Decay Scheme of Dy^{159}†*

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The electron capture decay of Dy^{159} has been shown to occur appreciably only to the 58-kev state and ground state of Tb^{159}, with branching ratios of 37% and 63%, respectively. The K internal conversion coefficient of the 58-kev transition has been measured to be $\alpha_K=8.5_{-1.2}^{+0.7}$, which is consistent with a predominantly $M1$ transition, with the possibility of some $E2$ mixing. The orbital electron capture ratio to the 58-kev state of Tb^{159} was obtained as $P_{LM\ldots}/P_K=0.17\pm0.15$. From this value, a minimum decay energy to the ground state of Tb^{159} was assigned as 230 kev. The upper limit on transitions to the 138-kev and 364-kev states of Tb^{159} was placed at 0.1%. A spin and parity of $\frac{3}{2}-$ was assigned to the ground state of Dy^{159} from a consideration of log ft values. An upper limit of 450 kev was placed on the decay energy to the ground state of Tb^{159}.

INTRODUCTION

THE decay of Dy^{159} has been shown to occur by orbital electron capture[1,2] with an upper limit of 0.1% on positron emission.[2] No gamma rays were found associated with this decay.

Coulomb excitation experiments[3–7] have shown that Tb^{159} has energy levels at 58 kev and 138 kev. The energies of these two levels are such as to suggest that they are part of the ground-state rotational band with a ground-state spin of $\frac{3}{2}$.[3,7] The ground-state spin of Tb^{159} has been measured from both hyperfine structure[8] and the paramagnetic resonance spectrum[9] to be $\frac{3}{2}$. The spins of the 58-kev and 138-kev states were therefore assigned as $\frac{5}{2}$ and $\frac{7}{2}$, respectively.[3,7] From the relative intensities of the 138-kev and 80-kev gamma radiations the 80-kev transitions, and hence the 58-kev transitions, were shown to be a mixture of 98.7% $M1$ and 1.3% $E2$.[7]

More recently Mihelich, Handley, and Harmatz[10,11] have investigated the internal conversion spectrum of Dy^{159}. The L_1, L_{11}, L_{111}, M and N conversion lines corresponding to the 58-kev transition were observed. From the relative intensities of the L conversion lines, the $M1$ to $E2$ mixing ratio of 58-kev transitions was found to be 65:1.

Grigorev *et al.*,[12] however, found no evidence of decay to the 58-kev level. Using a proportional counter they obtained the relative probability of orbital electron capture from the L and K shells, as $P_L/P_K=1.0\pm0.3$. This corresponded to a total decay energy to the ground state of Tb^{159} of 79_{-5}^{+10} kev.

The energy levels of Tb^{159} have been studied from the decay of Gd^{159} by many investigators.[13–16] An additional level at 364 kev was found in these investigations. This level has been assigned a spin and parity of $\frac{5}{2}-$ by Nielson *et al.*[16]

The spin and parity of the ground state of Tb^{159} has been assigned as $\frac{3}{2}+$ by Mottelson and Nilsson[17] from the Nilsson energy level diagram for odd proton nuclei[18] using a deformation parameter $\delta=0.31$. In a recent paper by Mottelson and Nilsson,[19] the ground-state rotational band of Tb^{159}, with $K=\frac{3}{2}$, was assigned asymptotic quantum numbers $N=4$, $n_z=1$, and $\Lambda=1$ (written normally as $[Nn_z\Lambda]$, i.e., [411] for the Tb^{159} ground-state rotational band).

EXPERIMENTAL

A. Gamma-Ray Scintillation Spectra

A source of Dy^{159} was produced by irradiating terbium oxide with 8-Mev protons. The gamma-ray spectra were studied with a scintillation detector consisting of a $1\frac{1}{2}$-in.×1-in. NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier tube. Pulse-height analysis was accomplished with a 20-channel pulse-height analyzer.

