COEXISTING STRUCTURES AT LOW– AND HIGH –SPIN IN EVEN–EVEN Cd AND Sn NUCLEI*

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Comprehensive spectroscopic studies of even-mass Cd, Sn and Te nuclei have been carried out within the Jyväskylä - Uppsala collaboration. A special emphasis is put on the systematics of collective intruder states and the role of proton excitations across the $Z = 50$ gap in these states.

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1. Even–mass Sn nuclei

1.1. Introduction

Many of the collective properties of even Sn nuclei can be reproduced in neutron-quasiparticle calculations. First evidence for possible low-lying proton excitations across the $Z = 50$ gap was found by Fielding *et al.* [1] in (^{3}He, n)-experiments, where population of the first excited 0^+ states in even $^{108-118}$Sn nuclei via the $L = 0$ two-proton transfer was found to be as strong as that of the ground states. Collective band structures up to spin 12^+ on these 0^+ states in even $^{112-118}$Sn nuclei were identified in γ-spectroscopic studies by Bron *et al.* [2]. Similarities in the energy systematics of these bands with the known proton-intruder bands in odd-mass In and Sb nuclei clearly indicated that these bands are based on the deformed proton $\pi(g^2_{9/2}g^{-2}_{7/2})$ 2p-2h configurations. Later the bands in ^{112}Sn and ^{114}Sn have been extended to higher spins [3, 4] and new bands involving also $h_{11/2}$ protons have been found in lighter Sn isotopes down to ^{106}Sn [5–7]. It is only in the midshell Sn isotopes where these band structures can

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be studied at low spins. In the light Sn isotopes these bands appear yrast just after the alignment of $h_{11/2}$ neutrons.

1.2. Low-spin states

In order to obtain more systematic information about the collective behaviour of the low-spin states of even Sn isotopes we successfully used low-energy proton-inelastic scattering for populating the low-lying states. Various pγ and pe$^-$ coincidence methods were employed in lifetime measurements [8] as well as in obtaining more selectivity for the γ-ray and conversion-electron measurements. Various types of magnetic lens plus Si(Li) electron spectrometers were designed and constructed for in-beam conversion–electron measurements [9–11]. Light-ion beams from the Jyväskylä MC20 cyclotron and from the Uppsala EN tandem were used. Methods for multiple Coulomb excitation of vibrational nuclei were developed [12]. Oxygen beams from the Uppsala EN tandem were used in these measurements.

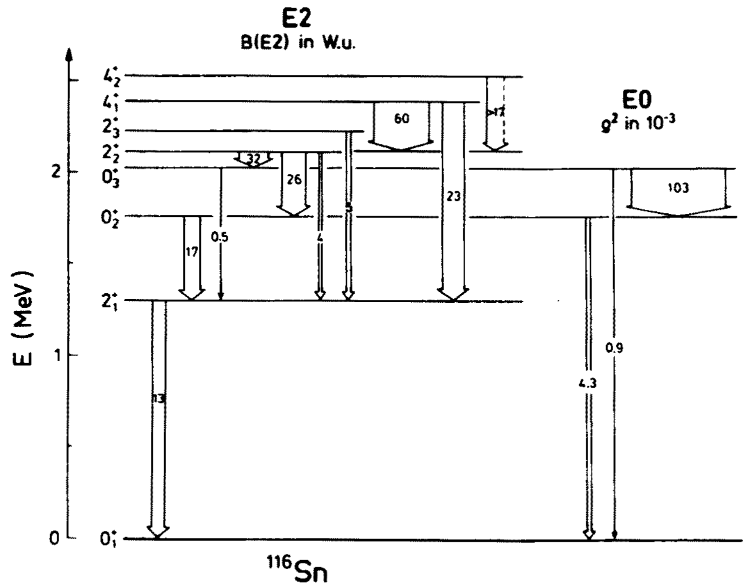

Fig. 1. Level scheme of ^{116}Sn [13]. The widths of the arrows are proportional to the reduced transition probabilities. Observed weak E2 branches are not shown in this figure.

