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Determination of It/Total Branching in Decay of ^{160m}Ho(5.02h) Isomer

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Abstract. Energies and intensities of $Kx(\mathrm{Ho}), Kx(\mathrm{Dy})$ and γ-quanta with energies 59.98 and 86.79 keV from the decay $^{160}\mathrm{Er}\rightarrow\ ^{160m,g}\mathrm{Ho}\ \rightarrow\ ^{160}\mathrm{Dy}$ are measured with a high accuracy. The branching factor for the isomeric state $^{160m}\mathrm{Ho}(2^-)$ is found from the results of the measurements. The value $0.733(30)$ is obtained for the $E3$ transition to the ground state.

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Decay of nuclei $^{160}\mathrm{Er}\ \longrightarrow^{160m,g}\ \mathrm{Ho}\ \longrightarrow\ ^{160}\mathrm{Dy}$ has been thoroughly investigated in recent work [1], where, in addition to obtaining extensive new data on γ-transitions and excited states, the decay fraction for the EC/β^+ decay of $^{160m}\mathrm{Ho}(2^-)$ directly to ^{160}Dy levels was determined from the intensity of the 59.98 keV isomeric $E3$ transition. It was $26.4(52)\%$ of decays in equilibrium with ^{160}Er. Accordingly, the $E3$ transition accounts for $73.6(52)\%$ of decays.

Our precision measurements of γ-radiation with an HPGe detector (36 mm diameter by 13 mm long), whose energy resolution was 335 and 580 eV for the energies of 5.9 and 122 keV, respectively, allowed energies and intensities of $59.98(5)$ and $86.79(2)$ keV $Kx(\mathrm{Ho})$, $Kx(\mathrm{Dy})$ and γ-quanta to be determined. Intensities of these radiations are related to the main characteristics of the decay chain

$$\begin{array}{l} ^{160}\mathrm{Er}(A) \longrightarrow\ ^{160m}\mathrm{Ho}(B) \longrightarrow\ ^{160g}\mathrm{Ho}(C) \longrightarrow\ ^{160}\mathrm{Dy} \\ \qquad\qquad\qquad\ \downarrow \\ \qquad\qquad\qquad\ -\,-\,-\,-\,-\,-\,-\,-\,- \longrightarrow\ ^{160}\mathrm{Dy} \end{array}$$

in the following way:

$$\frac{S_{Kx}(\mathrm{Ho})}{\epsilon_{Kx}(\mathrm{Ho})} = \frac{K}{\epsilon}(\mathrm{Er})\,\omega_k(\mathrm{Ho})\,R_A\,(t_2,t_3)\frac{t_3(\mathrm{live})}{t_3(\mathrm{real})} \tag{1}$$

$$\frac{S^m_{Kx}(\text{Dy})}{\epsilon_{Kx}(\text{Dy})} = \left[\frac{K}{\epsilon}(\text{Ho})^m \sum_{m'}(I_\gamma \alpha_k)_{m'}\right] \omega_k(\text{Dy})(1-f_{BC})R_B(t_2,t_3)\frac{t_3(\text{live})}{t_3(\text{real})} \tag{2}$$

$$\frac{S^g_{Kx}(\text{Dy})}{\epsilon_{Kx}(\text{Dy})} = \left[\frac{K}{\epsilon}(\text{Ho})^g \sum_{g'}(I_\gamma \alpha_k)_{g'}\right] \omega_k(\text{Dy})R_C(t_2,t_3)\frac{t_3(\text{live})}{t_3(\text{real})} \tag{3}$$

$$\frac{S_\gamma(59.98)}{\epsilon_\gamma(59.98)} = f_{BC}\frac{R_B(t_2,t_3)}{1+\alpha_{tot}(59.98)}\frac{t_3(\text{live})}{t_3(\text{real})} \tag{4}$$

$$\frac{kS_\gamma(86.79)}{\epsilon_\gamma(86.79)} = \left[(1-f_{BC})R_B(t_2,t_3)+R_C(t_2,t_3)\right]\frac{t_3(\text{live})}{t_3(\text{real})} \tag{5}$$

$$S^m_{Kx}(\text{Dy})_{\text{exp}} = S^m_{Kx}(\text{Dy}) + S^g_{Kx}(\text{Dy}) \tag{6}$$

