

K X-RAY YIELDS, M1 STRENGTH AND THE γ -RAY QUASICONTINUUM IN ^{153}Ho

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The presence of highly converted transitions at high spin in the quasicontinuum spectrum of ^{153}Ho was established from the measurement of K-shell ionization yields. The occurrence of these transitions and the onset of collectivity appear to be correlated. The quasicontinuum γ -ray spectrum was also measured. The X-ray yields cannot be explained solely by internal conversion of transitions with $E_\gamma \geq 350$ keV. Other sources are considered.

In the study of nuclear structure at high spins, possible M1 components in quasicontinuum γ -ray spectra from heavy-ion induced reactions are of considerable interest. Various sources for strong M1 γ -ray emission have been suggested [1]; they include statistical M1 transitions in nuclei where rotation takes place around a symmetry axis, cross-over transitions between high-K rotational bands and transitions within a high- j shell. Magnetic dipole radiation has also been proposed as a possible signature for the occurrence of oblate shapes at very high spins [2] or for the relaxation of triaxial collective modes [3].

In this context, the study of M1 strength in quasicontinuum spectra of nuclei at the beginning of the rare earth region could provide important information on the nature of collective motion known to occur at high spin [4]. Around $A \approx 150$, discrete states up to spin $I \approx 40$ are generated from the alignment of nucleons in high- j orbitals. However, studies of unresolved γ rays reveal the existence of fast transitions with predominantly stretched E2 character at energies between ≈ 1.0 and ≈ 1.4 MeV. The properties of these "E2-bumps" resemble those of similar structures in rotational nuclei and suggest the onset of collectivity. At roughly half the energy of the E2-bump, dipole radiation has also been reported [4]. Due to experimental difficulties associated with the presence of numerous discrete lines, information on this component is somewhat uncertain; nevertheless, the γ -rays were shown to originate from states with high spin ($I \geq 40$).

It is tempting to assign magnetic character to these transitions and to relate them to some of the models mentioned above.

With this in mind, we have performed measurements of the K-shell ionization of ^{153}Ho , resulting from the γ -ray deexcitation process, as a function of angular momentum input from a heavy-ion fusion-evaporation reaction. The data are combined with γ -ray intensities to obtain information on the distribution of M1 strength. It is found that the observed X-ray yield is greater than can be accounted for by internal conversion of quasicontinuum transitions with $E_\gamma \geq 350$ keV. Other possible sources of ionization are considered.

In the present experiment, the contribution from K-shell internal conversion of the quasicontinuum γ rays to the measured X-ray yield is deduced by subtracting the sum of contributions from conversion of all known discrete transitions. The ^{153}Ho nucleus is an excellent candidate to render such a measurement most meaningful since levels located on the yrast line or in its vicinity have been studied extensively up to a spin of $81/2 \hbar$, and a 229-ns isomer allows very clean selection of the reaction channel [5].

Beams from the Argonne superconducting linac were used to produce ^{153}Ho via the $^{120}\text{Sn} (^{37}\text{Cl}, 4n)$ reaction at 150–175 MeV incident energies. The experimental arrangement consisted of a multiplicity- and time-filter of 16 NaI detectors covering 55% of 4π , two Ge detectors and a 12.7×12.7 cm NaI coun-

ter. Events in the Ge and/or large NaI detectors were accepted only if at least three elements of the filter fired in prompt coincidence and at least one element fired in a time interval of 40–500 ns following the reaction. The X-rays and low-energy γ -rays were observed with the first Ge detector (of small volume and high resolution) while the entire spectrum of discrete lines was measured with the other (large-volume coaxial) Ge counter. Both Ge detectors were at 55° with respect to the beam. The large NaI detector was collimated, and was also located at an angle of 55° with respect to both the beam and the large Ge counter. The target-to-detector distance of 26 cm was large enough to discriminate against neutrons by time-of-flight. This NaI counter was used to obtain quasicontinuum spectra and its coincidence rate with the large Ge detector was used to measure the γ -ray multiplicity associated with different discrete lines.

As mentioned above, the contribution to the X-ray yield due to K-conversion in ^{153}Ho was obtained from the intensity of the discrete transitions at six beam energies. Use was made of the well-established multiplicities of ref. [5] (established by means of both angular distribution and conversion coefficient measurements). The open circles in fig. 1a give the resulting number of X-rays per reaction, $M_{\text{K-X}}$, as a function of the beam energy or alternatively as a function of the average entry spin $\langle I \rangle$. The latter quantity was determined from the measured γ -ray multiplicity M_γ using the formula $\langle I \rangle = 1.5(M_\gamma - N_{\text{st}}) + 31/2$, where the factor 1.5 represents the average spin removed by a prompt transition, N_{st} is the number of statistical γ rays and $31/2$ is the spin of the isomer. It is seen that the contribution to $M_{\text{K-X}}$ from the discrete transitions grows from a value of ~ 0.2 at 150 MeV to ~ 0.45 at 175 MeV, reflecting the increased population of known high spin states, which decay largely via low energy M1 and E2 transitions. At the two lowest beam energies, the ionization due to the discrete lines accounts for most of the measured X-ray multiplicity (full circles in fig. 1a). However, as more angular momentum is added to the nucleus the increase in the measured values of $M_{\text{K-X}}$ is much larger than that calculated from the discrete lines, implying the presence of other highly converted transitions populated at spins in excess of $40\hbar$.