As an example from our low-spin studies [13–15], results for $N = 66$ midshell nucleus ^{116}Sn are shown in Fig. 1. The B(E2) values shown in this figure indicate much more collectivity for the 0_2^+, 2_2^+, 4_1^+ and 4_2^+ states than predicted by the neutron-quasiparticle calculations. Concerning the deformed structures, the 0_2^+, 2_2^+ and 4_2^+ states are the members of the intruder band proposed by Bron et al. [2]. The resulting $B(\mathrm{E2})$ values in Fig. 1. clearly indicate that a possible band structure at low spins in ^{116}Sn is more complicated.

The observed pattern of the E0 transitions (Fig. 1.) between the 0^+ states in even $^{114-120}$Sn is quite unique. While the E0 transitions from the excited 0^+ states to the ground state are rather weak, the ones between the excited 0^+ states are found to be exceptionally strong. The strong E0 transition in ^{116}Sn can be generated if the associated 0^+ states are strongly mixed and involve deformation. A rough calculation [13] indicates deformation of the order of $\beta = 0.2$. This value is not far from β-values extracted from the strongest observed $B(\mathrm{E2})$ values shown in Fig. 1.

As a conclusion, our E2 and especially E0 data supports the idea of having deformed states present already among the lowest excited states of even-mass Sn nuclei near the neutron midshell. Our results also clearly evince strong mixing at low spins, which makes the identification of the rotational band structure difficult.

In the calculations where proton 2p-2h excitations are coupled to the quadrupole vibration of the even Sn core, Wenes *et al.* [16] have obtained a quite good agreement with our experimental E0 and E2 data.

1.3. High-spin states and systematics

As a side product from a comprehensive study of very light Sn region nuclei at NORDBALL, we also obtained more information about the decay properties of the intruder band in ^{108}Sn [17].

Good statistics in this thick target experiment allowed us to determine DCO ratios for some key transitions. As a consequence, we identify the close-lying levels in ^{108}Sn at 5754 keV and 5765 keV with $I^\pi = 10^+$ instead of $I^\pi = 12^+$ of Refs [6, 18]. Therefore, for the collective band on the top of these states our spin values are $2\hbar$ units smaller than those in Refs [6, 18].

Our results included, Fig. 2 shows the energy systematics of the observed collective bands in even Sn isotopes together with the first excited 2^+ state energies and the energies of the proposed $\nu\mathrm{h}_{11/2}^2$ 10^+ states. An interesting change in the excitation energy behaviour of the intruder bands is observed with the decreasing neutron number. In light isotopes the energy pattern seems to follow the energy of the suggested $\nu\mathrm{h}_{11/2}^2$ 10^+ states. This energy trend indicates that $\mathrm{h}_{11/2}$ neutrons might play an important role in generating the collective bands of light Sn nuclei, giving some support to the suggestion of Viggars *et al.* [5].

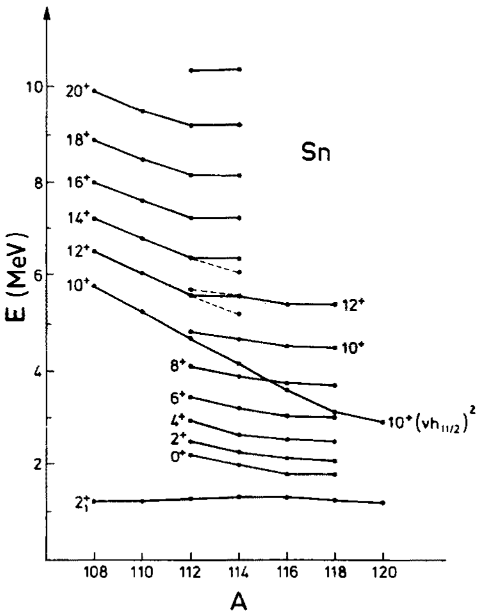

Fig. 2. Energy systematics of the observed collective bands in even Sn nuclei. The energies of the 2_1^+ states and the neutron $h_{11/2}^2$ 10^+ states are also shown.

