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# Lifetime measurements of scissors mode excitations in $^{162,164}$Dy

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The inelastic neutron scattering reaction has been used to populate known $1^+$ scissors mode states in the deformed rare-earth nuclei $^{162}$Dy and $^{164}$Dy. The electromagnetic decay properties of these states have been examined and the Doppler-shift attenuation method has been used to measure directly the lifetimes of these states. The $M1$ strengths determined are in general agreement with those measured previously in nuclear resonance fluorescence experiments and support the conclusion that these are collective structures; however, a significant discrepancy is found for three states near 3.1 MeV in $^{164}$Dy. Candidates for $2^+$ rotational band members have been identified, and a previously suggested $\gamma$-ray branch from a spin-1 state to the $\gamma$ vibration in $^{164}$Dy has been observed.

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## I. INTRODUCTION

Since their discovery [1] in 1984, weakly collective $M1$ scissors mode states, so called because of the their interpretation as arising from scissorslike oscillations of the proton and neutron distributions [2,3], have been observed in nuclei from $^{46}$Ti to $^{238}$U [4]. In numerous studies, the low-energy magnetic dipole strength distribution in deformed even-even rare-earth nuclei has been determined and has been shown to be concentrated near 3 MeV in excitation energy [4,5]. Theoretical approaches [2,3,6–11] have included various collective models as well as a variety of microscopic calculations, and it is now generally agreed that, in any successful description of these states, protons and neutrons must be treated as distinguishable and that this is predominantly an orbital mode.

Two dysprosium nuclei, $^{162}$Dy and $^{164}$Dy, have been shown to display particularly interesting characteristics [12]. A $1^+$ state at 2900 keV in $^{162}$Dy has the largest measured $B(M1)$ of any known scissors mode state. Significantly greater fragmentation of $M1$ strength exists in $^{164}$Dy as seven levels with $J^\pi=1^+$ have been identified below 3.2 MeV [12], and the reported summed $M1$ strength for these levels is anomalously large when compared to the systematics of neighboring nuclei [13]. In a $^{165}$Ho$(t,\alpha)^{164}$Dy reaction study, a $K^\pi=1^+$ band was found [14] with an approximate bandhead energy of $2557\pm15$ keV. If this state corresponds to the nearby states at 2539 or 2578 keV identified in nuclear resonance fluorescence (NRF) studies [12], the large $M1$ strength would appear to be dominated by a single pure two-quasiproton configuration, an observation clearly inconsistent with a collective interpretation for the structure of this state [14]. In addition, intermediate-energy proton scattering at small angles has been used to confirm that spin contributions are small in scissors mode states, except possibly in $^{164}$Dy [15]. No satisfactory explanations have yet emerged for these puzzling results in $^{164}$Dy.

A large amount of data on scissors mode excitations has been collected for nuclei in the rare-earth region, primarily through electron scattering and NRF measurements, and it has been shown that the accurate determination of $M1$ strengths is important for understanding the structure of these excitations [5]. The present inelastic neutron scattering (INS) studies were initiated to determine directly the lifetimes of the scissors mode states of the heaviest stable even-$A$ Dy isotopes and thus assess the degree of fragmentation of the scissors mode $M1$ strength.

The specific information provided by our INS measurements of scissors mode excitations is complementary to that obtained from electron scattering and NRF. While those reactions are more selective in exciting these states than INS, they are also somewhat restricted in the information that can be obtained. Electron scattering is limited in the resolution attainable and provides no information about the important decays of these states, while NRF suffers from a high bremsstrahlung background at lower energies that makes it difficult to observe the decay branches to states other than the lowest-lying states. Both methods, however, can be used to obtain level parities, to determine $M1$ transition strengths, and to provide other structural information. On the other hand, the INS reaction, combined with the Doppler-shift attenuation method (DSAM), provides a means for determining the $B(M1)$ values from the measured lifetimes, if the parities of the states can be confirmed with independent methods, and an improved environment for searching for predicted decay branches. Therefore, in addition to confirming the spin assignments and decay properties of these $1^+$ states and measuring their lifetimes, other objectives of this study were to identify additional branchings from previously identified $1^+$ states and to search for other rotational members which are not accessible with NRF. Problems associated with the high level densities in these nuclei were anticipated, however, and the development of extensive level schemes was not a considered goal.