The coefficient k takes into account the share of 86.79 keV γ-quanta in the number of decays of the isomeric (R_B) and ground (R_C) states of ^{160}Ho. According to [1], $k = 7.38(32)$. In our experiments this value very weakly depends upon the measurement time t_3 and the hold-up time t_2 after separation of ^{160}Er because the ratio R_B/R_C practically does not change in the intervals of real t_2 and t_3 values in the experiment. Moreover, the total intensity of the 86.79 keV transition from the first excited state to the ground state in ^{160}Dy is 77% of ^{160}Er decays. In this case the state mentioned is not directly populated from the ^{160}Ho β-decay. The symbols $\frac{K}{\epsilon}$(Er), $\frac{K}{\epsilon}$(Ho)^m and $\frac{K}{\epsilon}$(Ho)^g designate the K-capture fractions in the EC decays of Er, isomeric and ground states of Ho respectively. The ^{160m,g}Ho β^+- decay fraction is small ($< 0.3\%$) and we ignore it. The sums $\sum_{m'}(I_\gamma\alpha_K)_{m'}$ and $\sum_{g'}(I_\gamma\alpha_K)_{g'}$ take into account contributions from internal conversion electrons to formation of holes in the shell of the Dy atom in the decay of the isomeric or ground Ho states respectively. We assume that these contributions are approximately identical in the decays of the isomeric and ground states. The symbols ω_K(Ho) and ω_K(Dy) designate Ho and Dy K-fluorescence yields. If S_{Kx} and S_γ are the numbers of X-ray and γ radiation quanta detected by the Ge detector with the absolute efficiencies ε_{Kx} and ε_γ, then their absolute intensities are $I_{Kx} = S_{Kx}/\varepsilon_{Kx}$ and $I_\gamma = S_\gamma/\varepsilon_\gamma$. The quantities $R_A(t_2,t_3)$, $R_B(t_2,t_3)$ and $R_C(t_2,t_3)$ are the numbers of the nuclei ^{160}Er $- A$, ^{160m}Ho $- B$ and ^{160g}Ho $- C$ that decayed in the measurement time t_3 after the hold-up for time t_2 since the moment of separation of ^{160}Er. The ratio $t_3(live)/t_3(real)$ takes into account the "dead" time of the spectrometer. The numbers of decays are calculation by the formulas given in [2]

$$R_A(t_2,t_3) = N_A(t_0)\xi(\lambda_A) \tag{7}$$

$$R_B(t_2,t_3) = N_A(t_0)\Big[\xi(\lambda_A)\frac{\lambda_B}{\lambda_B-\lambda_A} + \xi(\lambda_B)\frac{\lambda_A}{\lambda_A-\lambda_B}\Big] \tag{8}$$

$$R_C(t_2,t_3) = f_{BC}N_A(t_0)\Big[\xi(\lambda_A)\frac{\lambda_B}{\lambda_B-\lambda_A} + \xi(\lambda_B)\frac{\lambda_A}{\lambda_A-\lambda_B} + \xi(\lambda_C)\frac{\lambda_A}{\lambda_A-\lambda_C}\Big] \tag{9}$$

$$\xi(\lambda_j) = \exp(-\lambda_j t_2)\,[1-\exp(-\lambda_j t_3)] \tag{10}$$

We put $f_{AB} = 1$. This means that ^{160}Er decays via the non-delayed γ-transition to the ^{160}Ho level of energy 67.11 keV with $I^\pi = 1^+$, which is followed by population of the isomeric state ^{160m}Ho with $I^\pi = 2^-$ by the 7.113 keV γ-transition. The total conversion coefficient α_{tot} of the $58.98(5)$ keV $E3$ transition (the possible $M4$ admixture is assumed to be zero) which connects the isomeric and ground states of ^{160}Ho was calculated by the code of I.M. Band and M.B. Trzhaskovskaya [3]. It was found to be $\alpha_{\text{tot}} = 935.1(24)$. Its error includes the inaccuracy of the calculation ($\sim 2\%$) and the uncertainty in determination of the γ-transition energy ($\sim 0.5\%$).

Table 1 presents the results of two measurements ($t_2 = 17.4667$ and 25.8667 h, t_3(real) $= 8.3767$ and 32.6119 h).

Table 1.

	Measurement 1		Measurement 2	
	$I(\Delta I)$ [rel.un.]	$E(\Delta E)$ [keV]	$I(\Delta I)$ [rel.un.]	$E(\Delta E)$ [keV]
$K\alpha_2$(Dy)	$45.217(20)$	$1753(41)$	$45.212(19)$	$1769(37)$
$K\alpha_1$(Dy)	$46.004(19)$	$3147(67)$	$46.000(19)$	$3157(63)$
$K\alpha_2$(Ho)	$46.708(20)$	$1154(30)$	$46.698(20)$	$1119(27)$
$K\alpha_1$(Ho)	$47.552(19)$	$1996(45)$	$47.550(19)$	$1906(47)$
$K\beta_1'$(Dy)	$52.063(18)$	$984(22)$	$52.062(18)$	$982(23)$
$K\beta_2'$(Dy)	$53.526(28)$	$313(33)$	$53.490(25)$	$264(27)$
$K\beta_1'$(Ho)	$53.839(21)$	$581(36)$	$53.821(20)$	$604(29)$
$K\beta_2'$(Ho)	$55.315(19)$	$161(14)$	$55.314(18)$	$153(5)$
γ(Ho)	$59.918(19)$	$4.83(23)$	$59.916(18)$	$4.71(16)$
γ(Dy)	$86.788(13)$	$853(12)$	$86.786(13)$	$854(12)$

Relative intensities $K\alpha_2$, $K\alpha 1$, $K\beta_1'$ and $K\beta_2'$ for ^{160}Dy and ^{160}Ho from different measurements were compared with each other and with the data from the tables of isotopes [4]. Though the lines are not completely resolved (see Figure 1), there is very good agreement between particular measurements and with the literature data (within 2% for $K\alpha$-lines and 5% for $K\beta$-lines though the $K\beta_2'(Dy)$ and $K\beta_1'$(Ho) lines differ in energy only by 0.3 keV).

