Lifetimes of high spin states in ^{181}Ir and ^{180}Os

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The ^{150}Nd(^{35}Cl,4n)^{181}Ir and ^{150}Nd(^{34}S,4n)^{180}Os reactions have been used to study the lifetimes of high-spin states in ^{181}Ir and ^{180}Os using the recoil-distance technique. The lifetimes of four states in ^{181}Ir and three yrast states in ^{180}Os have been determined. The mean weighted values of quadrupole moments deduced for the measured rotational transitions between yrast states in ^{181}Ir and ^{180}Os, $Q_0=(6.0\pm0.2)\ e$ b and $Q_0=(6.1\pm0.4)\ e$ b, respectively, are equal within experimental errors.

INTRODUCTION

The osmium and iridium nuclei lie in the beginning of the transitional region between the well-deformed rare-earth nuclei and the spherical lead isotopes. Nuclei in this region are believed to be soft to changes in deformation. Therefore the different backbending behavior of the Ir and Os isotones (e.g., in ^{181}Ir, a distinct backbending is observed in the yrast band at $\hbar\omega=0.30$ MeV while in the core nucleus, ^{180}Os, only an upbending has been observed at a close but different value of $\hbar\omega=0.27$ MeV)[1] has sometimes been attributed to significantly larger deformation of the Ir isotones. This change in deformation would be caused by the polarization of the Osmium core by the odd proton. Indeed, the different backbending behavior of the $h_{9/2}$ proton band in ^{181}Re and the rotational bands in ^{181,182}Os has been interpreted by Frauendorf *et al.*[2,3] as arising from the driving of the Re nucleus by the $h_{9/2}$ proton configuration to a deformation that is $\sim 10\%$ larger than that for the Os nuclei. Faessler *et al.*,[4] on the other hand, explain existing puzzles in the Os-Re region in terms of the γ softness of these nuclei combined with a substantial variation of β_2 and β_4 ground-state deformations in this mass region. These hypotheses have not yet been verified experimentally, however. Indeed, there is no straightforward way to measure the nuclear deformation even though the dependence of some physical observables (such as the moment of inertia and the quadrupole moment) on deformation parameters can be easily calculated in the framework of the rotational model. Unfortunately, the moment of inertia deduced from level spacings may be strongly influenced by the spin-alignment phenomenon. Therefore, the quadrupole moment seems to be a more appropriate experimental quantity for deducing nuclear deformation parameters. This moment can be calculated in a model-dependent way from the lifetimes of the rotational levels.

With the specific purpose of testing the hypotheses mentioned above, we have measured the lifetimes of the rotational states in the pair of $N=104$ isotones, ^{181}Ir and ^{180}Os. Both of these nuclei can be produced using the same ^{150}Nd target, thereby reducing the uncertainties associated with differences in the target structures. The respective level schemes are known from previous studies[1,5–7] and partial level schemes relevant to this work are reproduced in Fig. 1. In this paper, we discuss the results of the lifetime measurements together with the possible physical interpretation of these results. We find that the values of the quadrupole moments Q_0 for ^{180}Os and ^{181}Ir are equal within experimental errors and our results do not support the picture of a significant change in the deformation parameter β_2; however, rather small changes in β_4 and/or γ deformations might be responsible for the observed differences in the backbending behavior of these nuclei.

EXPERIMENTAL PROCEDURES

The experiments are carried out with ^{35}Cl and ^{34}S beams obtained from the Argonne Tandem Superconducting Linear Accelerator system (ATLAS) at energies of 155 and 157 MeV, respectively. These energies were found to optimize the yield of the 4n reaction channels. An enriched ($\sim 96\%$), self-supporting, 1-mg/cm^2 ^{150}Nd target was used and gamma rays were detected at 0° with an intrinsic Ge detector in coincidence with an 8-element large Na(Tl) Sum Spectrometer. The 4n reaction channel was optimized by using appropriate cuts on the total energy spectra and the selection of high-spin states was enhanced by requiring that at least three of the eight segments of the sum spectrometer fire in prompt coincidence with the Ge detector for an event to be acceptable.

