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Letter

Multi-quasiparticle states in ^{184}W via multi-nucleon transfer

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Abstract. A multi-nucleon transfer reaction using an 850 MeV ^{136}Xe beam incident on a ^{198}Pt target was used to populate high-spin states in ^{184}W, 14 nucleons from the target. A 4-quasiparticle isomer with $t_{1/2} = 188 \pm 38$ ns has been observed for the first time and its de-excitation through collective and intrinsic structures studied. The results are compared with predictions of blocked BCS Nilsson calculations. Observation of this metastable state completes the tungsten 4-quasiparticle isomer systematics from $A = 176$ to 186. Mapping out the most yrast 4-quasiparticle isomers in these even-even tungsten isotopes suggests the existence of a highly favoured state in ^{188}W, within reach of current experimental set-ups.

PACS. 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 27.70.+q $150 \leq A \leq 189$

High-seniority states in well-deformed neutron-rich $A = 180 \rightarrow 190$ nuclei are difficult to study due to the lack of suitable reaction mechanisms. The stable nucleus ^{184}W lies in this historically difficult-to-reach landscape. Recently, advances have been achieved in this mass-region using deep inelastic reactions, including both inelastic and multi-nucleon–transfer mechanisms, *e.g.* refs. [1,2]. This enables the study of the interplay between intrinsic and collective states as the nucleus accommodates angular momentum and as a function of neutron number. Previous studies of ^{184}W [3,4] have observed 2-quasiparticle states up to $7\hbar$ including a $t_{1/2} = 8.3$ μs $K^\pi = 5^-$ level. In this Letter, new data on seniority-2 and -4 structures are reported, observed as the 4-proton, 10-neutron channel in a deep inelastic reaction; a by-product, well away from the strongest reaction channels.

An 850 MeV $^{136}_{54}$Xe beam provided by the 88″ cyclotron at Lawrence Berkeley National Laboratory, was incident on a thin, 420 μg cm^{-2}, self-supporting target of $^{198}_{78}$Pt enriched to > 92%. The beam energy was chosen to be ≈ 25% above the Coulomb barrier in order to maximise the population of high-spin states. The beam had a natural micro-pulsing period of 178 ns. Gamma rays were detected using the GAMMASPHERE array of 102 Compton-suppressed Ge detectors. The CHICO gas-filled PPAC ancillary detector [5], was used to measure the angles (both θ and ϕ) of, and time-of-flight difference between, the 2 heavy-ion recoils. The trigger condition for a good event required 2 CHICO elements and at least 3 Ge detectors to fire. The timing condition was set in software such that the 4th (and subsequent) Ge signals could be delayed by up to 670 ns with respect to the first 3 prompt (within ±45 ns of the detection of the recoils) Ge energies. Isomers in the ns → μs range are observable as the recoiling products stop in the PPACs, at a distance

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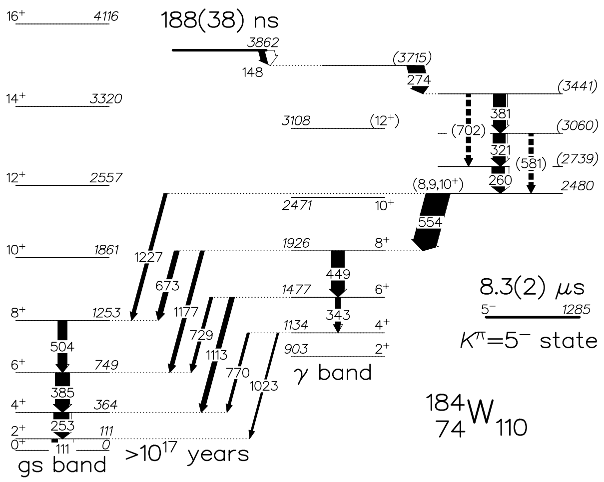

Fig. 1. Partial level scheme for ${}^{184}_{74}W_{110}$ showing the newly observed 4-quasiparticle isomer at $E_x = 3862$ keV (this work) together with relevant previously known levels [3,4,6]. The widths of the arrows are proportional to the relative γ-ray intensity (black) and deduced/assumed electron conversion intensity (white) except for the tentative transitions (dashed arrows). Level energies in parentheses indicate unestablished level ordering.

