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

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ABSTRACT

The evolution of the γ quasicontinuum spectrum with neutron number has been investigated in the sequence of dysprosium isotopes ^{152,154,156}Dy. The three nuclei display a pronounced collective E2 component. In ^{154}Dy this component shows an unexpected splitting into two distinct parts, signifying a structural change along the γ cascade. The E2 and statistical components can be reproduced in simple γ cascade calculations; in ^{152}Dy and ^{156}Dy only rotational bands were included, whereas in ^{154}Dy additional vibration-like transitions were 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. It is of interest to determine, for example, when chaos sets in and the role of collectivity and spin in delaying its onset.[3,4]

Several experiments have investigated the shapes of rotating nuclei at high temperature (U $\gtrsim$50 MeV) by examining the giant dipole resonance component of the γ spectrum[5], but manifestations of phase transitions have proven elusive. 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, striking shape changes may also be expected at significantly lower U. Indeed, T_{cr} is predicted to decrease quickly with the approach towards the transitional region.[8] Alternative methods have to be developed for studying the interesting nuclear physics near a predicted phase transition in the lower U domain, where giant dipole photon emission 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. Differences in the spectral features as a function of neutron number have also been observed, reflecting the persistence of order in excited states.

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 provide guidance on 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. We have found that the quasicontinuum E2 spectrum probes mainly states with U ~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, allow study of 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 about 1.6 ps for the nuclei recoiling with an initial velocity of v/c ~0.020. Prompt γ-γ coincidences have been measured in 8 Compton-suppressed Ge detectors placed at 34°, 90° and 146° with respect to the beam axis. High multiplicity events were selected by requiring that at least two out of an array of 14 BGO crystals fired.

From the coincidence data, clean ^{154}Dy and ^{156}Dy spectra were generated by gating on low-lying lines for each detector angle, 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 using their different angular distributions. For each spectral component, the average multiplicity, and total spin and energy removed were computed, allowing a determination of the entry spin and excitation energy. (Details of the analysis are described in Ref. 9.) The results are summarized in Table 1, including data on ^{152}Dy from Ref. 9.

Fig. 1 shows the E2 continuum spectra for the three dysprosium isotopes investigated. The E2 component of ^{152}Dy and ^{156}Dy consists of one discernible broad peak, differing in multiplicity and energy. In ^{154}Dy this component is split into two distinct parts, the first time that such a feature has been observed in the quasicontinuum γ spectrum. (Note that yrast transitions, which have been subtracted, are not responsible for this feature.) Both the average multiplicity and energy of the upper peak increase with beam energy [see Fig. 2(a)], consistent with a rotational origin. In contrast, the low-energy component stays remarkably constant; in particular, its average γ-ray energy of 780 keV does not change noticeably 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.

The emission times of the spectral components 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 components of the E2 peak 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 components 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, with a clustering around 780 keV in the lower peak from the later decay stage. 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 1) to that of the first part in ^{154}Dy. However, in ^{152}Dy the collective flow terminates around $\bar{U}$ = 1-1.5 MeV and $\bar{I}$ ~34 $\hbar$, as aligned-particle configurations dominate in the vicinity of the yrast line. (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 $\bar{U}$ ~0.7 MeV and $\bar{I}$ ~26, resulting 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 J_{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 peak seen in ^{154}Dy. However, by assuming a change from rotational to vibration-like behavior for excitation energy $E^* < 16.5$ MeV, the observed features at all beam energies could be reproduced (see Fig. 2) with one common set of parameters (Table 1). (The term vibration-like 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)). A collective B(E2) of 300 W.u. 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. (Attempts to reproduce all data by increasing J_{eff} for $E^* < 18.5$ MeV were unsuccessful.) The simulations suggest that the lower peak arises from states with U ~1-5 MeV and I~ (30-40), (25-38) and (21-33) $\hbar$ for beam energies of 165, 155 and 148 MeV, respectively.

