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LIFETIME MEASUREMENTS AND THE ISSUE OF IDENTICAL SUPERDEFORMED BANDS

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Lifetime measurements for superdeformed bands in ^{151,152}Dy and ^{192,194}Hg have been performed at GAMMASPHERE using the Doppler shift attenuation method. The transition quadrupole moments for several bands in these nuclei have been extracted from an analysis of centroid shift data. Of particular interest are the quadrupole moments associated with the so-called "identical" superdeformed bands in these nuclei. A preliminary analysis indicates that the values of the quadrupole moments in the identical bands are equal within experimental errors. This result suggests that the deformations associated with the identical bands are very similar.

1 Introduction

The phenomenon of "identical" superdeformed (SD) bands was first discovered for pairs of SD bands in the nuclei (^{151}Tb, ^{152}Dy)[1], (^{150}Gd, ^{151}Tb)[1], and (^{153}Dy, ^{152}Dy)[2]. These results were quite unexpected and were shortly followed by the discovery of identical SD bands in the (^{194}Hg, ^{192}Hg) pair[3]. Many cases of identical bands in SD and normally deformed nuclei are now known to exist[4]. A number of theoretical explanations of this phenomenon have been proposed, ranging from the possible presence of a new symmetry to subtle cancelation effects. One explanation involves pseudo SU(3) symmetry[5] in the strong coupling limit of the particle-rotor model. This framework leads to a natural explanation of the pairs of identical SD bands (^{151}Tb, ^{152}Dy), (^{150}Gd, ^{151}Tb), and (^{153}Dy, ^{152}Dy) as limiting cases where the decoupling parameter "a" takes on the values of +1, +1, and 0, respectively. This scheme also led to the prediction of a band in ^{151}Dy "identical" to the yrast SD band in ^{152}Dy, corresponding to a value of the decoupling parameter of $a = -1$, which results in a band having transitions lying at the midpoint energies of the ^{152}Dy band. Motivated by this prediction, an experimental search for additional SD bands in ^{151}Dy was performed using the early implementation phase of GAMMASPHERE. This experiment resulted in the discovery of 4 new SD bands[6], one of which (band 4 in the notation of Nisius *et al.*) exhibited a γ-transition energy relationship to the yrast SD band in ^{152}Dy differing by an r.m.s value of 1.70 keV; i.e., in excellent agreement with the prediction of Nazarewicz *et al.* for the pseudo-spin identical band.

Inherent in the pseudo-spin picture of identical SD bands is the assumption that the nuclear moments of inertia for the identical bands are equal to each other. This equality must hold to the 0.2% level in order to account for the observed relationships of the γ-ray energies. Identical SD bands have been found in nuclei differing by up to 4 mass units, thus, the simple $A^{5/3}$ mass dependence of the moment of inertia would seem to make the possibility of the identical bands very remote. The most common explanation for the lack of mass dependence involves effects in which the occupation of the pseudospin orbitals by a particle (or hole) results in a change in deformation that compensates for the change in the moment of inertia due to mass differences.

In order to ascertain the deformation associated with identical SD bands and to test this scenario, it is necessary to measure the lifetimes of states in the bands using the Doppler shift attenuation method (DSAM). While DSAM measurements have previously established the superdeformed character of a number of the known bands, the experimental sensitivity needed to determine differences in deformation between various excited SD bands was not present in the previous generation of γ-ray detector arrays. Furthermore, systematic stopping power uncertainties used in the analysis of DSAM data in the past have made the comparison of results from different nuclei problematic.

The advent of large detector arrays such as GAMMASPHERE has ushered in a new era in which it is possible to obtain high quality DSAM data not only for the yrast SD bands but also for much weaker excited bands. However, the problem of stopping power formulations greatly limits the number of identical pairs of bands for which data free from systematic uncertainties is accessible. One way around this particular problem is to populate and measure the identical bands under experimental conditions that are as similar as possible. The optimum condition is to produce the nuclei in the same reaction, i.e. neighboring isotopes originating from the same compound nucleus. We refer to this type of measurement as a "differential" DSAM measurement since the two isotopes will then have the same initial recoil velocity, same stopping medium and since the isotopes have the same Z, the stopping powers will be essentially the same.