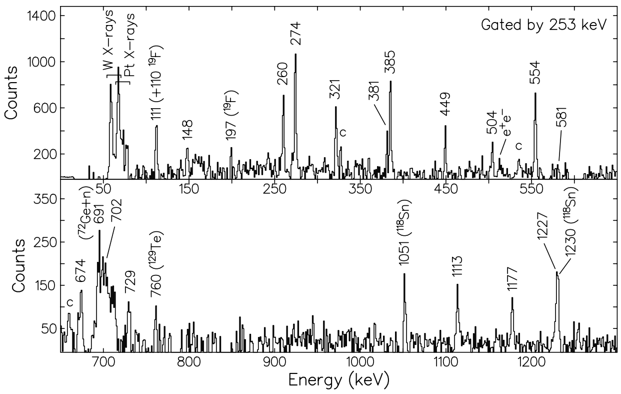

Fig. 2. Gamma ray coincidence spectrum gated by the delayed 253 keV transition in the ground-state band of ${}^{184}W$. The transitions labelled only by energy are assigned to ${}^{184}W$. Known contaminants in coincidence with 253 ± 1 keV are indicated and those which are unknown are labelled by "c". The isomeric ${}^{19}F$ lines are the strongest in the delayed projection and originate from the segmented Ge detectors. Intense X-rays from the platinum target appear in the delayed spectra.

of ≈ 13 cm from the target position. This places delayed events in view of the Ge detectors which were used without the usual heavy-metal collimators, assisting the observation of isomeric transitions.

The level scheme established in the current work is shown in fig. 1 and was constructed using delayed (out-of-beam) γ-γ coincidences (fig. 2) from the stopped nuclei implanted in the CHICO detector. Several time gates on the delayed data were used ranging from 45 ns $\rightarrow$ 200 ns.

The transitions at 1227 and 554 keV link the newly observed structure at $E_x = 2480$ keV to members of the known ground-state and γ bands, respectively, for which the spins and parities have been established [6]. The states are fed by an isomer at $E_x = 3862$ keV with $t_{1/2} = 188 \pm 38$ ns (see fig. 3), established for the first time in this work. This isomeric level de-populates via a series of γ rays, some of which are regularly spaced in energy, characteristic of a strongly coupled band structure. The regular spacing of the 260, 321 and 381 keV transitions and tentative evidence for crossover transitions of 581 ($= 260 + 321$) and 702 ($= 321 + 381$) keV suggest a possible band structure.

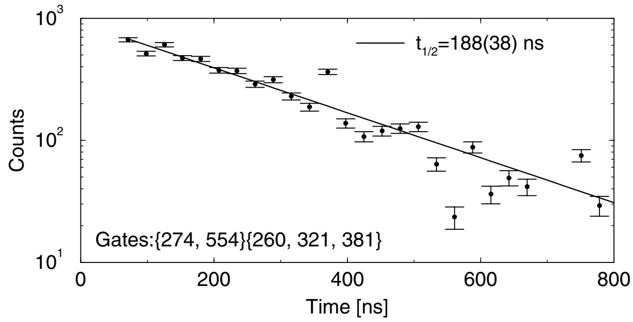

Fig. 3. Time spectrum showing the 188 ± 38 ns half-life and an exponential fit to the data (solid line) for the 3862 keV isomer in ${}^{184}W$. An E_γ-*versus*-time matrix was produced gated by 274 and 554 keV delayed γ rays. Subsequent gates of 260, 321 and 381 keV were set on the energy axis of the resulting matrix to obtain the time spectrum shown (filled circles).

Table 1. Energy systematics in the $A \approx 184$ region for 2- and 4-quasiparticle states. Energies in brackets indicate tentative assignments. Where multiple states of the same spin and parity are known the energy of the lowest-lying state is quoted.

Nucl.	Excitation energy (keV)								
	8^-	9^-	10^+	12^+	14^-	15^+	15^-	16^+	17^-
${}^{180}_{74}W^{(a)}_{106}$	1529				3263	3388	3744	3546	
${}^{182}_{74}W^{(b)}_{108}$	2120		2230	(3415)		3754		3893	4040
${}^{186}_{74}W^{(c)}_{112}$		(2118)						(3544)	
${}^{184}_{76}Os^{(d)}_{108}$	2046	2301	2367		(3792)				
${}^{186}_{76}Os^{(e)}_{110}$		2166	2564	3187		3732			

References: ([a]) [7], ([b]) [8], ([c]) [1,9], ([d]) [10,11], ([e]) [12].

