Structure in the $E2$ Quasicontinuum Spectrum of ^{154}Dy

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The evolution of the γ quasicontinuum spectrum with neutron number has been investigated in the sequence of isotopes ^{152,154,156}Dy. The three nuclei display a pronounced collective $E2$ component. In ^{154}Dy this component shows a splitting into two distinct parts, signifying a structural change along the γ cascade above the yrast line. The $E2$ and statistical components are reproduced in simple γ-cascade calculations; in ^{152}Dy and ^{156}Dy only rotational bands are included, whereas in ^{154}Dy additional vibration-like transitions are required to reproduce the two $E2$ peaks.

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Hot nuclei provide opportunities to study several aspects of physics. In nuclear structure it is interesting to examine the change of shapes, thermal shape fluctuations, and the melting of shell effects with increasing temperature. Calculations based on the Landau theory of phase transitions[1] and the finite-temperature Hartree-Fock-Bogoliubov method[2] predict that nuclei which are prolate along the yrast line become triaxial with increasing excitation energy above the yrast line, U, and undergo a phase transition to oblate shape at a critical temperature T_{cr}. There is also a possibility to learn about chaos in a quantum system, since the excursion from the cold yrast line with increasing U represents a transition from order to chaos. For example, it is of interest to search for signatures of order at high excitation energy and to study the role of collectivity and spin in preserving order.[3,4]

Several experiments have investigated the shapes of rotating nuclei at high temperature ($U \gtrsim 40$ MeV) by examining the giant-dipole-resonance component of the γ spectrum,[5] but manifestations of phase transitions have proven elusive. Striking shape changes may also be expected at significantly lower U in transitional nuclei, where the structure along the yrast line has been observed[6,7] to vary rapidly with both spin I and neutron number N. Indeed, T_{cr} is predicted to decrease quickly with the approach towards the transitional region.[8] Alternative methods have to be developed for the study of the interesting nuclear physics near a predicted phase transition in the lower U domain, where photon emission in the giant dipole region is negligible.

To probe nuclear behavior in the $U=1$–8-MeV range, we have measured quasicontinuous spectra of γ rays which connect excited states in the region of high-level densities. We have found evidence for structural changes in the quasicontinuum states and, perhaps, also for the large fluctuations which are expected near a phase transition.

A solid understanding of structural change with I and U requires knowledge of the flow pattern of the deexciting γ cascade. Our approach starts with experimental determination of the initial and end points of the quasicontinuum cascade. With these points as constraints, Monte Carlo calculations of the γ cascade, which reproduce *all* observed spectral features, are used to indicate the U-I region being studied. Although the actual decay pathway is not delineated completely from experiment, this approach nevertheless provides the best definition to date. Our analysis suggests that the quasicontinuum $E2$ spectrum probes mainly states with $U \sim 1$–7 MeV.

In this Letter we report on the quasicontinuum spectra in the transitional nuclei ^{154,156}Dy. The results, together with our previous data[9] on ^{152}Dy, elucidate the evolution of $E2$ continuum properties in a sequence of isotopes with increasing ground-state deformation.

The nuclei ^{154,156}Dy were produced in the ^{122,124}Sn(^{36}S,$4n$) reactions with beams provided by the Argonne superconducting linac, ATLAS. The 1-mg/cm^2 targets were evaporated on a 25-mg/cm^2 Pb backing, resulting in stopping times of ~ 1.6 ps for the nuclei recoiling with an initial velocity of $v/c \sim 0.020$. Prompt γ-γ coincidences were measured in eight Compton-suppressed Ge detectors placed at 34°, 90°, and 146° with respect to the beam axis. High multiplicity events were selected with the requirement that at least two out of an array of fourteen bismuth-germanate crystals fired. From the coincidence data, clean ^{154}Dy and ^{156}Dy spec-

TABLE I. Average entry points and multiplicities of the γ-ray quasicontinuum components measured in the $^{120,122,124}Sn(^{36}S,4n)^{152,154,156}Dy$ reactions. The average entry spins and energies have been determined by the addition of the angular momenta and energies removed by each one of the spectral constituents, including the discrete lines. The parameters used in our γ-cascade model to reproduce the data are also listed, where Q_t is the electric quadrupole moment, a is the level-density parameter, and $\mathcal{J}_{\rm eff}$ is the effective moment of inertia.