Lifetimes in the picosecond region were measured using the recoil distance method[8] (RDM) with the Argonne plunger device.[9] The target could be moved by three computer-controlled dc actuators, allowing for an accuracy of 1 μm in the positioning of the catcher foil. The actual distance between target and catcher was also determined by measuring the capacitance; such measurements were carried out before, during and after the beam was on the target. In a least-squares procedure, a relation between capacitance and distance was fitted to the data points with two free parameters: the capacitance of surrounding material and a zero-offset distance. The re-

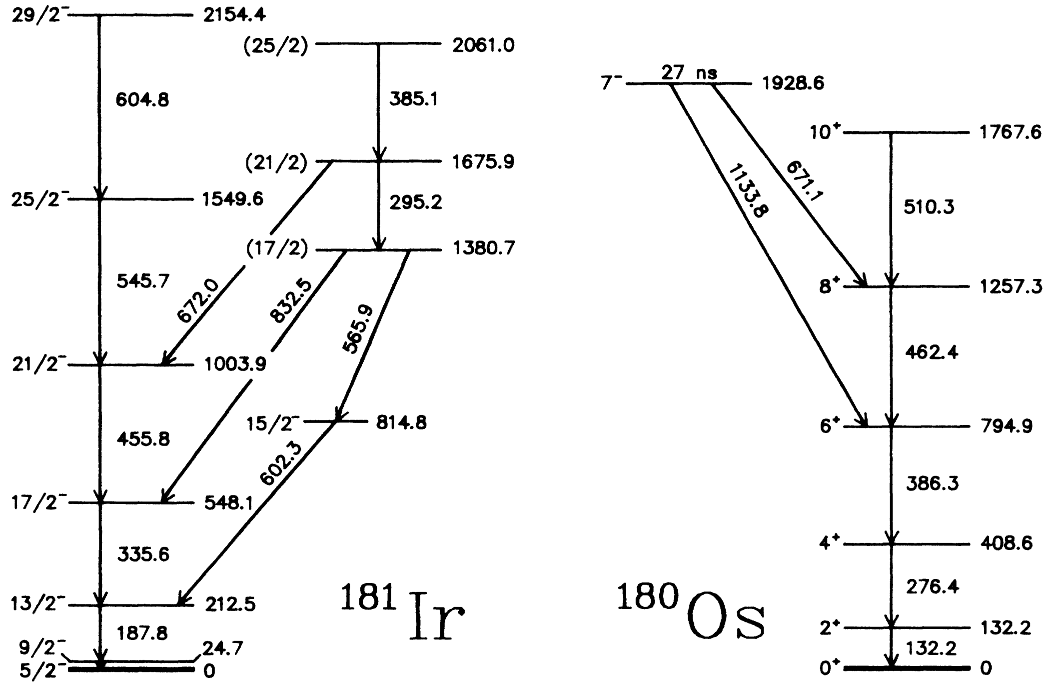

FIG. 1. Partial level schemes of ^{181}Ir (Refs. 1 and 5) and ^{180}Os (Ref. 7).