The ordering of the transitions above 2480 keV in the level scheme has not been uniquely determined. One possible scenario, with the 148 keV transition de-populating the isomer (favoured due to its low energy), is shown in fig. 1. Under this assumption comparison with the Weisskopf singe-particle estimates restricts the 148 keV decay to $E1$, $M1$ or $E2$ character for $F_W > 1$ $\left(F_W = \frac{t^{\gamma}_{1/2}(\mathrm{expt.})}{t^{\gamma}_{1/2}(\mathrm{Weiss.})}\right)$.

The same constraint is achieved by balancing the intensities of the 148 and 274 keV transitions, independent of the level ordering. The resulting total electron conversion coefficient for the 148 keV transition is

Table 2. Low-lying 2- and 4-quasiparticle states in ^{184}W. The calculated energy from the blocked BCS calculations is E_{mqp} (see text for details), $E_{\mathrm{res.}}$ is the residual nucleon-nucleon interaction energy [13] and $E_{\mathrm{calc.}} = E_{\mathrm{mqp}} + E_{\mathrm{res.}}$ and is directly comparable with the experimentally determined energies. Experimental energies quoted in parentheses are states observed in the current work for which the spins and parities are uncertain. All other values of $E_{\mathrm{expt.}}$ are from ref. [6]. A "−" sign in front of a $\frac{1}{2}^-[510]$ orbital indicates a configuration with a less than maximal K coupling. In the final column, $\Delta E = E_{\mathrm{calc.}} - E_{\mathrm{expt.}}$.

K^π	Configuration		Energy (keV)				
	ν	π	E_{mqp}	$E_{\mathrm{res.}}$	$E_{\mathrm{calc.}}$	$E_{\mathrm{expt.}}$	ΔE
2^+	$\frac{3}{2}^-[512]$, $\frac{1}{2}^-[510]$		1167	−150	1017	1386	−369
3^+	$\frac{7}{2}^-[503]$, $-\frac{1}{2}^-[510]$		1567	−150	1417	1425	−8
5^-	$\frac{11}{2}^+[615]$, $-\frac{1}{2}^-[510]$		1458	−150	1308	1285	+23
6^+		$\frac{7}{2}^+[404]$, $\frac{5}{2}^+[402]$	1740	−154	1586	–	
7^-	$\frac{11}{2}^+[615]$, $\frac{3}{2}^-[512]$		1655	−150	1505	1502	+3
8^-		$\frac{9}{2}^-[514]$, $\frac{7}{2}^+[404]$	2395	−123	2272	(2480)	(−208)
9^-	$\frac{11}{2}^+[615]$, $\frac{7}{2}^-[503]$		2067	+184	2251	(2480)	(−229)
10^+	$\frac{11}{2}^+[615]$, $\frac{9}{2}^+[624]$		2244	+200	2444	(2480)	(−36)
11^+	$\frac{11}{2}^+[615]$, $\frac{9}{2}^+[624]$ $\frac{3}{2}^-[512]$, $-\frac{1}{2}^-[510]$		2902	−250	2652	–	
12^+	$\frac{11}{2}^+[615]$, $-\frac{1}{2}^-[510]$	$\frac{9}{2}^-[514]$, $\frac{5}{2}^+[402]$	3018	−91	2927	–	
13^+	$\frac{11}{2}^+[615]$, $\frac{1}{2}^-[510]$	$\frac{9}{2}^-[514]$, $\frac{5}{2}^+[402]$	3036	−44	2992	–	
13^-	$\frac{11}{2}^+[615]$, $\frac{3}{2}^-[512]$	$\frac{7}{2}^+[404]$, $\frac{5}{2}^+[402]$	3396	−339	3057	–	
14^+	$\frac{11}{2}^+[615]$, $\frac{3}{2}^-[512]$	$\frac{9}{2}^-[514]$, $\frac{5}{2}^+[402]$	3215	−63	3152	–	
14^-	$\frac{11}{2}^+[615]$, $\frac{7}{2}^-[503]$ $\frac{7}{2}^-[514]$, $\frac{3}{2}^-[512]$		3940	−168	3772	(3862)	(−90)
15^+	$\frac{11}{2}^+[615]$, $\frac{9}{2}^+[624]$ $\frac{7}{2}^-[503]$, $\frac{3}{2}^-[512]$		3500	+80	3580	(3862)	(−282)
15^-	$\frac{11}{2}^+[615]$, $\frac{7}{2}^-[503]$	$\frac{7}{2}^+[704]$, $\frac{5}{2}^+[402]$	3808	−66	3742	(3862)	(−120)
16^+	$\frac{11}{2}^+[615]$, $\frac{7}{2}^-[503]$	$\frac{9}{2}^-[514]$, $\frac{5}{2}^+[402]$	3627	−87	3540	–	
17^-	$\frac{11}{2}^+[615]$, $\frac{9}{2}^+[624]$	$\frac{9}{2}^-[514]$, $\frac{5}{2}^+[402]$	3804	−42	3762	(3862)	(−100)
18^-	$\frac{11}{2}^+[615]$, $\frac{9}{2}^+[624]$	$\frac{9}{2}^-[514]$, $\frac{7}{2}^+[404]$	4639	−8	4631	–	
19^-	$\frac{11}{2}^+[615]$, $\frac{7}{2}^-[503]$	$\frac{11}{2}^-[505]$, $\frac{9}{2}^-[514]$	5034	−44	4990	–	
20^+	$\frac{11}{2}^+[615]$, $\frac{9}{2}^+[624]$	$\frac{11}{2}^-[505]$, $\frac{9}{2}^-[514]$	5211	+45	5256	–	