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## II. EXPERIMENTAL METHODS AND RESULTS

Studies of the scissors mode states in $^{162}$Dy and $^{164}$Dy have been conducted at the University of Kentucky 7.0 MV Van de Graaff accelerator and associated neutron scattering facilities. The experimental apparatus, methods, and the latest developments in our laboratories, including the DSAM-INS lifetime methodology, have recently been described [16,17].

Cylindrical scattering samples consisting of $Dy_2O_3$ powder packed into thin-walled polyethylene vials were used in all measurements. The $^{162}$Dy target contained 82.4 g of the oxide with an isotopic enrichment of 96.2%, while 88.4 g of oxide enriched to 95.7% served as the $^{164}$Dy target. Protons, incident on a tantalum-lined cell containing about one atmosphere of tritium gas, were employed to produce neutrons by the $^3$H$(p,n)^3$He reaction. These neutrons were used to bombard the targets which were suspended 4 to 6 cm from the end of the gas cell. Gamma-ray spectra were obtained using either of two $n$-type coaxial HPGe detectors; one exhibited a relative efficiency of 32% and a resolution of 1.9 keV at 1.33 MeV, while the other, with 52% relative efficiency, displayed a resolution of 2.0 keV. The detector employed was located approximately 1 m from the scattering sample and was operated in conjunction with a BGO Compton suppression system. Time-of-flight discrimination was employed to reduce the effect of events that were not prompt with the beam pulses, and massive shielding was used to reduce unwanted background. Representative $\gamma$-ray spectra from the $^{164}$Dy$(n,n'\gamma)$ in the energy region around 3 MeV, collected at three incident neutron energies, are shown in Fig. 1. Evaluations of the $\gamma$-ray data were performed with a modified version of the HYPERMET code [18].

Energy and detector efficiency calibrations were performed primarily using the well-known $\gamma$ rays from $^{152}$Eu and $^{56}$Co. In addition, $^{24}$Na sources were placed near the detector during the measurements to monitor the electronic stability of the system.

The nonselective nature of the INS reaction, which occurs predominantly by the compound nucleus mechanism at the neutron energies employed in these measurements, and the high level densities in the region of the scissors mode states in $^{162,164}$Dy result in complex $\gamma$-ray spectra, but careful selection of the incident neutron energy can help alleviate some complexities (see Fig. 1). Since the $1^+$ scissors mode excitations that were the subject of this study had previously been identified through the selective electron and photon scattering reactions [12], the focus of our measurements was on confirming the measured decay properties of these states and on determining their lifetimes.

Excitation function data were initially acquired in the energy region from 2.2 to 3.6 MeV to characterize the spectra in the vicinity of the known $1^+$ states. Data were taken usually at 200 keV intervals with a few strategically placed measurements at intermediate energies. The decays of the $1^+$ states were examined, and the results of our $\gamma$-ray measurements are presented in Tables I and II.

Using the DSAM-INS, we have made direct measurements of lifetimes of the known $1^+$ states in $^{162,164}$Dy. DSAM has been used in a variety of nuclear reactions to obtain lifetimes of various excited states in the femtosecond