2 Experiment

We have performed DSAM measurements for SD bands in the nuclei ^{151,152}Dy and ^{192,194}Hg at GAMMASPHERE. For the Dy measurement we used the reaction ^{122}Sn(^{34}S,xn)$^{156-x}$Dy at a beam energy of 175 MeV. The target consisted of 1.0 mg/cm^2 Sn on a $\sim$ 20 mg/cm^2 Au backing. The GAMMASPHERE configuration at that time consisted of 56 detectors, 32 of which were situated at backward angles, 18 at forward angles, and 6 at 90° with respect to the beam direction. With an event condition of 4 or more detectors firing in prompt coincidence, we obtained a total of $\sim 1.5 \times 10^9$ triple and higher fold events.

The Hg measurement was performed using the same configuration of GAMMASPHERE. In this experiment, SD states in ^{192}Hg were populated in the reaction ^{148}Nd(^{48}Ca,4n)^{192}Hg at 205 MeV and those in ^{194}Hg with the reaction ^{150}Nd(^{48}Ca,4n)^{194}Hg at 202 MeV. In each case the target consisted of $\sim$ 1 mg/cm^2 Nd on a Au backing of about 15 mg/cm^2 thickness. The choice of beam energies was determined by the desire to populate the SD states under similar conditions (excitation energy, input angular momentum) while keeping the difference in initial recoil velocity to a minimum. As was the case in the "differential" Dy measurements, the recoiling nuclei have the same Z and were slowed down and stopped in the same backing material. In this experiment $\sim 0.8 \times 10^9$ and $\sim 1.0 \times 10^9$ triple and higher fold events were obtained for the ^{192}Hg and ^{194}Hg runs, respectively.

3 Analysis

The present paper will focus primarily on the preliminary results from the $^{151,152}Dy$ measurement, although some preliminary results from the Hg experiment will also be presented. We have extracted angle-sorted spectra gated on transitions in 4 SD bands in ^{151}Dy, and the yrast SD bands of ^{152}Dy and ^{151}Tb. To illustrate the quality of our data, spectra gated on transitions in the yrast SD band of ^{151}Dy as measured in the 90° and most forward and backward rings of GAMMASPHERE are presented in Figure 1. As seen in the figure, all of the SD transitions are sharp (i.e., no Doppler broadened lineshapes) and exhibit large Doppler shifts as a function of angle.

3.1 Extraction of Fractional Doppler Shifts

We have extracted the fraction of the full Doppler shift F(τ) for the transitions in this band as well as the other bands observed in the experiment. The F(τ) values are determined from the centroid of the γ-ray peak at each angle using the first-order relationship:

$$F(\tau) = \frac{<E_\gamma> - E_{\gamma 0}}{E_{\gamma 0}\beta_0 cos\theta}, \tag{1}$$

where $E_{\gamma 0}$ is the unshifted γ-ray energy and $<E_\gamma>$ is the corresponding centroid derived from spectra measured in the detectors at angle θ with respect to the beam direction. We define β_0 to be the initial v/c of the recoils formed at the center of the target, which has the value $\beta_0 = 0.0227$ in the present experiment.

The fractional shifts for the 4 SD bands of ^{151}Dy and the yrast SD band of ^{152}Dy are presented in Fig. 2. The error bars are obtained from the process of averaging the centroid information from all rings in GAMMASPHERE and the statistical uncertainties of the individual centroids. From the figure it is clear that the lifetimes within the bands of ^{151}Dy are very similar, implying similar quadrupole moments. Of particular interest is the fact that there is a consistent reduction in the $F(\tau)$ values for the ^{152}Dy band compared to those for the ^{151}Dy bands over the full range of the measurement. It is important to note that these data points were obtained in exactly the same way as those in ^{151}Dy and since both isotopes were produced in the same reaction, it is difficult to see how this result could be an artifact of the analysis.