$\alpha_{\mathrm{T}}(\mathrm{expt.}) = 4.3 \pm 2.4$. The large uncertainty arises from the subtraction of the background, which is considerable at low energies. However, this is consistent (within 2σ) only with $E1$, $M1$ and $E2$ character and (marginally) favours $M1$ ($\alpha_{\mathrm{T}}(E1) = 0.14$, $\alpha_{\mathrm{T}}(M1) = 1.62$ and $\alpha_{\mathrm{T}}(E2) = 0.89$ [14]).

Considering the direct feeding of the $I^\pi = 8^+$ states in both the ground-state and γ bands and the absence of any direct decays to the corresponding $I^\pi = 6^+$ levels, possible spins and parities for the 2480 keV state are $I^\pi = 8^-$, 9^+, 9^- and 10^+. Multipolarities of $E1$, $M1$ and $E2$ have been considered in the absence of a significant half-life for the initial (2480 keV) state. The population of only yrast and near-yrast states in deep inelastic reactions [15] suggests a limit of $I \geq 14$ for the 3862 keV isomer.

For comparison, the energy systematics of 2- and 4-quasiparticle states in nearby even-even nuclei are shown in table 1. The energies of the $K^\pi = 8^-$, 9^- and 10^+ states in the tungsten and osmium isotopes shown in table 1 have excitation energies close to that of the 2480 keV level witnessed in ^{184}W. However, it is the $K^\pi = 10^+$ configuration that matches most closely, especially when taking into account the increase in the energy of the $K^\pi = 10^+$ arrangement with increasing neutron number (N). For $\Delta N = +2$, $\Delta E^+_{10} \approx 200$ keV for $^{184}\mathrm{Os} \rightarrow {}^{186}\mathrm{Os}$. For the same neutron numbers in the tungsten isotopes one might naïvely expect an energy $E^+_{10} \approx 2430$ keV in ^{184}W. Note that the energy of the first $\Delta I = 1$ transition in the $K^\pi = 10^+$ band in ^{182}W is 262 keV [8], very close to the 260 keV transition observed in the present work. However, when examining the alignment of the 260, 321 and 381 keV structure, the transition energies increase extremely quickly, adjacent energies differing by ≈ 60 keV. None of the 2-quasiparticle bands observed in the nuclei listed in table 1 demonstrate such a low alignment suggesting that the seemingly band-like behaviour occurs by chance. A g-factor analysis using the rotational model expressions [16] and assuming a strongly coupled band structure for the 260, 321 and 381 keV transitions was unable to discriminate between different 2-quasiparticle configurations. This is due to only upper limits for the $\Delta I = 2/\Delta I = 1$ branching ratios being available, both of which are < 0.38, consistent with the $K^\pi = 8^-$, 9^- and 10^+ configurations (table 2). Considering the 4-quasiparticle energy systematics in table 1 the $I = 14$, 15 and 16 configurations are closest to the 3862 keV energy of the isomer reported here.