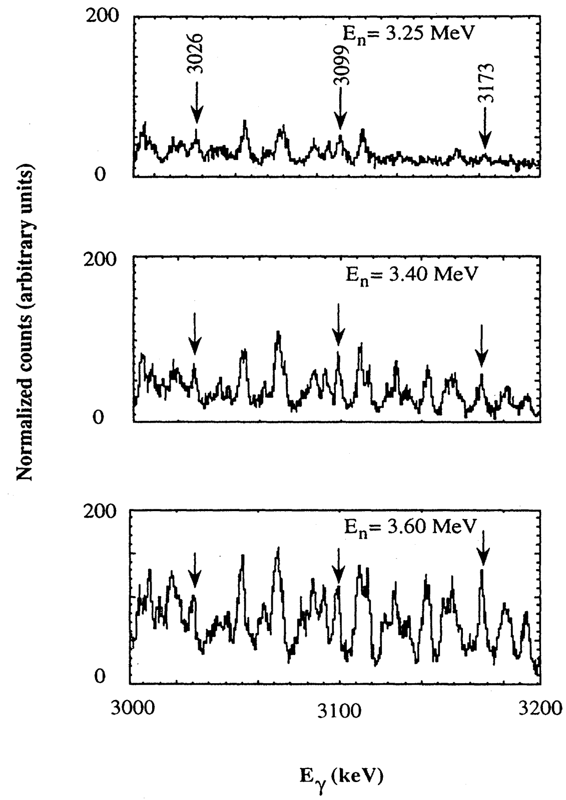


FIG. 1. Portion of $\gamma$-ray spectra obtained from the $^{164}$Dy$(n,n'\gamma)$ reaction at incident neutron energies of 3.25, 3.40, and 3.60 MeV. The 3026, 3099, and 3173 keV $\gamma$ rays discussed in the text are indicated.

to picosecond range, and the reliability of DSAM-INS has been demonstrated in recent work [16,17]. The decay $\gamma$ ray from a recoiling, excited nucleus produced by an INS reaction is subject to a Doppler shift with a magnitude which depends upon the instantaneous velocity and the relative direction of emission. If the recoil slowing process induced by interactions with bulk target material can be accurately described, the lifetime of the decaying state can be obtained from the observed Doppler shift. The measured energy of the emitted $\gamma$ ray is [19]

$$E_\gamma(\theta)=E_0[1+F(\tau)\beta\cos\theta],$$

where $\theta$ represents the angle between the recoil and $\gamma$-ray emission directions, $E_\gamma(\theta)$ is the observed $\gamma$-ray energy at angle $\theta$, $E_0$ is the unshifted $\gamma$-ray energy, $F(\tau)$ is the attenuation factor, and $\beta=v/c$ gives the initial recoil velocity.

Measurements at angles ranging from 40° to 145° and at incident neutron energies of 2.65 and 3.6 MeV were performed to obtain Doppler shifts of the $\gamma$ rays deexciting the known $1^+$ scissors mode states in $^{162,164}$Dy. In addition, a separate measurement at an incident neutron energy of 3.25 MeV was performed with the $^{164}$Dy sample. These measurements simultaneously provided angular distribution data which could be used for determination of the level spins for ground-state transitions. The $a_2$ coefficients determined, un-

TABLE I. Decay properties of $1^+$ states in $^{162}$Dy.

| $E_x$ (keV) | $J^\pi$ | $E_\gamma$ (keV) | $E_f$ (keV) | $J_f^\pi$ | $a_2$ | Branching ratio (%) | $F(\tau)$ | $\tau$ (fs) | $B(M1)\uparrow$ ($\mu_N^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 2395.0(2) | $1^+$ | 2394.9(2) | 0.0 | $0^+$ | −0.20(2) | 66(3) | 0.80(9) | 12(5) | 0.43(20) |
| | | 2314.1(2) | 80.9 | $2^+$ | | 34(3) | | | |
| 2900.1(3) | $1^+$ | 2900.3(4) | 0.0 | $0^+$ | −0.17(3) | 74(4) | 1.02(5) | <5 | >1 |
| | | 2819.0(4) | 80.9 | $2^+$ | | 26(4) | | | |
| 3061.4(3) | $1^+$ | 3061.4(4) | 0.0 | $0^+$ | −0.25(5) | 71(4) | 0.88(5) | 8(4) | 0.50(25) |
| | | 2980.3(4) | 80.9 | $2^+$ | | 29(4) | | | |