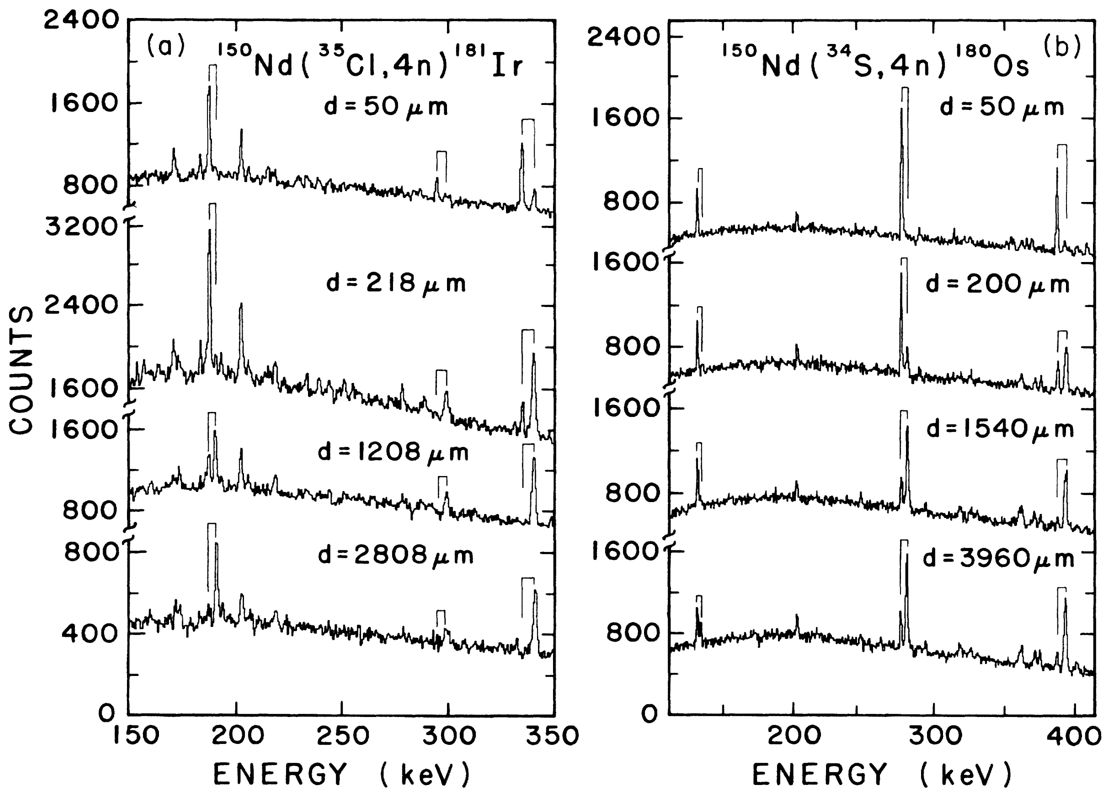

FIG. 2. (a) Sample spectra for ^{181}Ir at several target-to-stopper distances as noted. The positions of the unshifted and shifted components of the Ir lines are indicated. (b) Same as (a) for ^{180}Os.

sulting closest average target-catcher distance (corresponding to electrical contact) was 23 μm. Observed variations of ± 3 μm were probably caused by target heating during irradiations. The γ-ray spectra were measured at 16 distances in the range 30-4000 μm and recorded in coincidence mode. Sample spectra for the two nuclei at several target-to-stopper distances are displayed in Fig. 2.

DATA ANALYSIS

The area of the shifted (in flight) and unshifted (stopped) components of γ peaks of interest were extracted using the peak-fitting code SKEWGAUSS,[10] modified to include different shapes of both components of a given transition. The lifetimes were extracted from the distance dependence of the ratios, R, of the unshifted component intensity to the sum of the unshifted and shifted component intensities, using a computer code PLUNGER[11] that includes cascade feeding as an integral part of the time behavior of each transition. The program also includes a number of higher-order corrections. Listed in decreasing order of importance, they are finite target thickness, ion position, and velocity dependence of subtended solid angles, detector size and differential absorption, detector efficiency, and attenuation of angular distribution. The program was written as the FCN subroutine to the minimization code MINUIT[12] which is capable of extracting errors reliably even when correlations among the various fitting parameters are strong. A complete set of available RDM data on a given nucleus can, therefore, be fitted in one computer minimization run. However, due to the highly nonlinear behavior of the functions describing the feeding and the strong correlations between some fitted parameters, we have adopted the procedure of fitting the data beginning from the highest transition and adding the data for transitions lower down in the cascade in each successive step. This approach is particularly useful from the point of view of error analyses.