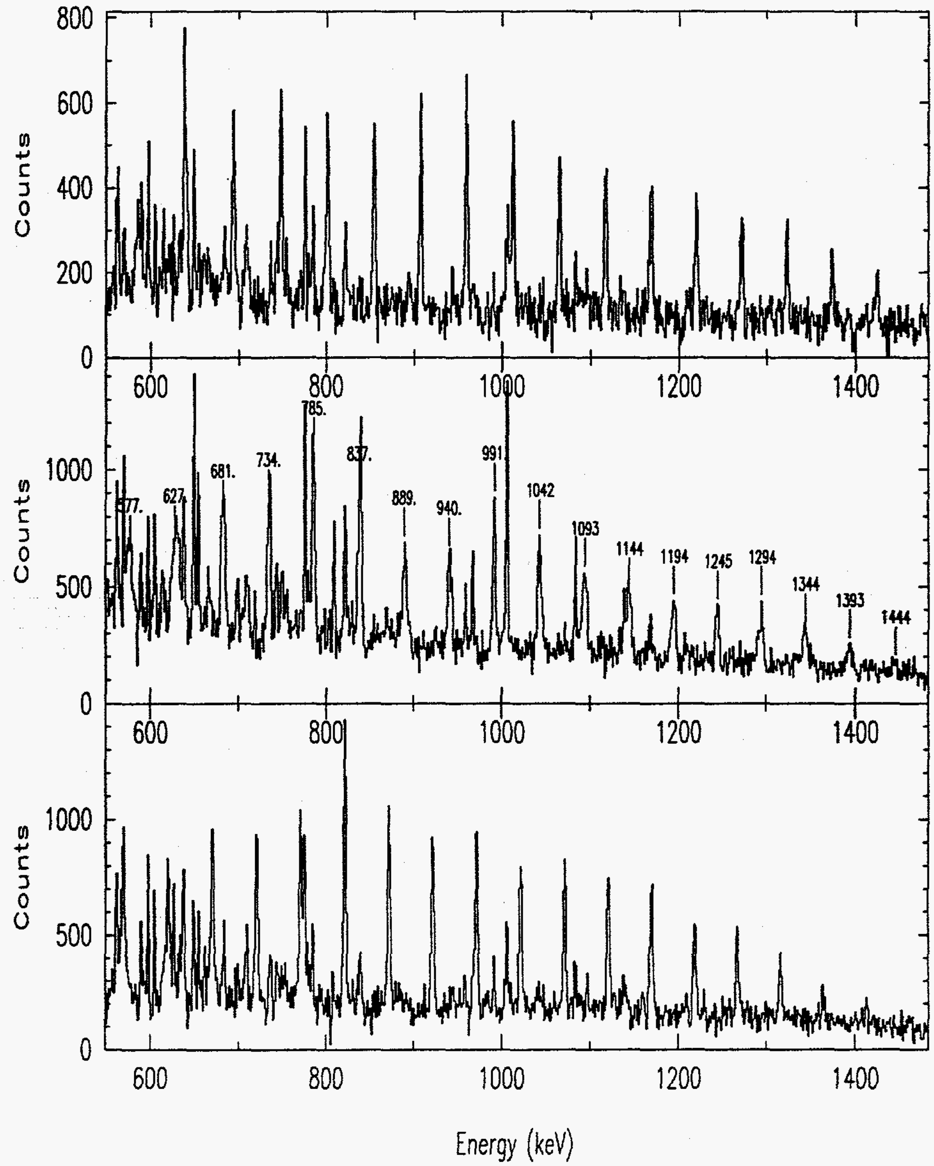

Figure 1: Coincidence spectra gated on transitions in the yrast SD band of ^{151}Dy. The spectra were measured in the 17° (top), 90° (middle), and 163° (bottom) rings of GAMMASPHERE. The unshifted γ-ray energies are indicated on the plot of the 90° spectrum.