In ^{154}Dy structural changes have been observed in the yrast region for $I \geq 32$ $\hbar$, where there is transition from prolate to oblate shape, followed by a return to moderate collectivity at higher spins.[6] Marked changes also occur above the yrast line, giving rise to the unexpected low-energy E2 peak.

The origin of this peak needs further elucidation. For near-yrast states the change from prolate to oblate for a particular band occurs through triaxial shapes; many triaxial bands are calculated[7] to occur above the yrast line and may have been observed.[6] As U increases the densities of such bands, as well as those of prolate and oblate configurations, will increase. 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 vibrational-like transitions associated with the lower energy E2 peak. An alternative, more general viewpoint is that the transitions connect states near the critical temperature T_{cr} for transition to oblate shapes. In the vicinity of T_{cr}, large shape fluctuations should occur, leading again to a potential energy surface which is flat in the β-γ direction. Experiments have shown[6,7] that some oblate states already occur at lower temperature along some parts of the yrast line. In a transitional nucleus like ^{154}Dy, T_{cr} is predicted to be low;[2,8] Goodman calculates that in the isotone ^{158}Yb it decreases with spin, reaching 0 at 40 $\hbar$. It remains to be shown through further theoretical study whether large fluctuations give rise to a vibration-like spectrum. It is also a challenge for theory to explain the re-emergence of collective structures at higher I and U (leading to the upper E2 peak), as well as along the yrast line[6], after the predicted transition to oblate shapes.

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 and U $\lesssim$5 MeV, reflecting the persistence of shell effects and some degree of order up to U ~5 MeV. (In the chaotic limit, no differences with N would have been observed.) While the system is clearly ordered at the yrast line, evidence for chaotic behavior has been found[11] at low spin for U ~8 MeV and also for U ~1-3 MeV (Ref. 4). The persistence of order up to U ~5 MeV at I ~30-40 $\hbar$ 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 vibration-like behavior, with the transition energies remaining nearly constant with spin, and gives rise to a lower energy peak. This work shows that the quasicontinuum E2 spectrum can reveal structural changes in excited states.

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REFERENCES

1. Y. Alhassid, S. Levit and J. Zingman, Phys. Rev. Lett. 57, 539 (1986); Nucl. Phys. A469 205 (1987).
2. A. Goodman, Phys. Rev. C35, 2338 (1987); private communication.
3. T.H. Seligmann, J.J.M. Verbaarschot and H.A. Weidenmüller, Phys. Lett. 167B, 365 (1986).
4. A.Y. Abul-Magd and H. A. Weidenmüller, Phys. Lett. B162, 223 (1985).
5. K. Snover, Ann. Rev. Part. Nucl. Sci. 36, 545 (1986) and references therein.
6. W.C. Ma et al., preprint 1988.
7. H.W. Cranmer-Gordon et al., Nucl. Phys. A465, 506 (1987).
8. Y. Alhassid, private communication; J.M. Manoyan, Ph.D. thesis, Yale University (1987).
9. R. Holzmann et al., Phys. Lett. B195, 321 (1987).
10. R. Holzmann et al., Nucl. Inst. and Meth. A260, 153 (1987).
11. R. U. Haq, A. Pandey and O. Bohigas, Phys. Rev. Lett. 48, 1086 (1982).