In the spectra obtained, no evidence was found of

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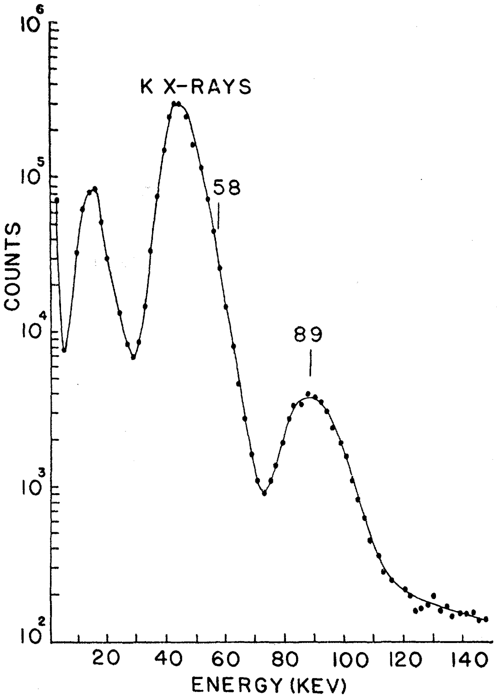

FIG. 1. Singles gamma-ray spectrum of Dy^{159} measured with a $1\frac{1}{2}$-inch $\times$1-inch NaI(Tl) crystal.

decay occurring to the 364-kev and 138-kev states of Tb^{159}. An upper limit of 0.1% of the total disintegration rate was placed on decay to these states. The low-energy spectrum of Dy^{159} is shown in Fig. 1. Three peaks can be seen in this spectrum, the Tb K x-ray peak and its associated escape peak together with a peak at 89 kev. This 89-kev peak cannot be associated with the decay of the 138-kev level of Tb^{159} since no 138-kev gamma radiation was observed.[3,7] It was found that the intensity ratio of the 89-kev peak and Tb K x-ray peak was proportional to the solid angle subtended by the source at the detector. This indicated that the 89-kev peak was a summing peak. However, its intensity was too great to be caused by random Tb K x-ray coincidences. It was concluded, therefore, that K orbital capture occurs to the 58-kev state. The peak at 89 kev was interpreted to be caused by Tb K x-rays from the orbital electron capture process entering the crystal in coincidence with either the 58-kev gamma radiations or Tb K x-rays from the K internal conversion of this 58-kev transition. The absence of a distinct peak at 58 kev can be explained by the following considerations. Since the 58-kev transition is mainly $M1$ in nature, a large K internal conversion coefficient is expected. Combining this with the closeness in energy of the Tb K x-rays to 58 kev (the Tb K_α x-ray pulse distribution has a maximum at 44.2 kev and the Tb K_β x-ray pulse distribution at 50.3 kev), one would expect the 58-kev peak to be contained under the Tb K x-ray peak.

B. Coincidence Experiments

To confirm further that Dy^{159} decays to the 58-kev state of Tb^{159}, a coincidence study was undertaken. The detectors consisted of $1\frac{1}{2}$-in.$\times$1-in. NaI(Tl) crystals mounted on Dumont 6292 photomultiplier tubes. The coincidence circuit used had a resolving time of 10^{-7} sec. A 20-channel anaylzer was used in conjunction with this coincidence circuit. The gamma spectrum in coincidence with Tb K x-ray was obtained, the low-energy portion of this spectrum being shown in Figs. 2 and 3. The presence of a strong Tb K x-ray coincidence peak in this spectrum confirmed that K capture occurs to the 58-kev state of Tb^{159}. The small peak at 84 kev, in Fig. 2, can be explained by random coincidence processes, hence an upper limit of 0.1% of the total disintegration rate was assigned to the possibility of decay occurring to the 138-kev state of Tb^{159}.

It was not possible to obtain an accurate value for the K internal conversion coefficient, α_K, of the 58-kev transition from these spectra since there was no marked asymmetry on the Tb K x-ray peak at 58 kev. However, from Fig. 3, it can be stated that α_K is greater than 6.