RESULTS

^{181}Ir nucleus

The lifetimes of all levels and transitions for which reliable data could be obtained are summarized in Table I. An example of fits to the experimental data is shown in Fig. 3. No reliable lifetime information could be obtained for the $\frac{25}{2}^-$ level at 1549.6 keV (Fig. 1) because the 604.8-keV feeding transition is quite weak and not sufficiently resolved from contaminant transitions of similar energy observed in the experiment. However, an upper limit can be given from the apparent lifetime of the 545.7-keV transition deexciting this level. The experimental values of R for this transition exhibit a steep slope with $\tau_{\text{slope}} \cong 4$ ps at relatively large distances (36-78 μm) and can be fitted only by assuming a cascade of several feeding transitions with mean lifetimes much smaller than τ_{slope}. In order to take this effect into account while keeping the number of free parameters to a minimum, an analytical formula was derived for the ratio, R_n, of the

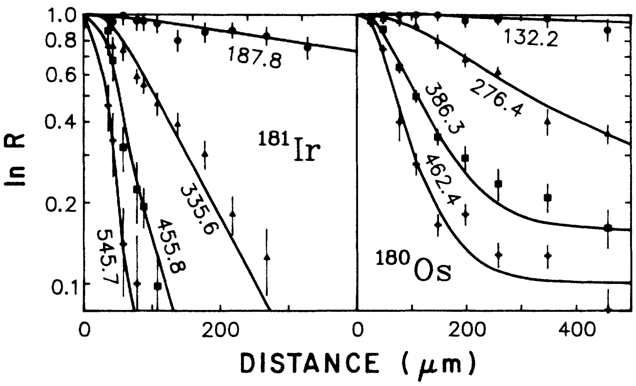

FIG. 3. Examples of fits to the RDM experimental data for the indicated transitions.

intensity of unshifted component to the sum of intensities of shifted and unshifted components of the n^{th} transition in the cascade of n transitions with the same mean lifetime τ:

$$R_{n(d)}=\exp\left[-\frac{d}{v\tau}\right]\sum_{k=0}^{n-1}\frac{\left[\frac{d}{v\tau}\right]^k}{k!}\,, \qquad (1)$$

where d is target to stopper distance and v is recoil velocity.

Assuming $\tau=1$ ps for the cascade of preceding transitions, the best fit to experimental R values for the 545.7-keV transition can be obtained for $n=6$ transitions which appears to be a reasonable multiplicity of the feeding rotational transitions. This choice of τ and n is obviously not unique—a fit of similar quality can be obtained by using other, not very different, pairs of values of τ and n fulfilling approximately the experimental condition $n\tau \cong 6$ ps necessary to get a good fit in this particular case. Therefore, the resulting lifetime of the 545.7-keV transition, $\tau=(2.7\pm0.8)$ ps, should be treated as an approximate upper limit of the lifetime of the deexciting level.

The effect discussed above can also be taken into account in the fitting procedure, to a very good approximation, by treating the distance d as a free parameter and this procedure is much less time consuming than the use of formula (1). The resulting shift $\Delta d \cong nv\tau$ gives a rough estimate of n and τ in formula (1). For the case discussed above, this procedure gives $\tau(546\text{ keV})=(3.4\pm1.2)$ ps and $\Delta d_{\text{fit}} \cong (-30\pm8)$ μm compared to the values (2.7 ± 0.8) ps and $\Delta d_{\text{est}}=-28$ μm (estimated using $n=6$, $v=4.62$ μm/ps and $\tau=1$ ps), respectively, obtained under assumption of cascade feeding of the 1549.6-keV level with the use of formula (1). For the levels with lifetimes much longer than $n\tau$ the differences in results obtained using both approaches becomes negligible compared to the statistical errors.

Another effect that could contribute to a higher value of R than expected for a given distance d and lifetime τ is the roughness of the target and/or stopper surface which leads to an averaging of the R value over the target-stopper distances d. However, as shown below, this effect is rather small in our measurements. Assuming a Gauss-

TABLE I. Mean lifetimes, $B(E2)$ values and quadrupole moments.