FIGURE CAPTIONS

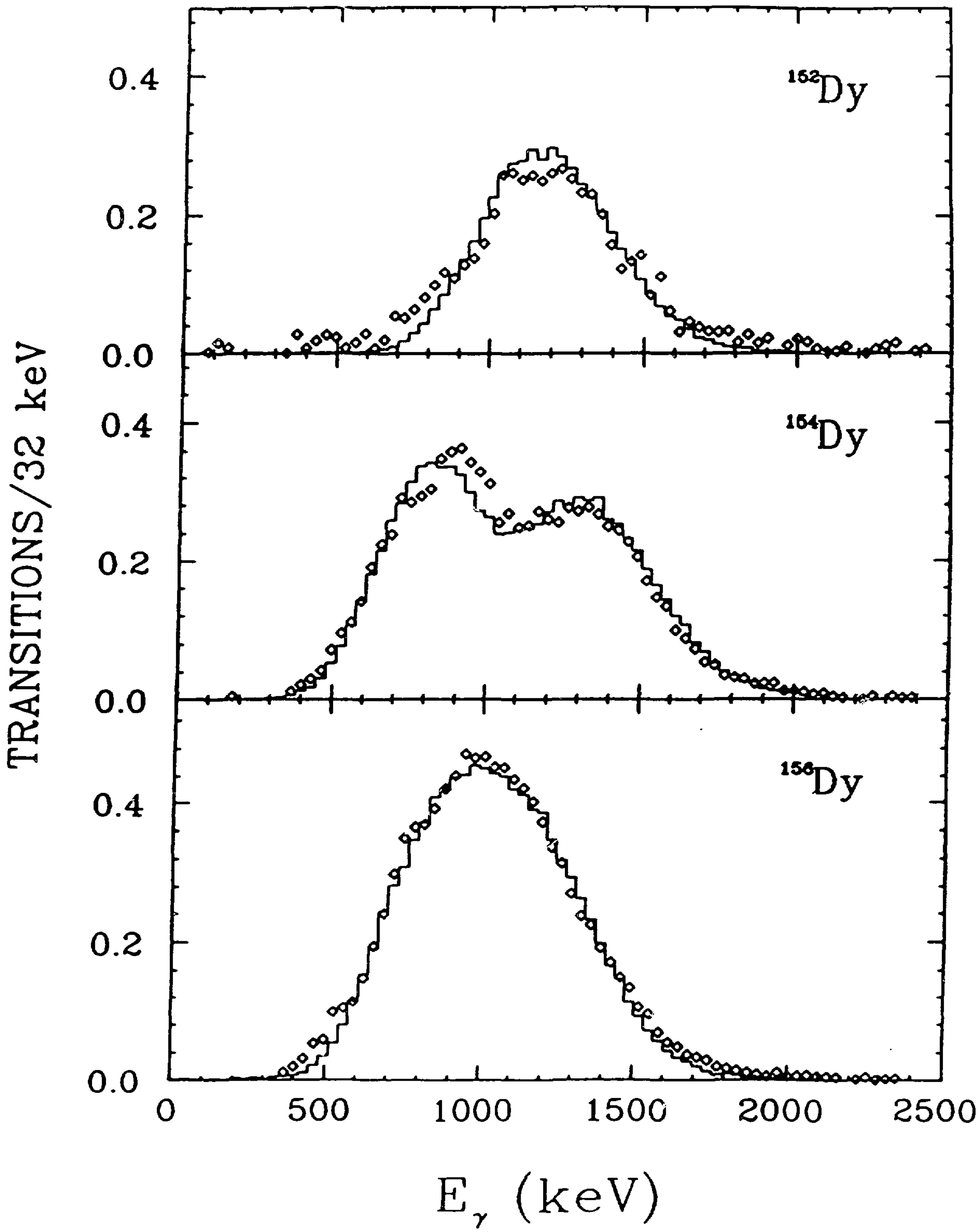
Fig. 1. Measured (•) E2 γ-quasicontinuum components in ^{152,154,156}Dy. Discrete lines have been subtracted and the spectra corrected for Doppler shifts and angular-distribution effects. Calculated spectra are shown as histograms.

Fig. 2. (a) Measured (•) E2 quasicontinuum components 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 points 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.

Table 1. 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 calculated by adding 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 J_{eff} is the effective moment of inertia.

