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Lifetime Measurements and Identical SD Bands in the A=190 and A=150 Regions

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The lifetimes of states in Superdeformed (SD) bands in ^{192,194}Hg, ^{151,152}Dy, and ^{151}Tb have been measured using the Doppler shift attenuation method. Intrinsic quadrupole moments Q_0 have been extracted for SD bands in these nuclei. It was found that the quadrupole moments for the "identical" SD bands in these nuclei are the same. In the A=150 region, changes were found in the Q_0 values as a function of the number of high-N intruder orbitals. Changes are present also for excited SD bands with the same high-N content. Recent calculations account for most of the observations in the A=150 region.

I. INTRODUCTION

Following the discovery of a band of coincident γ rays with nearly constant energy separation in ^{152}Dy [1], the large deformation associated with this band was established [2] with a lifetime measurement. With the discovery of similar bands in this mass region, lifetime measurements confirmed their superdeformed character. Similarly, the large deformation associated with a band in ^{191}Hg [3] was confirmed with lifetime measurements. The limited sensitivity of the early generation of γ-ray detection arrays, however, restricted lifetime measurements to the most strongly populated (yrast) SD bands. With the new generation detector arrays coming online, the possibility of performing detailed lifetime measurements on excited SD bands has become a reality.

One of the most intriguing aspects of superdeformation is the existence of pairs of "identical" SD bands [4]. These bands have γ-ray energies that are equal or exhibit a simple relationship to each other (i.e., energies in one band fall at the mid-point energies in the other). Of interest to the present work are two spectacular examples of identical SD bands in both the A=150 and A=190 regions; band 4 of ^{151}Dy has γ-ray energies that fall almost exactly at the mid-point energies of band 1 of ^{152}Dy, and the γ-ray energies of ^{194}Hg band 3 are identical to those in ^{192}Hg band 1 over nearly the entire energy range [4]. The equality of the γ-ray energies requires that the nuclear moments of inertia to be equal to $\sim 0.2\%$. With the improved resolving power provided by the new arrays, it now becomes possible to perform precise lifetime measurements which may shed light on the properties of the identical bands.

II. MEASUREMENTS IN THE A=190 REGION

A. Experimental conditions

In order to establish the relative deformations associated with SD bands, care must be taken to minimize systematic uncertainties, especially those associated with stopping powers. We have used (^{48}Ca,4n) reactions on ^{148}Nd and ^{150}Nd targets to measure lifetimes in the SD bands of ^{192}Hg and ^{194}Hg, respectively. The beams were supplied by the 88 inch cyclotron at Lawrence Berkeley National Laboratory. In each case, the Nd targets were 1.0 mg/cm^2 thick and the recoiling nuclei were slowed down and brought

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to rest in Au backings. For the ^{192}Hg measurement, the beam energy of 205 MeV results in a calculated mid-target $v_0/c = 0.0230$, $l_{max} = 47\hbar$, and $E^* = 19$ MeV. In the case of ^{194}Hg the beam energy of 202 MeV results in $v_0/c = 0.0226$, $l_{max} = 45\hbar$, and $E^* = 21$ MeV. It is important to note that since the same stopping material was used and the velocity profiles and nuclear charges are the same for both ^{192}Hg and ^{194}Hg, the difference in stopping powers is negligible.

The γ rays were measured at Gammasphere during two separate beamtimes. The first experiment was performed at a time when Gammasphere consisted of 55 detectors arranged into 11 angular rings, ranging from 17° to 163° with respect to the beam direction. Approximately 1×10^9 triples and higher fold events were recorded for both ^{192}Hg and ^{194}Hg. The second experiment was performed when 85 detectors were present in Gammasphere and were arranged into 16 angular rings ranging from 32° to 163° with respect to the beam direction. In this beamtime, some 1.8×10^9 quadruple and higher fold events were recorded for ^{194}Hg.

B. Analysis and results

Angle sorted spectra were constructed by combining double gates set on stopped and nearly stopped transitions at the bottom of each of the SD bands. Care was taken to ensure that consistent gating conditions were applied to each of the SD bands studied. As is customary for this type of measurement, fractions of the full Doppler shift $F(\tau)$ were extracted from the spectra using the first order relation

$$F(\tau) = \frac{\overline{E_\gamma} - E_{\gamma 0}}{E_{\gamma 0}\beta_0 \cos\theta},$$

where $\overline{E_\gamma}$ is the centroid of the γ-ray energy distribution as measured in a detector located at angle θ with respect to the beam direction, $E_{\gamma 0}$ is the unshifted γ-ray energy, and β_0 is the mid-target initial recoil velocity.

