26 July 2001

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 513 (2001) 9–14

www.elsevier.com/locate/npe

Evidence for octupole vibration in superdeformed ^{196}Pb

D. Roßbach [a], A. Görgen [a,1], H. Hübel [a], E. Mergel [a], G. Schönwaßer [a], A.N. Wilson [b,2], F. Azaiez [c], A. Astier [d], D. Bazzacco [e], M. Bergström [f], C. Bourgeois [c], N. Buforn [d], F. Hannachi [g], K. Hauschild [h], A. Korichi [g], W. Korten [h], T. Kröll [e], A. Lopez-Martens [g], R. Lucas [h], H.J. Maier [i], N. Redon [d], P. Reiter [i], C. Rossi-Alvarez [e], O. Stezowski [d], P. Thirolf [i]

[a] *Institut für Strahlen- und Kernphysik, Universität Bonn, Nußallee 14–16, D-53115 Bonn, Germany*
[b] *Department of Physics, University of York, Heslington, York YO10 5DD, UK*
[c] *IPN Orsay, IN2P3/CNRS, F-91406 Orsay, France*
[d] *IPN Lyon, IN2P3/CNRS, Univ. Lyon-1, F-69622 Villeurbanne Cedex, France*
[e] *Dipartimento di Fisica e INFN, Sezione di Padova, I-35131 Padova, Italy*
[f] *Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[g] *CSNSM Orsay, IN2P3/CNRS, F-91405 Orsay Campus, France*
[h] *CEA/Saclay, DAPNIA/SPhN, F-91191 Gif sur Yvette, France*
[i] *Sektion Physik der Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany*

Received 29 March 2001; received in revised form 30 May 2001; accepted 6 June 2001
Editor: V. Metag

Abstract

Evidence for a low-lying octupole vibrational excitation in the superdeformed energy minimum of ^{196}Pb is presented. High-spin states in this nucleus have been populated in the ^{170}Er(^{30}Si, 4n)^{196}Pb reaction. The in-beam γ-ray decay has been investigated using the EUROBALL IV Ge-detector array. The linear polarization of γ-ray transitions connecting an excited superdeformed band with the yrast superdeformed band has been measured from which E1 multipolarity is determined. These E1 transitions, which compete with the highly collective in-band E2 transitions, are strongly enhanced. This is an important step towards establishing that low-lying octupole vibrations are a wide spread phenomenon in the $A = 190$ region of superdeformation. © 2001 Elsevier Science B.V. All rights reserved.

PACS: 21.10.Re; 21.60.Ev; 23.20.En; 27.80.+w
Keywords: Superdeformation; Linear polarization; Enhanced E1 inter-band transitions; Octupole vibration

In the region around mass number $A = 190$ about 70 superdeformed (SD) rotational bands have been discovered in 25 different nuclei [1]. In many of these nuclei several bands have been found, which are built on excited states in the SD potential energy minimum. The odd-A nucleus ^{193}Pb is a prominent example where nine SD bands have been associated with neutron excitations [2]. The nature of the excited bands in even–even SD nuclei in this mass region is less clear. The energy of quasiparticle excitations is

E-mail address: hubel@iskp.uni-bonn.de (H. Hübel).

1 Present address: Lawrence Berkeley Nat. Lab., Berkeley CA 94720, USA.

2 Present address: Department of Nuclear Physics, RSPhS, ANU, Canberra ACT 0200, Australia.

0370-2693/01/$ – see front matter
PII: S0370-2693(01)00749-3

difficult to estimate since the pairing gap energy is not precisely known in the second well. Superdeformation is observed to persist to rather low spin ($I \approx 6$–8). Therefore, it may be expected that pairing is still large (see, e.g., [3]) and two-quasiparticle states should have similar excitation energies as those at normal deformation. On the other hand, calculations [4–7] have predicted for some time that octupole vibrational states may occur at rather low excitation energies in SD nuclei in this mass region. One may, therefore, expect that such states might be competitive with (or even favoured over) the lowest two-quasiparticle excitations.

One signature for octupole vibrations is the presence of anomalously large electric transition dipole moments associated with the charge asymmetry of the vibration, which would result in enhanced E1 transitions. Recently, experimental evidence has been presented for dipole transitions between SD bands, which are not signature partners, competing with the highly collective E2 in-band transitions in ^{190}Hg [8–10], ^{194}Hg [11] and ^{196}Pb [12–14]. However, it is only in the case of ^{190}Hg that the electric dipole nature of the inter-band transitions has been determined experimentally through a linear polarization measurement [10] and that their enhancement has been deduced from a lifetime measurement [9]. These results confirm the octupole vibrational nature of the excited SD bands in this nucleus. A similar confirmation of the enhanced E1 character of the inter-band transitions in the other nuclei is required to confirm that low-lying octupole vibrations occur as a general phenomenon in this mass region.

