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First observation of excited states in ^{197}At: the onset of deformation in neutron-deficient astatine nuclei

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Abstract. Excited states in the $Z = 85$ nucleus ^{197}At have been identified for the first time using the recoil-decay-tagging (RDT) technique. The excitation energy of these states is found to be consistent with the systematics of neutron-deficient astatine nuclei and with theoretical calculations indicating that the nucleus may be deformed in its ground state.

PACS. 23.20.Lv Gamma transitions and level energies – 27.80.+w $190 \leq A \leq 219$

1 Introduction

Many theoretical predictions for nuclei far from stability have suggested an extended region of stable ground-state deformation in nuclei above the $Z = 82$ proton shell gap and below the neutron shell closure at $N = 126$ (see for example [1]). Experimentally, this region is largely uninvestigated and little information about the predicted deformed shapes exists. The experimental evidence for such an effect would be a rotational sequence of levels based on the ground state, accompanied by significant lowering of the first excited state relative to more neutron-rich spherical nuclei. For the most deformed species we might expect to see the excitation energy of the first excited state fall as low as 100 keV, corresponding to a (predicted oblate) deformation with $|\beta_2| = 0.20$.

Experimental studies of the $N < 126$ isotopes ^{205,207,209}At [2–4] and of ^{201,203}At [5] reveal that the yrast $J^\pi = \frac{11}{2}^-$ and $\frac{13}{2}^-$ states remain at a fairly constant excitation energy of ~ 650 keV relative to the $\frac{9}{2}^-$ ground state. Recent studies of ^{199}At$_{114}$ [6] show that the first excited state is ~ 200 keV lower than for $^{201-209}$At, suggesting that ^{199}At may be deformed. However, no collective structures have yet been observed in the At isotopes down to $N = 114$. Similar investigations of very neutron-deficient radon nuclei ($Z = 86$) have shown that ^{202}Rn$_{116}$ [7] is not strongly deformed in its ground state, in agreement with the predictions [1]. However, it has also been shown that ^{200}Rn$_{114}$ [8], which the predictions suggest should have a deformation of $\beta_2 = -0.20$, also remains stable against the onset of deformation. For astatine nuclei the onset of deformation is predicted to occur sharply between ^{199}At and ^{198}At, with a change in the deformation from $\beta_2 = 0.08$ to $\beta_2 = -0.20$. We report here on experimental evidence concerning the low-lying levels of ^{197}At$_{112}$, which is predicted to be the first odd-A At nucleus to exhibit ground-state deformation. The α-decay of this nucleus is well known [9, 10] and, although no γ-rays have previously been reported, a metastable $\frac{1}{2}^+$ intruder state has been observed to decay via α-emission [10], in addition to the ground-state decay. The present work has revealed two further excited states in ^{197}At. The deduced nuclear structure is discussed with reference to the shape predictions and the systematics of neutron-deficient astatine nuclei below the $N = 126$ shell closure.

2 Experimental details

Spectroscopic studies of nuclei in this region, following heavy-ion fusion-evaporation reactions, are particularly difficult because of a very strong background due to fission. In order to overcome this problem the recoil-decay-tagging (RDT) technique [11,12] has been used. A beam of ^{36}Ar was incident on a ^{165}Ho target of thickness 500 μg/cm^2, producing ^{197}At via the 4n evaporation channel. The beam was provided by the $K = 130$ MeV cyclotron at the Accelerator Laboratory of the University of Jyväskylä, Finland, at a bombarding energy of 178 MeV. Prompt γ-rays were detected using the SARI

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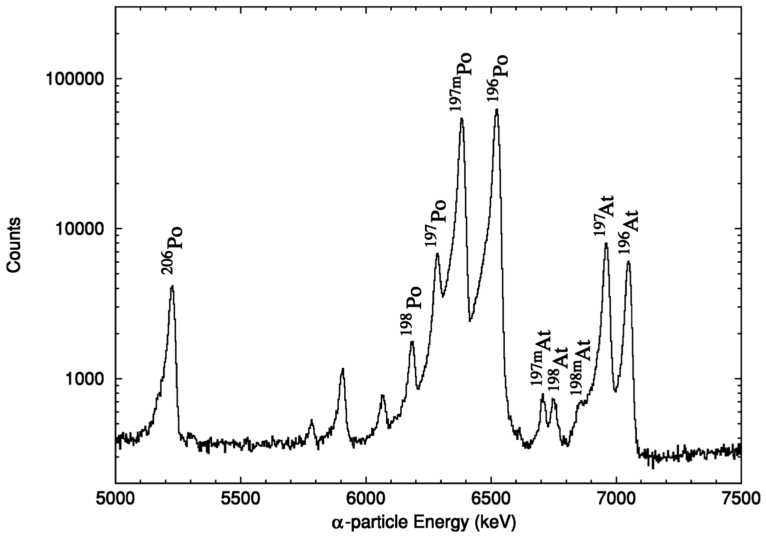