2. Even–mass Cd nuclei

2.1. Introduction

It was actually the appearance of additional 0^+ and 2^+ states among the well-developed triplet of two-quadrupole-phonon states in ^{112}Cd and ^{114}Cd, which gave rise to ideas of having coexisting deformed states present at low spins in even-even nuclei near the Z=50 shell closure [19]. Later the two-proton transfer results [1] indicated that this deformation could be induced by the two-proton excitations across the $Z = 50$ gap. The role of proton intruder configurations in the development of collectivity in even Cd nuclei has remained an intriguing question. Especially the role of mixing has been dubious [20]. In the calculations mixing is strongest in the middle of the neutron shell while in the two-nucleon transfer selective feeding of certain 0^+ states is observed [1, 21].

Before our systematic studies attempts to follow the behaviour of the suggested intruder states, when moving away from the midshell ^{112}Cd and ^{114}Cd nuclei, have failed because of the surprisingly scarce experimental data.

2.2. Systematics of low-spin states

For the systematic study of low-lying levels in even $^{106-116}$Cd [22, 23] we employed various in-beam and off-beam γ-ray and conversion-electron spectroscopy methods available at the MC20 cyclotron laboratory in Jyväskylä. Inelastic proton scattering, (d,p), (p,2n) and (α,2n) reactions, as well as EC/β-decay of odd-odd In isomers, were found particularly advantageous in the population of low-lying non-yrast levels. Proton-γ, proton-electron, $\gamma\gamma$ coincidence, γ-ray angular-distribution and excitation-function measurements were carried out, as well as conversion-electron spectroscopy following the (p,p') reaction and In decay.

Results of these studies combined with the available data for ^{118}Cd and ^{120}Cd [24] render it possible to relate low-lying levels of similar character and for the first time follow the systematic behaviour of the 0_2^+, 2_2^+, 4_1^+, 0_3^+, 2_3^+ quintuplet of states from ^{106}Cd to ^{120}Cd (Fig. 3).

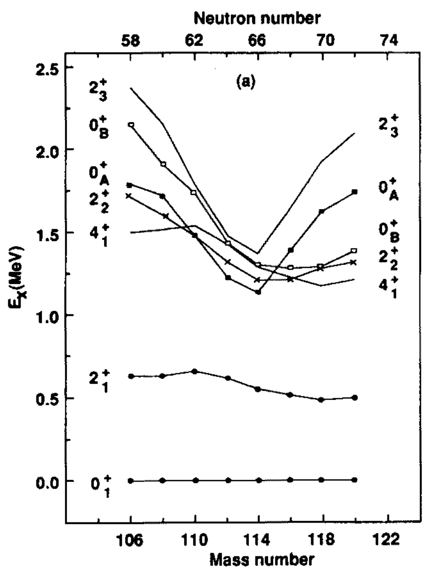

Fig. 3. Systematics of low-lying low-spin states in $^{106-120}$Cd [23].

The most conspicuous feature of the level systematics in Fig. 3 is the behaviour of the 0_A^+, 0_B^+ and 2_3^+ states. The 0_2^+ (0_A^+) states in the even $^{106-114}$Cd are characterized by enhanced E2($0_2^+ \rightarrow 2_1^+$) transitions, which is reflected in the small value of the observed B(E0;$0_2^+ \rightarrow 0_1^+$/B(E2;$0_2^+ \rightarrow 2_1^+$) ratio. In ^{116}Cd we identify the 0_3^+ state as the 0_A^+ state, since this state but not the 0_2^+ state is populated in Coulomb excitation (B(E2;$0_3^+ \rightarrow 2_1^+$) = 30 W.u.) [25]. This interpretation is supported by the lifetime measurements in Ref. [26]. On the basis of excitation energies it is now straightforward to identify the 0_3^+ states in ^{118}Cd and ^{120}Cd [24] as the 0_A^+ states. This interpretation *i.e.* the crossing of the 0_A^+ and 0_B^+ states between the Cd isotopes with $A = 114$ and 116, is also supported by the (t,p) study of O'Donnell *et al.* [21]. However, contrary to their suggestion, our data do not reveal any corresponding crossing on the neutron-deficient side.

