Pd on 10 mg/cm^2 of gold). A total of 1.3×10^9 and 2.3×10^8 events have been collected in the thin- and in the backed-target experiments, respectively. With the ^{19}F beam only a gold-backed target (1 mg/cm^2 of ^{123}Sb on 10 mg/cm^2 of gold) was used and 4×10^8 events were collected. The experiments with backed targets had the

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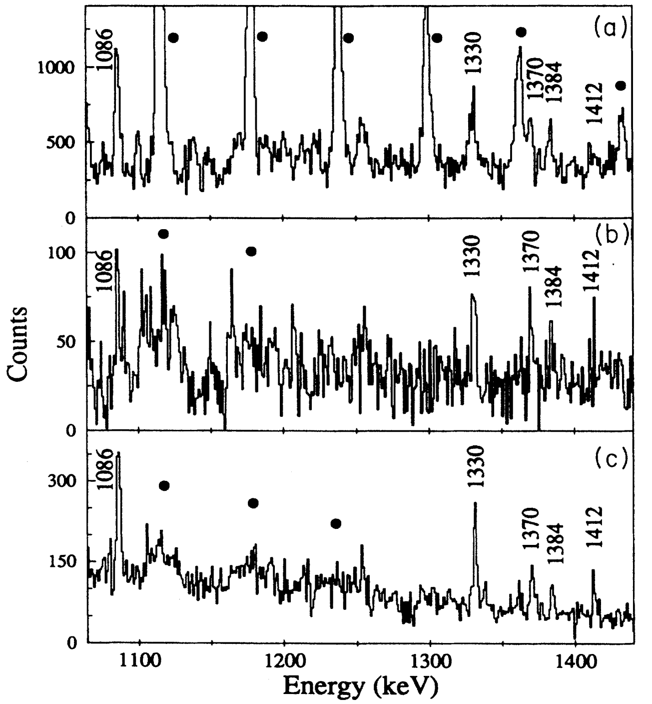

FIG. 1. (a) High energy part of a doubly-gated spectrum, with gates set on transitions in the HD band of ^{137}Nd, obtained using the ^{110}Pd+^{30}Si reaction with thin self-supporting targets. (b) Same as (a) but with a gold-backed target and gates set on transitions in the HD band below E_γ=900 keV. (c) Same as (b) but for the ^{123}Sb+^{19}F reaction. Transitions belonging to the HD band are labeled with full dots; transitions connecting the HD band to the ND states are labeled with their energies.

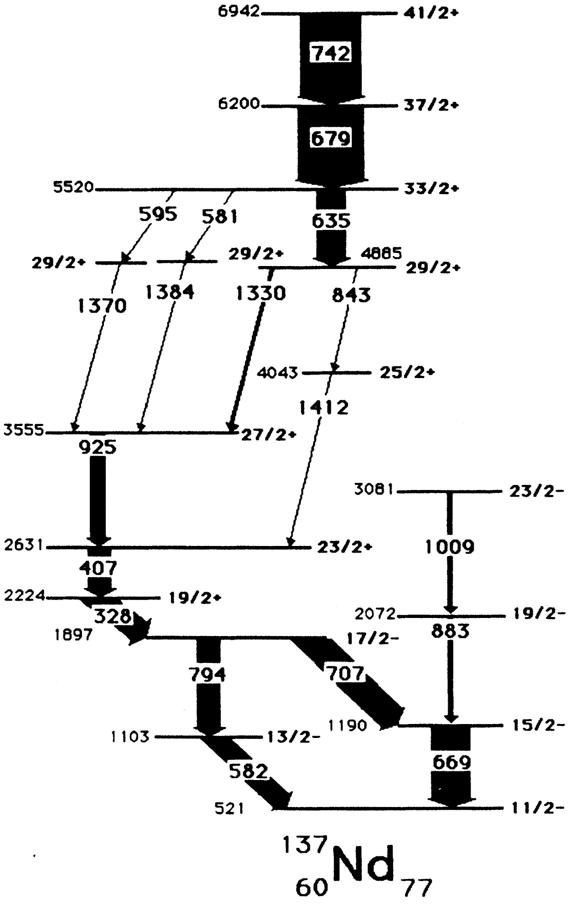

FIG. 2. Partial level scheme of ^{137}Nd showing the bottom of the HD band and the part relevant for the decay-out process of the HD band. Only states above the 11/2$^-$ isomer are drawn. The thickness of the arrows is proportional to the intensity seen in coincidence with the HD band.