In ^{196}Pb one of the excited SD bands (band 3) is connected to the yrast SD band (band 1) by several dipole transitions of similar energy [12–14], see Fig. 1. If these linking transitions are shown to be of E1 multipolarity, band 3 is also a candidate for an octupole vibration. In this work, we report on a measurement of the linear polarization of the inter-band transitions which shows that they are indeed E1 transitions. An estimate of the B(E1) values (extracted from branching ratios) confirms that they are strongly enhanced as expected for an octupole vibration.

The experiment was performed at the Institut de Recherches Subatomiques (IReS), Strasbourg, using the EUROBALL IV γ-ray detector array [15]. High-spin states were populated in the ^{170}Er(^{30}Si, 4n)^{196}Pb reaction at a beam energy of 144 MeV. The beam, provided by the Vivitron Tandem accelerator, was incident upon a Au-backed ^{170}Er target of 1.65 mg/cm^2 thickness.

The 30 coaxial, 26 four-element Clover [16] and 15 seven-element Cluster [17] Ge detectors of the EUROBALL array are mounted in rings at forward, perpendicular and backward angles with respect to the beam direction, respectively. An Inner Ball consisting of 210 BGO detectors for measuring sum energy and multiplicity of the γ-rays emitted in each reaction was mounted inside the Ge-detector array. An event was written to tape when more than three escape-suppressed Ge detectors and more than four BGO detectors of the Inner Ball recorded γ-rays in coincidence. In the off-line data analysis Compton suppression, pile-up rejection, gain matching and add-back for the Ge detectors were performed and a prompt time gate was set. A total of 1.1×10^9 three- and higher-fold events remained for subsequent analysis.

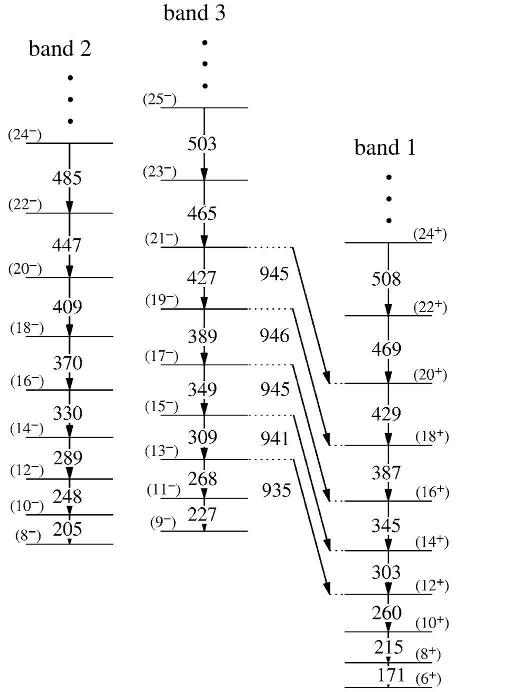

Fig. 1. Partial level scheme of ^{196}Pb showing the decay of the second excited SD band (band 3) to the yrast SD band (band 1). Bands 2 and 3 are thought to be signature partners with signature $\alpha = 0$ and 1, respectively, [12–14]. The transition energies are given in keV.