Fig. 1. Singles α-particle energy spectrum for the ^{36}Ar + ^{165}Ho reaction. The prominent peaks are assigned to known decays

array of three segmented clover detectors without Compton suppression shields. The detectors were placed at a distance of 100 mm from the target, giving an absolute efficiency of $\sim 2\%$ at 1.3 MeV. Recoiling fusion-evaporation products were magnetically separated in-flight from the primary beam and fission products using the RITU gas-filled recoil separator [13]. The recoils were then implanted into a 16-strip Si detector, covering approximately 70% of the RITU focal plane. Each of the strips measured 5 mm in the horizontal direction and 35 mm in the vertical direction, and each was position-sensitive in the vertical direction with a position resolution of 400 μm. Four unsuppressed TESSA-type [14] Ge detectors were placed beyond the focal plane of RITU in order to detect delayed γ-rays emitted from isomeric states.

3 Results

For each recoil and subsequent α-decay, the position, energy and time of detection was recorded. Figure 1 shows the energy spectrum for singles α-decay events. The spectrum was calibrated using the following α-particle energies from literature [15]: ^{206}Po $E_\alpha = 5223.7 \pm 1.5$ keV, ^{197m}Po $E_\alpha = 6383.4 \pm 2.4$ keV and ^{196}Po $E_\alpha = 6520.0 \pm 3.0$ keV. Due to the long half-life of ^{206}Po ($T_{1/2} = 8.8$ days) it was still decaying in the Si detector at the time of the experiment, having been produced in an earlier measurement involving the ^{40}Ar + ^{174}Yb reaction. In this work, α-particle energies of $E_\alpha(^{197g}\mathrm{At}) = 6960 \pm 5$ keV and $E_\alpha(^{197m}\mathrm{At}) = 6707 \pm 5$ keV have been measured, for decays from the ground state and intruder state respectively. These energies are consistent with the previously measured values of $E_\alpha(^{197g}\mathrm{At}) = 6958 \pm 5$ keV [9], $E_\alpha(^{197g}\mathrm{At}) = 6957$ keV [10] and $E_\alpha(^{197m}\mathrm{At}) = 6707$ keV [10]. The number of ^{197}At decays recorded was $(100 \pm 2) \times 10^3$ for the ground state and $(4 \pm 1) \times 10^3$ for the metastable state, implying that the production of the $\frac{1}{2}^+$ state is $3.9 \pm 1.2\%$ relative to the $\frac{9}{2}^-$ ground state. In reference [10] this production ratio was measured as $< 1\%$ following the ^{20}Ne + $^{\mathrm{nat}}$Re reaction at a beam energy of 240 MeV.

A spectrum of prompt γ-rays in coincidence with all recoils detected at the focal plane of RITU is shown in Fig. 2(a). The spectrum is dominated by γ-rays associated with polonium isotopes, produced in (^{36}Ar, pxn) channels, and by γ-rays following the Coulomb excitation of the ^{165}Ho target. The γ-rays emitted by ^{197}At nuclei were identified using the RDT technique, by selecting events for which a recoil and an α-decay from the state of interest were detected at the same position in the Si detector within a time interval of approximately three times the half-life of the state. Using a time interval of one second, and the method described in reference [16], a half-life of 0.388 ± 0.006 s has been measured for the ^{197}At ground state. This is consistent with the previously measured values of 0.4 ± 0.1 s [9] and 0.35 ± 0.04 s [10]. The half-life of the metastable intruder state has been measured as 2.0 ± 0.2 s, using the same method with a maximum time interval of ten seconds between the implantation of a recoil and an α-particle. This is in agreement with the literature value of 3.7 ± 2.5 s from reference [10].