two-fold goal of obtaining a detailed level scheme of ^{137}Nd at low excitation energy and of identifying the transitions which depopulate the HD band. In fact, only a few levels at low spin were known in the literature for this nucleus [8]; however, in order to study the decay out of the HD band into the ND levels, one needs a detailed level scheme at medium and high spins. The second and important reason to choose a backed target for the study of the decay out comes from the knowledge of the lifetimes of the band levels. From the previous backed-target experiment [7] it results that the transitions of the HD band with energies higher than $E_\gamma \approx 800$ keV suffer from the Doppler broadening effect; on the contrary, the transitions deexciting the lowest levels of the HD band appear as sharp lines in the γ-ray spectrum, which means that they are emitted from states with lifetimes longer than the stopping time of the recoiling nuclei in the backing. As the transitions which link the HD band to the states of normal deformation are expected to have similar lifetimes but also to be very weak, it is easily realized that one can enhance their detection by taking advantage of the much better energy resolution achieved in a backed-target experiment.

Figure 1 is a nice example proving how, for our case, the use of a backed target helped to find the decay out of the HD band. The upper part of the figure shows the region above 1 MeV of a doubly-gated spectrum obtained bombarding a thin ^{110}Pd target with a ^{30}Si beam. The gates are set on all transitions assigned to the HD band in ^{137}Nd. It is evident from this spectrum that the band is in coincidence with a few other transitions in the energy range 1–1.5 MeV. A striking effect is observed in the two analogous spectra obtained in the backed-target experiments (middle and lower part of the figure for the ^{30}Si+^{110}Pd and the ^{19}F+^{123}Sb reactions, respectively). The new transitions in coincidence with the HD band appear as sharp lines, like the low-lying transition in the HD band (not shown in the figure), whereas the transitions of the HD band above 1 MeV are completely smeared out by the Doppler broadening. This fact strongly suggests that the transitions of 1086, 1330, 1370, 1384, and 1412 keV are related to the decay-out process of the band.

From the analysis of the triples data we could observe clear coincidence relationships between four of these transitions and other transitions belonging both to the HD band and to the ND structures of ^{137}Nd. Four decay paths for the HD band have been established, each one consisting of two transitions, 925–1330, 595–1370, 581–1384, and 843–1412 keV, respectively, which unambiguously fix the excitation

TABLE I. Energies, relative intensities, and DCO ratios for the transitions in the lower part of the HD band of ^{137}Nd and for the transitions relevant for its decay out.

Energy (keV)	$I_i^\pi \rightarrow I_f^\pi$	Intensity	DCO ratio
	HD band transitions		
634.7(3)	$33/2^+ \rightarrow 29/2^+$	54(2)	1.06(9)
678.5(3)	$37/2^+ \rightarrow 33/2^+$	109(4)	1.03(5)
741.6(3)	$41/2^+ \rightarrow 37/2^+$	100	1.01(6)
802.4(4)	$45/2^+ \rightarrow 41/2^+$	99(4)	1.01(6)
	Decay-out transitions		
581.2(4)	$33/2^+ \rightarrow 29/2^+$	5(3)	
595.1(4)	$33/2^+ \rightarrow 29/2^+$	5(2)	
842.6(5)	$29/2^+ \rightarrow 25/2^+$	3(2)	
924.5(1)	$27/2^+ \rightarrow 23/2^+$	20(3)	0.96(5)
1330.4(5)	$29/2^+ \rightarrow 27/2^+$	6(2)	<0.2
1370.0(5)	$33/2^+ \rightarrow 31/2^+$	6(2)	<0.2
1383.9(5)	$33/2^+ \rightarrow 31/2^+$	5(2)	<0.2
1412(1)	$29/2^+ \rightarrow 27/2^+$	3(1)	<0.2

energy of the HD band. A partial level scheme of ^{137}Nd which shows only the part related to the decay out of the HD band is drawn in Fig. 2. In the proposed level scheme only one of the above mentioned transitions (1330 keV) deexcites directly the HD band. On the basis of intensity relationships and considering that the intermediate levels should not be yrast, we prefer for the other three decay paths an ordering with the low energy transition preceding the high energy one. Energies and relative intensities of the transitions which are relevant for the decay-out process are given in Table I: it is seen that only ≈20% of the intensity of the HD band is carried out by the observed linking transitions. We know that other γ lines (e.g., 1086 keV, see Fig. 1) link the HD band to the normal-deformed states but we have not been able to place them in the level scheme.