The result presented in fig. 1a is in good agreement with a similar measurement performed on the neigh-

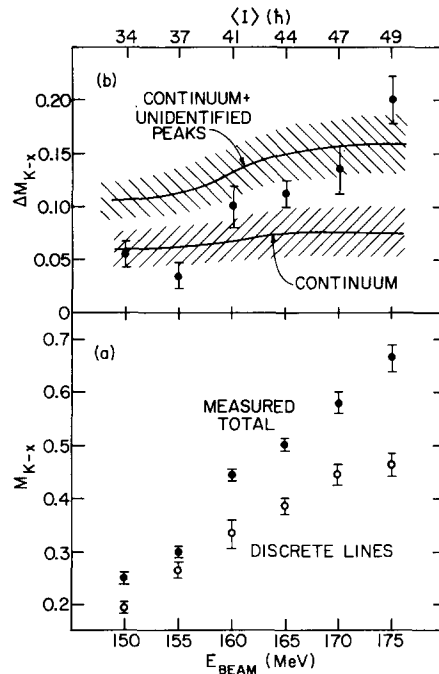


Fig. 1. (a) Number of X-rays per nuclear reaction, $M_{\text{K-X}}$, as a function of the beam energy and the average entry spin. The full circles present the measured values, while the open circles give the contribution due to the conversion of the known discrete lines. (b) The difference between the points plotted in fig. 1a, $\Delta M_{\text{K-X}}$. The lower solid curve presents the maximum contribution to $\Delta M_{\text{K-X}}$ from the quasicontinuum obtained under the extreme assumption that all transitions with $0.35 \leq E_\gamma \leq 0.95$ MeV are of M1 multipolarity while the upper curve also includes the additional contributions due to conversion of unidentified weak peaks with $E_\gamma < 350$ keV under a similar assumption. See text for details.

boring nucleus ^{154}Er [6], but disagrees with an earlier report on ^{152}Dy [7]. Using the energy dependence of the evaporation residue atomic-charge state distributions, Cormier et al. [8] also reported strongly enhanced internal conversion probabilities at high spin in the nuclei $^{156}, ^{158}\text{Er}$. In all measurements, the enhancement (when observed) is found to occur at a spin value of about $35\text{--}40\hbar$ and to persist up to the highest angular momenta observed. The one exception is ^{156}Er , where, after a sharp initial enhancement in the spin range $40\text{--}45\hbar$, the internal conversion probability drops for higher angular momenta.

The results of the present work also suggest that the increase in X-ray multiplicity is associated with the on-

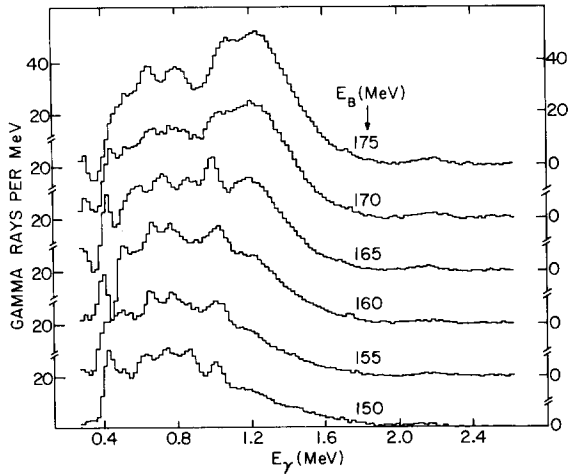


Fig. 2. Unfolded quasicontinuum γ -ray spectra at different beam energies, from the large NaI detector, corrected for detector efficiency and coincidence summing. The fitted contribution of the statistical transitions has been subtracted.

set of collectivity at high spin in ^{153}Ho . Fig. 2 presents unfolded NaI spectra measured at the different beam energies. In these spectra, the discrete lines have been carefully subtracted using intensities extracted from the Ge spectra and measured response functions. A detailed description of the unfolding and subtraction procedures is given in ref. [9]. The spectra have also been divided by the detector efficiency, and the contribution of the statistical γ -rays obtained from a fit with the usual expression $N_{st}(E_\gamma) = E_\gamma^3 \exp[-E_\gamma/T]$ to the spectrum for $E_\gamma > 2.2$ MeV has been removed. With increasing angular momentum (fig. 2) a "bump" of transitions develops between 1.0 and 1.6 MeV, similar to those observed in neighboring nuclei [10,11]. These "bumps" contain mostly transitions of stretched E2 character, and are usually ascribed to the onset of collectivity.