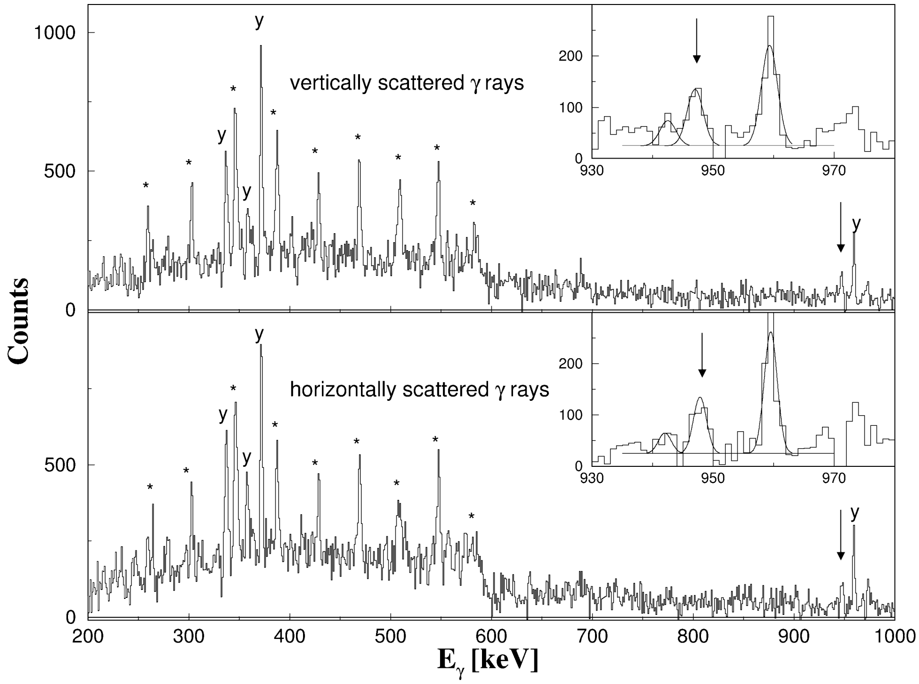

Fig. 2. Projection spectra created from matrices with vertically (upper part) and horizontally (lower part) scattered γ-rays. See text for details. The group of transitions around 945 keV connecting band 3 to band 1 is marked by the arrow.

In a previous study of SD ^{196}Pb [12–14] γ-rays were observed to connect states of the second excited band (band 3) to states of the yrast band (band 1), see Fig. 1. A directional correlation (DCO) analysis indicated that these transitions are dipoles. However, the measurement of their linear polarization was not successful due to the lack of statistics [12]. It was the aim of the present experiment to measure the linear polarization of the linking transitions using the Clover detectors of the EUROBALL array as Compton polarimeters [18]. The high efficiency of the array and the reaction chosen in our experiment, which results in less background from other reaction channels compared to the previously used ^{186}W(^{16}O, 6n)^{196}Pb reaction, were necessary to measure the linear polarization of the weak linking transitions. Their intensity is of the order of 10^{-4} of the intensity of the 4n reaction channel.

The γ-ray coincidence data were sorted into two asymmetric matrices, which were gated on transitions from the lower part of band 1 (215, 260, 303, 345 and 387 keV transitions) and on transitions of band 3 (349, 389, 427, 465, 503 keV transitions). Two coincident γ-rays were incremented in these matrices, if they were detected in prompt coincidence with one of these gates and if one of the two γ-rays was scattered either vertically or horizontally in two Clover-detector crystals. Thus, each matrix contains on one axis the energies of scattered γ-rays (vertically or horizontally for the two matrices, respectively) and on the other axis the energies of the second γ-ray. In both matrices gates were set on clean transitions in both bands to create spectra projected onto the axes with the scattered γ-ray energies. In this way, spectra were created which contain only γ-rays that were scattered either vertically or horizontally between two Clover segments and that were in coincidence with at least two γ-rays from SD band 1 and/or SD band 3.

Two such spectra are shown in Fig. 2; the lower part of the figure shows the spectrum of horizontally scattered γ-rays while the upper part shows the spectrum containing only vertically scattered γ-rays, both created under the same gating conditions. In-band transitions are marked by an asterisk, transitions which belong to the normal-deformed (ND) level scheme of ^{196}Pb are labelled y. The high-energy region of each spectrum together with the results of a fit to the peaks is expanded in the insets. The background contribution has been removed by subtracting a normalized spectrum created under the same gating conditions but with only one gate (rather than two) required. The energies of the inter-band transitions lie between 935 and 946 keV (see Fig. 1). The three transitions around 945 keV cannot be resolved in the γ-ray spectra and appear as one broadened peak marked by the arrow in Fig. 2. As the multipolarities of these transitions are necessarily the same, we have been able to use the summed peak to make a combined measurement of the polarization. This increases the statistical accuracy of the measurement. In the following discussion and analysis this peak has therefore been treated as one. The spectrum shown in Fig. 2 contains only a fraction of the total statistics used to determine the linear polarization. Several spectra were created with different gating conditions. In the least squares fits to the 945 keV peaks different backgrounds were subtracted in order to estimate this source of uncertainty. Average counts in the peaks are 743(63) and 561(50) in the spectra of vertically and horizontally scattered γ-rays, respectively.