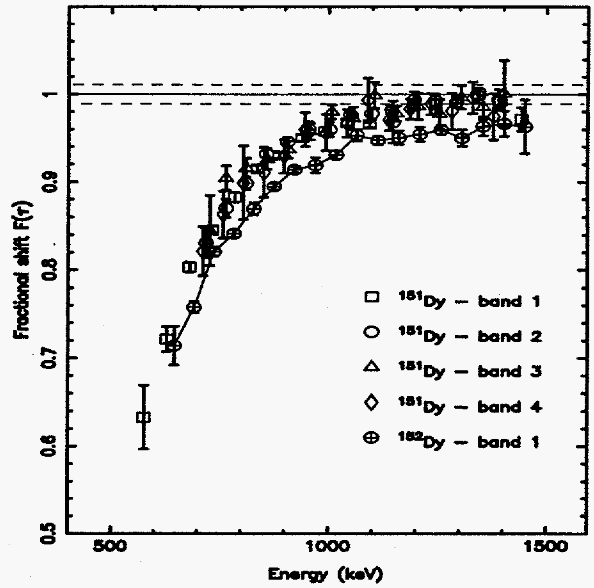

Figure 2: Experimental fractional Doppler shifts $F(\tau)$ for SD bands of ^{151,152}Dy vs. transition energy. The line connecting the ^{152}Dy data points is there to guide the eye. The line for $F(\tau) = 1.0$ corresponds to the mid-target recoil velocity and the dashed horizontal lines indicate the spread in recoil velocities due to target thickness (see text for details).

3.2 Determination of Quadrupole Moments

The transition quadrupole moments Q_0 associated with the SD bands were derived from the fractional shift data under the following assumptions: (i) The Q_0 value remains constant for all states within each band; (ii) The side-feeding time structure is the same as the in-band cascade; (iii) Any feeding delays were approximated by a single-step delay at the top of the band. Thus, the $F(\tau)$ data were fit using two parameters, the quadrupole moment Q_0 and the feeding delay τ_{delay}.

In addition to the basic assumptions outlined above, we have included the (small) correction due to internal conversion. The decay-out branching ratios for those states near the bottom of the band where the in-band flux decreases were also accounted for. We have investigated the question of a possible decrease in the Q_0 values near the bottom of the band. However, as will be discussed later, uncertainties in the stopping power parametrization are of the same order if not larger than any effects present in the data. Finally, we have attempted to account for the fact that the SD band in ^{152}Dy is populated in a $4n$ reaction whereas those in ^{151}Dy are populated after the evaporation of 5 neutrons. Consequently, there is a difference in the SD production cross section across the thickness of the target, resulting in slightly different average initial recoil velocities for the $4n$ and $5n$ channels. We used the combination of excitation function measurements and statistical model calculations to model this energy dependence.

The stopping powers calculated by the code TRIM, version 1995 by Ziegler[7] were used in our analysis. This code produces tables of both electronic and nuclear stopping powers as a function of energy. For comparison purposes, we have also used the tabulated electronic stopping power values of Northcliffe and Schilling[8] scaled to the α stopping of Sie *et al.*[9]. The nuclear component of the stopping powers was calculated using the parametrization of Winterbon[10]. Multiple scattering was treated according to the Blaugrund approximation[11]. In most cases, the agreement between the two approaches was rather good, with differences in the fitted Q_0 values amounting to less than 5%. However, the differences between the two stopping power parametrizations were at their greatest at exactly the velocities reached by the recoiling nuclei at the time of the decay out of the SD bands. This result is illustrated in Fig. 3, where the total stopping power as a function of β/β_0 is plotted for Dy ions in Au. Given this uncertainty in $\frac{dE}{dx}$ at the point of decay, it is difficult to extract any reliable information on changes in the Q_0 values near the bottom of the SD bands.

4 Results

Using the procedure outlined above, we have extracted preliminary Q_0 values for the SD bands in ^{151,152}Dy and ^{151}Tb. The best fit to the yrast SD band in ^{151}Dy is presented in Fig. 4, and corresponds to a Q_0 value of 17.1 ± 0.6 eb and $\tau_{delay} < 0.5$ fs. Similarly, the best fit Q_0 value for the yrast SD band in ^{152}Dy is 17.7 ± 0.6 eb (see Fig. 4), but in this case, a feeding delay value of 26 fs was needed to fit the data. The Q_0 results in are summarized in Table 1. The quoted error bars correspond to the statistical errors on the fit parameters. From a comparison of the best fit Q_0 values in the yrast SD bands in ^{151}Dy and ^{152}Dy using the two different stopping power formulations discussed above, we find that the systematic errors due to differences in $\frac{dE}{dx}$ are similar in magnitude to the statistical errors.