der the assumption that $a_4=0$, for these $\gamma$ rays are also listed in Tables I and II. The transition multipolarities are based on previous positive-parity assignments for these states [12,20–23]. However, it should also be noted that, while the parities of these states could not be determined from our data, all of the $\gamma$ rays listed in Tables I and II displayed angular distributions consistent with dipole transitions. Moreover, the $\gamma$-ray branching ratios obtained are in good agreement with those given in NRF studies [12,20,21] and are consistent with those expected for $I^\pi K=1^+1$ states.

A typical experimental $E_\gamma(\theta)$ versus cos $\theta$ plot is shown in Fig. 2. An experimental $F_{\rm exp}$ $(\tau)$ value can be extracted from a linear fit of these data, and the lifetime can then be obtained from a comparison of $F_{\rm exp}$ $(\tau)$ to a theoretically generated $F_{\rm th}(\tau)$ based on stopping theory. The basic convention for describing the deceleration of heavy ions in amorphous materials is presented in the theory of atomic collisions [24]. The method of Winterbon [25] was used to obtain $F_{\rm th}(\tau)$ values for these analyses. Results of DSAM lifetime determinations of the $J^\pi=1^+$ states in $^{162}$Dy and $^{164}$Dy are summarized in Tables I and II, respectively, and comparisons of $B(M1)\uparrow$ values from NRF and our INS measurements are shown in Figs. 3 and 4.

### III. DISCUSSION

The lifetimes determined in this study are in good agreement with those obtained from NRF for $^{162}$Dy and for the four states near 2.6 MeV in $^{164}$Dy; however, we find significantly lower strengths for the grouping of states near 3.1 MeV in $^{164}$Dy. While at first it might be tempting to dismiss these differences as a result of the complex nature of the $\gamma$-ray spectra in the region near 3 MeV (see Fig. 1), we note that, for these states, (a) the observed branching ratios are in good agreement with those expected and measured previously, (b) the angular distributions of the ground-state transitions are consistent with dipole transitions, and (c) the Doppler-shift plots of $E_\gamma$ vs cos $\theta$ are linear. It is anticipated that significant contributions from unresolved $\gamma$ rays would be betrayed by one of these three quantities. A second possibility is that undetected slow feeding of these levels from higher-lying states is affecting the observed lifetimes. This possibility also seems unreasonable, since the measurements were performed as near the level thresholds as reasonable to permit sufficient population of the level. Moreover, such influences are not observed for lower-lying levels where feeding effects might be expected to be more apparent. In short, the source of these discrepancies is not understood at present.

A few ambiguities exist in our data which may or may not also be manifest in other measurements. For example, in the level scheme of Wesselborg *et al.* [12], a state at 3173 keV was assigned in $^{164}$Dy on the basis of $\gamma$ rays at 3173 ($1^+\to0_1^+$) and 3100 keV ($1^+\to2_1^+$). Gamma rays at 3026 and 2337 keV were observed but not placed in the level scheme. It was subsequently suggested that the 2337-keV $\gamma$ ray is a decay from a previously unidentified level at 3099 keV to the $2^+$ $\gamma$ vibrational bandhead [26]. Our INS results support the

TABLE II. Decay properties of $1^+$ states in $^{164}$Dy.