It has proved impossible to correlate any prompt or delayed γ-rays with the $\frac{1}{2}^+$ intruder state of ^{197}At; however two transitions associated with the ground state have been assigned. Figure 2(b) shows the prompt γ-rays correlated with ^{197}At ground-state α-decay. A γ-ray transition, of energy 324.3 ± 0.1 keV, is clearly observed with the astatine X-rays. The only other intense γ-ray in the spectrum has energy 517 keV and appears strongly in the spectrum of Fig. 2(a). It arises from the Doppler correction of 511 keV annihilation photons (the unshifted component with energy of 511 keV is also apparent), and is thus discounted as a transition in ^{197}At. On the basis of energy-level systematics for low-lying states in odd-A At isotopes, the prompt 324.3 keV γ-ray is tentatively assigned to decay to the ground state from a $J^\pi = \frac{11}{2}^-$ level. Although it is possible that this transition feeds an isomeric state, and not the ground state, we consider this

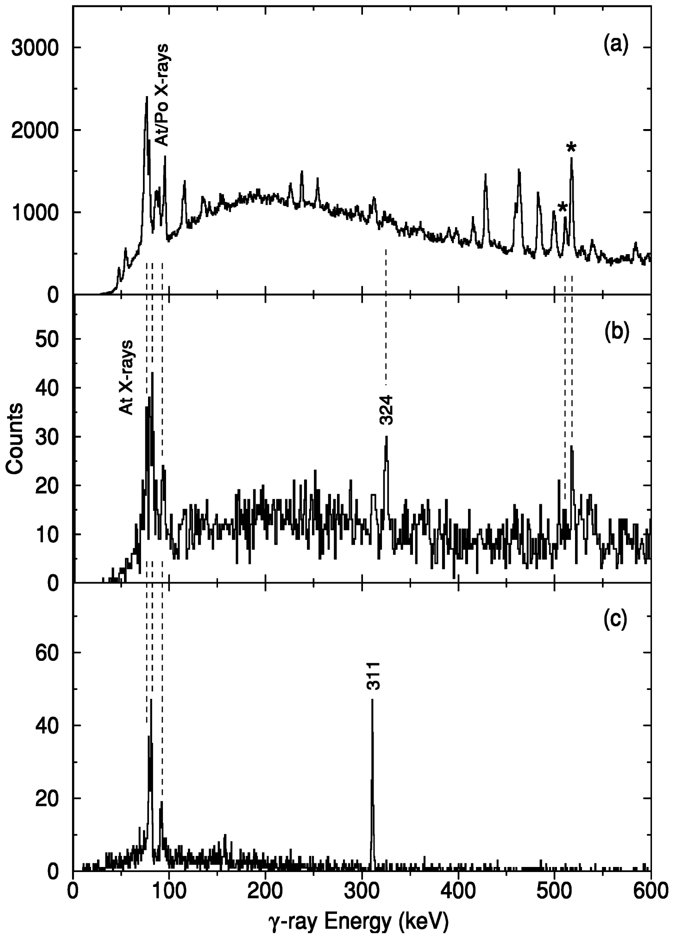

Fig. 2. Singles γ-ray spectra (a) showing prompt γ-rays in coincidence with all fusion-evaporation products detected at the RITU focal plane (b) showing prompt γ-rays correlated with ^{197}At α-decay and (c) showing delayed γ-rays associated with ^{197}At. Annihilation peaks are labelled with a " * " and ^{197}At γ-rays are labelled with their transition energy. The dispersion of all γ-ray spectra is 0.5 keV/channel except for spectrum (b) which is compressed to 1 keV/channel

