Total γ-Ray Spectrum in ^{153}Ho: From the Yrast Line into the Continuum

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The γ radiation from ^{153}Ho has been measured with Compton-suppressed Ge detectors. At least four components can be identified; the energy and spin removed by each of these have been measured, and their Doppler shifts analyzed. New fine structure is observed in the pre-yrast γ spectrum which arises from single-particle transitions forming the link between the yrast and continuum cascades. Near the yrast line the single-particle character of the states is preserved, but at higher energies collective modes begin to dominate.

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Many nuclei at the beginning of the rare-earth region ($A \sim 150$) exhibit high-spin yrast states obtained from single-particle alignment.[1] In contrast, studies of quasicontinuum γ radiation in this region reveal evidence of collective structures at higher excitation energies and spin.[2] Whereas the detailed properties of the yrast configurations are now well understood,[3] the exact nature of the excited continuum states is still an open problem. Several questions remain unanswered, for example, about the character of the collective modes associated with the high-spin aligned-particle configurations, the evolution of nuclear structure as one moves above the observed yrast line in both excitation energy and spin, and the link between the continuum and the yrast states.

In order to address these questions a detailed characterization of the complete γ-ray spectrum feeding into the yrast line is necessary. To see *all* features of the spectrum, a detector with both a good response function, i.e., peak-to-total ratio, and high resolution is desirable. The good response greatly reduces many of the errors inherent in the process of removing the Compton background from spectra (unfolding) to obtain the actual distribution of γ rays. The high resolution allows reliable subtraction of the known yrast transitions, thereby leaving only the pre-yrast γ rays, and enables one to search for possible fine structure in the quasicontinuum. For these reasons, Compton-suppressed Ge (CSG) detectors are preferable to the more commonly used NaI counters. A further advantage of CSG's is their superior gain stability and linearity, which enhances the reliability of anisotropy and Doppler-shift measurements in the quasicontinuum.

A characterization of the complete γ spectrum also requires selection of a single final reaction product and elimination of contributions from contaminants, which is particularly important in the investigation of quasicontinuum γ rays. These requirements can be achieved, with high efficiency, by accepting only events followed by the detection of delayed γ rays from an isomer.

The nucleus ^{153}Ho is an excellent laboratory for such a study, since the yrast line has been extensively studied to high spin and established to be of single-particle character,[4] the continuum states exhibit the onset of collective motion,[5] and a 229-ns isomer provides the means for the necessary channel selection.

In the present work, we employed the reaction ^{120}Sn(^{37}Cl,4n)^{153}Ho with a 165-MeV ^{37}Cl beam from the Argonne superconducting linac. Gamma rays were detected in two CSG's, with a peak-to-total ratio of ~ 0.55 at 1.2 MeV, which were positioned 19 cm from the target at 0° and 90° with respect to the beam axis. Details of the CSG's are given by Holzmann.[6] An array of twelve NaI crystals, positioned around and fairly close to the target, served as both a multiplicity filter and a detector of the delayed γ rays. Response functions of the suppressed detectors to monoenergetic photons were measured with a variety of sources.

The only observable contaminant γ rays in the spectra were from ^{152}Dy, formed by the (^{37}Cl,4np) reaction, which were removed by subtraction of a spectrum obtained with a time window appropriate for detecting γ rays from its 60-ns isomer. Contributions due to random delayed coincidences and Ge(n,n') peaks (where were already reduced by time of flight) were also subtracted. The final spectra thus obtained were then unfolded by interpolation between the measured response functions and subtraction of the remaining Compton events with the procedure described by Radford.[7] The unfolding routine was tested on source spectra (^{152}Eu, ^{133}Ba, ^{56}Co), as well as delayed spectra from the in-beam measurements, and found to work extremely well, with a final peak-to-total ratio of better than 0.99 for ^{152}Eu, compared to 0.70 before the unfolding.

