minus-two even-even nuclei with theoretical predictions. In the δ limit this separation is found to be[38]

$$\tfrac{1}{2}(2j+1)^2[(j\tfrac{1}{2}j-\tfrac{1}{2}|jj00)^2-\tfrac{1}{5}(j\tfrac{1}{2}j-\tfrac{1}{2}|jj20)^2]F^{(0)}$$

for a pair of nucleons in the state (l, j). Comparing this expression with the experimental data[11] on Ca^{42} and Pb^{206}, two nuclei which differ by one nucleon pair from double-magic nuclei, one obtains

$$g(\nu^3/2\pi)^{\frac{1}{2}}\approx 800 \text{ kev}.$$

The same value is obtained by considering the pairing energy.[39]

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Decay of $_{66}Dy^{165m}$(1.2 min) and $_{66}Dy^{165}$(2.3 hr)

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The activities induced by neutron capture in Dy^{164} have been studied with 180° photographic internal conversion electron spectrometers and a scintillation coincidence spectrometer. The metastable transition energy is 108.0±0.2 kev. Other gamma rays of approximately 160, 360, and 515 kev are associated with the 1.2-min activity and appear to follow beta decay from the metastable level. Gamma rays of 94.4±0.2, 279.4±0.8, 361.2±1.0, 634±3, 710±20, and 1020±30 kev follow the 2.3-hr beta decay from the ground state. Coincidences are observed between members of the pairs (279)–(710) and (361)–(634). The 94-kev gamma ray is coincident with a beta transition of about 1.2 Mev, while the other gamma radiations are coincident with a softer beta component (~0.3 Mev).

INTRODUCTION

In 1935, Marsh and Sugden[1] and, independently, Hevesy and Levi[2] reported that a very strong beta activity was produced when Dy was exposed to neutrons from a Ra–Be source. They found the half-life to be about 2.5 hr. A recently reported value is 2.310 ±0.002 hr.[3] Several measurements of the beta energy using cloud chamber and absorption techniques have been made.[2,4–8] The values reported from these investigations range from 1.1 to 1.9 Mev. Two spectrometer measurements have listed the maximum beta energy as 1.18 Mev[9] and 1.24 Mev.[10] In addition to the 1.24-Mev beta ray, Slätis[10] has resolved two lower-energy components of 0.42 and 0.88 Mev. Meitner[6] reported gamma radiation with an average energy of about 0.6 Mev to be associated with this Dy activity. From a study of the internal conversion electron spectrum and the spectrum of electrons from secondary radiators, Slätis[10] concluded that gamma transitions of 0.91, 0.36, and 0.76 Mev were present. With the postulation of one additional unresolved beta component, he was able to propose a reasonable level scheme. Another measurement of the gamma-ray energies has been made by Miller and Curtiss,[11] who report energy values of 0.37 and 1.0 Mev. Clark[9] has set an upper limit of 1.1 Mev for the gamma energy and has also detected beta-gamma and gamma-gamma coincidences.

A short-lived Dy activity with a half-life of 1.25 min was first reported by Flammersfeld.[12] Electrons with an energy of approximately 130 kev were detected. These were interpreted as arising from internal conversion of an isomeric transition in Dy^{163}. Later work by Inghram *et al.*[13] has established that this, as well as the 2.3-hr activity, is associated with Dy^{165}. The cross sections for production of the 1.25-min and 2.3-hr activities were observed to be approximately equal, indicating that only the metastable state is formed directly in the capture process. Since growth of the 2.3-hr activity had not been observed,[12] it was suggested that a small percentage of the decay of the metastable state was by emission of a beta particle. In the present research some additional evidence for the existence of such a transition has been found.

The conversion electron spectrum of this activity has been investigated with spectrometers by Hole[14] and Caldwell.[15] The former noted that conversion was pre-

[1] J. Marsh and S. Sugden, Nature **136**, 102 (1935).
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[15] R. Caldwell, Phys. Rev. **78**, 407 (1950).

dominantly in the L shell and found the transition energy to be 102 kev. The latter resolved five conversion lines and reported a value of 109.0 kev for the transition energy. By means of a scintillation spectrometer, Kahn[16] found a value of 102 kev. Caldwell also investigated the conversion electron spectrum of the 2.3-hr activity in the region below 300 kev. He observed several electron lines associated with conversion of an 87.8-kev gamma ray, and in addition, a single line at 219 kev. The latter has been interpreted[17] as the K line of a transition which could be fitted into the level scheme proposed by Slätis. As indicated in a preliminary report[18] of the present study, energy values of the transitions involved and the results of coincidence experiments are inconsistent with this interpretation.

