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Short Note

Rotational bands in ^{169}Re

X.H. Zhou[1,a], M. Oshima[2], Y. Toh[2], Y.H. Zhang[1], Y. Zheng[1], M. Koizumi[2], A. Osa[2], T. Hayakawa[2], Y. Hatsukawa[2], T. Shizuma[2], and M. Sugawara[3]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, PRC
[2] Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan
[3] Chiba Institute of Technology, Narashino, Chiba 275-0023, Japan

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Abstract. High-spin states in ^{169}Re have been investigated by means of in-beam γ-ray spectroscopy techniques with the ^{144}Sm(^{28}Si, 1p2nγ)^{169}Re reaction. X-γ and γ-γ-t coincidences, γ-ray anisotropies, and DCO ratios were measured. A strongly coupled band based on the $9/2^-[514]$ Nilsson state and a decoupled band built on the $h_{9/2}$ intruder proton orbital (nominally $1/2^-[541]$) have been established. The AB neutron crossings are observed at $\hbar\omega = 0.23$ and 0.27 MeV for the $9/2^-[514]$ and $1/2^-[541]$ bands, respectively. The $9/2^-[514]$ band in ^{169}Re shows the largest signature splitting at low spin among the odd-mass Re isotopes. Band properties of the AB neutron crossing frequencies, alignment gains, and signature splittings are discussed, and compared with those in the heavier odd-A Re isotopes. Additionally, a three-quasipariticle band is observed, and the $\pi 9/2^-[514] \otimes \nu AE$ configuration is proposed tentatively.

PACS. 21.10.Re Collective levels – 23.20.-g Electromagnetic transitions – 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

The very neutron-deficient Re isotopes are located on the outer edge of the deformed rare earth nuclei. These nuclei are expected to be rather soft with respect to β and γ deformations, and the polarizing effects of individual nucleons make the nuclear shapes strongly configuration dependent [1–3]. For light odd-A Re isotopes, the proton Fermi surface is at the top of the $h_{11/2}$ and $d_{5/2}$ shells and below the down-sloping $1/2^-[541]$ and $1/2^+[660]$ Nilsson orbits of the $h_{9/2}$ and $i_{13/2}$ spherical parentages. A less deformed shape is favored with the $9/2^-[514]$ and $5/2^+[402]$ orbitals occupied. These strongly coupled bands have been observed systematically in the odd-A Re isotopes [1–3]. These bands show small but distinct signature splitting before the AB neutron alignment [1–3], suggesting a certain γ deformation at low spins. On the other hand, the $h_{9/2}$ and $i_{13/2}$ orbitals with $\Omega = 1/2$ are strongly down-sloping as a function of deformation. The nucleus will be driven towards large deformation when the down-sloping orbitals are occupied by the unpaired proton. Therefore, the AB neutron crossing should be delayed to higher frequencies, and lower alignment is associated with these low-Ω bands. By increasing deformation, the neutron Fermi surface is moved further from the low-Ω components of the $\nu i_{13/2}$ subshell, thereby reducing the Coriolis mixing. This results in a decreased alignment gain and a higher crossing frequency associated with the alignment of $i_{13/2}$ neutrons [4]. Prior to this work, the rotational bands in ^{169}Re were reported in a symposium [5], but a high-spin level scheme has not yet been published in the literature. The ground state of ^{169}Re was assigned to be the $\pi 9/2^-[514]$ Nilsson configuration [6]. In ^{173}Ir α-decay studies, the α-γ coincidence measurement revealed a 136 keV γ-ray which was proposed to depopulate the $11/2^-$ member of the $9/2^-[514]$ band in ^{169}Re [7].