| $E_x$ (keV) | $J^\pi$ | $E_\gamma$ (keV) | $E_f$ (keV) | $J_f^\pi$ | $a_2$ | Branching ratio (%) | $F(\tau)$ | $\tau$ (fs) | $B(M1)\uparrow$ ($\mu_N^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 2530.8(2) | $1^+$ | 2530.7(2) | 0.0 | $0^+$ | −0.12(2) | 69(4) | 0.74(5) | 17(4) | 0.43(10) |
| | | 2457.5(2) | 73.4 | $2^+$ | | 31(4) | | | |
| 2539.1(2) | $1^+$ | 2539.1(2) | 0.0 | $0^+$ | −0.10(3) | 73(4) | 0.73(5) | 18(4) | 0.40(10) |
| | | 2465.7(2) | 73.4 | $2^+$ | | 27(4) | | | |
| 2577.9(2) | $1^+$ | 2577.9(2) | 0.0 | $0^+$ | −0.33(7) | 69(4) | 0.80(7) | 13(5) | 0.53(20) |
| | | 2504.5(2) | 73.4 | $2^+$ | | 31(4) | | | |
| 2694.0(3) | $1^+$ | 2694.1(4) | 0.0 | $0^+$ | −0.23(3) | 72(4) | 0.81(4) | 11(3) | 0.50(10) |
| | | 2620.5(4) | 73.4 | $2^+$ | | 28(4) | | | |
| 3111.1(3) | $1^+$ | 3111.0(4) | 0.0 | $0^+$ | −0.32(8) | 73(5) | 0.84(6) | 10(4) | 0.43(20) |
| | | 3037.8(4) | 73.4 | $2^+$ | | 27(5) | | | |
| 3159.0(3) | $1^+$ | 3159.4(4) | 0.0 | $0^+$ | −0.17(5) | 64(5) | 0.85(7) | 9(4) | 0.40(20) |
| | | 3085.3(4) | 73.4 | $2^+$ | | 36(5) | | | |
| 3173.6(3) | $1^+$ | 3173.6(4) | 0.0 | $0^+$ | −0.21(7) | 68(5) | 0.70(6) | 20(6) | 0.19(7) |
| | | 3100.1(4) | 73.4 | $2^+$ | | 32(5) | | | |

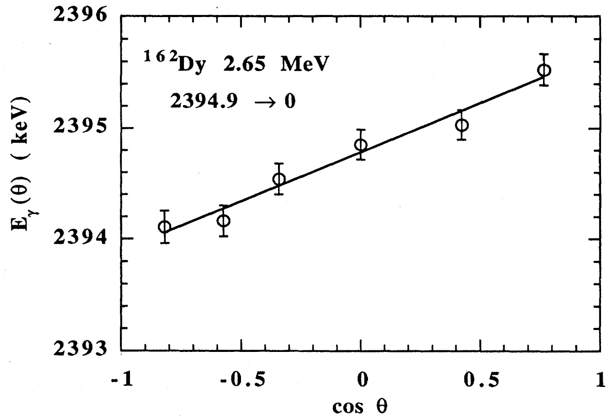


FIG. 2. Plot of $\gamma$-ray energy versus $\cos\theta$ used to determine the experimental attenuation factor $F_{\rm expt}(\tau)$ of the 2395-keV $\gamma$ ray of $^{162}$Dy.

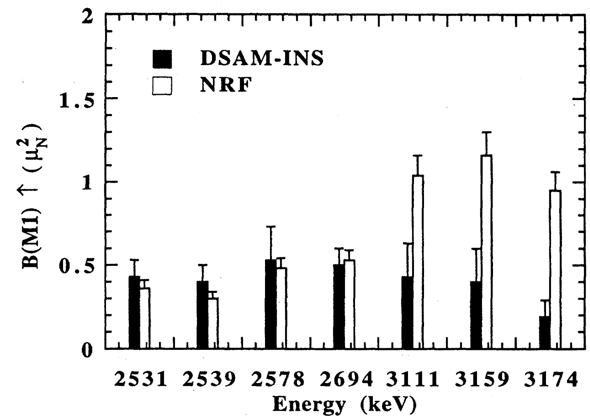


FIG. 4. Comparison of $B(M1)\uparrow$ values of scissors mode states in $^{164}$Dy determined from INS (this work) and NRF[12] experiments.

existence of a level at 3099.4 keV which decays to the $0_1^+$ (42%), $2_1^+$ (43%), and $2_\gamma^+$ (15%) levels, although the branchings appears to be indicative of a negative-parity state with possible $K$ mixing. If, as indicated, the transition at 3100 keV in NRF is a 3099.4/3100.1 keV doublet, the $M1$ strengths reported for the 3173-keV $1^+$ state [12] would be slightly altered, but this explanation would not resolve the larger discrepancies noted above.