The asymmetry ratio $A(E_\gamma) = (I_v(E_\gamma) - I_h(E_\gamma))/(I_v(E_\gamma) + I_h(E_\gamma))$, which depends on the electromagnetic character of the radiation, can be deduced from these peak intensities. For the peak around 945 keV we obtain a value of $A = 0.14 \pm 0.06$. In order to calculate the linear polarization $P = A(E_\gamma)/Q(E_\gamma)$, the polarization sensitivity $Q(E_\gamma)$ of the polarimeter [16, 18–20] has to be known. For an ideal polarimeter (i.e., pointlike detectors) this quantity can be calculated from the Klein–Nishina formula [21], which gives $Q_{\text{ideal}} = (1+\alpha)/(1+\alpha+\alpha^2)$ with $\alpha = E_\gamma/m_0c^2$, where m_0 is the electron rest mass. The energy dependent polarization sensitivity of a finite crystal-size detector setup $Q(E_\gamma)$ is obtained by introducing a scaling factor a, $Q(E_\gamma) = a \cdot Q_{\text{ideal}}(E_\gamma)$.

The polarization sensitivity has been determined experimentally by sorting ungated matrices for both, horizontally and vertically scattered γ-rays as described above. From these matrices spectra were created by setting gates on known pure stretched E2 transitions in the ND level scheme of ^{196}Pb, and the asymmetry ratio for these transitions was determined. By calculating the linear polarization of the E2 transitions, the polarization sensitivity is deduced. From the fit to the experimental sensitivity we obtain the scaling factor $a = 0.27 \pm 0.03$, which is in good agreement with previous measurements for the Clover detectors [16,18, 20] of the EUROBALL array.

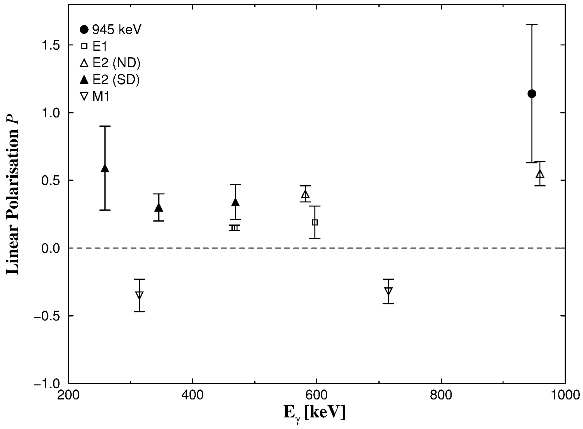

Fig. 3. Polarization of the SD inter-band transitions (full circle), SD in-band transitions (full triangles) and transitions from the ND decay scheme of known multipolarity (open symbols). For pure stretched electric transitions P is positive, for magnetic transitions it is negative.

Using the sensitivity derived in this work, the polarization P has been calculated for the group of inter-band transitions (the sum peak at 945 keV), for in-band E2 transitions between the SD states and several ND transitions of known multipolarity. The results are shown in Fig. 3. Although the uncertainty in the value for the linking transitions, P (945 keV) $= 1.14 \pm 0.51$, is quite large due to their low intensity, we can strongly assert that they are electric transitions. This result for ^{196}Pb represents only the second case in the $A = 190$ region in which the E1 character of the transitions connecting an excited SD band to the yrast SD band has been determined experimentally.

Although no lifetime measurement is available from which the E1 transition probability could be obtained, the existence of E1 transitions competing with the highly collective in-band E2 transitions is, in itself, an indication that they are significantly enhanced. An estimate of the B(E1) values may be obtained from the inter-band (E1) to the in-band (E2) branching ratios,

$B(\mathrm{E1})/B(\mathrm{E2})$. We have assumed the same quadrupole moment as has been deduced for the yrast SD band ($Q_t = (19.5 \pm 0.4)$ b) from a lifetime measurement [22] and obtain $B(\mathrm{E1}) = (1.0 \pm 0.2) \times 10^{-4}$ Wu. This value is much larger than E1-transition strengths normally found between excited quasiparticle states [23,24].