In order to extract the intrinsic quadrupole moments Q_0 for the various SD bands, computer simulations of the γ-decay of the recoiling nuclei were performed using the code FITFTAU. The simulations all used stopping powers obtained from the 1995 version of the code TRIM by Ziegler [5]. The simplest version of the simulation makes the following basic assumptions: (1) the Q_0 values are constant within a given SD band, and the partial decay rate T (in ps^{-1}) of a band member of spin I is described within the rotational model by the expression:

$$T(I \rightarrow I{-}2) = 1.22 E_\gamma^5 Q_0^2 <IK20|(I{-}2)K>^2$$

where E_γ is the γ-ray energy in MeV, (2) the sidefeeding into each SD state has exactly the same time structure as the main band, (3) any delay in feeding a band was approximated by a one-step delay. This model (referred to as model I) then describes the band in terms of two fit parameters, namely Q_0 and τ_{delay} and a two-dimensional χ^2 minimization was performed.

In addition to the model described above, a more realistic model (model II) of the sidefeeding was also used in the analysis. In this model, the sidefeeding is assumed to consist of rotational bands having the same moment of inertia (γ-ray energies) as the main cascade. All sidefeeding cascades were assumed to have a common quadrupole moment Q_{SF} with additional one-step feeding delays (τ_{delay}) at the top. Furthermore, the number of transitions in the sidefeeding cascades was assumed to be proportional to the length of the main cascade above the state of interest. Three fit parameters were therefore used in this case, Q_0, Q_{SF}, and τ_{delay}, and a three-dimensional χ^2 minimization was performed.

The results of the centroid shift analysis are presented in table I, and examples of fits to ^{192}Hg band 1 are shown in Fig. 1. From these results it is clear that model II gives much better fits to the data. This is an indication that the simple treatment of sidefeeding used in model I is inadequate to describe the complicated feeding patterns of the SD bands. The values of Q_{SF} obtained from model II fits to the data are significantly lower than those in the main band. However, given the incomplete knowledge of the "true" characteristics of the sidefeeding and the assumptions that went into this model (i.e. same $\mathcal{J}^{(2)}$, number of transitions in SF cascades), it would be premature to assign too much significance to the Q_{SF} values. One should note that the in-band Q_0 values increase by $\sim 10\%$ when this model of the sidefeeding is used.

With the exception of ^{194}Hg band 1, the in-band Q_0 values are very similar from band to band. The measured value for band 1 in ^{194}Hg is larger than that reported by Hughes *et al* [6], while the value obtained for band 2 is similar to that measured previously. A detailed lineshape analysis is in progress for all of the SD bands reported here. Preliminary results for the yrast SD bands in ^{192,194}Hg indicate that the difference in average Q_0 values is somewhat smaller, 17.6 ± 1.8 eb versus 18.4 ± 1.1 eb for ^{192}Hg and ^{194}Hg, respectively. The lineshape fits also indicate that the Q_0 values are essentially constant over the range of transition energies measured.

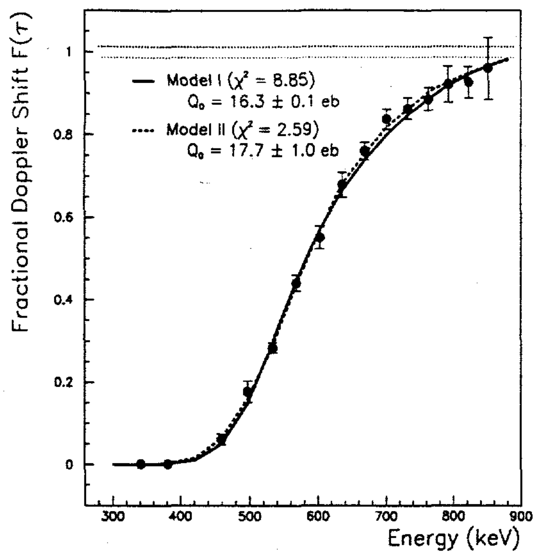

FIG. 1. Fits to the fraction of the full Doppler shift for band 1 in ^{192}Hg using both models described in the text. The dotted horizontal lines represent the spread in recoil velocities due to the slowing down of the beam through the target.