From both the Dy^{159} singless gamma-ray spectrum (such as shown in Fig. 1) and the coincidence spectra just described, a value for the relative probability of a K-shell vacancy or a 58-kev gamma ray occurring in a real coincidence with a K-shell vacancy to the total number of K-shell vacancies plus 58-kev gamma rays was obtained. Denoting this ratio by S_{K+K}, then $S_{K+K}=0.228_{-0.006}^{+0.015}$.

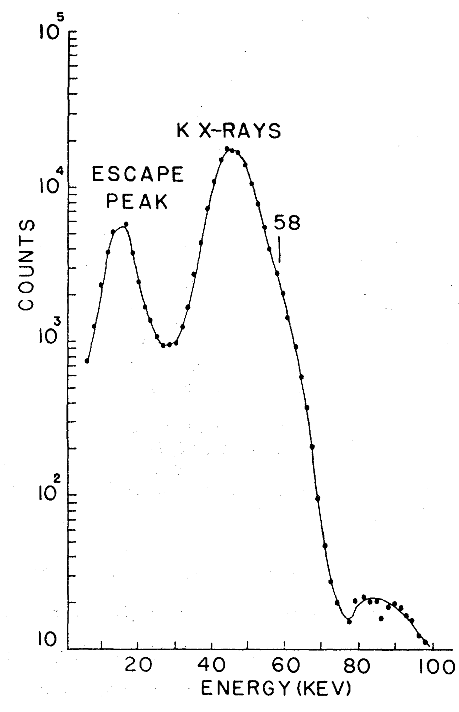

FIG. 2. Gamma spectrum of Dy^{159} in coincidence with Tb K x-rays.

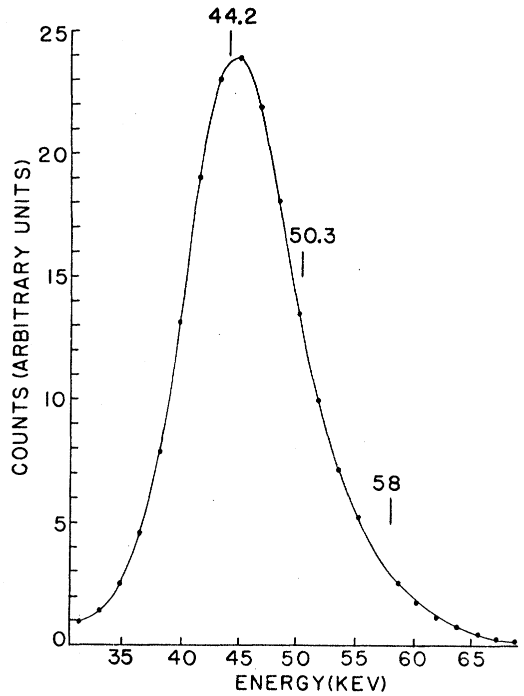

FIG. 3. Gamma spectrum of Dy^{159} in coincidence with Tb K x-rays.

C. The Escape Peak Gated Spectra

Since scintillation detectors do not have sufficient energy resolution to separate out directly the Tb K x-ray peaks and the 58-kev gamma-ray peak, a method was devised which effectively improved the resolution. This was achieved by counting only those pulses in which an iodine K_α x-ray escaped from the crystal, i.e., the escape peak. This was accomplished in the coincidence circuit used previously, with one channel (the "fixed" channel) set to detect the iodine K_α x-rays escaping from the other crystal (in the "free" channel). The escape peaks would then be at the following energies; the Tb K_α escape peak at 15.7 kev, the Tb K_β escape peak at 21.8 kev and the 58-kev gamma peak at 29.5 kev. A partial separation of these three peaks was therefore achieved. An ideal experimental arrangement would be to have the entrance windows of the two crystals parallel to each other, with the path between them unobstructed. The source would ideally be placed outside of this path and collimated onto the central region of the crystal in the "free" channel with the source completely shielded from the crystal in the "fixed" channel. In this arrangement the experimental results obtained would require few corrections. However, a fairly strong source would be required for this arrangement, much stronger than those available in this investigation. Consequently, the source was located midway between the two crystals. This particular arrangement presented added difficulties because the 58-kev gamma escape peak is at 29.5 kev and the iodine K_α x-ray at 28.5 kev. Therefore, a 58-kev gamma ray could be detected in the "fixed" channel with an iodine K_α x-ray escaping into the "free" channel. This process could also occur to a lesser extent with the Tb K_β x-rays. Correcting for these two processes was the largest source of error in the experiment. Further correction was required because a relatively small amount of iodine K_β x radiation could be detected in the "fixed" channel. Another correction factor applied was due to the variation with energy of the detection efficiency of the escape peak gated system. This occurs since the more energetic the gamma rays, the deeper the average penetration into the crystal and the smaller the probability for an iodine K x-ray to escape and be detected in the "fixed" channel. The correction factors were obtained by calculating the probability, for the different photon energies, of an iodine K_α x-ray escaping from the crystal in the "free" channel into the crystal in the "fixed" channel, using the particluar geometry of this experimental arrangement. The correction factors, normalized to unity for the Tb K_α x-ray escape peak, were 1.10 for the Tb K_β x-ray escape peak and 1.30 for the 58-kev gamma escape peak.