A characteristic feature of the 0_B^+ (0_3^+) states in the even $^{106-114}$Cd isotopes is the large value for the $B(\mathrm{E2};0_3^+ \to 2_2^+)/B(\mathrm{E2};0_3^+ \to 2_1^+)$ ratio (= R), apparently due to the hindrance of the $\mathrm{E2}(0_3^+ \to 2_1^+)$ transition. For the 0_B^+ (0_2^+) states in even $^{116-120}$Cd, this ratio is not known, since it is difficult to observe the low-energy $\mathrm{E2}(0_B^+ \to 2_2^+)$ transitions. An indication of noncollectivity of the $\mathrm{E2}(0_B^+ \to 2_1^+)$ transitions in ^{116}Cd and ^{118}Cd is observed in the lifetime measurements by Mach *et al.* [26].

Considering the observed E2 rates, in the simple quadrupole-vibrator picture, the 0_2^+ (0_A^+) together with the 2_2^+ and 4_1^+ states form a two-phonon triplet in $^{106-114}$Cd. The 0_B^+ state is the three-phonon state which due to unharmonicities is pushed down in energy, in even $^{116-120}$Cd down below the two-phonon 0_A^+ state. This interpretation conflicts with that of Ref. [27], where ^{118}Cd is introduced as an almost perfect harmonic vibrator up to the three-phonon excitation.

Concerning possible proton intruder states, it is interesting to note that the 2_3^+ state in Fig. 3 has a similar energy behaviour as the 0_A^+ state. The V shape in Fig. 3 for these states is very similar to the behaviour of the proton 2p-1h intruder states in odd Sb nuclei. The intruder states in the even Cd isotopes should involve proton 2p-4h excitations, *i.e.* 6 valence quasiprotons. The total neutron-proton interaction in these states should be similar to that in the ground state band of the Ru ($Z = 50 - 6$) and Ba ($Z = 50 + 6$) isotones. In Fig. 4 the energy differences between the 0_A^+ and 2_3^+ states of Fig. 3 are compared to the energy of the 2_1^+ states in Ru and Ba isotones. The similarities are remarkable and indicate that these 0_A^+ and 2_3^+ states could represent the two lowest members of the intruder band. In Fig. 4 also the energies of candidates for the 4^+ and 6^+ members of the intruder band in ^{112}Cd observed in our (α,2n) reaction studies [28], together with the candidates for ^{110}Cd and ^{114}Cd [29, 30] are shown and compared with the ground-state bands of Ru and Ba isotopes.

The above considerations lead to a paradoxical conclusion: The intruder-like behaving 0_A^+ state is the state which in the phonon picture plays the role of the two-phonon 0^+ state. This interpretation is different from the one in Ref. [31], where the intruder 0^+ state in even Cd nuclei is associated with the 0^+ state having the large R-value, *i.e.* 0_B^+ state in our notation.