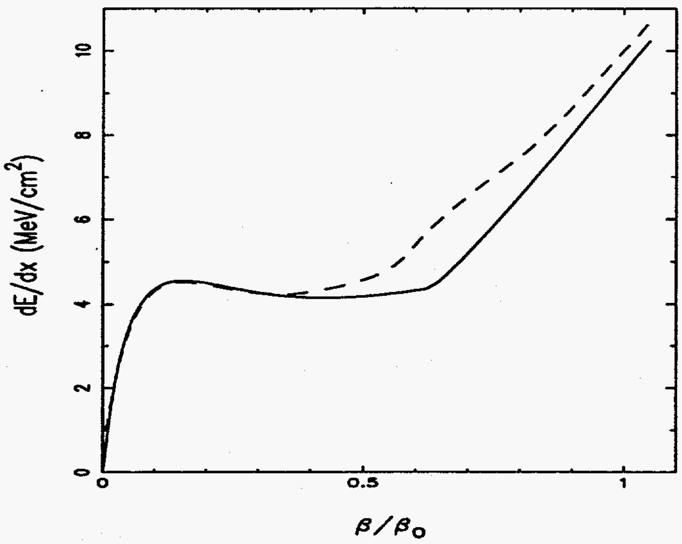

Figure 3: Comparison of total stopping power for ^{151}Dy ions in Au calculated using TRIM95 (solid line) and by scaling the Northcliffe and Schilling tabulated values (dashed line). The $\beta/\beta_0 = 1$ value corresponds to the initial recoil velocity of $\beta_0 = 0.02266$.

A careful examination of the calculated $F(\tau)$ curve for the yrast SD band in ^{151}Dy (see Fig. 4) reveals that the calculation for constant Q_0 slightly overpredicts the experimental values for the two lowest transitions. This occurs at the bottom of the band where the SD flux decays toward the normal states. It is possible that the smaller $F(\tau)$ values indicate a slight reduction in the transition quadrupole moment in the region of decay. However, as pointed out above, the discrepancy between the two stopping power treatments that we have examined reaches the maximum value at exactly the velocities attained by the recoiling nuclei at the time of the decay out. Therefore, it is premature to attribute the small differences in $F(\tau)$ to a change in Q_0 alone.

A comparison of the Q_0 value of the "identical" SD band in ^{151}Dy (band 4) with that of the yrast SD band of ^{152}Dy reveals the similarity in deformation between the two bands. Figure 5 presents the difference between the experimental $F(\tau)$ values in band 4 of ^{151}Dy and the interpolated values in ^{152}Dy as a function of γ-ray energy. Also plotted are the calculated differences in $F(\tau)$ corresponding to $\Delta Q_0 = 0$ and ± 1.0 eb. While the experimental error bars are large (mainly due to poorer statistics in the excited band of ^{151}Dy), it is clear