The excited states in ^{169}Re were populated via the ^{144}Sm (^{28}Si, 1p2n)^{169}Re reaction. The ^{28}Si beam was provided by the tandem accelerator at the Japan Atomic Energy Research Institute (JAERI). The target is an isotopically enriched ^{144}Sm metallic foil of 1.3 mg/cm^2 thickness with a 7.0 mg/cm^2 Pb backing. A γ-ray detector array [8], GEMINI, comprising 12 HPGe's with BGO anti-Compton (AC) shields was used. To obtain the DCO ratios, the detectors were divided into 3 groups positioned at 32° (148°), 58° (122°), and 90° with respect to the beam direction. The detectors were calibrated with ^{60}Co, ^{133}Ba, and ^{152}Eu standard sources; the typical energy resolution

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[a] e-mail: `zxh@impcas.ac.cn`

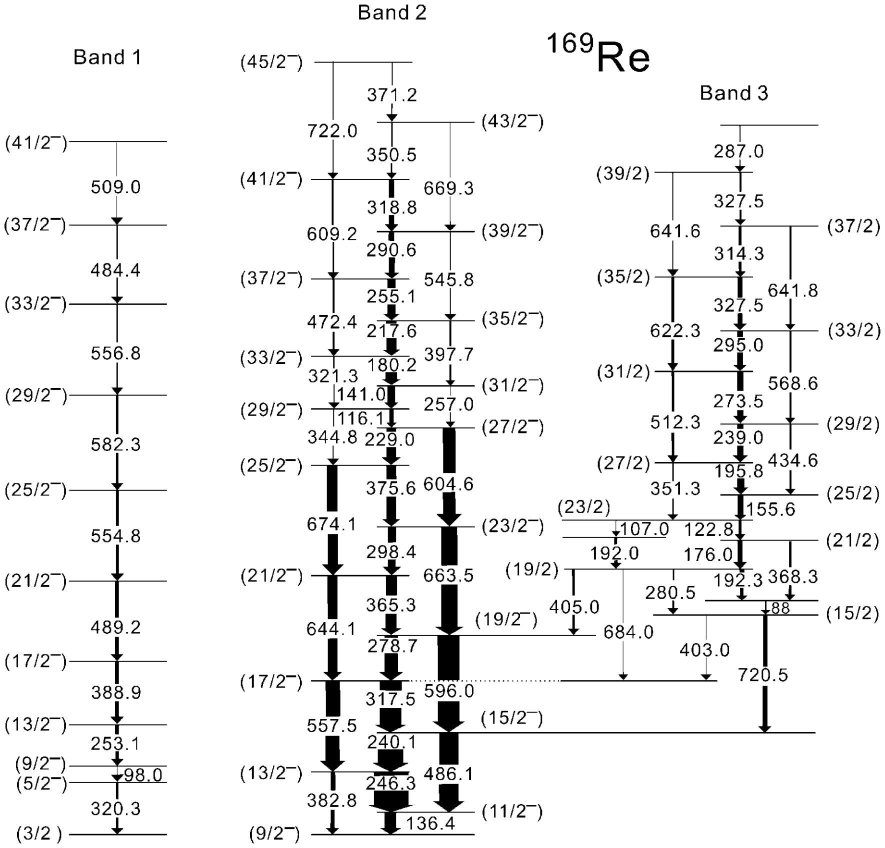

Fig. 1. Level scheme of ^{169}Re deduced from the present work.

was about 2.0–2.4 keV at FWHM for the 1332.5 keV line. In order to identify the in-beam γ-rays belonging to ^{169}Re and to determine the optimum beam energy, first, we measured the relative γ-ray yields at the beam energies of 140, 145, and 150 MeV. Then, the beam energy of 145 MeV, at which the yield of the 136 keV γ-ray was maximum, was chosen to populate the high-spin states in ^{169}Re. γ-γ-t and X-γ-t coincidence measurements were performed at this optimum beam energy. A total of 250×10^6 coincidence events were accumulated. After accurate gain matching, these coincidence events were sorted into a symmetric matrix and a DCO matrix for off-line analysis.

The measured relative γ-ray yields, combined with Re K X-ray coincident information, helped us assign γ-rays to ^{169}Re. The level scheme of ^{169}Re, including three rotational bands, is proposed from the present work and shown in fig. 1. A selected sum gate spectrum is displayed in fig. 2, showing the quality of the data. The ordering of transitions in each band is determined according to the γ-ray relative intensities, γ-γ coincidence relationships and γ-ray energy sums. The multipolarities of the transitions are deduced from the measured DCO ratios. The relative intensities for some uncontaminated γ-rays were measured in the total projection spectrum. Most of the relative intensities were extracted from the spectra gated on the bottom transitions in the band. The band head of band 1 is most likely the $5/2^-$ state which de-excites by the 320.3 keV transition of dipole character. The 98 keV transition was found to be very weak because of its highly converted nature. Since we did not observe linking transitions from band 1 to the other part of the level scheme, the band head energy of band 1 could not be determined in the present work.