	^{152}Dy[a]	^{154}Dy	^{156}Dy
$E_{\rm beam}$ (MeV)	160	165	155
$\langle I_{\rm entry}\rangle$ ($\hbar$)	46.7	50.2	48.8
$\langle E_{\rm entry}\rangle$ (MeV)	25.6	26.9	25.4
$\langle M_{\rm stat}\rangle$	4.0	3.9	3.9
$\langle M_{\rm dipole}\rangle$	1.9	1.6	1.1
$\langle M_{\rm quad}\rangle$	5.3	9.1	10.3
$\langle M_{\rm total}\rangle$[b]	30.5	28.8	27.8
Q_t (e b)	$7.0^{+2.5}_{-1.5}$	6.5 ± 1[c]	6.0 ± 1.5
a	$A/(7\pm1)$	$A/(7\pm1)$	$A/(7\pm1)$
$\mathcal{J}_{\rm eff}$ ($\hbar^2$ MeV^{-1})	76.0	72.0[c]	75.5

[a]From Ref. 9.
[b]Includes discrete lines.
[c]Properties of initial rotational cascade; in the second stage, corresponding to $E^* < 17$ MeV, $E_\gamma = 780$ keV with a 500-keV spread (FWHM), and $B(E2) = 300$ Weisskopf units.

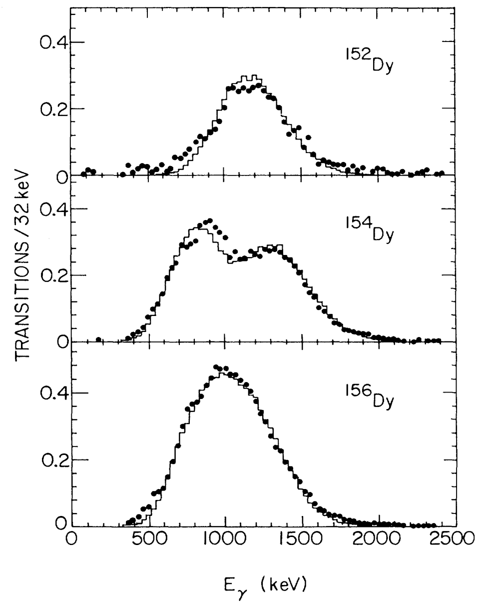

FIG. 1. Measured (●) quasicontinuum $E2$ γ spectra in ^{152,154,156}Dy. Discrete lines have been subtracted and the spectra corrected for Doppler shifts and angular-distribution effects. Calculated spectra are shown as histograms.

tra were generated by gating on low-lying lines for each detector angle. These spectra were corrected for neutron-induced background[10] and unfolded. The strong discrete lines and the statistical γ rays were subtracted, yielding the true γ quasicontinuum spectra, which could then be decomposed into dipole and quadrupole parts with use of their different angular distributions. For each spectral component, the average multiplicity, and total spin and energy removed were determined, allowing the entry spin and excitation energy to be specified. (Details of the analysis are described in Ref. 9.) The results are summarized in Table I, including data[9] on ^{152}Dy.

Figure 1 shows the $E2$ continuum spectra for the three Dy isotopes investigated. In ^{152}Dy and ^{156}Dy one broad peak can be discerned, differing in multiplicity and energy, whereas in ^{154}Dy two distinct parts are observed. There have been earlier indications[11-15] of structure in the quasicontinuum spectra of translational nuclei. However, the spectral shape and the extent of the quasicontinuum contribution were not known since discrete lines, which are largely responsible for structure in the total γ spectra below 1 MeV, were not subtracted. For example, double bumps were observed in the total spectra of ^{154,155}Er, but the lower bump is drastically reduced after subtraction[13] of discrete lines, and the residuum has almost no $E2$ contribution,[13] as in the isotone ^{152}Dy; see Fig. 1 and Ref. 9. In the present work, two broad $E2$ peaks remain in the ^{154}Dy after yrast transitions have been subtracted, unambiguously demonstrating that both peaks must be due to transitions above the yrast line. The average multiplcity and energy of the upper peak both increase with beam energy [Fig. 2(a)], consistent with a rotational origin. In contrast, the low-energy peak stays remarkably constant; in particular, its average energy of 780 keV does not change noticeably

