Decay of 3 sec $^{160}Ho^{m}$

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The decay of $^{160}Ho^{m}$ (3 sec) has been studied using high resolution detectors. The activities were produced using the reaction $^{159}Tb(\alpha,3n)$ and were transported with the help of a gas jet recoil transport system. From the observed γ-ray and K x-ray intensities, the multipolarities of all the assigned transitions have been deduced. No evidence of any other isomer of ^{160}Ho with a half-life between 1 sec and 1 h has been obtained.

The energy levels of ^{160}Ho have been studied earlier mostly by in-beam gamma-ray spectroscopy[1,2] and also from the decay of ^{160}Er (28.6 h).[3,4] According to the latest Nuclear Data Sheets (NDS) compilation[5] for $A = 160$, the only established isomer above the 25.6 min ground state (5^+) of ^{160}Ho is at 60 keV (2^-), which decays with a half-life of 5.02 h. Several isomeric levels of ^{160}Ho with half-lives of 3 sec (Ref. 1), 2 min (Ref. 4), 7 min (Ref. 6), and 1 h (Ref. 6) have also been reported in the literature though the decay modes of these isomers are uncertain and need to be established. The in-beam studies[1,2] have established several members of the $K^{\pi}=5^+$ ground state band and the decoupled $[i_{13/2}]_n[h_{11/2}]_p$ band with $K=6$ (Ref. 5), but there is uncertainty as to whether the 118-keV or the 169-keV level is the $K=6$ band head. The present work is aimed at searching for isomers in ^{160}Ho with half-lives greater than 1 sec and to establish their decay schemes.

The nucleus ^{160}Ho was produced in the $^{159}Tb(\alpha,3n)$ reaction with the ^{4}He beam from the variable energy cyclotron at the Variable Energy Cyclotron Centre (VECC), Calcutta. The target used was a self-supporting (5 mg/cm^2) foil of ^{159}Tb. The energy of the incident alpha particles was varied between 29 and 45 MeV in order to study the gamma ray excitation function. The reaction products were transported a distance of 10 m from the target using a gas jet recoil transport (GJRT) system.[7] To obtain the best transport with a minimum of 511 keV annihilation background, 99.99% pure helium gas, bubbled through cyclohexane cooled to near its freezing point, was used as the carrier gas. The activities were collected on thin aluminum foils and were counted *in situ* using a 200 mm^2 LEPS and a 30% GMX detector. The energy resolution of the LEPS detector [620 eV (FWHM) at 50 keV] was sufficient to resolve the $K\alpha_1$ and $K\alpha_2$ lines of Ho and Dy.

In order to search for short-lived activities, the target was bombarded for 4 sec and eight singles spectra were accumulated consecutively for a period of 2 sec each using a CANBERRA-88 multi-parameter analyzer operated in a spectrum multiscaling (SMS) mode. This sequence of bombardment and counting was repeated a sufficient number of times to achieve adequate counting statistics. For long-lived activities, the data were collected for longer periods, typically of 2 to 30 min duration, and the decay was followed for several half-lives.

A typical gamma ray spectrum taken in the LEPS detector two seconds after irradiation is shown in Fig. 1. Gamma rays with energies of 51.2, 107.3, and 118.4 keV were found to decay with a half-life of 3 sec (Fig. 2). The K x-ray multiplet of Ho (Fig. 3) also decays with a 3 sec component, thereby confirming the existence of a 3 sec activity in Ho. The identification of this 3 sec activity as one of the ^{160}Ho isomers is based on the observed gamma ray excitation function relative to other known gamma rays associated with the decay of $^{159}Ho^{m}$ (8.3 sec), ^{160}Ho (25.6 min), and $^{161}Ho^{m}$ (6.7 sec). No other gamma rays with energies greater than 10 keV, associated with the 3 sec activity, could be identified.

No direct evidence of any gamma rays decaying with half-lives of 2 min, 7 min, and 1 h (Ref. 6) has been obtained in the present work. Of these, the 2 min activity is not expected to be produced with appreciable cross section in α bombardment of Tb. Search for any long-lived component of K x rays from Ho was also unsuccessful, which sets an upper limit of 2 mb for the production of isomers in ^{160}Ho with half-lives ranging between 2 min and 1 h. The cross section for the production of the 3 sec isomer in the reaction $^{159}Tb(\alpha,3n)$ at 42 MeV incident energy is estimated to be 100 mb from the measured isomeric ratio of 0.06 ± 0.02 relative to the ground state of ^{160}Ho. The 2^- level in ^{160}Ho at 60 keV (5.02 h) is strongly excited in the present reaction with an estimated production cross section of 500 mb.