The unfolded in-beam spectrum was corrected for photopeak efficiency, angular distribution effects, and Doppler shifts (see Ref. 8). The result, given in Fig. 1(a), is the actual γ-ray spectrum emitted by the nucleus, showing both yrast and pre-yrast transitions. Figure 1(b) shows the spectrum with transitions between known levels in ^{153}Ho removed, leaving only the so-called quasicontinuum. All remaining peaks have intensity less than 3% of the isomeric intensity, and none of these could be identified as transitions in neighboring nuclei, assuring that the remaining spectrum contained only γ rays from ^{153}Ho.

The gross features of the pre-yrast spectrum [Fig. 1(b)] are similar to those observed in studies with NaI detectors. However, as an improvement we have now been able to measure reliably the spectrum down to ~ 130 keV, compared to the previous thresholds of ~ 350 keV. The new feature which is observed is that the quasicontinuum spectrum is not continuous but actually consists of sharp lines, constituting 7% of the total multiplicity (see Table I), superimposed on an underlying smooth background.

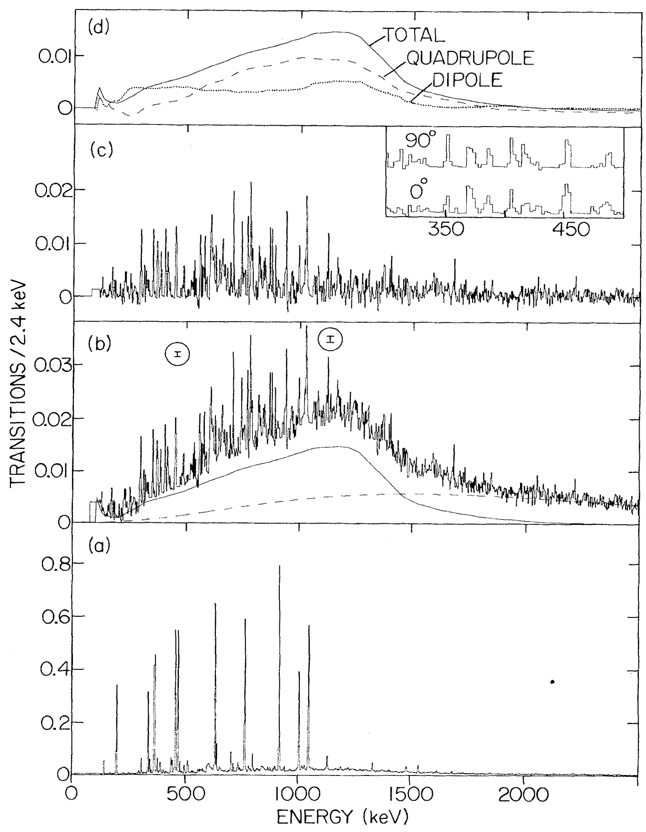

FIG. 1. Unfolded γ spectra from the reaction ^{120}Sn(^{37}Cl,4n) at 165 MeV. (a) Total spectrum. (b) Spectrum with the trees removed, showing grass (fine structure), soil (full line), and statistical (dashed line) components. Typical statistical errors are enclosed in circles. (c) Grass spectrum; the inset shows the 0° and 90° grass spectra between 300 and 500 keV on an expanded scale. (d) Multipole decomposition of the soil obtained from the observed anisotropies assuming stretched transitions.

We propose a classification of the spectrum into four components: (i) discrete lines (to facilitate future reference we call these "trees"), which deexcite known yrast and near-yrast levels and which dominate the spectrum, as seen in Fig. 1(a); (ii) weak ($<3\%$) but resolvable peaks ["grass," Fig. 1(b)] which are too weak to be placed in the level scheme and which would be normally attributed to the unresolved quasicontinuum in studies with NaI detectors; (iii) a smooth continuum ["soil," solid curve in Fig. 1(b)] underlying the grass; and (iv) statistical γ rays [dashed curve in Fig. 1(b)], which have been obtained from a least-squares fit to the spectrum between 2.4 and 3.9 MeV by use of a functional form $E_\gamma^3 \exp(-E_\gamma/T)$, where $T=0.5$ MeV from the fit.