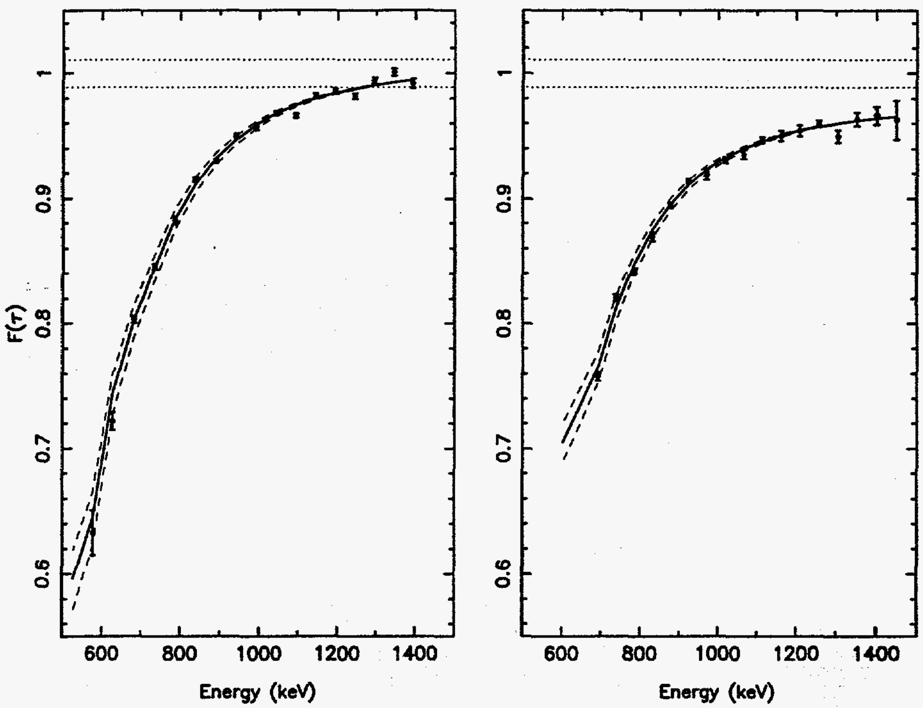

Figure 4: Measured and calculated fractional shifts F(τ) for the yrast SD bands of ^{151}Dy (left) and ^{152}Dy (right). The solid lines denote the best-fit Q_0 values and the dashed curves show the calculated F(τ) curves corresponding to the error bars on the Q_0 values. The horizontal dotted lines represent the spread in initial recoil velocity due to target thickness.

Table 1: Best fit transition quadrupole moment values obtained from the Dy experiment.

Nucleus	Band	Q_0(eb)
^{151}Dy	yrast	17.1 ± 0.6
	2	18.0 ± 1.0
	3	19.0 ± 1.1
	4	17.8 ± 1.3
^{152}Dy	yrast	17.7 ± 0.6
^{151}Tb	yrast	16.7 ± 1.0

that the data are consistent with $\Delta Q_0 = 0$. One should also note that the offset from $\Delta F(\tau) = 0$ present for the data points and the calculated curves reflects the difference in feeding delay time. Unfortunately, due to the γ-ray energies involved, the SD bands de-populate just as the $F(\tau)$ values become the most sensitive to differences in Q_0.

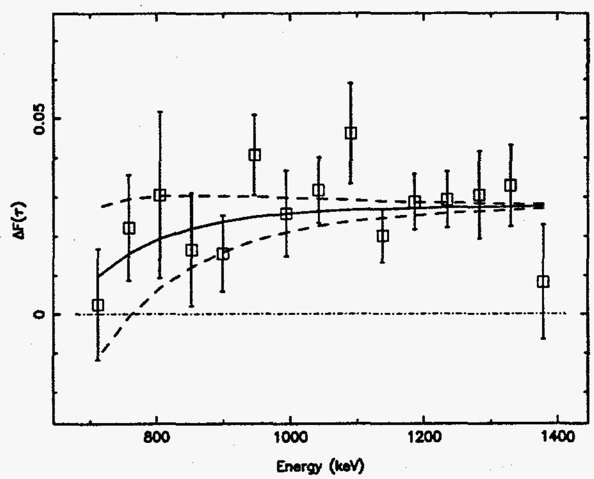

Figure 5: Difference in $F(\tau)$ between the "identical" band (band 4) in ^{151}Dy and the interpolated values from the yrast SD band in ^{152}Dy. The solid curve represents the calculated difference for $\Delta Q_0 = 0$ and the dashed curves correspond to $\Delta Q_0 = \pm 1$ eb.

As pointed out above, we have also performed DSAM measurements for SD bands in ^{192,194}Hg. In this case, band 3 of ^{194}Hg (in the notation of Stephens *et al.*[3]) is identical to the yrast SD band of ^{192}Hg. In this case, the preliminary fits to the Q_0 values are within 0.1 eb of each other. The similarity in Q_0 is illustrated in Fig. 6, where the measured and calculated $\Delta F(\tau)$ are plotted as a function of γ-ray energy. In contrast to the Dy case, the data and calculations span the region in γ-ray energy where the sensitivity to ΔQ_0 reaches a maximum. Again, even though the experimental error bars are rather large, the results are consistent with $\Delta Q_0 = 0$.