TABLE I. Summary of centroid shift analysis results for SD bands in ^{192,194}Hg. The last column for each model lists the total and reduced best-fit χ^2 values.

Model I Band	Q_0 (eb)	τ_{delay} (fs)	χ^2/χ^2_ν
^{192}Hg (1)	16.2 ± 0.1	1^{+7}_{-1}	8.85/0.68
^{194}Hg (1)	17.3 ± 0.2	34^{+8}_{-12}	8.11/0.62
^{194}Hg (2)	$17.2^{+0.2}_{-0.3}$	24^{+13}_{-19}	4.88/0.44
^{194}Hg (3)	$16.3^{+0.3}_{-0.1}$	1^{+18}_{-1}	7.13/0.71

Model II Band	Q_0 (eb)	Q_{SF} (eb)	τ_{delay} (fs)	χ^2/χ^2_ν
^{192}Hg (1)	17.7 ± 1.0	10.9 ± 1.0	6 ± 6	2.59/0.22
^{194}Hg (1)	$19.2^{+0.4}_{-0.8}$	$10.0^{+1.2}_{-0.4}$	39 ± 6	4.01/0.33
^{194}Hg (2)	17.6 ± 0.6	11.6 ± 1.2	28^{+3}_{-6}	3.03/0.28
^{194}Hg (3)	17.7 ± 0.8	10.8 ± 0.8	$3.5^{+5.0}_{-3.5}$	2.95/0.33

The most interesting result obtained from this analysis is that the Q_0 values for the identical SD bands, ^{192}Hg (1) - ^{194}Hg (3), are equal to each other. *This result is independent of the sidefeeding assumptions used in the analysis.* While the experimental errors are too large to determine whether the deformation in ^{194}Hg (3) is slightly smaller to compensate for the increase in mass with respect to ^{192}Hg, it is clear that there can be no *large* differences in deformation. As will be shown below, similar results have been obtained from differential DSAM measurements in the A~150 region. For SD bands in ^{151}Dy [7] and ^{149}Gd [8], which are identical to the yrast SD band in ^{152}Dy, the intrinsic quadrupole moments were all found to have the same value.

III. MEASUREMENTS IN THE A=150 REGION

A. Experimental conditions

The differential lifetime measurements in the A=150 region were performed at a time when 56 Compton-suppressed Ge detectors were present in Gammasphere. A 175 MeV ^{34}S beam was provided by the 88 Inch cyclotron at LBNL on a target which consisted of a 1 mg/cm^2 ^{122}Sn layer evaporated on a 20 mg/cm^2 Au backing. In this experiment, ^{151}Dy nuclei were produced via the dominant (^{34}S,5n) fusion-evaporation reaction while the ^{152}Dy and ^{151}Tb nuclei resulted from the weaker (^{34}S,4n) and (^{34}S,p4n) channels, respectively. A total of 1.5×10^9 triple and higher fold coincidence events were recorded.

The fractional Doppler shifts F(τ) were obtained for transitions in four SD bands in ^{151}Dy, as well as for γ rays in the yrast SD bands in ^{152}Dy and ^{151}Tb. The F(τ) values were extracted from the data, as described earlier, under the assumption that F(τ) = 1.0 corresponds to the v/c of nuclei formed at the center of the target. For the present experiment, a calculation of the mid-target recoil velocity gives $\beta_0 = 0.0227$. If one assumes isotropic evaporation of particles in the rest frame of the recoiling compound nuclei, all residues should have the same value for β_0. Furthermore, the velocity profiles for the ^{151,152}Dy nuclei should be the same over the full stopping range, while that for ^{151}Tb may be somewhat different due to electronic stopping power differences resulting from the different Z value. The experimental F(τ) points are presented in Fig. 2. With the exception of ^{152}Dy, all data points approach F(τ) = 1.0 at the highest γ-ray energies.