It is extremely unlikely that the above results can be satisfactorily explained, if band 3 and its signature partner, band 2, are assumed to be quasiparticle excitations. First of all, the strength of the E1 transitions is much larger than what would be expected for transitions between different quasiparticle excitations. Secondly, a consequence of the E1 character of the linking transitions is that, under the reasonable assumption that the yrast SD band is of positive parity, band 3 must be of negative parity. Various calculations have been performed including Woods–Saxon cranking and Hartree–Fock calculations (e.g., [25]), all of which indicate that the lowest available two-quasiparticle excitations are of positive parity. The only relatively low-lying negative parity states would involve the coupling of the positive parity [624] 9/2 orbital to the favoured signature of one of the negative parity orbitals close to the Fermi surface. However, such an excitation should result in a pair of signature partners exhibiting strong M1 cross-talk transitions. Although bands 2 and 3 appear to be signature partners, no such cross-talk has been observed. In addition, as has been stated above, such a configuration would give no explanation for the enhanced E1 decay out of band 3. A third reason is the relatively low excitation energy of 815 keV above the yrast SD band at spin $I = 10\,\hbar$. Extrapolating to $I = 0$ gives a relative excitation of only 845 keV. This would be remarkably small for a two-quasiparticle excitation in the region where pairing should still be important [3]; indeed, large energy gaps which appear in quasiparticle Routhians at superdeformation persist to high spins.

In contrast, all of the above points support the interpretation of band 3 as an octupole vibrational state. The most natural explanation of the enhanced E1 transitions is the presence of octupole correlations. Recent RPA calculations by Nakatsukasa et al. [26] suggest that the lowest excitations in ^{196}Pb will be the $K = 2$ octupole states. The signature partners based on this state (which are calculated to be degenerate over a large frequency range) are predicted to lie about

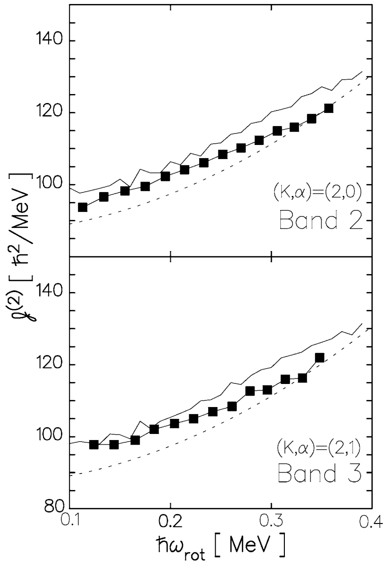

Fig. 4. Dynamical moments of inertia of SD bands 2 and 3 in ^{196}Pb; comparison between theory (curves) [26] and experiment (full points). The dashed curves show the dynamical moment of inertia of the yrast SD band.

850 keV above the SD vacuum at spin $I = 0$. This is remarkably close to the extrapolated excitation energy of band 3 relative to band 1. The calculations also predict that only the $\alpha = 1$ signature of this mode will exhibit a strong decay branch to the yrast SD band, as is observed experimentally for band 3. Such decay becomes possible only through mixing with lower-K wave functions. The degree of mixing for the $K = 2$ signature $\alpha = 1$ is predicted to be much greater than for the $\alpha = 0$ state. Band 2, whose energies lie at the midpoints of band 3, thus seems a likely candidate for the $K = 2$, $\alpha = 0$ octupole state.

Fig. 4 shows a comparison between the experimental dynamic moments of inertia $\Im^{(2)}$ of bands 2 and 3 and the results of the RPA calculations [26] for these lowest predicted octupole states; it is clear that the behaviour of the bands is quite well reproduced. The only discrepancy between the calculations for the lowest octupole mode and the results for band 3 is that the measured $B(\mathrm{E1})$ values are larger than the values predicted by the RPA calculations. The situation is similar to ^{190}Hg, where SD band 2 is also explained as the $K = 2$, $\alpha = 1$ octupole vibration [7,10,26,27]. Experimental and calculated $B(\mathrm{E1})$ values for these states are compared in Table 1. The same quantities are included

Table 1
Experimental and calculated $B(\text{E1})$ values (in Wu) for transitions between excited ($K = 2$, $\alpha = 1$) and yrast ($K = 0$, $\alpha = 0$) SD bands in the $A = 190$ region

	^{196}Pb	^{190}Hg	^{194}Hg
$B(\text{E1})_{\text{exp}}$	$1.0(2) \times 10^{-4}$	$2 \times 10^{-3\text{b}}$	$10^{-5\text{c}}$
$B(\text{E1})^{\text{a}}_{\text{calc}}$	10^{-6}	10^{-6}–10^{-4}	10^{-8}–10^{-6}

[a] From [7,26].
[b] From [10].
[c] From [11].