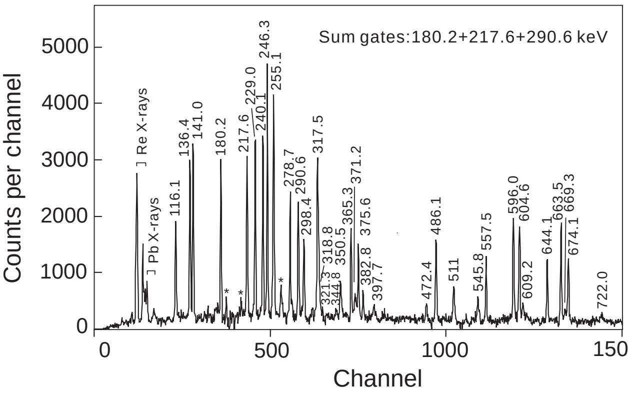

Fig. 2. Representative spectrum illustrating band 2 in ^{169}Re from a sum of gates as indicated on the panel. The * symbols indicate contaminations.

Mueller *et al.* have calculated the equilibrium deformations for ground states and intruder configurations in odd-A Re isotopes [9]. The calculations indicate that for ^{169}Re the deformation-aligned bands are expected

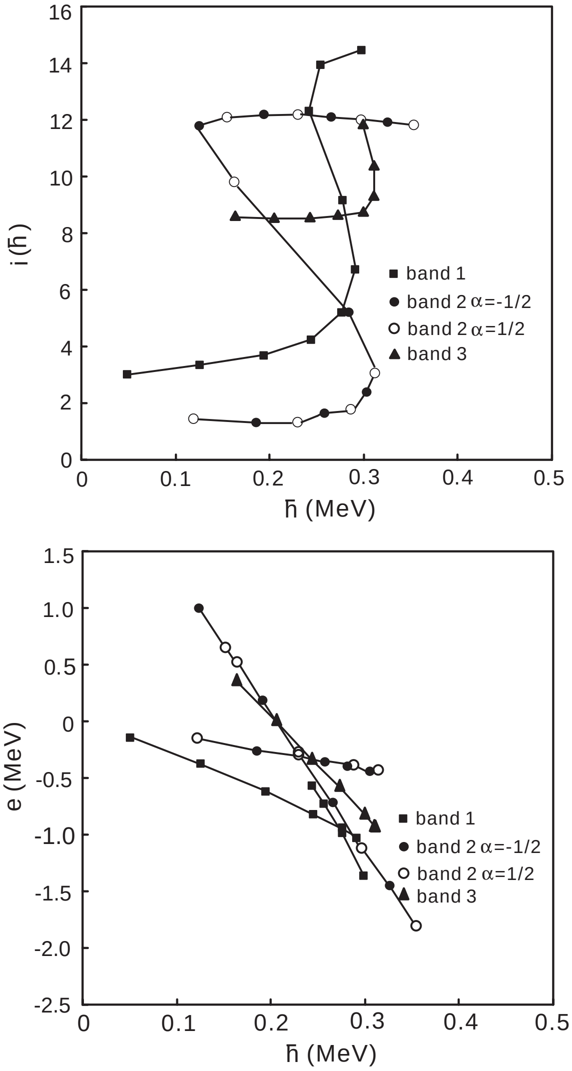

Fig. 3. Extracted alignment and Routhian energy for measured rotational bands in ^{169}Re. The labels in the legends indicate the bands as they are labeled in fig. 1. The Harris reference parameters are chosen to be $J_0 = 20\hbar^2$ MeV^{-1} and $J_1 = 60\hbar^4$ MeV^{-3}.