	^{152}Dy	^{154}Dy	^{156}Dy	
E_{beam} (MeV)	160	165	155	MeV
$\bar{I}_{entry}$ ($\hbar$)	46.7	50.2	48.8	$\hbar$
$\bar{E}_{entry}$ (MeV)	25.6	26.9	25.4	MeV
$\bar{M}_{stat.}$	4.0	3.9	3.9	
$\bar{M}_{dipole}$	1.9	1.6	1.1	
$\bar{M}_{quad.}$	5.3	9.1	10.3	
$\bar{M}_{total}$	30.5	28.8	27.8	
Q_t (eb)	7.0 ± 2.5 ±1.5	6.5 ± 1[a]	6.0 ± 1.5	eb
a	$A(7\pm1)$	$A(7\pm1)$	$A(7\pm1)$	
$J_{eff}(\hbar^2 MeV^{-1})$	76.0	72.0[a]	75.5	$\hbar^2 MeV^{-1}$

[a] Properties of initial rotational cascade; in the second stage E <16.5 MeV, $E\gamma$ = 780 keV with a 500 keV spread (fwhm) and B(E2) = 300 W.u.



0.4
0.2
0.0
^{152}Dy
^{154}Dy
^{156}Dy
TRANSITIONS/32 keV
0
500
1000
1500
2000
2500
E_γ (keV)

Fig. 1

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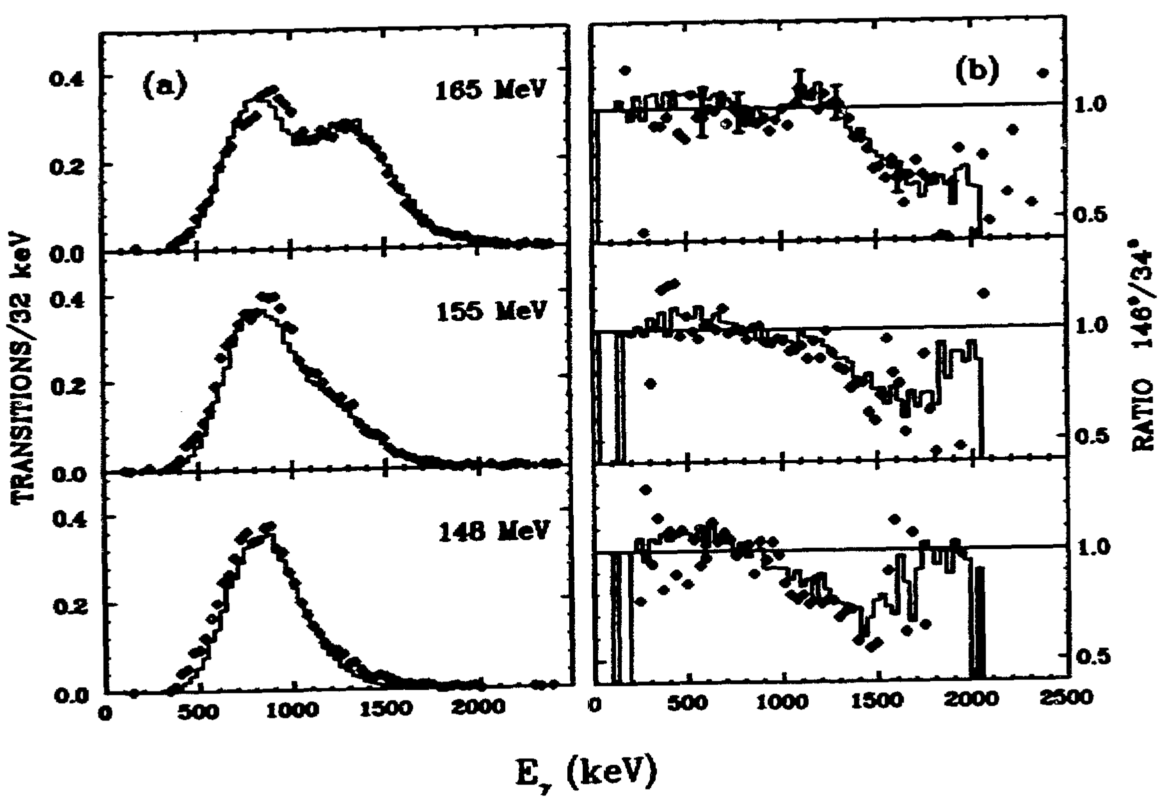

Fig. 2