The relative intensities of the gamma rays associated with the decay of the 3 sec isomer are listed in Table I. Because of its importance in the multipolarity assignments, the portion of the LEPS spectrum covering the

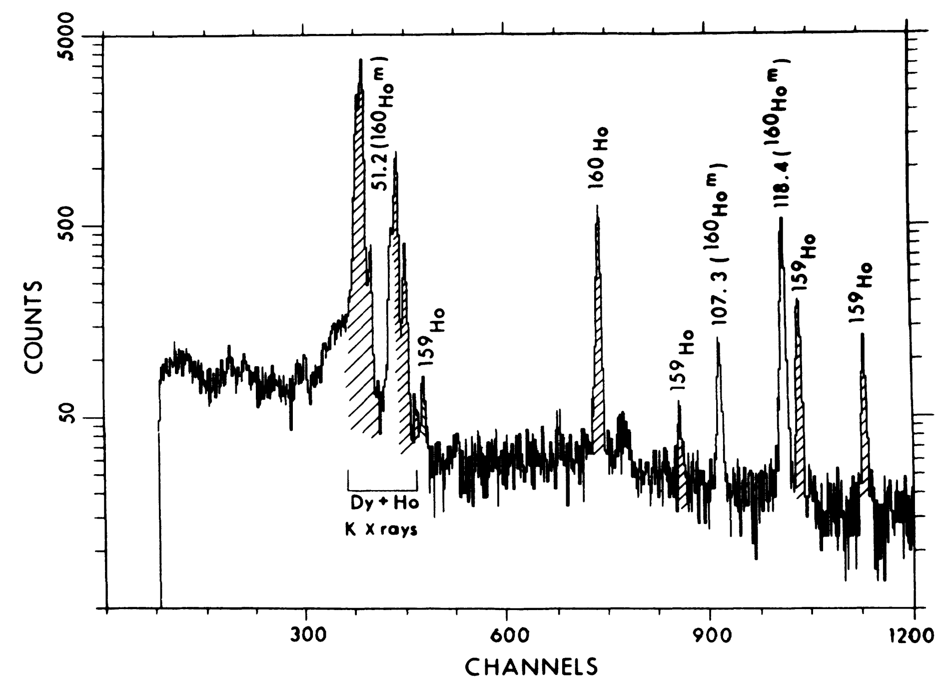

FIG. 1. Gamma-ray spectrum in the energy region 10–130 keV from the decay of $^{160}Ho^{m}$. The spectrum was taken in the LEPS detector 2 sec after irradiation.