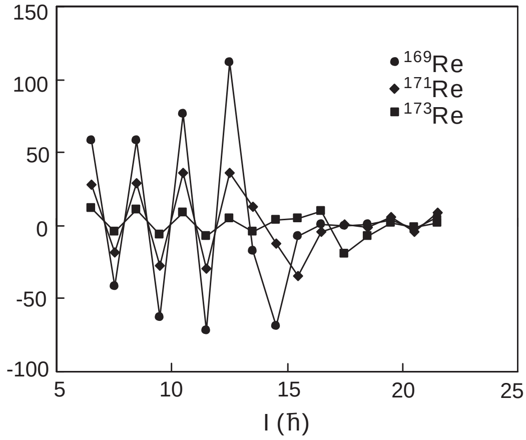

Fig. 4. Signature splitting $S(I)$ as a function of spin I for the $\pi 9/2^-[514]$ bands in ^{169}Re (this work), ^{171}Re [1,2], and ^{173}Re [3].

to have quadrupole deformations around 0.18, while the rotational-aligned bands based on the $1/2^-[541]$ and $1/2^+[660]$ Nilsson orbitals tend to have larger deformations [9]. Thus, the available Nilsson orbitals for ^{169}Re at the predicted prolate deformations are the $1/2^+[411]$, $5/2^+[402]$, $7/2^+[404]$, $9/2^-[514]$, $1/2^-[541]$ and $1/2^+[660]$, among which the high-j orbitals $9/2^-[514]$, $1/2^-[541]$ and $1/2^+[660]$ of the $h_{11/2}$, $h_{9/2}$ and $i_{13/2}$ parentages are particularly important for the high-spin states. The different orbitals will give rise to rotational bands with different spectroscopic characters. When the high-K orbitals are occupied, strongly coupled bands with strong $\Delta I = 1$ transitions will occur. The unpaired proton in the low-K orbitals will, on the other hand, easily be decoupled and align their spins, and bands with large signature splittings should be observed. At high spins a pair of intruder high-j particles are expected to break up and align their angular momenta along the rotation axis producing an upbend or a backbend. In the mass region around ^{169}Re, the experimental results and theoretical calculations [1–3,10,11] have demonstrated that the aligned i_{13}^2 neutron configuration is responsible for the first band crossing. Experimental Routhians and alignments have been extracted according to ref. [12] and they are presented in fig. 3. In those plots, the common Harris parameters $J_0 = 20\hbar^2$ MeV^{-1} and $J_1 = 60\hbar^4$ MeV^{-3} were used [13].

Band 1 has a decoupled structure suggesting that the configuration includes proton from an $\Omega = 1/2$ orbital. Candidate orbitals are $1/2^+[411]$, $1/2^-[541]$ and $1/2^+[660]$. From the level spacing systematics in the $1/2^-[541]$ bands in the neighboring odd-Z nuclei [1–3], band 1 is assumed to be based on the $1/2^-[541]$ Nilsson orbital and the band head has a spin-parity of $5/2^-$. The unfavored branch has not been observed because of its large signature splitting. The calculations indicated that the band based on the $1/2^-[541]$ configuration in light Re isotopes has a larger quadrupole deformation than the strongly coupled bands, and a small positive γ deformation is favored [14,12,9]. As shown in fig. 3, the band crossing takes place at $\hbar\omega = 0.27$ MeV, where the gain in the alignment is about $10.5\hbar$. The crossing frequency is almost the same as those in the heavier odd-A Re isotopes [1–3]. Inspecting the alignment gains in the $1/2^-[541]$ bands in the odd-A Re isotopes [1–3], it is found that the alignment gain is increased while decreasing the neutron number. By decreasing the neutron number, the neutron Fermi surface is moved closer to the low-Ω components of the $\nu i_{13/2}$ orbital, resulting in an increased gain in aligned angular momentum. In the present work, the $1/2^-[541]$ band head energy in ^{169}Re was observed to be higher than 320 keV, which might explain the low population for the $1/2^-[541]$ band in ^{169}Re comparing those in the heavier odd-A Re isotopes [1–3].