	E_γ (keV)	I_i^π	τ (ps)	$B(E2)$ ($e^2\,b^2$)	Q_0 (e b)	$\tau_{\rm calc}^{\rm a}$ (ps)
^{181}Ir	187.8	$\frac{13}{2}^-$	215±15	1.13±0.08	6.0±0.2	210
	335.6	$\frac{17}{2}^-$	14±3	1.3±0.3	6.3±0.7	14.8
	455.8	$\frac{21}{2}^-$	3.4±1.2	1.2±0.4	6.0±1.0	3.2
	545.7$^{\rm b}$	$\frac{25}{2}^-$	2.7±0.8			1.3
	295.2	($\frac{21}{2}$)	10±2	2.4±0.6	8.6±1.2	26.5
	385.1$^{\rm b}$	($\frac{25}{2}$)	15±5			7.3
^{180}Os	132.2	2^+	$(1.16^{+0.3}_{-0.2})\times10^3$	0.70±0.15	5.9±0.6	1094
	276.4	4^+	39±5	1.16±0.15	6.4±0.4	42.9
	386.3	6^+	9.7±2.5	0.9±0.2	5.5±0.7	7.9
	462.4$^{\rm b}$	8^+	10±2			3.1

$^{\rm a}\tau_{\rm calc}$ obtained using a constant $Q_0=6.1$ e b.
$^{\rm b}$Apparent mean lifetime of gamma transition under assumption of delayed cascade feeding; see discussion of results.

ian distribution of distances around mean distance d_0 with sharp cutoff at $d_0\pm2\sigma$, where the mean deviation σ is a measure of target surface irregularities, the effective value of R for a single transition with mean lifetime τ is

$$R_{\rm eff}(d_0)\cong\exp\left[-\frac{d_0}{v\tau}\right]\exp\left[\frac{\sigma^2}{2v^2\tau^2}\right]. \qquad (2)$$

This effect can be easily accounted for in the fitting procedure by an artificial distance shift $\Delta d=-\sigma^2/(2v\tau)$. The contribution of this effect can be estimated using the closest experimental target to catcher distance 23 μm as an approximate value of 2σ. Thus, with the observed recoil velocity $v\cong4.62$ μm/ps and a mean lifetime of the order 3 ps as deduced for the 545.8-keV transition, one obtains a Δd of about -6 μm, much lower than $\Delta d\cong-30$ μm necessary to fit the experimental data for the 545.7-keV transition, as discussed above.

The lifetime of the ($\frac{25}{2}$) level at 2061 keV also could not be obtained because the observed feeding transition is very weak. The apparent lifetime $\tau=(15\pm5)$ ps of the deexciting 385-keV transition is surprisingly high, probably indicating the existence of feeding from an isomeric level with a lifetime of similar value. In this case, the effect of fast-cascade feeding discussed above is too small to be extracted reliably.

The RDM data for the 565.9-, 602.3-, 672.0-, and 832.5-keV interband transitions could not be extracted from this experiment because the observed transition intensities were either too low or obscured by unresolved transitions. Hence, the lifetime of the ($\frac{17}{2}$) level at 1380.7 keV could not be measured directly and was only crudely estimated to be 20±15 ps from simultaneous fits to all available data.

^{180}Os nucleus

The 510.3-keV transition feeding the 8^+ level in ^{180}Os is obscured by the background of the annihilation radiation and therefore no lifetime could be obtained for this level. The RDM data for the 462.4-keV transition deexciting the same level indicate the presence of a long-lived component with $\tau\gg4$ ns which can be attributed to feeding from the known 27 ns isomeric level at 1929 keV (Fig. 1). A good fit to the experimental data for this transition can be obtained only by assuming the presence of a fast cascade feeding this level (as in the case of the 545.7-keV transition in ^{181}Ir). For this transition, the best fit values of parameters in formula (1) are $n=7$ and $\tau=1$ ps. The alternative approach of fitting the distance d gives $\Delta d\cong-28\pm6$ μm, which is consistent with the estimated -33 ps obtained from $\Delta d\cong-nv\tau$ using n and τ from the previous approach and the experimental value of $v=4.70$ μm/ps for the recoil velocity. All these parameters, which gave the best fit to the 462.4-keV transition data, were used in subsequent fits of the cascade transitions below this transition. The results for this nucleus are also given in Table I and an example of the fits to the experimental data is shown in Fig. 3.