Blocked BCS Nilsson-type multi-quasiparticle calculations, as described by Jain *et al.* [17], have been performed for ^{184}W. The neutron and proton monopole pairing strengths were chosen as $G_\nu = 21.5/A$ MeV and $G_\pi = 23.1/A$ MeV, respectively. The neutron value is that used for the even-even isotone ^{186}Os [12] and the proton value is chosen to be 1.6 MeV/A higher, consistent with ref. [17]. Deformation parameters $\varepsilon_2 = 0.216$ and $\varepsilon_4 = 0.061$ [18] have been used, and an axially symmetric potential assumed. The single-particle energies were adjusted to reproduce the 1-quasineutron energies in $^{183}_{74}W_{109}$ and $^{185}_{74}W_{111}$ and the 1-quasiproton energies in $^{183}_{73}Ta_{110}$ and $^{185}_{75}Re_{110}$ [6,19]. The averages of these single-particle energies were used for $^{184}_{74}W_{110}$. Residual nucleon-nucleon interactions using the Gallagher-Moskowski coupling rules [20] are included [13]. The results (important also for future studies when firm experimental assignments are known) for the most energetically favoured 2- and 4-quasiparticle states are shown in table 2. Similar calculations for ^{184}Os [10] and ^{186}Os [12] are generally accurate to $\lesssim 160$ keV ($\lesssim 300$ keV) for 2- (4-) quasiparticle states.

In table 2 the energy of the 2480 keV state is compared with the energies of the $K^\pi = 8^-$, 9^- and 10^+ states, all of which have calculated energies close to that observed. There are several 4-quasiparticle states for which the measured excitation energy of 3862 keV lies within < 300 keV of the calculated configurations, specifically the $K^\pi = 14^-$, 15^+, 15^- and 17^- arrangements, all within the appropriate spin range of the 3862 keV state.

To aid future work the most energetically favoured 6-quasiparticle configurations are: $K^\pi = 19^-$: $E_{\text{calc.}} = 4316$ keV and $K^\pi = 22^-$: $E_{\text{calc.}} = 4849$ keV. Two favoured 8-quasiparticle states are also predicted: $K^\pi = 28^+$: $E_{\text{calc.}} = 6858$ keV and $K^\pi = 31^+$: $E_{\text{calc.}} = 7370$ keV.

The observation of the 3862 keV, $t_{1/2} = 188 \pm 38$ ns isomer in ^{184}W completes the tungsten 4-quasiparticle isomer systematics which now span the well-deformed region ranging from ^{176}W to ^{186}W [1,6–8,21]. In order to quantify the trends across this range, blocked BCS calculations have been performed for the even-even tungsten isotopes, $A = 176 \rightarrow 190$ with fixed monopole pairing strengths $G_\nu = 0.1236$ MeV and $G_\nu = 0.1291$ MeV (equivalent to $G_\nu = 22.5/A$ MeV and $G_\pi = 23.5/A$ MeV for ^{182}W), chosen to reproduce well the 4-quasiparticle energies in ^{182}W, the heaviest W isotope for which firm configuration assignments have been made [8]. Deformation parameters have been taken from ref. [18] and no adjustment of the single-particle energies was made. The results for the most yrast 4-quasiparticle isomers are shown in fig. 4.

The trends and magnitudes in the excitation energies are well reproduced by the calculations, across the whole range spanned by the experimental data. Even for ^{176}W, 6 mass units from ^{182}W for which the pairing strengths were chosen, the calculated and experimental energies agree within 220 keV. Though making extrapolations always has inherent uncertainties, these results imply the existence of energetically favoured 4-quasiparticle states in the neutron-rich nucleus ^{188}W and also, though somewhat less favoured, in the more exotic ^{190}W nuclide. The states in question are $K^\pi = 15^-$, $E_{\text{calc.}} = 2832$ keV (^{188}W) and $K^\pi = 17^-$, $E_{\text{calc.}} = 3586$ keV (^{190}W). The possibility of long-lived yrast traps existing in ^{188}W and ^{190}W is topical as these nuclei are now within reach of current experimental facilities, via, for example, multi-nucleon transfer from osmium targets, or relativistic fragmentation [22].