In order to establish the spins and the parity for the HD band levels, we extracted the DCO ratios for the ^{137}Nd transitions using the data of the ^{19}F+^{123}Sb reaction. A DCO γ-γ matrix has been created with the detectors at 90° with respect to the beam direction on one axis and the detectors at 34° and 146° on the other axis. Gates were set along both axes on known stretched quadrupole $E2$ transitions and the intensities $I_\gamma(90°)$ and $I_\gamma(34°)$ of the transitions of interest (with 90° and 34° indicating the axis where the gate has been set) were extracted from the obtained spectra. The theoretical DCO ratios $R_{\mathrm{DCO}}=I_\gamma(90°)/I_\gamma(34°)$ are, in our geometry, $R_{\mathrm{DCO}}\approx 1$ for a stretched quadrupole transition and ≈0.5 for a pure dipole one. For a transition with mixed multipolarity ($L=1$ and $L=2$) the DCO ratio is strongly dependent on the mixing ratio δ. One can in principle distinguish between $E1$ and mixed $M1+E2$ transitions when gating on stretched quadrupole transitions, if the degree of mixing in the later case gives a DCO ratio significantly different from 0.5, which is the value for a pure dipole transition (e.g., $E1$). For example, the two transitions of 582 and 707 keV in the lower part of the level scheme of ^{137}Nd show DCO ratios of 0.27(2) and 0.28 (2), respectively, which are indicative of a mixed $M1+E2$ multipolarity; on the other side of the DCO ratio of the 328 keV ($19/2^+ \rightarrow 17/2^-$) transition is 0.50(2), which is indicative of a pure $L=1$ multipolarity (in this case $E1$). The 1330, 1370, 1384, and 1412 keV transitions are all characterized by a strong anisotropy in the spectra produced by gating on the HD band transitions (proved to be of $\Delta I=2$ character from this analysis) as well as on other low-lying $E2$ transitions in coincidence with the band. The anisotropy is such that the transitions are not visible in the spectrum obtained when gating on the 90° axis, whereas in the one obtained by gating on the 34° axis they have intensities comparable to those shown in the γ-ray spectrum of Fig. 1(c). An upper limit of 0.2 for the DCO ratios of the four γ rays can be extracted, which is compatible only with $\Delta I=1$ transitions of mixed $M1+E2$ character. With such multipolarity for the 1330 keV transition and with that ($\Delta I=2$, $E2$) of the 925 keV transition a spin and parity of $29/2^+$ is determined for the lowest level of the HD band which lies at 4885 keV of excitation energy. The other three linking transitions (581, 595, and 842 keV) are degenerate with other strong transitions of ^{137}Nd and therefore a meaningful value for their DCO ratios could not be extracted. They are assumed to have an $\Delta I=2$, $E2$ character.

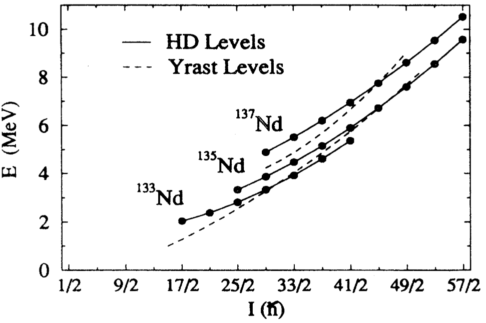

FIG. 3. Excitation energy vs spin for the HD bands of ^{133}Nd, ^{135}Nd, and ^{137}Nd. The yrast lines, which for ^{133}Nd and ^{135}Nd are almost coincident, are also drawn. The data are from Ref. [3] (^{133}Nd), Ref. [4] (^{135}Nd), and the present work (^{137}Nd).