In addition to determining the properties of the known scissors mode states in these nuclei, we have searched for additional decay branches from these states. With the possible exception of the aforementioned 2337-keV $\gamma$ ray from the 3099-keV spin-1 state to the $2^+$ $\gamma$ vibration in $^{164}$Dy, no other transitions from scissors mode states to levels not in the ground-state band could be positively identified in this study.

If the scissors mode excitations are, as believed, the bandheads of $K^\pi = 1^+$ bands, higher-lying rotational states would be anticipated. We have searched for additional band members. Candidates for $2^+$ members of scissors mode rotational bands built on each of the known $1^+$ states have been identified at 2448.9, 2953.4, and 3114.8 keV in $^{162}$Dy and at 2584.0, 2592.5, 2629.7, 2750.6, 3145.7, 3195.7, and 3205.4 keV in $^{164}$Dy. Unfortunately, the data are generally insufficient to characterize with certainty even the spins of these states, so these assignments remain tentative. These assignments are based only on energy and on probable spins and parities; the low-energy intraband transitions between band members could not be observed.

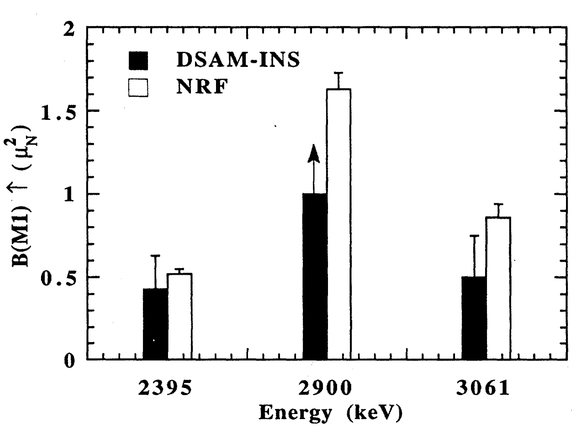


FIG. 3. Comparison of $B(M1)\uparrow$ values of scissors mode states in $^{162}$Dy determined from INS (this work) and NRF[20] experiments. The arrow for the 2900-keV state indicates that only a lower limit was determined.

## IV. SUMMARY

Using DSAM methods we have measured the lifetimes of *all* the previously identified $1^+$ scissors mode states in $^{162,164}$Dy, and the $M1$ strengths to these states have been determined from these lifetimes. The transition strengths determined support previous conclusions that these are indeed collective excitations. The vast majority of experimental evidence relating to scissors mode excitations has been obtained by techniques utilizing electromagnetic excitation [4,5]; we have demonstrated that these states can also be populated and studied with inelastic neutron scattering. However, the nonselective nature of INS reaction, coupled with high level densities in deformed nuclei, results in very dense $\gamma$-ray spectra.

In a state-by-state comparison of $B(M1)\uparrow$ values with the results from photon scattering measurements, we find our values to be in general agreement with the previous determinations [12,20]. The agreement for $^{162}$Dy is, in fact, quite good, but a serious discrepancy exists for the three states near 3.1 MeV in $^{164}$Dy where our measured values are lower than the NRF values by nearly a factor of 3. Weak branches from the scissors mode states were sought, but the large $\gamma$-ray spectral density made identification of such branchings difficult. A number of candidates for $2^+$ rotational members of scissors mode rotational bands have been proposed, but the attendant small cross sections have made the characterization of rotational members speculative.

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