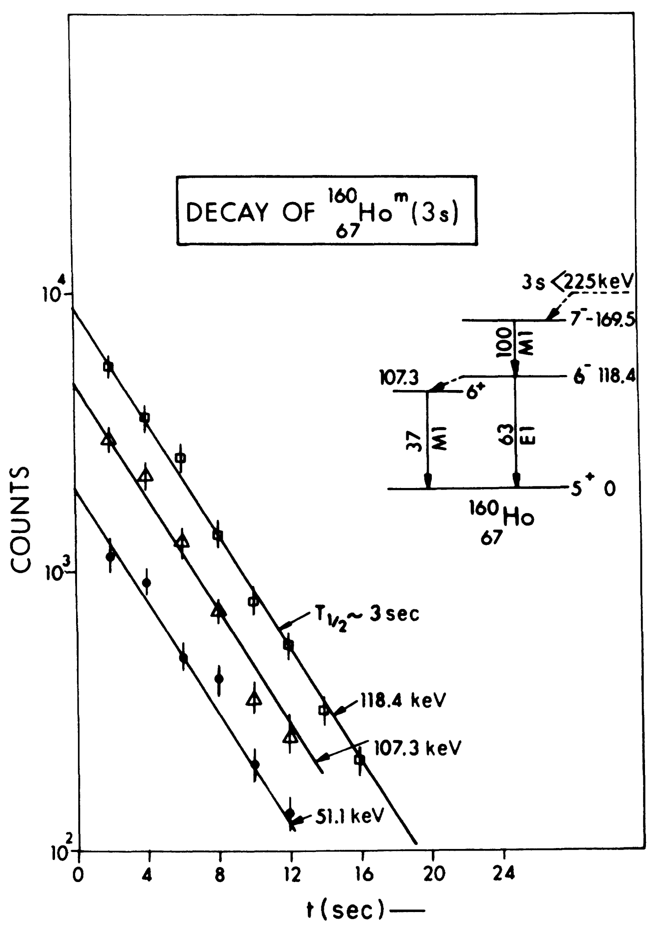

FIG. 2. Decay curves for gamma rays associated with the 3 sec $^{160}Ho^{m}$ isomer. The inset shows the adopted level scheme indicating the multipolarity and total transition strength $(I_\gamma + I_{ce})$ for each transition as obtained in the present work.

energy region 40–60 keV (Fig. 3) was carefully analyzed to obtain the relative contributions from the K x-ray multiplet of Ho and Dy. From the extracted $K\alpha_1$ intensity, the total K-vacancy production rate was calculated from known $K\alpha_2/K\alpha_1$, K_β/K_α ratios[8] and the fluorescence yield ω_K.[9]

From K-shell binding energy considerations, the 107 and 118 keV transitions alone can contribute to the observed K x-ray intensity. One can therefore set an upper limit of 0.5 for the K conversion coefficient, α_K, for the 118 keV transition. This is consistent with a multipolarity assignment of $E1$ only $[\alpha_K(E1)=0.17]$.[10] Leigh *et al.*[1] placed the 107 keV transition between the 6^+ and 5^+ members of the ground state rotational band and suggested that it be of $M1$ multipolarity. The calculated conversion coefficient of this transition, after subtracting the theoretical K x-ray intensity from a 118 keV $E1$ transition, is $\alpha_K = 1.8 \pm 0.3$ compared to a theoretical value of 1.89 (Ref. 10), confirming the $M1$ multipolarity assignment. As a cross check, the K conversion coefficient for the 118 keV transition is estimated to be 0.13 ± 0.10 if the 107 keV transition is taken to be purely $M1$.

The knowledge of the multipolarities of the 107 and 118 keV transitions, together with the gamma-ray intensities measured in the present work, can be used to calculate the total conversion coefficient $(\alpha_{L+M+N+\cdots})$ for the 51 keV transition. The calculated value α_{total} (51 keV)$=3.8 \pm 0.4$ is consistent with an assignment of $M1$ multipolarity. It follows, therefore, that the 118 and 169 keV levels have the same parity. Leigh *et al.*[1] assigned $J=6$ to the 169 keV level and $J=5$ to the 118 keV level, although an assignment of $J=6$ is not ruled out by their data. The reported signature splitting[2] for the levels in the $[i_{13/2}]_n[h_{11/2}]_p$ decoupled band favors even spin values for the 118 keV level. We have adopted in our de-