unlikely because the $\frac{11}{2}^- \to \frac{9}{2}^-$ (or $\frac{13}{2}^- \to \frac{9}{2}^-$) transition is the most intense in all of the heavier At nuclei. A second γ-ray, of energy 310.7 ± 0.1 keV, can be seen in Fig. 2(c), which shows the delayed γ-rays associated with ^{197}At. Since no other γ-rays appear in this spectrum, this transition thus feeds the ground state directly from an isomer. The transition is believed to arise from an intruder $\frac{13}{2}^+$ state decaying via a delayed $M2$ transition. The lifetime of the isomeric state has been determined by fitting a spectrum of the time difference between the implantation of a recoiling ^{197}At nucleus, selected by coincidence with a ^{197}At α-decay, and the detection of a coincident 311 keV γ-ray in the Ge detectors beyond the RITU focal plane. A decay time of $\tau = 8 \pm 2$ μs has been measured for the lifetime of the state, corresponding to a transition strength of $B(M2) = 0.02$ W.u. The transition is thus strongly hindered (by a factor of ~ 45) over the single-particle Weisskopf estimate. The same $\frac{13}{2}^+ \to \frac{9}{2}^-$ transition in ^{195}Bi, an isotone of ^{197}At, has been observed [18] to have a similar hindrance factor (≈ 20). This hindrance was attributed to the spin-flip character of the transition; the large hindrance factor for the transition in ^{197}At probably occurs for the same reason. The similarity of the hindrance factors for the ^{195}Bi and ^{197}At transitions is supportive of our assignment that the isomeric γ-ray observed in this work is of $M2$ nature. Although no isomeric $(\frac{13}{2}^+)$ state has been observed in ^{199}At, the same state in ^{201}At decays via a 749 keV $M2$ transition with a lifetime of $\tau = 23 \pm 2$ ns [5]. The associated transition strength is $B(M2) = 0.5$ W.u. and the transition is thus hindered by a factor of two relative to the Weisskopf estimate.

The new transitions observed in this work are shown as a level scheme for ^{197}At in Fig. 3, together with the excitation energy E^* of low-lying states in odd-A astatine nuclei in the range $112 \leq N \leq 126$. The energy levels and spin-parity assignments for the heavier nuclei are taken from references [2–6,17]. Figure 3 clearly shows that the excitation energy of both the $(\frac{11}{2}^-)$ and $(\frac{13}{2}^+)$ state decreases significantly for ^{197}At.

4 Discussion

In nuclei close to doubly-magic ^{208}Pb, most low-lying nuclear states are interpreted in terms of a few valence particles in shell-model configurations. The level schemes of the odd-A At isotopes with $116 \leq N \leq 128$ [2–5,17, 19] have been interpreted using configurations which consist of three protons coupled to up to ten neutron holes (for ^{201}At$_{116}$) in the ^{208}Pb core. The orbitals available to the valence protons are $1h_{9/2}$, $2f_{7/2}$ and $1i_{13/2}$ while the neutron holes involve the orbitals $3p^{-1}_{1/2}$, $2f^{-1}_{5/2}$ $3p^{-1}_{3/2}$ and $1i^{-1}_{13/2}$. Shell-model calculations for such large numbers of quasiparticles are essentially impossible and so the interpretation is based on the systematics of levels in odd-A astatines in comparison to those of the corresponding even-A lead nuclei. In these isotopes the $J^\pi = \frac{9}{2}^-$ ground state has dominant configuration $(\pi h_{9/2})^3$ and the yrast $\frac{11}{2}^-$ and $\frac{13}{2}^-$ states appear to be predominantly described by the coupling of the 2^+ core excitation in the corresponding Pb isotopes to the $\frac{9}{2}^-$ ground state configuration. Similarly the yrast $\frac{17}{2}^-$ states, which appear at a remarkably constant energy of ~ 1230 keV for $^{201-207}$At, are interpreted in terms of the coupling to the 4^+ Pb core excitation. The approximate constancy of the $\frac{11}{2}^-$ and $\frac{13}{2}^-$ yrast energies may be contrasted with the steady increase of the 2^+ excitation energy from 803 keV in ^{206}Pb to 1064 keV in ^{198}Pb. Similarly the 4^+ core excitation increases from 1274 keV in ^{204}Pb to 1626 keV in ^{198}Pb, in contrast with the constancy of the $\frac{17}{2}^-$ states in $^{201-207}$At. The level pattern of the low-lying $\frac{11}{2}^-$, $\frac{13}{2}^-$ and $\frac{17}{2}^-$ yrast states in the odd-A At isotopes is analogous to observations for the corresponding even-even polonium ($Z = 84$) [20,21] and radon ($Z = 86$) [7,8,22] nuclei. The behaviour of the