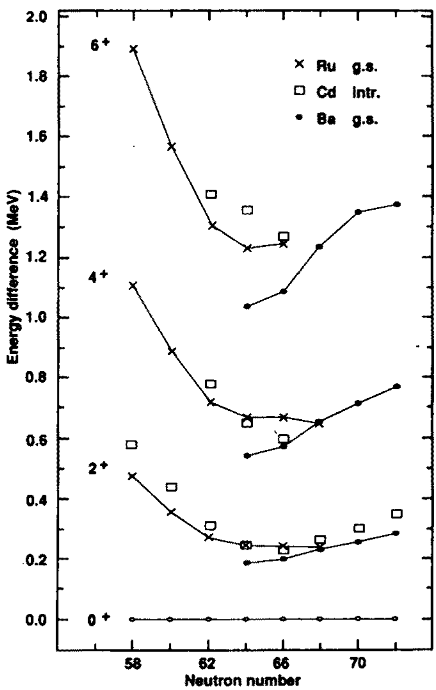

Fig. 4. Proposed members of the intruder bands in even $^{106-120}$Cd compared to the members of the ground-state bands of the even-even Ru and Ba isotones [23]. The energies of the intruder 0^+ states (0^+_A) in Cd isotopes are normalized to 0 MeV.

In this connection we point out that it is clearly the 0^+_A (0^+_2) state (but not the 0^+_B (0^+_3) state) in ^{110}Cd and ^{112}Cd which is populated in the (^{3}He,n) two-proton transfer reactions [1].

The similarities in Fig. 4 indicate that the 2^+_3 - 0^+_A energy differences are not seriously affected by the mixing. Moreover, the selective population in the (^{3}He,n) [1] and (t,p) reactions [21] does not support the idea of strong mixing.

As a conclusion, on the basis of our experimental results, the concepts of intruder and phonon states in even Cd nuclei represent different approaches, which may not fit into the same frame.

2.3. Coexisting structures at high spin

For probing collective properties of ^{108}Cd and ^{110}Cd at higher spin, we used the NORDBALL array to detect $\gamma\gamma$ coincidences from ^{12}C, ^{13}C, ^{16}O and ^{18}O induced reactions on thin as well as gold-backed ^{100}Mo and ^{96}Zr targets [32, 33]. We also employed a plunger device, specially designed for the NORDBALL array by the Uppsala-Jyväskylä group, in RDM lifetime measurements for low- and intermediate-spin states of ^{108}Cd and ^{110}Cd [34, 35]. Preliminary lifetime values for the high-spin states of the yrast band in ^{110}Cd were also extracted in the DSAM analysis of the backed-target data [36].