for ^{194}Hg, the only other case in which transitions have been observed between excited and yrast SD bands in this mass region. Although there is no direct experimental evidence that these transitions are electric dipoles, it is reasonable to assume their E1 multipolarity from the observed decay of the excited band [11]. In all three cases, the E1 transition probabilities are unusually large. In fact, they are considerably larger than those predicted by the RPA calculations [7,26]. This may indicate a systematic error in the calculations. As was mentioned above, the E1 strength depends upon the degree of mixing between the different K states, and this consistent under-estimation indicates that the calculations are not reproducing the mixing correctly. It may be speculated that the $\alpha = 1$ signature of the $K = 0$ octupole mode lies much closer in energy to the $K = 2$ mode than suggested by Nakatsukasa et al. [7, 26], which would enhance the E1 decay still further. However, in general the calculations provide a good explanation of the features of the excited bands in all three nuclei.

In summary, we have used the Ge Clover detectors of the EUROBALL γ-ray spectrometer array as Compton polarimeters to measure the linear polarization of transitions linking states of the second excited SD band (band 3) to states of the yrast SD band. The identification of these transitions as enhanced electric dipoles gives strong evidence that the excited band is built on an octupole vibration. Together with ^{190}Hg [10], this is the second case where the E1 multipolarity of transitions between SD bands has been determined experimentally. This measurement not only provides evidence that the low-lying SD excited states in ^{196}Pb are of octupole vibrational character, it also is an important step towards establishing that this phenomenon is wide spread in the $A = 190$ region of superdeformation.

Acknowledgements

The authors are grateful to the technical staff at IReS associated with running the Vivitron accelerator and the EUROBALL IV array. Financial support of the European Community — Access to Research Infrastructure Action of the Human Potential Program — is acknowledged. The work of the Bonn group is supported by BMBF (Germany) under contract No. 06 BN 907. One of us, D.R., acknowledges the fellowship by the Studienstiftung des Deutschen Volkes and T.K. acknowledges financial support by the EC under TMR contract ERBFMRXCT97-0123.

References

[1] X.-L. Han, C.-L. Wu, At. Data Nucl. Data Tables 73 (1999) 43.
[2] D. Roßbach et al., Nucl. Phys. A 660 (1999) 393.
[3] J. Terasaki et al., Nucl. Phys. A 593 (1995) 1.
[4] D. Skalski et al., Nucl. Phys. A 551 (1993) 109.
[5] S. Mizutori et al., Prog. Theor. Phys. 83 (1990) 666.
[6] J. Meyer et al., Nucl. Phys. A 588 (1995) 597.
[7] T. Nakatsukasa et al., Phys. Rev. C 53 (1996) 2213.
[8] A.N. Wilson et al., Phys. Rev. C 54 (1996) 559.
[9] H. Amro et al., Phys. Lett. B 413 (1997) 15.
[10] A. Korichi et al., Phys. Rev. Lett., in press.
[11] G. Hackman et al., Phys. Rev. Lett. 79 (1997) 4100.
[12] S. Bouneau, Thesis, Orsay (1997), Orsay internal report IPNO 97-08.
[13] S. Bouneau et al., Z. Phys. A 358 (1997) 179.
[14] F. Azaiez et al., Acta Phys. Hung. 6 (1997) 289.
[15] J. Simpson et al., Z. Phys. A 358 (1997) 139.
[16] G. Duchene et al., Nucl. Instrum. Methods A 432 (1999) 90.
[17] J. Eberth et al., Nucl. Instrum. Methods A 369 (1996) 135.
[18] P.M. Jones et al., Nucl. Instrum. Methods A 362 (1995) 556.
[19] F.A. Beck, Ann. Phys. (Paris) 1 (1966) 503.
[20] A. Görgen et al., Nucl. Phys. A 683 (2001) 108.
[21] O. Klein, Y. Nishina, Z. Phys. 52 (1929) 853.
[22] U.J. van Severen et al., Phys. Lett. B 434 (1998) 14.
[23] I. Ahmad, P.A. Butler, Annu. Rev. Nucl. Part. Sci. 43 (1993) 71.
[24] P.A. Butler, W. Nazarewicz, Rev. Mod. Phys. 68 (1995) 349.
[25] A. Prevost et al., Eur. Phys. J. A, in press.
[26] T. Nakatsukasa et al., in: Proceedings of the International Conference on Nuclear Structure at the Limits, Argonne, Illinois, USA, 1996, p. 111, ANL/PHY-97/1.
[27] P. Fallon et al., Phys. Rev. C 55 (1997) R999.