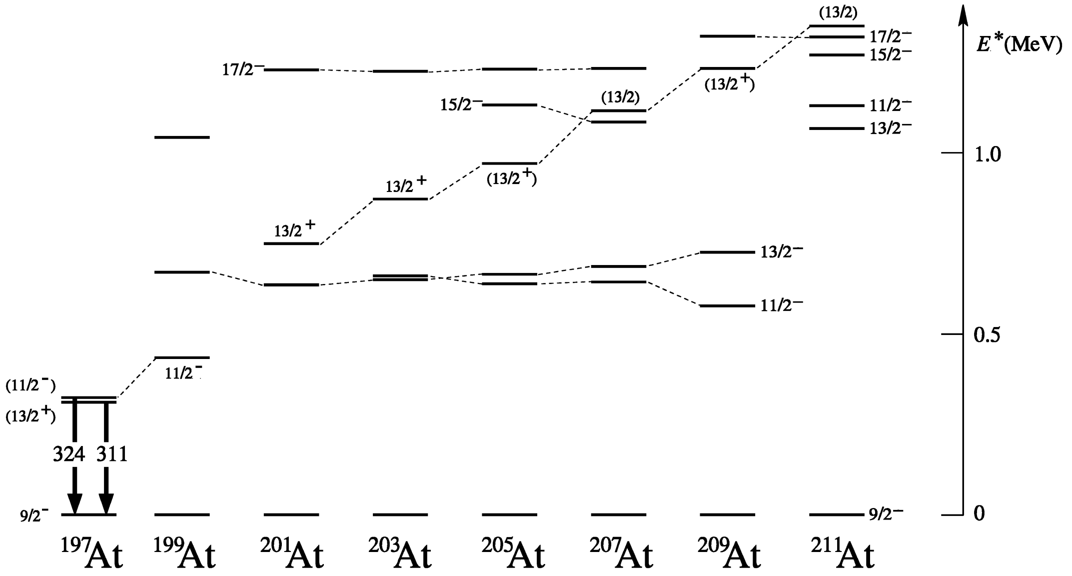

Fig. 3. Excitation energy E^* of low-lying levels of odd-A At isotopes, with new transitions assigned to ^{197}At in this work indicated. States interpreted to have similar configurations are linked with dashed lines and, unless otherwise labelled, have the same spin and parity assignments

2^+ and 4^+ states in these nuclei has been interpreted [21, 22] as a sign of increasing collectivity with decreasing neutron number. The non-yrast $\frac{13}{2}^+$ states in $^{201-207}$At are believed to be based mainly on the $(\pi h_{9/2})^2(\pi i_{13/2})\frac{13}{2}^+$ proton excitation coupled to the 0^+ Pb ground states. The decrease in the excitation energy of these states with decreasing neutron number has further been interpreted as a sign of increasing collectivity.

In such a shell-model description, the levels of ^{197}At involve configurations consisting of three protons coupled to 14 neutron holes in the ^{208}Pb core. The $\frac{9}{2}^-$ ground state is believed to have the configuration $(\pi h_{9/2})^3$, as for the heavier At nuclei, and the $(\frac{11}{2}^-)$ level is based on the coupling of this ground state to the 2^+ core excitation of ^{194}Pb. The isomeric $(\frac{13}{2}^+)$ state is again based on the $(\pi h_{9/2})^2(\pi i_{13/2})\frac{13}{2}^+$ excitation coupled to the 0^+ ^{194}Pb ground state. Continuing the comparison to the lead isotopes we find that the excitation of the 2^+ state decreases slightly for even-even Pb nuclei with $A < 198$. The 2^+ excitation energy is 1049 keV for ^{196}Pb and 965 keV for ^{194}Pb, compared to 1064 keV in ^{198}Pb. So although the excitation energy of the 2^+ state in the corresponding lead isotopes is decreasing, in contrast to the increase for $^{198-206}$Pb, the sharp decrease in the excitation energies of the $\frac{11}{2}^-$ state between ^{203}At (660 keV) and ^{197}At (324 keV) provides evidence for an increase in collectivity with decreasing neutron number. Similarly, the continued decrease in the excitation energy of the $\frac{13}{2}^+$ intruder state also implies an increase in collectivity.