DISCUSSION

In addition to the results shown in Table I, the partial lifetime for the interband 672.0-keV transition can be calculated as τ_γ (672 keV)=(38±13) ps using the lifetime of the 1675.9-keV level and experimental branching ratio I_γ(295 keV)/I_γ(672 keV)=0.4±0.1. The Weisskopf estimates of mean lifetime τ of this transition are 1.0×10^{-3}, 98, and 0.10 ps assuming, respectively, $E1$, $E2$, and $M1$ multipolarity. Resulting hindrance factors relative to the single-particle estimates would be 3.0×10^4, 0.4, and 3.6×10^2, respectively. These values are quite common in this nuclear region for transitions of the respective multipolarities; no definite multipolarity assignment of this transition and, consequently, of the parity of the side band can, therefore, be made on the basis of these data.

The reduced transition probabilities $B(E2)$ have been calculated[13] for all rotational transitions using the measured lifetimes, internal conversion coefficients[14] and, wherever necessary, the respective experimental branching ratios. All intraband rotational transitions have $B(E2)$ values of the order of 200 W.u., implying a high degree of collectivity; both nuclei are good rotors. The use of the rotational model formula for deducing the quadrupole moments and estimating deformation parameters, thus, appears to be justified.

In the framework of the rotational model with axial symmetry, the quadrupole moments can be calculated using relation

$$B(E2,I\rightarrow I-2)=\frac{5}{16\pi}Q_0^2\langle IK20|I-2K\rangle^2 \ . \tag{3}$$

The weighted mean values of quadrupole moments Q_0 in the yrast cascades are (6.0 ± 0.2) e b and (6.1 ± 0.4) e b for ^{181}Ir and ^{180}Os, respectively; the latter is in excellent agreement with the value of $Q_0=6.14$ e b calculated by Ragnarsson *et al.*[15] The deformation parameter β_2, although model dependent, is quite useful because of its easy visualization. It is related to Q_0, in the first order approximation, by the formula

$$\beta_2=\frac{(5\pi)^{1/2}}{3ZR_0^2}Q_0 \tag{4}$$

with $R_0=1.2$ A$^{1/3}$ fm. In this approximation, the quadrupole deformation parameters 0.223 ± 0.008 and 0.231 ± 0.015, deduced for ^{181}Ir and ^{180}O, respectively, are equal within experimental errors, in apparent contrast with the aforementioned hypothesis that these two nuclei might have significantly different deformations.

The deduced quadrupole moment, however, depends not only on the quadrupole deformation parameter but also on parameters related to other degrees of freedom, such as the triaxial and hexadecapole deformations. Therefore, it is not possible to deduce all deformation parameters in a unique way. However, from the experimental value of Q_0, it is possible to extract pairs of β_2 and β_4 which, for a given γ, reproduce this value of Q_0 within the framework of the used model dependence. An example of dependence of deformation parameters β_4 on β_2 for $\gamma=0°$ and $\gamma=15°$ in ^{181}Ir is shown in Fig. 4 for $Q_0=6.0$ e b. In the vicinity of $\beta_4=-0.04$, the value expected[15-17] for this nuclear region, the experimental values of Q_0 restrict the quadrupole deformation parameter to values very close to $\beta_2\approx0.22$ for both ^{181}Ir and ^{180}Os, assuming the same value of the triaxial deformation γ.

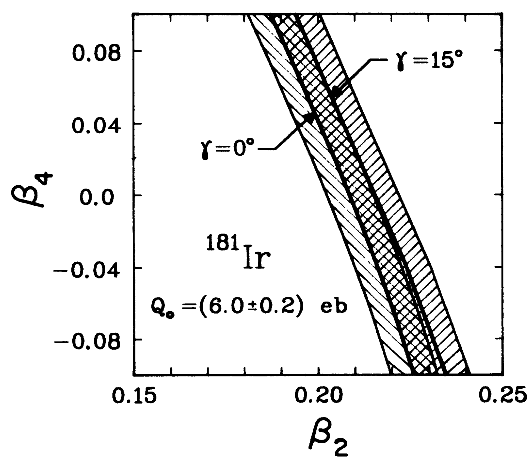

FIG. 4. Pairs of β_2 and β_4 values reproducing the experimental value of Q_0 for ^{181}Ir, assuming $\gamma=0^0$ and $\gamma=15°$, respectively.