Band 2 was most strongly populated and extended up to $(45/2^-)$. This band must be based on the $9/2^-[514]$ ground state. This configuration assignment is supported by the α-decay studies of ^{173}Ir [7]. Band 2 experiences a strong backbending at $\hbar\omega = 0.23$ MeV with a gain of $10.5\hbar$

in alignment (see fig. 3), corresponding to the AB neutron crossing in the $9/2^-[514]$ bands of the neighboring odd-A Re isotopes [1–3]. Figure 4 present a plot of the signature splitting defined as [15]

$$S(I) = [E(I) - E(I-1)] - \frac{1}{2}[E(I+1) - E(I) + E(I-1) - E(I-2)]\,. \quad (1)$$

Here $E(I)$ is the level energy of state I; $S(I)$ is directly proportional to the energy difference of the two signatures, but magnified by approximately a factor of two. There is a clear energy splitting between the two signatures at low frequencies, and the splitting disappears quite suddenly when the alignment increases. Figure 4 also shows the signature splittings for the $9/2^-[514]$ bands in ^{171,173}Re [1–3]. In the odd-A Re isotopes with mass number larger than 173, there is almost no signature splitting in the $9/2^-[514]$ bands [16,17]. Figure 4 displays that the signature splitting for the $9/2^-[514]$ bands becomes larger and larger while decreasing the neutron number, and signature splitting as high as about 30 keV is observed at low spin in ^{169}Re. Cranked shell-model calculations of quasiproton energies as a function of γ deformation [14,12] predict that the $9/2^-[514]$ configuration in light Re isotopes tends to drive the nucleus towards negative γ deformation, leading to a small signature splitting at low frequencies. At higher frequencies, the alignment of $i_{13/2}$ neutrons in very neutron-deficient Re isotopes favors positive γ [18, 19]. The observed disappearance of signature splitting after the $i_{13/2}$ neutron alignment might indicate that the opposite γ driving forces of the strongly coupled proton and the aligned $i_{13/2}$ neutrons may cancel each other, and resulting in a near prolate shape after the backbending. The systematics of the signature splitting shown in fig. 4 may suggest that the nucleus becomes more γ soft and has larger γ deformation with decreasing the neutron number. It is worth pointing out that the $\Delta I = 2$ transition intensities in band 2 drop apparently comparing with the $\Delta I = 1$ transition intensities after the band crossing. The similar intensity change at high spins was also observed in the $\pi 9/2^-[514]$ bands in the neighboring odd-A Re nuclei, and it was interpreted by the $i_{13/2}$ neutron alignment [1, 3]. According to the semiclassical formula [20,21], the $i_{13/2}$ neutron alignment would result in a large increase in the $B(M1)/B(E2)$ ratios duo to the opposite signs of the proton *versus* neutron g-factors.

As shown in fig. 3, band 3 has the largest aligned angular momentum with a value of about $8.5\hbar$ at low spins. The alignment was deduced by assuming a band head K value of 4.5; the alignment in such high-spin levels is expected to be less influenced by the uncertainty of the K-value. This band shows an upbend at $\hbar\omega \approx 0.31$ MeV, and there is no signature splitting up to the highest level observed. In view of such a large alignment, band 3 must be based on a configuration of at least three quasiparticles. The band crossing frequency of $\hbar\omega \approx 0.31$ MeV is much higher than the AB neutron crossing in the neighboring nuclei [1,3,19, 22,23], indicating that band 3 involves an $i_{13/2}$ neutron. A one-quasiparticle occupation of the lowest $\nu i_{3/2}$ state would inhibit the normal $\nu i_{13/2}$ alignment from occurring at the expected rotational frequency. This well-known blocking effect can be seen in odd-N nuclei throughout the rare-earth region. Inspecting the level structure in the nuclei around ^{169}Re [13,19,22,23], we propose that band 3 is likely based on the $\pi 9/2^-[514] \otimes \nu AE$ configuration. Here, A ($\pi = +$, $\alpha = +1/2$) and E ($\pi = -$, $\alpha = +1/2$) are the conventional Cranked Shell Model orbits labelling the lowest configurations in the $\nu i_{13/2}$ and $\nu f_{7/2}h_{9/2}$ subshells [19], respectively. The A and E orbitals were observed at very low excitation energies at the neighboring odd-N nuclei [13,22,19]; the AE configurations were also identified at excitation energies around 1.6 MeV in the neighboring even-even nuclei [13,19,22,23], which are comparable with the band head energy of band 3. Thus, the $\pi 9/2^-[514] \otimes \nu AE$ configuration would be expected to be energetically favorable in ^{169}Re. Most of the alignment in band 3 would be contributed by the $\nu i_{13/2}$ quasiparticle, while the rest might be associated with the other two quasiparticles. Additional support for the configuration assignment comes from the non-existence of signature splitting as discussed for band 2 after the AB neutron alignment. The upbend at $\hbar\omega \approx 0.31$ MeV may be caused by the BC neutron alignment because the crossing frequency is similar to those for the BC neutron alignments observed in the nuclei around ^{169}Re [13,19,22,23].