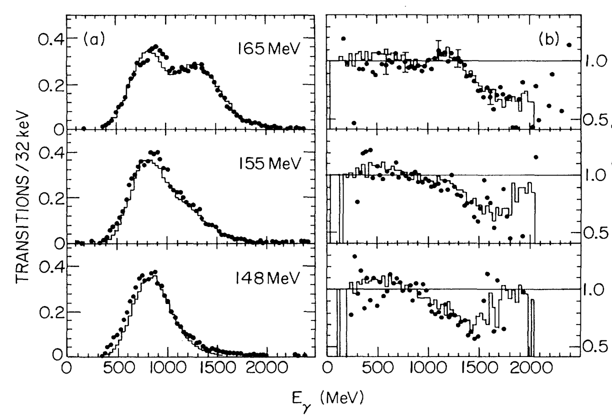

FIG. 2. (a) Measured (●) quasicontinuum $E2$ spectra for ^{154}Dy at beam energies of 148, 155, and 165 MeV, after correction for Doppler shift and angular anisotropy. Simulated spectra are shown as histograms. The measured average entry and end spins of the quasicontinuum $E2$ cascades are (50.2, 30.0)$\hbar$, (42.7, 25.1)$\hbar$, and (35.9, 21.2)$\hbar$ at 165, 155, and 148 MeV, respectively. (b) Measured (●) and simulated (histograms) backward/forward $E2$ intensity ratios, which reflect the Doppler shifts. Some estimated errors are shown.

when the average input spin decreases from $50\hbar$ at a beam energy of 165 MeV to $36\hbar$ at 148 MeV. These observations demonstrate that the transitions associated with the upper peak precede the ones giving rise to the lower peak. Quasicontinuous dipole transitions are also observed in $^{152-156}$Dy, which probably follow the $E2$ cascades.[9] The dipole multiplicities decrease with increasing neutron number (see Table I).

The emission times of the γ rays were extracted[9] from the observed Doppler shifts with knowledge of the slowing-down process in the Pb-backed targets. The measured backward/forward intensity ratios, which reflect the Doppler shifts, are shown in Fig. 2(b) for ^{154}Dy. The upper edges of both $E2$ peaks are nearly fully shifted, proving that the lifetimes of the levels involved are much shorter than the slowing-down time of the recoiling nuclei, i.e., $\ll 1.6$ ps. Hence both peaks originate from fast stretched-quadrupole transitions.

The appearance of two broad peaks in ^{154}Dy results from a redistribution of transition energies along the γ deexcitation pathway; in the later decay stage transition energies are shifted downwards, causing the clustering around 780 keV and the dip around 1.1 MeV. *The two peaks provide clear signature for a change in nuclear structure above the yrast line.* In ^{152}Dy the collective $E2$ cascade[9] is similar (see Table I) to that of the first part in ^{154}Dy. However, in ^{152}Dy the collective flow terminates, on average, at $U=1-1.5$ MeV and $I\sim 34\hbar$, as aligned-particle configurations dominate in the vicinity of the yrast line and dipole transitions emerge.[9] (Hence a rapid decrease of the $E2$ quasicontinuum intensity at low energies occurs.) Aligned-particle configurations are not dominant along the yrast line in ^{156}Dy, allowing the $E2$ cascade to continue to $U\sim 0.7$ MeV and $I\sim 26\hbar$, and this results in a larger $E2$ multiplicity. Only a single peak is observed, implying rotational behavior wherein the transition energy decreases with spin throughout the quasicontinuum cascade.

These conclusions were derived with the aid of Monte Carlo calculations[9] of the γ cascade, which take into account the competition of statistical $E1$ and collective $E2$ decay at high excitation energy. The calculations reproduced simultaneously *all* observed features of the $E2$ and statistical components, i.e., their multiplicities, spectral shapes, Doppler shifts, and entry points into the yrast region. The only free parameters are the level-density parameter, the average effective moment of inertia $\mathcal{J}_{\text{eff}}$, and the average electric quadrupole moment of the rotational bands responsible for the $E2$ peak. This simple model can reproduce the data for ^{152}Dy and ^{156}Dy (Fig. 1) but is unable to reproduce the splitting of the $E2$ component seen in ^{154}Dy. However, by our assuming a change from rotational to vibrationlike behavior for excitation energy $E^* < 17$ MeV, the observed features at all beam energies could be reproduced (see Fig. 2) with one common set of parameters (Table I). [The term vibrationlike refers to the assumption of transition energies which, instead of increasing with spin as for a rotor, remain constant at an average value of 780 keV, with a spread of 500 keV (FWHM); vibrational motion is not implied.] A collective $B(E2)$ of 300 Weisskopf units (with an estimated 30% uncertainty) was required to reproduce the measured Doppler shifts of the lower $E2$ peak [Fig. 2(b)], as well as the spectral shapes and yrast feeding. The simulations suggest that the lower peak arises from states with $U\sim 1-5$ MeV and $I\sim(30-40)\hbar$, $(25-38)\hbar$, and $(21-33)\hbar$ for beam energies of 165, 155, and 148 MeV, respectively. While requiring a structural change below $E^*=17$ MeV reproduces the data, this does not mean that a sharp transition necessarily occurs, or that a different boundary profile in E^*-I space could not also reproduce the data. However, it was not possible to reproduce the data at all beam energies by switching to vibrationlike motion below a fixed spin value, or by retaining rotational motion and increasing $\mathcal{J}_{\text{eff}}$ for $E^* < 17$ MeV.