The excited states in ^{197}At can be further compared to the levels of ^{196}Po. The $(\frac{11}{2}^-)$ state can then be considered as being based on the proton $h_{9/2}$ orbital coupled to the 2^+ state in ^{196}Po. Similarly, the $(\frac{13}{2}^+)$ state of ^{197}At is based on an $i_{13/2}$ proton coupled to the ^{196}Po ground state. The systematics of low-lying states in polonium isotopes [21] are remarkably similar to those of the corresponding At nuclei. Below the $N = 126$ shell closure (^{210}Po), the 2^+ states of $^{200-208}$Po appear at a constant energy of $E_{2^+} \sim$ 680 keV; this is in analogy with the systematics of the $\frac{11}{2}^-$ and $\frac{13}{2}^-$ states in $^{201-209}$At. There is then a slight drop in the excitation energy of the 2^+ states in going from ^{200}Po to ^{198}Po ($E_{2^+} = 605$ keV), and a bigger decrease between ^{198}Po and ^{196}Po ($E_{2^+} = 463$ keV). These systematics are analogous to the behaviour observed for ^{199}At and ^{197}At and have been interpreted [21] as evidence for an increase in collectivity and an onset of deformation of the even-even core. Due to the similarity between the Po and At nuclei, we propose that a similar increase in collectivity is occurring around ^{197}At.

5 Conclusions

In conclusion, the low-lying structure of ^{197}At has been elucidated for the first time. The excitation energy of the excited states is consistent with theoretical predictions that the nucleus is well-deformed in its ground state, providing evidence for the onset of deformation in neutron-deficient At nuclei. However, no deformed structures have yet been observed in astatines below the $N = 126$ shell closure.

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References

1. P. Möller, J.R. Nix, W.D. Myers and W.J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995)
2. T.P. Sjoreen, G. Schatz, S.K. Bhattacherjee, B.A. Brown, D.B. Fossan and P.M.S. Lesser, Phys. Rev. C **14**, 1023 (1976)
3. T.P. Sjoreen, U. Garg and D.B. Fossan, Phys. Rev. C **23**, 272 (1981)
4. T.P. Sjoreen, D.B. Fossan, U. Garg, A. Neskasis, A.R. Poletti and E.K. Warburton, Phys. Rev. C **25**, 889 (1982)
5. K. Dybdal, T. Chapuran, D.B. Fossan, W.F. Piel, Jr., D. Horn and E.K. Warburton, Phys. Rev. C **28**, 1171 (1983)
6. W. Męczyński *et al*, Eur. Phys. J. A **3**, 311 (1998) and private communication
7. S.J. Freeman *et al*, Phys. Rev. C **50**, R1754 (1994)
8. R.B.E. Taylor *et al*, Phys. Rev. C **54**, 2926 (1996)
9. W. Treytl and K. Valli, Nucl. Phys. **A97**, 405 (1967)
10. E. Coenen, K. Deneffe, M. Huyse, P. Van Duppen and J.L. Wood, Z. Phys. A **324**, 485 (1986)
11. R.S. Simon, K.–H. Schmidt, F.P. Heßberger, S. Hlavac, M. Honusek, G. Münzenberg, H.–G. Clerc, U. Gollerthan and W. Schwab, Z. Phys. A **325**, 197 (1986)
12. E.S. Paul *et al*, Phys. Rev. C **51**, 78 (1995)
13. M. Leino *et al*, Nucl. Instrum. Methods. Phys. Res. B **99**, 653 (1995)
14. P.J. Nolan, D.W. Gifford and P.J. Twin, Nucl. Instrum. Methods. Phys. Res. A **236**, 95 (1985)
15. A. Rytz, At. Data Nucl. Data Tables **47**, 205 (1991)
16. M.E. Leino, S. Yashita and A. Ghiorso, Phys. Rev. C **24**, 2370 (1981)
17. I. Bergström, B. Fant, C.J. Herrlander, P. Thieberger, K. Wikström and G. Astner, Phys. Lett. B **32**, 476 (1970)
18. T. Lönnroth, C.W. Beausang, D.B. Fossan, L. Hildingsson, W.F. Piel, Jr., M.A. Quader, S. Vadja, T. Chapuran and E.K. Warburton, Phys. Rev. C **33**, 1641 (1986)
19. T.P. Sjoreen, U. Garg and D.B. Fossan, Phys. Rev. C **21**, 1838 (1980)
20. S. Nagamiya and T. Inámura, Nucl. Phys. **A182**, 84 (1972)
21. L.A. Bernstein *et al*, Phys. Rev. C **52**, 621 (1995)
22. D. Horn, C. Baktash and C.J. Lister, Phys. Rev. C **24**, 2136 (1981)