Fig. 1b shows the excess K X-ray multiplicity ΔM_{K-X} (i.e. the difference between the measured M_{K-X} and the value calculated as arising from known discrete lines). The maximum possible contributions to ΔM_{K-X} from other components of the γ -ray spectrum are discussed below, in an attempt to explain the observed excess.

It is worthwhile to note that the transitions in the "E2-bump" do not contribute significantly to ΔM_{K-X} . Even though the γ -ray intensity between 1.1 and 1.9

MeV increases by a factor of 3.5 from 150 to 175 MeV, the largest contribution to ΔM_{K-X} is only 0.02. Clearly, significant contributions have to be found in a lower energy part of the spectrum. As mentioned above, several groups [4] have reported dipole radiation at energies roughly half that of the "E2-bump". This component of the quasicontinuum could add significantly to the X-ray multiplicity if it is of M1 character. In the present work, the γ -ray intensity for the range $0.35 \leq E_\gamma \leq 0.9$ MeV is found to increase by 20% when the average angular momentum increases from 37 to 44 \hbar . For higher bombarding energies the intensity remains constant. In view of the similarity between the known properties of ^{153}Ho and those reported for the adjacent isotones ^{152}Dy and ^{154}Er [10, 11] it is then natural to associate this increased γ -ray intensity with dipole radiation. The lower solid line in fig. 1b represents the contribution to ΔM_{K-X} calculated under the extreme assumption that the entire quasicontinuum γ -ray spectrum between 0.35 and 0.9 MeV is of M1 multipolarity. The shaded area surrounding this line shows the estimated uncertainty ($\approx \pm 30\%$) due to the unfolding process and the subtraction of the discrete lines. At the lowest angular momenta, the values calculated in this way exceed the measured ones, indicating that the radiation may be of mixed multipole character, in agreement with measurements using other techniques [4,8,10,11]. However, for the highest angular momenta the computed values still fall well below the measured values; the increase in internal conversion due to transitions in a "dipole bump" can, at best, account for half of the ionization excess. In this way, the present result raises questions about earlier speculations [1,6,8] that the measured ionization probabilities can be accounted for entirely by M1 transitions of energies half that of the collective E2 transitions in the quasicontinuum, at least for nuclei similar to ^{153}Ho .

The only possible remaining source of highly converted transitions is the lowest energy part of the γ -ray spectrum where the uncertainties in the unfolding and subtraction procedures are too large to extract reliable information from the NaI spectra. However, at these energies the Ge spectra offer the possibility of looking for very weak γ -rays whose contribution to the ionization yield can be estimated. Due to the channel selection achieved using the isomeric decay, extremely clean spectra of prompt transitions were

obtained. At the lowest beam energies, all lines seen in the spectra with intensities $\geq 1.2\%$ of the isomer feeding were identified as known transitions in ^{153}Ho . At the highest beam energies, lines belonging to ^{152}Dy [produced in the $(^{37}\text{Cl}, p 4n)$ reaction] also appear in the spectra due to the 60 ns high spin isomer in this nucleus; these lines were subtracted from the spectra and cannot affect the measured M_{K-X} since the Dy X-rays are of a different energy. Under the extreme assumption that the few unidentified very weak peaks (i.e. all lines not assigned to ^{153}Ho or ^{152}Dy) below 350 keV correspond to M1 transitions in ^{153}Ho , the additional contribution to ΔM_{K-X} can be calculated. This was added to the previous contribution from the continuum and plotted, together with associated errors, as the upper solid line and hatched region in fig. 1b. As an extreme upper limit, this seems to account for the observed X-ray yields reasonably well; however, it is clear that the general trend of this limit is different from that displayed by the data.

In conclusion, the present analysis provides evidence that low-energy M1 strength occurs at very high spin in ^{153}Ho . A substantial fraction of this strength is carried through very weak lines with $E_\gamma \leq 350$ keV. Although more precise identification will require further experimental efforts using more refined techniques, it is possible to suggest a plausible explanation for the origin of these transitions using known features of the γ -decay in nuclei in this region. Investigations of discrete transitions feeding the highest known yrast states [12] combined with measurements of the feeding times into these levels [13] show that the fast, collective cascades responsible for the E2-bump do not

persist down to the yrast line. Instead, the line is fed through states similar in nature to those observed on the yrast line. Low-energy M1 transitions may then compete favorably. They occur along the yrast line, and should also be present slightly above it. Thus, any ionization excess might well originate from single-particle transitions representing part of the link between the yrast line and the collective structures. Whether shape changes are also involved in the process remains an interesting speculation.

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