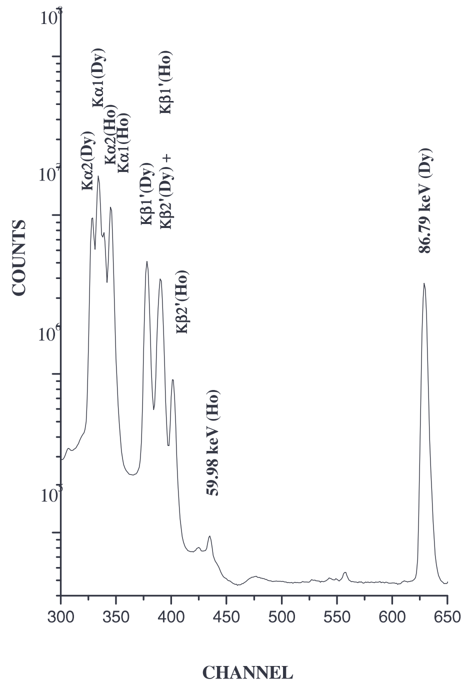

Figure 1. The fragment γ-spectrum from the decay ^{160}Er $\longrightarrow$ ^{160m,g}Ho $\longrightarrow$ ^{160}Dy (d36 mm $\times$ 13 mm HPGe-detector).

To suppress effects of summation of cascade γ-transitions or γ-transitions with Kx-rays, measurements were carried out with the radioactive source placed at a distance of 20 cm from the detector.

The intensities obtained Kx(Dy), Kx(Ho), I_γ(87 keV) and I_γ(60 keV) make it possible to consider three independent relations which allow one to determine the branching factor f_{BC} and the ratio of the K-capture to the total electron capture Er $- K/\epsilon$(Er).

Using (1)–(10) we get

$$f_{BC} = \frac{\dfrac{I_\gamma(60)}{I_\gamma(87)}}{\dfrac{k}{1+\alpha_{\text{tot}}(60)} + \left[1 - \dfrac{Z_C(\lambda_A, \lambda_B, \lambda_C)}{Z_B(\lambda_A, \lambda_B)}\right] \dfrac{I_\gamma(60)}{I_\gamma(87)}} \tag{11}$$

$$\frac{K}{\epsilon(\text{Er})} = \frac{\omega_k(\text{Dy})}{\omega_k(\text{Ho})} \left[\frac{K}{\epsilon(\text{Ho})} + \sum (I_\gamma \alpha_k)\right] \frac{Z_B(\lambda_A, \lambda_B)}{Z_A(\lambda_A)} \frac{I_{K_x}(\text{Ho})}{I_{K_x}(\text{Dy})} \tag{12}$$

$$\frac{K}{\epsilon(\text{Er})} = \frac{f_{BC}}{\omega_k(\text{Ho})(1+\alpha_{\text{tot}}(60)} \frac{Z_B(\lambda_A, \lambda_B)}{Z_A(\lambda_A)} \frac{I_{K_x}(\text{Ho})}{I_\gamma(60)} \tag{13}$$

Here $Z_A(\lambda_A) \equiv \xi(\lambda_A)$,

$$Z_B(\lambda_A, \lambda_B) = \frac{\lambda_B \xi(\lambda_A)}{\lambda_B - \lambda_A} + \frac{\lambda_A \xi(\lambda_B)}{\lambda_A - \lambda_B} \tag{14}$$

$$Z_C(\lambda_A, \lambda_B, \lambda_C) = \frac{\lambda_B \xi(\lambda_A)}{\lambda_B - \lambda_A} + \frac{\lambda_C \xi(\lambda_B)}{\lambda_C - \lambda_B} + \frac{\lambda_A \xi(\lambda_C)}{\lambda_A - \lambda_C} \tag{15}$$

From (11) we determine the branching factors f_{BC} for the first and second measurements. They are 0.722 and 0.706, respectively. The average is $\langle f_{BC} \rangle = 0.714(24)$. The number of K-holes in the Dy atom formed due to K-conversion electrons is established from the data [1] and comes out to $\sum(I_\gamma \alpha_K) = 0.2506(150)$. From (12), with $\omega_K(\text{Dy}) = 0.940$, $\omega_K(\text{Ho}) = 0.943$ and $K/\epsilon(\text{Ho}) = 0.870$, we get $K/\epsilon(\text{Er}) = 0.775$ and 0.825 for the first and second measurements. Their average is $\langle K/\epsilon(\text{Er}) \rangle = 0.80(4)$. Similarly, from (13) we get 0.716 and 0.776 with the average $\langle K/\epsilon(\text{Er}) \rangle = 0.746(30)$. Ultimately, the mean weighted value is $K/\epsilon(\text{Er}) = 0.765(30)$. Substituting this value into (13), we get the branching factor $f_{BC} = 0.733(30)$.

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