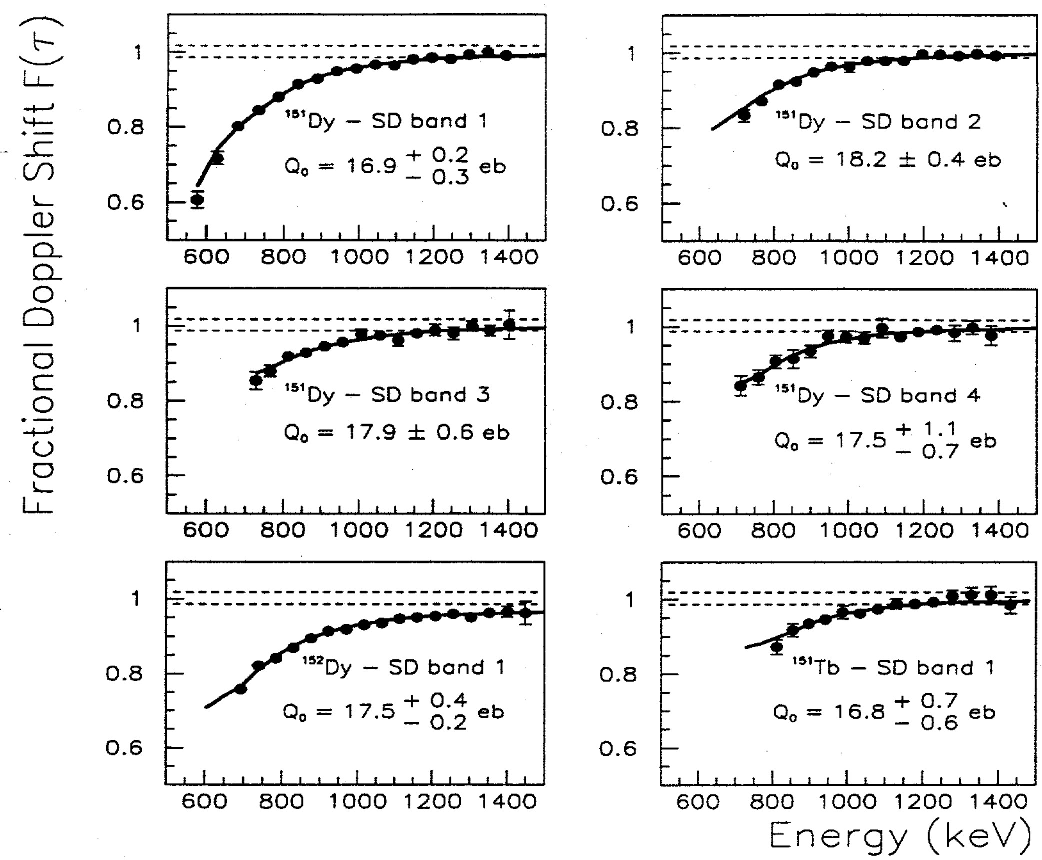

FIG. 2. Fits to the fraction of the full Doppler shift for SD bands in the A=150 region. The dotted horizontal lines represent the spread in recoil velocities due to the slowing down of the beam through the target.

TABLE II. Comparison of the results from this experiment and from the measurement of ref. [8] with recent theoretical calculations described in the text. The quoted errors do not include stopping power uncertainties. Most of the calculated values are taken at a spin value of 40 $\hbar$.

Nucleus	Q_0^{exp} (eb)	Q_0^{MO}	Q_0^{WS}	Q_0^{RMF}	Q_0^{SkP}	Q_0^{SKM*}	Q_0^{DD}
^{152}Dy	17.5 ± 0.2^{a} $17.5\,^{+0.4}_{-0.2}$	18.9	18.9	18.9	18.5	18.5	17.6
^{151}Dy	$16.9\,^{+0.2}_{-0.3}$	18.0	18.0	18.1	17.9	18.0	16.6
^{151}Tb	$16.8\,^{+0.7}_{-0.6}$	18.1	18.0	18.1	17.5	17.5	17.0
^{149}Gd	15.0 ± 0.2^{a}	16.5	16.2	16.0	16.1	16.2	15.6
^{148}Gd	14.6 ± 0.3^{a}	16.0	15.6	15.7	15.5	15.8	15.2

[a]from Savajols *et al.* [8].

B. Analysis and results

The extraction of intrinsic quadrupole moments Q_0 for the various SD bands proceeded in the same manner as described above for the A=190 region. The stopping powers for the various residual nuclei were all calculated using TRIM [5]. The best fit calculated $F(\tau)$ curves are presented in Fig. 2.

In the fit of the $F(\tau)$ values a χ^2 minimization was performed. For the SD bands in ^{151}Dy and ^{151}Tb, the sidefeeding delay was well described in terms of the parameters Q_0 and Q_{SF} only, (i.e., very good agreement with the data was obtained with $T_{SF} = 0$). However, in the case of ^{152}Dy, an additional delay of $T_{SF} \simeq 25$ fs was required to fit the data.