We have further decomposed components (ii) and (iii) into dipole and quadrupole transitions on the basis of their measured anisotropy with the usual assumption that they are composed solely of stretched ($\Delta I=\lambda$) transitions; the results for the soil component are shown in Fig. 1(d). We have also normalized to unity the sum of the areas of the two peaks which feed the isomer, so that the integrated areas of the various components directly give their multiplicities. The results are summarized in Table I. The total multiplicity agrees with a previous measurement[5] with the same reaction and beam energy. It should be noted that Table I does not include any transitions following the decay of the isomer.

By comparing the spectra at 0° and 90° [Fig. 1(c)] we examined the Doppler shifts of the different components. Limits on their lifetimes were then obtained by use of the information that the stopping time of residues in the Pb

TABLE I. Average properties of γ-ray components feeding 229-ns isomer in the reaction ^{120}Sn(^{37}Cl,4n)^{153}Ho at 165 MeV.

	$\overline{M_\gamma}$	$\overline{\Delta E}$ [a] (MeV)	$\overline{\Delta I}$ [a] ($\hbar$)
Trees[b]	9.1	5.76	14.9
Soil dipole	2.2	1.96	2.2
Soil quadrupole	3.2	3.32	6.3
Grass dipole	0.89	0.65	0.9
Grass quadrupole	0.55	0.63	1.1
Statisticals	5.2	10.26	2.6[c]
Total	21.1	22.58[d]	28.0[d]

[a]Total energy $\overline{\Delta E}$ and total spin $\overline{\Delta I}$ removed by each component; $\overline{\Delta E}=\overline{M}_\gamma \times \overline{E}_\gamma$.

[b]Corrections for internal conversion included.

[c]It is assumed that $\overline{\Delta I}$/transition$=0.5$.

[d]When the energy and spin removed in the isomer decay is included we obtain $\overline{\Delta E}=25.36$ MeV, $\overline{\Delta I}=43.5\hbar$ for the ^{153}Ho reaction channel.

target backing is ~ 2 ps. The upper edge of the soil quadrupole bump shifts with the full center-of-mass velocity ($v/c = 0.023$), indicating decay times of <0.3 ps.[8] (This is in agreement with the conclusions of Hübel *et al.*[9]) In contrast, none of the weak peaks in the grass has any observable shift, indicating an average delay of at least 8 ps before these γ rays are emitted.

Although the grass may appear to be weak, it should be emphasized that it cannot be regarded as either statistically insignificant [cf. typical error bars in Fig. 1(b)] or as arising from fluctuations in the strength of the soil. The spectra at 0° and 90° show distinct correlations, i.e., the peaks appear in both spectra [Fig. 1(c)]. Furthermore, the grass and soil exhibit different lifetimes, as discussed above, and their quadrupole-to-dipole ratios are quite different (roughly 0.6 and 1.5, respectively). Finally, the average width of the peaks in the grass spectrum has been determined to be about twice the detector resolution, indicating that it is composed of many partly overlapping peaks rather than fluctuations of the continuum.

It is of interest to consider the emission-time sequence of the different components of the γ-ray spectrum. The long lifetime of the grass establishes that this component arises from the last stage of the decay into the yrast line (as transitions between single-particle states), and is followed only by the known yrast cascade. This picture is supported by the observation of long feeding times ($\gtrsim 10$ ps) into single-particle yrast states in ^{152}Dy.[10] The ordering of the preceding components, i.e., statisticals, soil quadrupoles, and soil dipoles, remains unestablished and it is even possible that they intermix.