5 Summary

We have performed "differential" DSAM measurements for SD bands in ^{151,152}Dy and ^{192,194}Hg using GAMMASPHERE. Our preliminary results indicate that

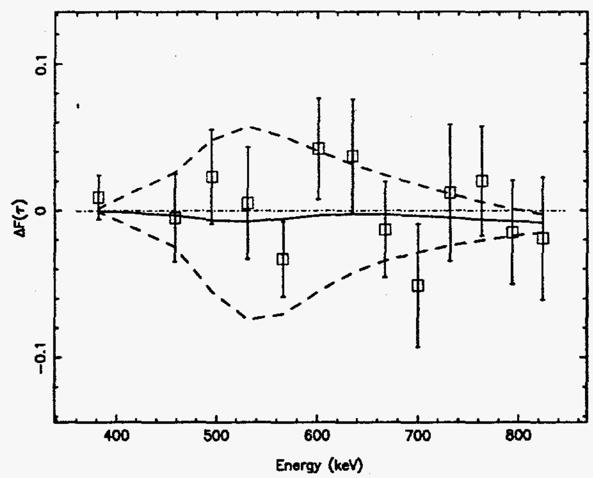

Figure 6: Difference in $F(\tau)$ values between the "identical" band (band 3) in ^{194}Hg and the yrast SD band in ^{192}Hg. The solid curve shows the calculated difference for $\Delta Q_0 = 0$ and the dashed curves correspond to $\Delta Q_0 = \pm 1$ eb (see text for details).

the SD bands have large and similar quadrupole moments. In particular, the quadrupole moments for the identical bands are equal to each other within experimental uncertainties. The data also indicate that there are some configuration dependent differences in deformation for the SD bands in ^{151}Dy. These results are independent of the choice of stopping power parametrization. We have also investigated the question of a reduction in the Q_0 values near the bottom of the SD bands. However, the accurate determination of small changes in Q_0 requires a detailed knowledge of the stopping powers which, as we have shown, is not yet available.

While our results suggest that the identical bands have equal quadrupole moments, it is not yet possible to determine if the deformation of the identical band in ^{151}Dy is larger than that for the yrast band in ^{152}Dy by an amount expected from the mass scaling of the moments of inertia and quadrupole moments. However, we can certainly rule out large differences in deformation. We are in the process of investigating more realistic models of the sidefeeding time structure in an effort to understand the large differences in feeding time between the SD bands in ^{151}Dy and ^{152}Dy. Furthermore, we have high-quality lineshape information for the SD bands in the Hg isotopes. From this we hope to be able to answer questions regarding the Q_0 values for individual states, as well as questions on the sidefeeding properties.

Acknowledgments

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References

1. T. Byrski *et al.*, *Phys. Rev. Lett.* **64**, 1650 (1990).
2. J. K. Johansson *et al.*, *Phys. Rev. Lett.* **63**, 2200 (1989).
3. F. S. Stephens *et al.*, *Phys. Rev. Lett.* **64**, 2623 (1990).
4. C. Baktash, B. Haas, and W. Nazarewicz, *Annu. Rev. Nucl. Part. Sci.* **45**, 485 (1995).
5. W. Nazarewicz, P. J. Twin, P. Fallon, and J. D. Garrett, *Phys. Rev. Lett.* **64**, 1654 (1990).
6. D. Nisius *et al.*, *Phys. Lett.* B **346**, 15 (1995).
7. J. F. Ziegler, private communication, 1995.
8. L. C. Northcliffe and R. F. Schilling, *Nucl. Data. Tables* **7**, 256 (1970).
9. S. H. Sie *et al.*, *Nucl. Phys.* A **291**, 443 (1977).
10. K. B. Winterbon, *Atomic Energy of Canada Limited Report, AECL-3914* (1968).
11. A. E. Blaugrund, *Nucl. Phys.* **88**, 501 (1966).