We have examined the possibility that this difference in feeding delay might be an artifact of the analysis. We note that these data points were obtained in exactly the same way as those in ^{151}Dy and ^{151}Tb. Since all the recoils are formed in the same reaction, it is difficult to see how a change in the condition of the target would produce such a difference. We have also investigated the possible difference in the 4*n* and 5*n* production cross sections across the target thickness. The combination of measured excitation functions [9] and statistical model calculations [10] indicate that this difference is too small to explain the observed deviations. The origin of this sidefeeding delay remains an open question which will be the subject of further investigation. It is important to note that the value of Q_0 obtained in the fitting process is most strongly determined by those data point having $F(\tau) < 0.9$, where there is little or no sidefeeding. Finally, we note that the value of Q_0 for ^{152}Dy obtained here is in excellent agreement with that of Savajols *et al.* [8] (see Table 2).

The results of the present analysis show that the quadrupole moment of the "identical" SD band in ^{151}Dy has the same value of the yrast SD band of ^{152}Dy. Furthermore, as shown in Tab. 2, our results combined with those of Savajols *et al.* [8] nicely illustrate the effect of the occupation of specific high-N intruder orbitals on the SD quadrupole moments.

Under the usual assumption that the yrast SD band in ^{152}Dy corresponds to a closed core configuration containing four N=6 protons and two N=7 neutrons ($\pi 6^4 \nu 7^2$), the yrast SD bands can be described as single neutron-hole ($\pi 6^4 \nu 7^1$) and single proton-hole ($\pi 6^3 \nu 7^2$) configurations, respectively. These high-N intruder orbitals are strongly deformation driving and can be expected to have a large influence on the SD Q_0 values, as is seen in the data: the Q_0 value in ^{152}Dy is larger than for the yrast SD bands in ^{151}Dy and ^{151}Tb. The data also suggest that the influence of proton and neutron intruder orbitals on the Q_0 values is similar.

The polarization effects resulting from the occupancy of specific intruder orbitals have recently been calculated in a variety of theoretical approaches, a number of which are compared in Table 2. The results of Nilsson-Strutinsky cranking of the modified oscillator potential with the parameters of ref. [11] are presented as Q_0^{MO} in Table 2, the results for the Gd isotopes and ^{152}Dy were published previously [8]. Results of cranked Strutinsky calculations with a Woods-Saxon potential [12] are given as Q_0^{WS}. The symbol Q_0^{RMF} refers to calculations using the cranked relativistic mean field approach [13]. Finally, the symbols Q_0^{SkP}, Q_0^{SKM*}, and Q_0^{DD} refer to the Hartree-Fock calculations with SkP and SKM* interactions of Satula *et al.* [14], and with density-dependent zero-range pairing interaction of Bonche *et al.* [15]. Clearly, all of these calculations reproduce the relative changes in Q_0 very well. It should be mentioned that the $\sim 10\%$ discrepancies between the experimental values and some of the calculations is not considered serious since they are well within the absolute uncertainties due to stopping powers and the r_0 parameter, for example.

The present measurements also probe the possible dependence of the Q_0 values on the specific configurations occupied in the ^{151}Dy SD well. The excited SD bands in ^{151}Dy are interpreted as excitations in which the the hole (with respect to ^{152}Dy) can occupy some of the natural parity orbitals in the vicinity of the Fermi surface. In contrast with the yrast SD band in ^{151}Dy, the intruder content of these excited bands is then the same as in ^{152}Dy band 1

TABLE III. Calculated Q_0 values for three orbitals which may be involved in the configurations of the excited SD bands in ^{151}Dy. Most of the calculated values are taken at a spin value of 40 $\hbar$. The intruder configuration for band 1 is given for comparison.

Configuration	Q_0^{MO}	Q_0^{RMF}	Q_0^{SkP}	Q_0^{SKM*}
$\nu 7^1$	18.0	18.1	17.9	18.0
[651]1/2	18.3	-	18.1	-
[642]5/2	18.4	18.7	18.3	18.3
[411]1/2	19.0	-	18.7	18.7

($\pi 6^4 \nu 7^2$) and single-particle Routhians indicate that the neutron holes will most likely be created in the [651]1/2, [642]5/2, or [411]1/2 orbitals [12,16]. From Fig. 1 it is clear that bands 2-4 in ^{151}Dy are characterized by Q_0 values which are larger than that of band 1, as would be expected for bands having an additional $\nu 7$ intruder occupied. More surprising is the observation that the Q_0 values for band 2 and, perhaps for band 3, may even be larger than that for ^{152}Dy SD band 1. In order to investigate this point the Nilsson-Strutinsky calculations described above were extended to some of the proposed orbitals. The results of the calculations are given in Table 3, together with values obtained from other approaches where available.