Using this escape peak gating technique, the ratio of the total number of K-shell vacancies to 58-kev gamma rays, was obtained as $N_K/N_\gamma=35_{-6}^{+5}$. In order to obtain the K internal conversion coefficient, of the 58-kev transition, the above mentioned escape peak gating coincidence arrangement was incorporated into a triple coincidence circuit. The third channel detector consisted of a 1-in.$\times\frac{1}{2}$-in. NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier tube. This third channel was set to detect Tb K x-rays. A spectrum obtained with this arrangement is shown in Fig. 4. A value for the K internal conversion coefficient of the 58-kev transition was obtained as $\alpha_K=8.5_{-1.2}^{+0.7}$.

INTERPRETATION

From the results obtained for N_K/N_γ, S_{K+K}, and α_K a value for the relative probabilities of L, M, N, . . . orbital electron capture to K orbital electron capture, in a decay to the 58-kev state of Tb^{159} was obtained. This ratio was obtained as $P_{LM\ldots}/P_K=0.17\pm0.15$. This ratio can be related to the decay energy using the theoretical results of Brysk and Rose[20] on the relative probabilities of L and K orbital capture, together with Robinson and Fink's[21] calculations of the ratios of electron densities of M, N, . . shells at the nuclear radius to those in the $L_{\rm I}$ and $L_{\rm II}$ shells. The value of $P_{LM\ldots}/P_K$ obtained in this experiment is such that only an estimate of the minimum decay energy can be made. The minimum decay energy to the ground state of Tb^{159} was calculated as 230 kev.

In order to obtain the branching ratios to the 58-kev state and the ground state of Tb^{159}, a knowledge of

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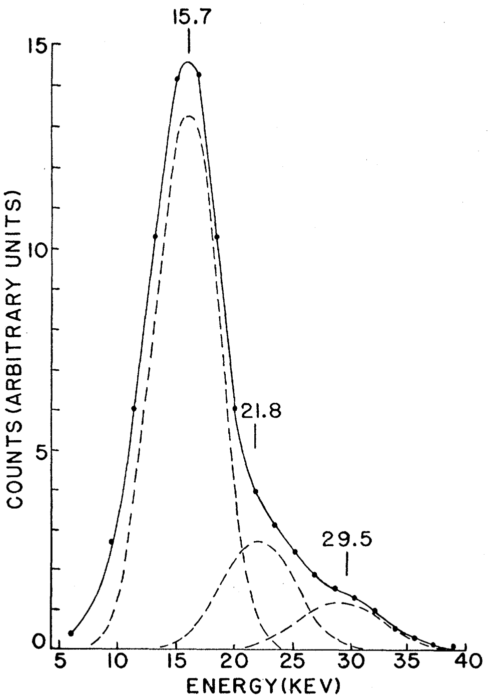

FIG. 4. Triple coincidence spectrum of Dy^{159}. The coincidence circuit was gated in one "fixed" channel by the escaping iodine K_α x-rays and in the other "fixed" channel by Tb K x-rays. Comparison with Fig. 3 shows the increased resolution obtained using escape peak gating.