The analysis of the thin-target data from the reaction ^{30}Si+^{110}Pd leads to the extension of the HD band at higher spins by three more transitions with respect to Ref. [7]; their energies are 1511, 1593, and 1683 keV, respectively. This gives for the highest observed level of the HD band a spin $I^\pi=97/2^+$ and an excitation energy of 24.0 MeV. The present results on spins and parity are in agreement with the theoretical interpretation given some time ago [5] for the HD bands of odd-even nuclei in this mass region. They are associated with one quasiparticle $i_{13/2}$ neutron excitation with signature $\alpha=+1/2$.

Knowing now the excitation energies and spins of the HD bands in the three odd Nd isotopes with $A=133-137$ we can compare their different behavior in the decay-out region. In Fig. 3 the excitation energies of the HD band levels of ^{133}Nd, ^{135}Nd, and ^{137}Nd are reported as a function of spin and, for comparison, the yrast lines of the three nuclei are also drawn. One can immediately see that the HD bands, which are yrast and therefore populated preferentially at higher spins, cross the ND yrast line at different points of the

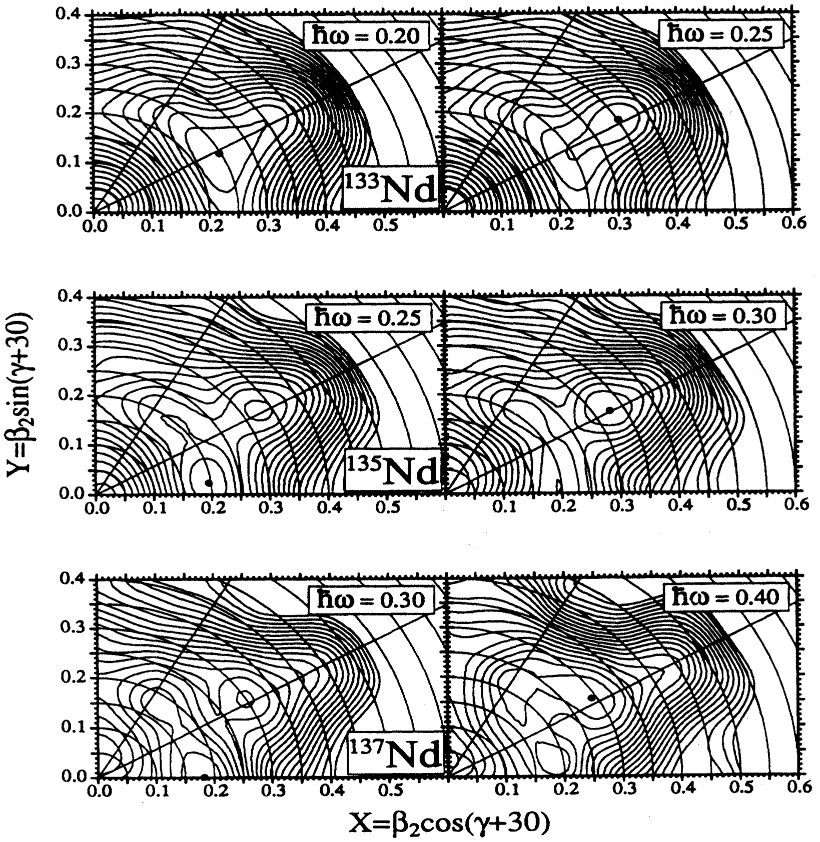

FIG. 4. Total Routhian surface calculations for the lowest $(\pi,\alpha)=(+,+1/2)$ configuration in ^{133}Nd, ^{135}Nd, and ^{137}Nd at two rotational frequencies. The prolate minimum at $\beta_2=0.30$–0.36 is associated with the $i_{13/2}$ configuration. At the lower frequency a less deformed minimum ($\beta_2=0.18$–0.25) associated with the odd neutron in a $N=4$ configuration appears. In ^{135}Nd and ^{137}Nd this minimum has some degree of triaxiality.

I-E^* plane and that they continue down to lower spins until ≈700 keV above the yrast lines where they suddenly disappear. The lowest observed spins ($17/2^+$ for ^{133}Nd, $25/2^+$ for ^{135}Nd, and $29/2^+$ for ^{137}Nd) of the HD bands seem, from this picture, to be somehow related to their excitation energy above the yrast line. We will show in the following that the different behavior of the HD bands in the decay-out region (e.g., the lowest spin observed in the band) can be explained by theoretical calculations.