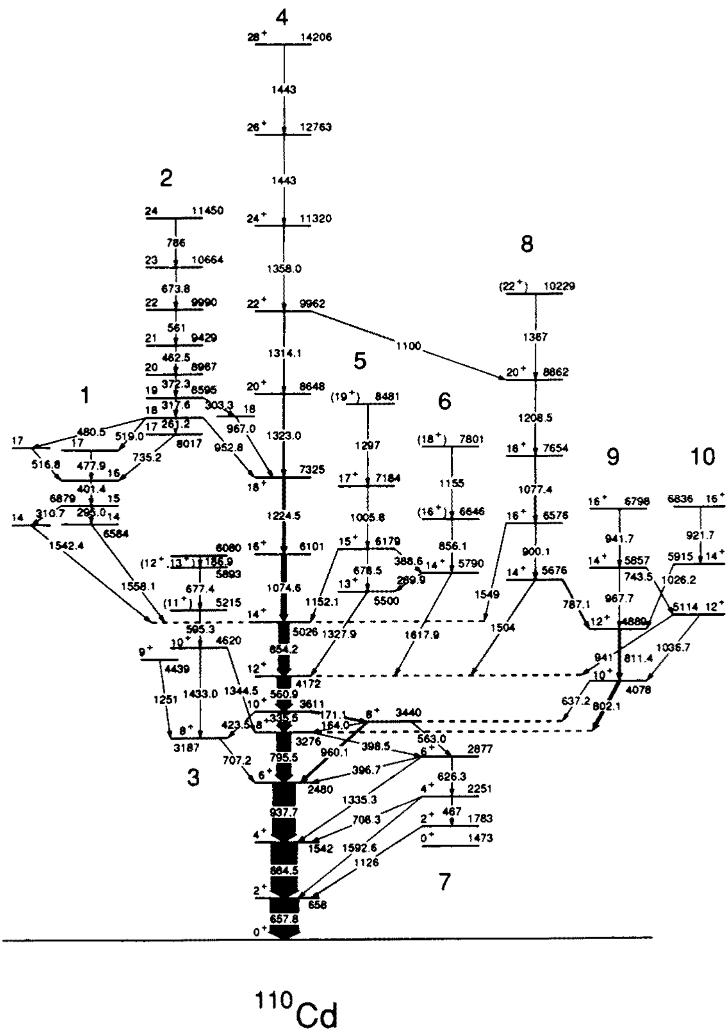

Fig. 5. A part of the level scheme of ^{110}Cd deduced from the ^{96}Zr(^{18}O, 4n) data [32]. Only positive-parity states are shown. For completeness, the 0^+ state (0_2^+) of Band 7 is also shown, although it was not seen in this reaction.

Our studies with the NORDBALL array revealed a number of coexisting structures close to the yrast line in ^{108}Cd and ^{110}Cd. As an example a part of the obtained level scheme of positive-parity structures in ^{110}Cd is shown in Fig. 5. A complete level scheme can be found in Ref. [32].

Concerning the proton-intruder structures, an interesting feeding pattern to the intruder band in ^{110}Cd is observed (Band 7). From our RDM measurement [34] we derived B(E2)= 26 W.u. for the 171 keV E2 transition from the 3611 keV $\nu h^2_{11/2}$ 10^+ state to the 3440 keV 8^+ state indicating that the 8^+ state is a less aligned member of the $\nu h^2_{11/2}$ multiplet. Considering the reduced transition rates [34], this 8^+ state favours the decay to the 6^+ member of the intruder band (Fig. 5) indicating a contribution of $h_{11/2}$ neutrons in the intruder band. A similar feeding of the intruder band we also observed in our (α,2n) experiment for ^{112}Cd [28]. An intriguing question is in which extend the deformation-driving $h_{11/2}$ orbitals are responsible for the intruding collective band structures in even-mass Cd nuclei. Identification of the high-spin members of the intruder band in ^{110}Cd is difficult. In principle Band 8 could be the continuation of the intruder band after the alignment of neutrons.

On the basis of feeding and de-excitation properties [34] we associate the 3187 keV 8^+ state with the height-K $\pi g^{-2}_{9/2}$ configuration. The level structure on the top of this state (Band 3) clearly resembles that of the ^{112}Sn core nucleus. Coupling of this 8^+ state with $h_{11/2}$ neutrons gives rise to collective M1 bands (Band 1 and 2). Differing from the similar bands of an oblate shape in the light Pb nuclei, these high-K bands observed in ^{108}Cd and ^{110}Cd are associated with a prolate shape.

Above the 3276 keV 8^+ state the ground-state band continues along Band 9. A vibrational character of the ground-state band up to five-phonon excitations is indicated by the increasing value of the transition-quadrupole moment up to $I^\pi = 10^+$ [36]. In the soft-rotor picture this behaviour would be explained by a stretching effect.

Above the aligned $\nu h^2_{11/2}$ 10^+ state, the alignment in the yrast band (Band 4) stays constant until from $I = 22$ up to $I = 28$ an upbend is observed. Results from our DSAM analysis reveal that the E2 transitions in this upbending region are fast [36]. The origin of this increasing collectivity is not yet understood.

REFERENCES

[1] H. Fielding *et al.*, *Nucl. Phys.* **A281**, 389 (1977).
[2] J. Bron *et al.*, *Nucl. Phys.* **A318**, 335 (1979).
[3] H. Harada *et al.*, *Phys. Lett.* **B207**, 17 (1988).
[4] H. Harada *et al.*, *Phys. Rev.* **C39**, 132 (1989).