The only possibility of obtaining significantly different β_2 values for these two nuclei, consistent with the Q_0 values deduced from these measurements, would require drastically different values of the triaxial parameter γ and/or the hexadecapole parameter β_4 for them. That, in turn, would imply that the $h_{9/2}$ orbital is very strongly shape driving. The calculations,[15-17] on the other hand, indicate that these shape parameters do not differ very much in these two nuclei. The question as to what causes the different backbending behavior in ^{180}Os and ^{181}Ir, therefore, still remains. Our measurements, while effectively ruling out very different deformations as the cause thereof, do leave the possibility that small differences in the γ deformation and/or different gamma softness for the $\frac{1}{2}^-$ [541] proton orbital in ^{181}Ir and ^{180}Os might be responsible for the different backbending behavior of their respective yrast bands.

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[1]U. Garg, E. R. Marshalek, A. Chaudhury, E. G. Funk, R. Kaczarowski, J. W. Mihelich, D. Frekers, R. V. F. Janssens, D. Radford, and A. M. van den Berg, Phys. Lett. **151B**, 335 (1985).
[2]S. Frauendorf, F. R. May, and V. V. Pashkevich, in *Proceedings of the International Symposium on Future Directions in Studies of Nuclei Far from Stability, Nashville, 1979,* edited by J. A. Hamilton (North-Holland, New York, 1980), p. 133.
[3]S. Frauendorf, Phys. Scr. **24**, 349 (1981).
[4]A. Faessler, M. Ploszajczak, and K. R. Sandhya Devi, Nucl. Phys. **A301**, 382 (1978).
[5]R. Kaczarowski, U. Garg, E. G. Funk, and J. W. Mihelich (unpublished).
[6]G. D. Dracoulis, C. Fahlander, and M. P. Fewell, Nucl. Phys. **A383**, 119 (1982).
[7]R. M. Lieder, A. Neskakis, J. Skalski, G. Sletten, J. D. Garret, and J. Dudek, Nucl. Phys. **A476**, 545 (1988).
[8]T. K. Alexander and J. S. Foster, Adv. Nucl. Phys. **10**, 197

(1979); U. Garg, A. Chaudhury, M. W. Drigert, E. G. Funk, J. W. Mihelich, D. C. Radford, H. Helppi, R. Holzmann, R. V. F. Janssens, T. L. Khoo, A. M. van den Berg, and J. L. Wood, Phys. Lett. B **180**, 319 (1986).

[9]F. Azgui, H. Emling, E. Grosse, C. Michel, R. S. Simon, W. Spreng, H. J. Wollersheim, T. L. Khoo, P. Chaudhury, D. Frekers, R. V. F. Janssens, A. Pakkanen, P. J. Daly, M. Kortelahti, D. Schwalm, and G. Seiler-Clark, Nucl. Phys. **A439**, 573 (1985).

[10]Computer code SWEWGAUSS available from National Technical Information Service, Dept. A., Springfield, VA 22151.

[11]S. Rozak, Doctoral thesis, University of Notre Dame, 1981 (unpublished); also computer code PLUNGER, available from Nuclear Spectroscopy Computer Library, Department of Physics, University of Notre Dame, Notre Dame, IN 46556.

[12]P. James and M. Roos, Comp. Phys. Comm. **10**, 343 (1975).

[13]A. Bohr and B. Mottelson, *Nuclear Structure* (W. A. Benjamin, New York, 1969), Vol. 1.

[14]F. Rosel, H. M. Fries, K. Alder, and H. C. Pauli, At. Data Nucl. Data Tables **21**, 291 (1978).

[15]I. Ragnarsson, A. Sobiczewski, R. K. Sheline, S. E. Larsson, and B. Nerlo-Pomorska, Nucl. Phys. **A233**, 329 (1974).

[16]S. G. Nilsson, Chin Fu Tsan, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I.-L. Lamm, P. Möller, and B. Nilsson, Nucl. Phys. **A131**, 1 (1969).

[17]C. Ekström, H. Rubinsztein, and P. Möller, Phys. Scr. **14**, 199 (1976).