Table I presents the average energy $\overline{\Delta E}$ and spin $\overline{\Delta I}$ removed from the nucleus by each component, as calculated from the centroids E_γ of the spectra and the dipole and quadrupole multiplicities M_γ. This information is also shown in Fig. 2. For each component, the spread in ΔE is estimated from the width of the spectra to be of the order of $\pm 50\%$. Despite the uncertain relative ordering or possible intermixing of the soil and statisticals, it is still possible to draw conclusions concerning the contributions of the different components to the process of cooling from the entry region to the yrast line. Each component removes energy above the yrast line $\overline{\Delta\epsilon} = \overline{\Delta E} - \overline{\Delta I}(dE/dI)_{\rm yrast}$. The statisticals remove $\overline{\Delta\epsilon} \sim 8.7$ MeV, while the quadrupole component of the soil runs roughly parallel to the yrast line, on average not cooling the nucleus ($\overline{\Delta\epsilon} = -0.08$ MeV). The grass and the soil-dipole components have intermediate slopes and run obliquely towards the yrast line, removing $\overline{\Delta\epsilon} \sim 0.4$ and 0.9 MeV, respectively. (From the slope of the grass we can infer that this component must be pre-yrast as opposed to part of the yrast cascade.)

The dipole transitions in the soil are almost uniformly distributed up to 1.5 MeV [Fig. 1(d)]. They certainly do not form a well-defined "dipole-bump" with half the energy of the quadrupole soil, making it unlikely that the bulk of them arise from transitions within rotational bands, as has been previously speculated.[11] Indeed, the similarity in energy distribution and $\overline{\Delta E}/\overline{\Delta I}$ between this component and the grass suggests that it may be simply a continuation of the grass to higher excitations and hence higher level densities. In any case, our results (grass and dipole soil) are inconsistent with the picture of the direct population of yrast states through bands generated by rotation perpendicular to an oblate symmetry axis.[12] This conclusion is also supported by a detailed examination of the population pattern of aligned-particle yrast states[13,14] and of the transitions feeding these states in well-studied cases,[4,15] which shows these transitions to be of single-particle character.

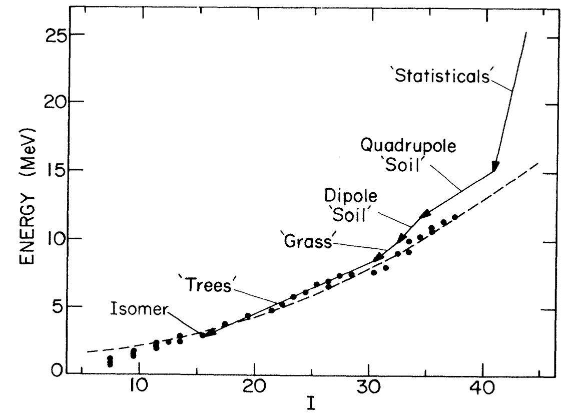

FIG. 2. Schematic representation of γ deexcitation (arrows) in ^{153}Ho, using $\overline{\Delta E}$ and $\overline{\Delta I}$ values from Table I. Circles indicate known yrast states, which are fitted with the dashed line. While the ordering of the trees and grass is certain, the figure should not be interpreted as favoring any one particular sequence for the soil dipoles, soil quadrupoles, and statisticals.

For nuclei with aligned-particle yrast configurations, the importance of single-particle transitions in the pre-yrast cascades has been anticipated by Åberg *et al.*[14] Their calculated energy spectra associated with these transitions are similar to those we have measured for the quadrupole part of the grass component, and for the sum of the dipole parts of the grass and soil components.

Finally, a clearer picture is beginning to emerge about the changing character of quasicontinuum γ transitions. Within ~ 1 MeV of the yrast line single-particle transitions dominate. With increasing internal excitation energy and spin these give way to collective cascades which have quadrupole character and short lifetimes. This implies an evolution of structure from aligned-particle to collective character with increasing intrinsic energy.

In summary, we have been able to isolate the pre-yrast cascade in sufficient detail to extract new information on the link between the yrast and quasicontinuum states and on the changing character of the latter. The new generation of Compton-suppressed Ge detector systems promises further insights into the evolution of nuclear structure with intrinsic energy and spin.

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[8]In the analysis of the spectra shown in Fig. 1, both the statisticals and the soil at 0° were corrected for Doppler shift and solid angle transformation, with assumption of the full recoil velocity. Without these corrections the spectra differ little, except in the vicinity of the upper edge of the soil component, and our conclusions are not affected.

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