[5] D. Viggars, H.W. Taylor, B. Singh, J.C. Waddington, *Phys. Rev.* **C36**, 1006 (1987).
[6] R. Wadsworth *et al.*, *Nucl. Phys.* **A559**, 461 (1993).
[7] R. Wadsworth *et al.*, *Phys. Rev.* **C50**, 483 (1994).
[8] R. Julin, J. Kantele, M. Luontama, A. Passoja, T. Poikolainen, *Nucl. Instrum. Methods* **152**, 471 (1978).
[9] J. Kantele, M. Luontama, A. Passoja, R. Julin, *Nucl. Instrum. Methods* **130**, 467 (1975).
[10] M. Luontama, J. Kantele, R. Julin, A. Passoja, T. Poikolainen, M. Pylvänäinen, *Nucl. Instrum. Methods* **159**, 339 (1979).
[11] R. Julin *et al.*, *Nucl. Instrum. Methods* **A270**, 74 (1988).
[12] N.-G. Jonsson, J. Kantele, A. Bäcklin, *Nucl. Instrum. Methods* **152**, 485 (1978).
[13] J. Kantele *et al.*, *Z. Phys. A* **289**, 157 (1979).
[14] A. Bäcklin *et al.*, *Nucl. Phys.* **A351**, 490 (1981).
[15] N.-G. Jonsson *et al.*, *Nucl. Phys.* **A371**, 333 (1981).
[16] G. Wenes, P. Van Isacker, M. Waroquier, K. Heyde, J. Van Maldeghem, *Phys. Rev.* **C23**, 2291 (1981).
[17] E.Mäkelä *et al.*, Dept. of Physics, Univ. of Jyväskylä, Annual Report 1993, p. 70.
[18] F.Asaiez *et al.*, *Nucl. Phys.* **A501**, 401 (1989).
[19] G. Gneuss, W. Greiner, *Nucl. Phys.* **A171**, 449 (1971).
[20] R. Casten *et al.*, *Phys. Lett.* **B297**, 19 (1992).
[21] G. O'Donnell, A. Kotwal, H.T. Fortune, *Phys. Rev.* **C38**, 2047 (1988).
[22] R. Julin *et al.*, *Z. Phys.* **A296**, 315 (1980).
[23] J. Kumpulainen *et al.*, *Phys. Rev.* **C45**, 640 (1992); J. Kumpulainen *et al.* , *Z. Phys.* **A335**, 109 (1990).
[24] A. Aprahamian, Ph.D. thesis, Clark University (1985).
[25] F.K. McGowan, R.L. Robinson, P.H. Stelson, J.L.C. Ford Jr., *Nucl. Phys.* **66**, 97 (1965).
[26] H. Mach *et al.*, *Phys. Rev. Lett.* **63**, 143 (1989).
[27] A. Aprahamian, D.S. Brenner, R.F. Casten, R.F. Gill, A. Piotrowski, *Phys. Rev. Lett.* **59**, 535 (1987).
[28] J. Kumpulainen *et al.*, Dept. of Physics, Univ. of Jyväskylä, Annual Report 1990, p. 91.
[29] R.A. Meyer, L. Peker, *Z. Phys.* **A283**, 379 (1977).
[30] C. Fahlander *et al.*, *Nucl. Phys.* **A485**, 327 (1988).
[31] A. Aprahamian *et al.*, *Phys. Lett.* **140B**, 22 (1984).
[32] S. Juutinen *et al.*, *Z. Phys.* **A336**, 475 (1990); *Nucl. Phys.* **A573**, 306 (1993).
[33] I. Thorslund *et al.*, *Nucl. Phys.* **A564**, 285 (1993).
[34] M. Piiparinen *et al.*, *Nucl. Phys.* **A565**, 671 (1993).
[35] I. Thorslund *et al.*, *Nucl. Phys.* **A568**, 306 (1994).
[36] E. Syrjälä *et al.*, Dept. of Physics, Univ. of Jyväskylä, Annual Report 1992, p. 92.