In conclusion, a level scheme consisting of three rotational bands in ^{169}Re has been established. The $i_{13/2}$ neutron alignments have been observed in the $1/2^-[541]$ and $9/2^-[514]$ bands at $\hbar\omega = 0.27$ and 0.23 MeV, respectively. The difference between the crossing frequencies can be interpreted in terms of shape effects. When the low-K proton $1/2^-[541]$ orbital is occupied, the nucleus is driven to a large near-prolate shape and this will increase the neutron crossing frequency. If the high-K proton $9/2^-[514]$ orbital is occupied, the nucleus tends to adopt a triaxial shape with a small quadrupole deformation and negative γ-value, resulting in the low AB neutron crossing frequency and apparent signature splitting at low spin. The observed systematics of the signature splitting for the $9/2^-[514]$ bands at low spin in the light odd-A Re isotopes suggests that the nucleus becomes more γ soft and has larger γ deformation while decreasing the neutron number. The observed disappearance in signature splitting after the $i_{13/2}$ neutron alignment in the $9/2^-[514]$ bands indicates that the opposite γ driving forces of the strongly coupled proton and the aligned $i_{13/2}$ neutrons may cancel each other, and resulting in a near-prolate shape after the backbending. By referring to the level structure in the nuclei around ^{169}Re, it is proposed that the three-quasiparticle band is likely built on the $\pi 9/2^-[514] \otimes \nu AE$ configuration.

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References

1. R.A. Bark *et al.*, Nucl. Phys. A **501**, 157 (1989).
2. H. Carlsson *et al.*, Nucl. Phys. A **551**, 295 (1993).
3. L. Hildingsson *et al.*, Nucl. Phys. A **513**, 394 (1990).
4. R. Bengtsson *et al.*, *International Review of Nuclear Physics*, Vol. **2**, edited by T. Engeland, J. Rekstad, J.S. Vaagen (World Scientific, Singapore, 1989).
5. G.D. Dracoulis *et al.*, in *International Conference Nuclear on Structure at High Angular Momentum, Ottawa, 1992*, AECL-10613 (1992) p. 36.
6. V.S. Shirley, Nucl. Data Sheets **64**, 505 (1991).
7. W.D. Schmidt-Ott *et al.*, Nucl. Phys. A **545**, 646 (1992).
8. K. Furuno *et al.*, Nucl. Instrum. Methods A **421**, 211 (1999).
9. W.F. Mueller *et al.*, Phys. Rev. C **59**, 2009 (1999).
10. S. Juutinen *et al.*, Nucl. Phys. A **526**, 346 (1991).
11. R.A. Bark *et al.*, Nucl. Phys. A **657**, 113 (1999).
12. R. Bengtsson, S. Frauendorf, Nucl. Phys. A **327**, 139 (1979).
13. K. Theine *et al.*, Nucl. Phys. A **548**, 71 (1992).
14. R. Bengtsson, S. Frauendorf, Nucl. Phys. A **324**, 27 (1979).
15. Y.H. Zhang *et al.*, Phys. Rev. C **65**, 014302 (2002).
16. T. Kibedi *et al.*, Nucl. Phys. A **539**, 137 (1992).
17. R.A. Bark *et al.*, Nucl. Phys. A **591**, 265 (1995).
18. J.C. Wells *et al.*, Phys. Rev. C **40**, 725 (1989).
19. R.A. Bark *et al.*, Nucl. Phys. A **514**, 503 (1990).
20. F. Dönau *et al.*, *Proceedings of the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge, 1982*, edited by N.R. Johnson (Harwood Academic, New York, 1983) p. 143.
21. A.J. Larabee *et al.*, Phys. Rev. C **29**, 1934 (1984).
22. J. Recht *et al.*, Nucl. Phys. A **440**, 366 (1985).
23. G.D. Dracoulis *et al.*, Nucl. Phys. A **486**, 414 (1988).