An accurate measurement of the low-energy gamma ray has been made by Mihelich and Church.[19] They found the energy to be 95.1 kev and the ratio of conversion in the K and L shells to be 5.9.

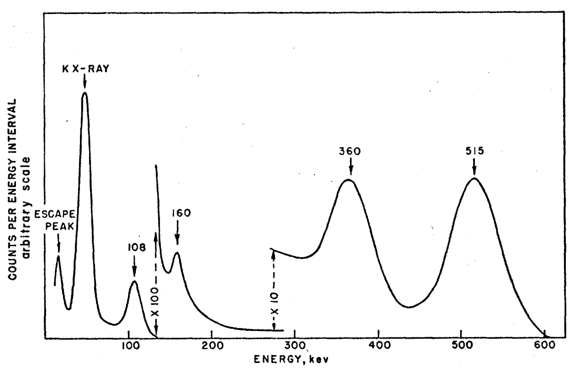

FIG. 1. Gamma-ray pulse-height distribution of $_{66}Dy^{165m}$(1.2 min).

EXPERIMENTAL PROCEDURE

The apparatus of the present investigation consists of several 180° photographic conversion electron spectrometers[20] and a scintillation coincidence spectrometer.[21]

Sources were normal Dy oxide irradiated in the Argonne heavy water—moderated reactor. Several samples of Dysprosium oxide were used. One was known to be spectrographically pure except for 0.4-percent holmium and 0.1-percent yttrium.

Eastman no-screen x-ray and NTB emulsions were used as detectors in the electron spectrometers. Film backings were used in survey work, but where density and accurate energy measurements were made, a glass plate backing was employed. Photodensitometer measurements of line intensities were practicable in the case of only two of the transitions. These measurements were made with a Leeds and Northrup recording photodensitometer. After the data were replotted on a linear scale and the background due to the beta distribution was subtracted, the area under a line profile was measured. This area, when corrected for variations due to the geometry of the spectrometer and sensitivity of the photographic emulsion, is taken as the relative intensity of the line. The geometry correction consists of simply multiplying each value by the corresponding radius of the electron path in the spectrometer. The emulsion sensitivity factor was determined according to the method described by Rutledge, Cork, and Burson.[20] No corrections are made for differential absorption of the electrons in the source.

TABLE I. Internal conversion electrons associated with the 1.2-min Dy activity.

Electron energy (kev)	Relative intensity	Interpretation	Energy sum (kev)	Transition energy (kev)	K/L
54.2	3	K (Dy)	108.0	108.0±0.2	0.15±0.05
99.4	10	L_2	108.0		
100.3	10	L_3	108.1		
106.3	5	M_2, M_3	108.1		
107.8	1.5	N	108.1		
461		K (Ho)	517	517±3	

RESULTS AND DISCUSSION

1.2 min

Internal conversion electrons associated with the 1.2-min metastable transition are easily detected. Five lines corresponding to a transition of 108.0 kev were observed (Table I). The energy is in fair agreement with the value 109 kev reported by Caldwell. A careful measurement of the separation of the two L-lines was made, and it was found that the energy difference is characteristic of conversion in the L_2 and L_3 sub-shells, as has been proposed by Mihelich.[22] It is interesting to

TABLE II. Internal conversion electrons associated with the 2.3-hr Dy activity.

Electron energy (kev)	Relative intensity	Interpretation	Energy sum (kev)	Transition energy (kev)	K/L
38.8	60	K (Ho)	94.4	94.4±0.2	7.7±2.0
85.0	7.8	L_1	94.4		
92.2	~1.5	M	94.3		
93.9		N	94.3		
223.8		K (Ho)	279.4	279.4±0.8	>5[a]
270.0		L_1	279.4		
305.8		K (Ho)	361.4	361.2±1.0	>5[a]
351.7		L_1	361.1		
578		K (Ho)	634	634±3	
~623		L	~632		

[a] Visual estimate.

[16] J. Kahn, Oak Ridge National Laboratory Report ORNL 1089, 1951 (unpublished).
[17] M. Goldhaber and R. Hill, Revs. Modern Phys. **24**, 179 (1952).
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[22] J. Mihelich, Phys. Rev. **87**, 646 (1952).