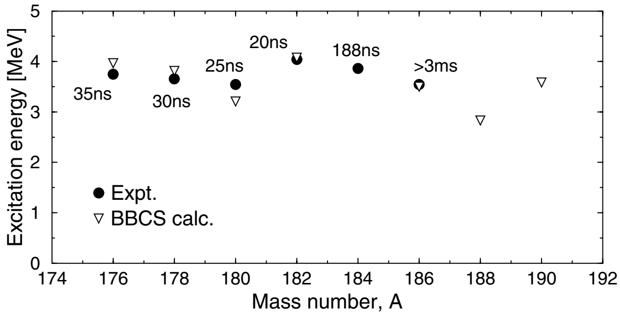

Fig. 4. Tungsten low-lying 4-quasiparticle isomer systematics for $A = 176 \rightarrow 190$, experimental energies (circles) and the corresponding blocked BCS energies including residual nucleon-nucleon interactions (triangles). (See text for details.)

In summary, a seniority-4 $t_{1/2} = 188 \pm 38$ ns isomer at 3862 keV has been identified in ^{184}W during the bombardment of a ^{198}Pt target by a ^{136}Xe beam. Comparisons with blocked BCS calculations indicate several candidates for the configurations of the newly observed states. The variations in the excitation energies of the most yrast 4-quasiparticle isomeric states are well reproduced by blocked BCS calculations and suggest exciting possibilities for future work to study, for example, ^{188}W, for which a highly favoured 4-quasiparticle state is predicted.

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References

1. C. Wheldon *et al.*, Phys. Lett. B **425**, 239 (1998).
2. R. D'Alarcao *et al.*, Phys. Rev. C **59**, R1227 (1999).
3. J. Glatz, K.E.G. Löbner, F. Oppermann, Z. Phys. **227**, 83 (1969).
4. P. Kleinheinz, P.J. Daly, R.F. Casten, Nucl. Phys. A **208**, 93 (1973).

5. M.W. Simon, D. Cline, C.Y. Wu, R.W. Gray, R. Teng, C. Long, Nucl. Instrum. Methods Phys. Res. A **452**, 205 (2000).
6. R.B. Firestone, V.S. Shirley (Editors), *Table of Isotopes*, 8th edition (John Wiley and sons, 1996).
7. K.C. Yeung, PhD Thesis, University of Surrey (1993), unpublished.
8. T. Shizuma, S. Mitarai, G. Sletten, R.A. Bark, N.L. Gjørup, H.J. Jensen, J. Wrzesinski, M. Piiparinen, Nucl. Phys. A **593**, 247 (1995).
9. C. Wheldon, PhD Thesis, University of Surrey (1999), unpublished.
10. C. Wheldon *et al.*, Nucl. Phys. A **699**, 415 (2002).
11. T. Shizuma, P.D. Stevenson, P.M. Walker, Y. Toh, T. Hayakawa, M. Oshima, K. Furuno, T. Komatsubar, Phys. Rev. C **65**, 064310 (2002).
12. C. Wheldon, P.M. Walker, P.H. Regan, T. Saitoh, N. Hashimoto, G. Sletten, F.R. Xu, Phys. Rev. C **59**, R2334 (1999); Nucl. Phys. A **652**, 103 (1999).
13. F.G. Kondev, PhD Thesis, Australian National University (1997), unpublished.
14. F. Rösel, H.M. Fries, K. Alder, H.C. Pauli, At. Nucl. Data Tables **21**, 291 (1978).
15. B. Fornal *et al.*, Acta. Phys. Pol. B **26**, 357 (1995).
16. P. Alexander, F. Boehm, E. Kankeleit, Phys. Rev. **133**, B284 (1964).
17. K. Jain, O. Burglin, G.D. Dracoulis, B. Fabricus, N. Rowley, P.M. Walker, Nucl. Phys. A **591**, 61 (1995).
18. R. Bengtsson, S. Frauendorf, F.-R. May, At. Data Nucl. Data Tables **35**, 15 (1986).
19. A.K. Jain, R.K. Sheline, P.C. Sood, Kiran Jain, Rev. Mod. Phys. **62**, 393 (1990).
20. C.J. Gallagher, S.A. Moskowski, Phys. Rev. **111**, 1282 (1958).
21. C.S. Purry *et al.*, Nucl. Phys. A **632**, 229 (1998).
22. Zs. Podolyák *et al.*, Phys. Lett. B **491**, 225 (2000).