the L, M, N,. . .conversion coefficient α_{LMN} of the 58-kev transition is required, in addition to N_K/N_γ, α_K, $P_{LM}.../P_K$, and $P_{LM}.../P_K$ for transitions to the ground state of Tb^{159}. A value of α_{LMN} was obtained using the results of Mihelich, Harmatz, and Handley[10,11] on the relative $L_{\rm I}$, $L_{\rm II}$, $L_{\rm III}$, M, and N conversion coefficients for the 58-kev transition, together with the theoretical $L_{\rm I}$ internal conversion coefficients of Sliv and Band,[22] and Rose.[23] A value of $\alpha_{LMN}=2.0$ was used. The branching ratios to the 58-kev state was calculated as 37_{-3}^{+5}% and to the ground state as 63_{-5}^{+3}%.

From the energy level diagrams of Nilsson for odd neutron nuclei, using a deformation parameter $\delta=0.31$, the ground state of Dy^{159} can be assigned tentatively a spin and parity of $\frac{3}{2}-$ with asymptotic quantum numbers [521]. However, quite close to this level on the Nilsson diagram are levels with quantum numbers [642] $\frac{5}{2}+$ and [523]$\frac{5}{2}-$. According to the selection rules of Alaga,[24] if Dy^{159} had quantum numbers [642] $\frac{5}{2}+$, transitions to the ground state, 58 kev, and 138-kev

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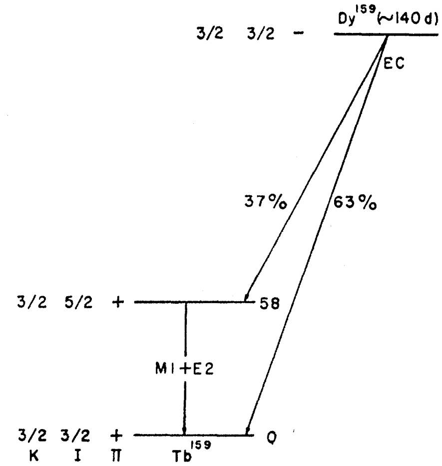

FIG. 5. scheme of Dy^{159}.

state of Tb^{159} would be allowed and hindered. Since the total decay energy is greater that 230 kev, a branching ratio to the 138-kev state of at least a few percent would be expected. A similar objection applies to a [523] $\frac{5}{2}-$ assignment to the ground state of Dy^{159} since transitions to the ground, 58 kev, and 138-kev states of Tb^{159} would all be first forbidden hindered. If, however, the Dy^{159} ground state is assigned the quantum number [521] $\frac{3}{2}-$ transitions to the ground and 58-kev states would be first forbidden unhindered while transitions to the 138-kev state would be first forbidden unique and hindered. With this assignment transitions to the 364-kev state of Tb 159 would be allowed. Since an upper limit of 0.1% has been placed on these transitions, the total decay energy must be less than 450 kev, on the basis of log *ft* values. An estimate of the maximum decay energy can be obtained from the fact that the log *ft* value for a first forbidden unhindered transition is, in general, less than 7.5.[19] On this basis the total decay energy should be less than approximately 500 kev. With this [521] $\frac{3}{2}-$ assignment for the ground state of Dy^{159} and with a total decay energy of less than 450 kev, transitions to the 138-kev state of Tb^{159} would be improbable. The ground state of Dy^{159} was therefore assigned a spin and parity of $\frac{3}{2}-$ with asymptotic quantum numbers [521].

The decay scheme of Dy^{159}, consistent with the observations reported in this paper, is shown in Fig. 5.

Since the completion of this investigation a paper has been published by Ketelle and Brosi[25] giving results of an investigation of the Dy^{159} decay scheme. These results are in substantial agreement with those presented here. However, there exists some disagreement on the K internal conversion coefficient of the 58-kev transition and consequently on the branching ratios between the 58-kev state and the ground state.

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