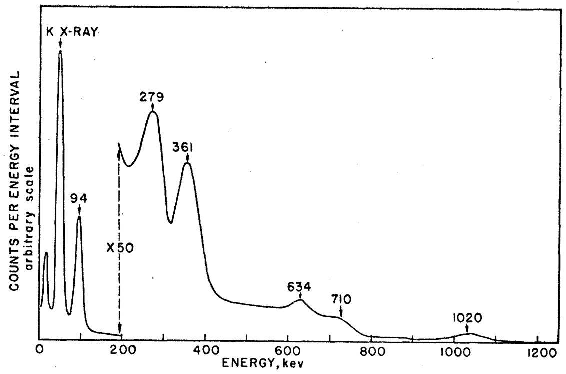

FIG. 2. Gamma-ray pulse-height distribution of $_{66}Dy^{165}$(2.3 hr).

note that the M conversion also appears to be in the M_2 and/or M_3 sub-shell.

The K/L conversion ratio is 0.15 ± 0.05, a somewhat higher value than that obtained by Caldwell, but in good agreement with the Goldhaber and Sunyar[23] empirical relation of Z^2/E *versus* K/L for an electric octopole transition.

An investigation of the 1.2-min activity with the scintillation spectrometer revealed the presence of higher energy gamma radiations. Peaks in the pulse-height distribution corresponding to gamma rays of approximately 160, 360, and 515 kev are present in addition to the K x-ray, its associated escape peak, and the 108-kev peak (Fig. 1). All of these decay with the 1.2-min period. The ratio of the heights of the 360- and 515-kev peaks can be varied by placing lead absorbers between the source and the detector. Therefore, the 360-kev peak is not due entirely to excitation of the crystal by Compton electrons of the 515-kev gamma ray.

Coincidences between the 360- and 515-kev gamma rays were not observed. Pulses in the region of the 360-kev peak were, however, observed to be coincident with those of the 160-kev region. It is probable that the 160- and 360-kev transitions are in cascade and that the 515-kev one is the crossover.

It might be assumed that these gamma transitions follow the 108-kev metastable transition. However, these radiations appear to be coincident with a beta ray and not with the radiations associated with the metastable transition. Beta decay of the metastable state has not been detected previously, although the possibility of its existence has been suggested.[13] Additional evidence of this beta transition was observed with the photographic spectrometers. The background darkening of the emulsion, due to the continuous beta distribution, is markedly different on a plate exposed for short periods immediately after irradiation of the source, as compared with a plate with an equivalent exposure to the 2.3-hr activity after the 1.2-min activity had decayed. An additional weak conversion line was noted which may be associated with the short activity. The energy of the electrons is 461 kev. These are probably K electrons for the $\sim$515-kev transition. If so, a better value for the energy of this transition is 517 kev, assuming the K binding energy of holmium is to be used.

By comparing the heights of the 108-kev and x-ray

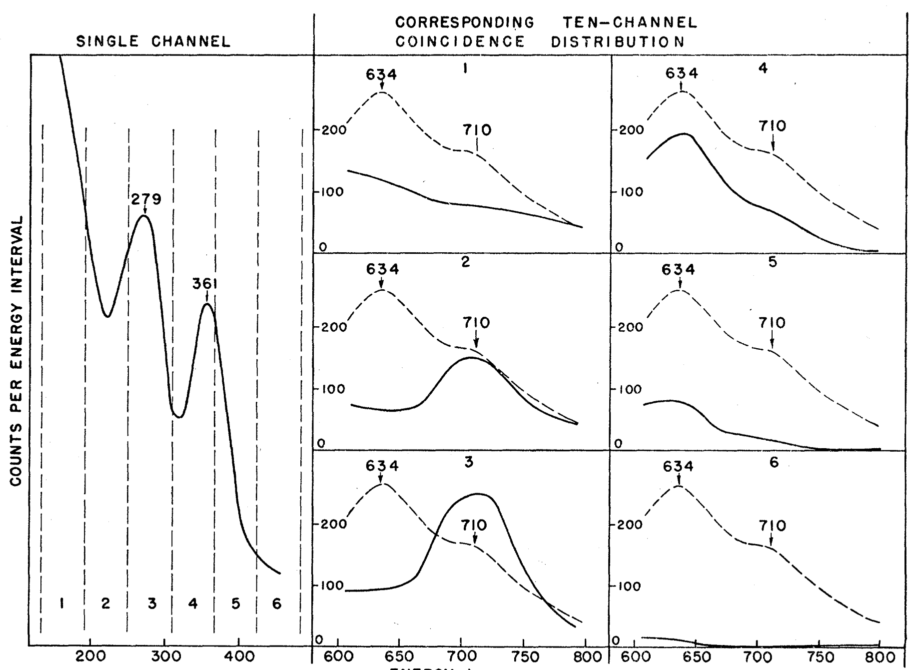

FIG. 3. Coincidence pulse-height distributions of $_{66}Dy^{165}$(2.3 hr). Six coincidence distributions corresponding to six window settings of the single-channel spectrometer are shown. For comparison, the normal spectrum is shown as a dashed curve in each case.