We have performed for the three nuclei ^{133}Nd, ^{135}Nd, and ^{137}Nd total Routhian surface (TRS) calculations based on a Woods-Saxon potential including monopole pairing correlations [5,6]. The shape of the nucleus is minimized with respect to the deformation parameters β_2, β_4, and γ for different rotational frequencies and quasiparticle configurations. The results are shown in Fig. 4 for the configuration $(+,+1/2)$ at two relevant rotational frequencies for each nucleus. At the higher frequency a secondary minimum is present at $\beta_2=0.30$–0.36 which has been associated with the occupation by the odd neutron of the strongly down-sloping $i_{13/2}$ intruder orbital. This minimum persists also at higher frequencies continuing to be prolate in the ^{133}Nd and ^{135}Nd nuclei and becoming triaxial in the case of ^{137}Nd. The calculations shown in Fig. 4 clearly demonstrate that at the lower frequency the minimum in the potential energy surface moves from the high β_2 deformation to a lower deformation, which is associated [5] with a configuration having the odd neutron placed in a $N=4$ Nilsson orbital (here N is the main oscillator quantum number). The frequency where the second minimum becomes energetically unfavored is different for the three nuclei and is very close to the experimental value of half the energy of the lowest transition observed in the band. At those frequencies (see Fig. 4) almost no barrier exists between the two minima and therefore the configuration mixing between the HD and the ND states may be significant [9]. The decay prefers then to go to the yrast levels of the normal deformed, energetically favored minimum instead of continuing along the HD band. This behavior seems to be general and to occur in all three Nd nuclei discussed here, as well as in the odd-even Sm and Gd nuclei [10]. The case of ^{133}Nd is peculiar in that there is a strong, accidental mixing of the $17/2^+$ HD state with the $17/2^+$ state of the $N=4[400]1/2^+$ band, which drives the major part of the decay-out flux towards the $[400]1/2^+$ band [3]. This band is built on the minimum at deformation $\beta_2=0.25$ shown in Fig. 4 (top left). The other decay branches from the lowest HD band members ($17/2^+$ and $21/2^+$) in ^{133}Nd have much lower intensities, being similar to those of the linking transitions in ^{135}Nd and ^{137}Nd.

It seems therefore that the decay-out process in the three Nd nuclei can be described in the same way. The lowest observed spin of the HD bands in the three nuclei ($17/2^+$, $25/2^+$, and $29/2^+$, respectively) is related to the frequency at which the change of the nuclear shape occurs. The TRS calculations predict such a nuclear shape change in each of the three nuclei discussed here, exactly at the frequency value which corresponds to the lowest transition of the HD band.

In summary, through the study of its decay out we have determined spins, parity, and excitation energy for the HD band in ^{137}Nd. The sudden disappearance at different spin values of the HD bands in the odd Nd nuclei has been discussed and found to be well described by cranked shell model calculations in terms of a change from a more deformed to a less deformed nuclear configuration.

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[1] R. Wadsworth *et al.*, J. Phys. G **13**, L207 (1987).
[2] C.M. Petrache *et al.*, Phys. Lett. B **335**, 307 (1994).
[3] D. Bazzacco *et al.*, Phys. Rev. C **49**, R2281 (1994).
[4] E.M. Beck *et al.*, Phys. Rev. Lett. **58**, 2182 (1987); R.M. Clark *et al.*, Conference on Physics from Large γ-ray Detector Arrays, Berkeley, 1994, Proceedings, unpublished, Vol. 1, p. 9; M.A. Deleplanque *et al.*, unpublished.
[5] R. Wyss *et al.*, Phys. Lett. B **215**, 211 (1988).
[6] W. Nazarewicz, R. Wyss, and A. Johnsson, Nucl. Phys. **A503**, 285 (1989).
[7] S.M. Mullins *et al.*, Phys. Rev. C **45**, 2683 (1992).
[8] J. Gizon *et al.*, Nucl. Phys. **A222**, 557 (1974).
[9] E. Vigezzi, R.A. Broglia, and T. Dössing, Phys. Lett. B **249**, 163 (1990); Y.R. Shimizu *et al.*, Nucl. Phys. **A557**, 99c (1993).
[10] C. Rossi-Alvarez *et al.*, Acta Phys. Pol., B **26**, 237 (1995).