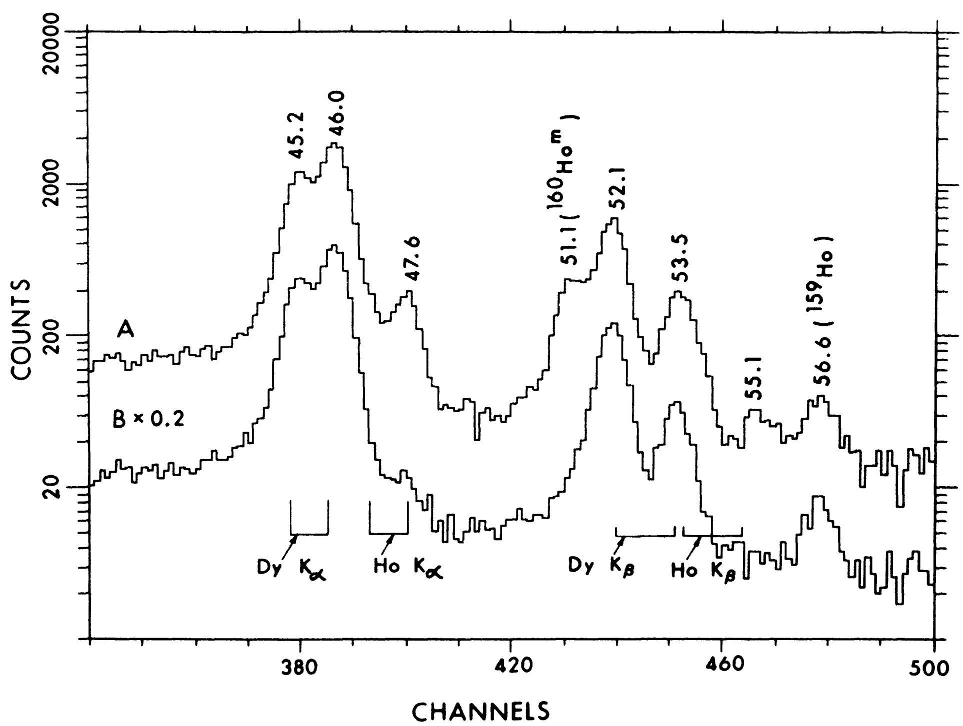

FIG. 3. Gamma ray spectrum from the decay of ^{160}Ho^m for the energy region 40–60 keV. A and B are "prompt" and "delayed" spectra taken 2 sec and 16 sec, respectively, after irradiation. For clarity, curve B has been multiplied by a factor of 0.2.

cay scheme $J=6^-$ and 7^-, respectively, for the 118 keV and 169 keV levels on the basis of the deduced multipolarities for the 118 and 51 keV transitions. This lends support to the interpretation of these levels as the members of the above-mentioned decoupled band with the 118 keV level as band head. The 11 keV transition from the 118 keV to the 107 keV state is expected to be almost fully converted and was not observed in our work.

It is not possible to specify unambiguously the energy or the spin of the isomeric level as no other transitions connecting the former with any of the states of lower energy could be observed. A tentative spin assignment of $J>7$ has been made on the basis of the absence of a direct transition to the 118 keV level. This is corroborated from the measured bombarding energy dependence of the isomeric cross section ratios of the 3 sec isomer and the 5 h isomer (2^-) relative to the 5^+ ground state.

Leigh *et al.*[1] have suggested that the energy of the unobserved isomeric transition is less than 30 keV and that of the isomeric level is below 200 keV. We would like to point out that even a 50 keV isomeric transition of $M2$ or $E3$ multipolarity, consistent with the 3 sec half-life, would be almost fully converted. Absence of any significant amount of K x ray associated with the isomeric transition limits its energy to be less than 55 keV, setting an upper limit of 225 keV for the energy of the isomeric level.

For transitions from the $K^\pi=6^-$ to $K^\pi=5^+$ band, the $B(E1)$ ratio for the 11 keV ($6^-\rightarrow6^+$) and 118 keV ($6^-\rightarrow5^+$) transitions is estimated to be ~24 assuming that the measured population of the 107 keV level is solely due to the unobserved 11 keV transition. This ratio is 2 orders of magnitude larger than Alaga rule predictions.[11] In most experimental tests of the $E1$ intensity relations, it has been found necessary to include higher order terms in the intrinsic moment,[12,13] and the failure of the Alaga predictions has been attributed to the strongly hindered character of the $E1$ transitions. For the 118

TABLE I. Relative intensities (I_γ), conversion coefficients (α_K or α_{total}), and deduced multipolarities of the gamma rays observed in the decay of ^{160}Ho^m (3 sec). The theoretical conversion coefficients are taken from Ref. 10.

Energy (keV)	I_γ	Conversion coefficient Expt.	Conversion coefficient Theory	Multipolarity
Ho K x-ray	50±10			
51.15±0.05	38±4	3.8±0.4[a]	3.13	$M1$
107.28±0.05	18±1	1.8±0.3[b]	1.89	$M1$
118.41±0.05	100	0.13±0.10[b]	0.17	$E1$

[a]Total conversion coefficient α_{total}.
[b]K conversion coefficient α_K.

keV level in ^{160}Ho, the measured half-life of 60 nsec (Ref. 1) is 4 orders of magnitude larger than the Weisskopf estimate, confirming the strongly hindered nature of the $E1$ transition. A comparison with the more generalized model[12,13] was, however, not possible as no other interband transitions in ^{160}Ho are known. An exhaustive in-beam gamma spectroscopy study of ^{160}Ho with a light ion beam may provide further information about the interband and intraband transitions in this nucleus.

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