The "identical" band (band 4) of ^{151}Dy was assigned [17] to the [411]1/2 orbital as the transition energies in this band lie half-way between those of band 1 in ^{152}Dy as predicted by Nazarewicz *et al.* [18]. Using the strong coupling picture, these authors showed that, within the pseudospin coupling scheme, the [411]1/2 orbital is associated with a decoupling parameter a having the exact value $a = -1$ (required to obtain transition energies at the half-way point). As shown in Table 3, the Q_0 value calculated for the [411]1/2 configuration is almost exactly equal to the value calculated for ^{152}Dy band 1 (as are the measured values), whereas the values calculated for the [642]5/2 and [651]1/2 orbitals are closer to that of ^{151}Dy band 1. The data seem to favor the scenario proposed by Ragnarsson [16], which assigns both bands 2 and 4 to the [411]1/2 orbital, although the measured Q_0 value for band 2 appears somewhat larger than expected from the calculations. Finally, the calculations of ref. [16] assign band 3 to the [642]5/2 configuration. However, the fact that the measured Q_0 value for this band is closer to that of ^{152}Dy band 1 than that of ^{151}Dy band 1 stands in contrast to the calculations. Further theoretical investigations may be required to account for these bands properly.

IV. SUMMARY

Lifetime measurements for identical SD bands in ^{151,152}Dy and ^{192,194}Hg have demonstrated that another observable, the intrinsic quadrupole moment, associated with these bands is the same. The results in the A=190 region have also shown that the Q_0 values obtained from centroid shift analyses are very sensitive to the treatment of sidefeeding. It is encouraging to note that these types of measurements are no longer limited by the statistical accuracy of the measurement but rather by the fundamental assumptions made in the analysis of the data.

The measurements in the A=150 region combined with those of Savajols *et al.* [8] dramatically illustrate the strong influence that the occupation of specific high-N intruder orbitals have on the Q_0 values. In addition, the present investigation indicates that in certain cases, the occupation of other, non-intruder orbitals can also affect the Q_0 values. It should be pointed out that while a clear picture appears to emerge for the A=150 region, the situation remains less clear for SD nuclei of the A$\sim$190 region. It is hoped that the results of detailed lifetime measurements in the A=190 region will stimulate detailed calculations of these quantities, similar to those now available for SD nuclei in the A=150 region.

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[1] P. J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).
[2] M. A. Bentley *et al.*, Phys. Rev. Lett. **59**, 2141 (1987)
[3] E. F. Moore *et al.*, Phys. Rev. Lett. **63**, 360 (1989).
[4] C. Baktash, B. Haas and W. Nazarewicz, Annu. Rev. Nucl. Part. Sci. **45** (1995) 485.
[5] J.F. Ziegler, J.P. Biersack, and U. Littmark, The Stopping and Range of Ions in Solids (Pergamon, New York,1985), J.F. Ziegler, private communication (1995).
[6] J. R. Hughes *et al.*, Phys. Rev. Lett. **72**, 824 (1994).
[7] D. Nisius *et al.*, to be published.
[8] H. Savajols *et al.*, Phys. Rev. Lett. **76** (1996) 4480.
[9] G. Smith *et al.*, Phys. Rev. Lett. **68** (1992) 158.
[10] F. Puhlhofer, Nucl. Phys. **A280** (1977) 267, and D. Hofmann, private communication.
[11] B. Haas *et al.*, Nucl. Phys. **A561** (1993) 251.
[12] W. Nazarewicz, R. Wyss and A. Johnson, Nucl. Phys. in press.
[13] A. V. Afanasjev, J. J. König and P. Ring, Nucl. Phys. in press.
[14] W. Satula, J. Dobaczewski, J. Dudek and W. Nazarewicz, private communication and to be published.
[15] P. Bonche, H. Flocard and P. -H. Heenen, Nucl. Phys. **A598** (1996) 169.
[16] I. Ragnarsson, Acta Polonica **B27** (1996) 33.
[17] D. Nisius *et al.*, Phys. Lett. **B346** (1995) 15.
[18] W. Nazarewicz et al., Phys. Rev. Lett **64** (1990) 1654.