It was suggested in Ref. 12 that the bumps in the total γ spectra in transitional Er nuclei are due to shell effects, the lower bump attributed to valence nucleons and the upper one to orbits of the next major shell. In ^{154}Dy, inspection of the yrast transitions[6] shows that they pile up to make the predominant contribution to the low-energy bump region. This results from structural changes occurring near the yrast line,[6] which are clearly of valence origin. We have now determined the extent to which the shell effects persist above the yrast line by isolating the quasicontinuum $E2$ component, and have found that such structural changes occur for U up to 5 MeV.

These changes are probably connected with variations of the nuclear shape. In the course of a prolate to oblate shape change near the yrast line, many triaxial bands may occur.[6,7] As U increases, the mixing among the closely lying families of states could give rise to a potential-energy surface soft in the β-γ plane, which in turn could account for the vibrationlike transitions associated with the lower-energy $E2$ peak. A more general viewpoint based on theories of shape changes at high temperature may be taken. In a transitional nucleus such as ^{154}Dy, the shape transition from triaxial to oblate is predicted[8] to occur at low U, even at the yrast line for $I \gtrsim 38\hbar$, in fair agreement with an established[6] oblate region for I between $32\hbar$ and $38\hbar$. For all bombarding energies the γ cascades cross the predicted phase transition boundary of Ref. 8, which resembles that calculated[2] for the isotone ^{158}Yb. The large shape fluctuations expected[1,8] in the transition region give a potential-energy surface flat in the β-γ plane and perhaps vibrationlike transitions.

The higher $E2$ peak exhibits collective behavior, seemingly contradicting mean-field theory,[2,8] which predicts that the first part of the cascade flows through noncollective oblate states. Fluctuations in the β-γ plane could account for the collectivity.[2] However, the observed rotational behavior ($E_\gamma \propto I$) may not be easy to explain in this context, and one may speculate about the additional role[12] of orbitals from the next higher shell in collective motion at the higher spins.

In the three Dy isotopes studied, the $E2$ properties are very similar at high I ($\gtrsim 40\hbar$) and U (up to ~ 7 MeV). However, there are clear differences observed in the $E2$ properties for $I \lesssim 40\hbar$ and $U \lesssim 5$ MeV, reflecting the persistence of shell effects and some degree of order up to $U \sim 5$ MeV. In the chaotic limit, no differences with neutron number would have been observed. While the system is clearly ordered at the yrast line, evidence for chaotic behavior has been found[16] at low spin for $U \sim 8$ MeV and even for U as low as ~ 1–3 MeV in some cases.[4] The persistence of elements of order up to $U \sim 5$ MeV at $I \sim (20$–$40)\hbar$ is interesting in this context and one may speculate on the role of collectivity in preserving order.[3,4]

In summary, excited states with U up to ~ 7 MeV have been investigated in ^{152,154,156}Dy. A collective, presumably prolate, $E2$ component has been observed in all cases. In ^{156}Dy this persists towards the yrast region. In ^{152}Dy it terminates at higher I and U as aligned-particle configurations in the yrast region are encountered. In ^{154}Dy, this collective structure changes to one which has a vibrationlike behavior, with the transition energies remaining nearly constant with spin, and gives rise to a lower-energy peak. This work demonstrates that the quasicontinuum $E2$ spectrum can reveal structural changes in excited states to higher excitation energy than has been observed before.

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