[23] M. Goldhaber and A. Sunyar, Phys. Rev. 83, 906 (1951).

peaks (Fig. 1), a rough estimate of the K conversion coefficient of the 108-kev transition may be obtained. Neglecting any contribution to the x-ray intensity from conversion of the higher energy gamma rays, this quantity may be estimated to be about four. Since conversion of this transition is only about 10 percent in the K shell, the total conversion coefficient would be about forty.

2.3 hr

Internal conversion electrons associated with the 2.3-hr activity are listed in Table II. The observed conversion lines are interpreted as arising from four transitions of 94.4, 279, 361, and 634 kev. The measured energy of the 94.4-kev transition is in fair agreement with the results of Mihelich and Church. They report the energy to be 95.1 kev and the type of radiation as a mixture of $M1$ and $E2$. The present measurement of the K/L ratio is in good agreement with the value predicted for a pure $M1$ transition; however, the accuracy is too poor to rule out the possibility of the mixture. In the decay scheme of Goldhaber and Hill,[18] this transition is assumed to be in cascade with the 279-kev one, while the 361-kev is the crossover transition. This is not consistent with the present data. The discrepancy in the energy sum is well outside the limits of experimental error.

An investigation of this activity with the scintillation spectrometer showed the presence of peaks in the pulse-height distribution corresponding to the previously mentioned transitions, plus two others of approximately 710 and 1020 kev (Fig. 2). Coincidence studies showed that the 279- and 710-kev gamma rays form one cascade pair and the 361- and 634-kev gamma rays are another. These conclusions are based on the results of two complementary experiments.

In one experiment the ten-channel analyzer was adjusted to cover the region of the 634- and 710-kev peaks, while the single-channel spectrometer was varied in steps across the region of the 279- and 361-kev peaks. The resulting coincidence distributions are shown in Fig. 3. The peak in the coincidence distribution is at the 634-kev position when the single-channel side is accepting pulses from the 361-kev transition, and at the 710-kev position when the single channel is accepting pulses from the 279-kev gamma ray. The complementary experiment, in which the coincidence spectra in the region of the 279- and 361-kev peaks were observed as the single channel was scanned over the 634–710-kev region, yielded results in agreement with these.

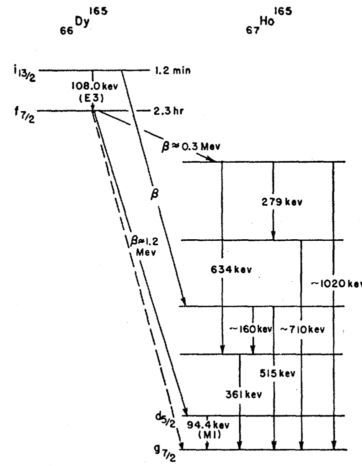

FIG. 4. Proposed decay scheme for $_{66}Dy^{165m}$(1.2 min) and $_{66}Dy^{165}$(2.3 hr). (The order of the 279–710-kev cascade is arbitrarily chosen.)

Coincidences between the other possible pairs of gamma rays were not detected.

The results of beta-gamma coincidence experiments indicate that the 94-kev transition is coincident with a beta ray of maximum energy approximately 1.2 Mev, while the other gamma radiations all appear to be coincident with a lower energy beta component of approximately 0.3 Mev.

The proposed nuclear energy level scheme shown in Fig. 4 is consistent with these data. It should be pointed out that the transition of about 360 kev associated with the 1.2-min activity has been assumed to be the same as the more accurately measured 361-kev transition associated with the 2.3-hr activity. Also, the order of the 279–710-kev cascade as shown in the figure is arbitrarily chosen.

The measured spin of the ground state of Ho^{165} is 7/2.[24] On the basis of shell structure, orbital assignments have been made[18] for the ground and first excited states of both Dy^{165} and Ho^{165}. The results of this investigation are in agreement with these assignments

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