At present, the accuracy with which the singlet and triplet-scattering amplitudes are known is more limited by the accuracy of the zero-energy (n,p) cross section than by the accuracy of the (n,p) scattering amplitude.

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Decay Studies of the Even-Even Isotopes, Er^{172} and Dy^{166}†

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Er^{172} and Dy^{166}, with half-lives of 48.7±0.5 hr and 81.8±0.2 hr, respectively, were produced by double neutron capture from Er^{170} and Dy^{164}. Gamma rays of the following energies were found in the decay of Er^{172}: two coincident 50-kev radiations, 72, 128, 170, 200, 410, 440, and 610 kev. The proposed energy levels for Tm^{172} consistent with the data are as follows: 410, 440, 482, 538, and 610 kev. Log*ft* values of beta transitions indicate that the 538- and 610-kev levels have spin assignments of 0 or 1 with positive parity. The following gamma transitions were found in the decay of Dy^{166}: 84, 291, 343, 373, and 427 kev. In addition to showing conversion electrons of the 84-kev transition, permanent-magnet spectrometer studies revealed the presence of two additional transitions of 30 and 54 kev which were not observed in scintillation studies. The multipolarity of the low-energy transitions are as follows: 30 kev-*M*1, 54 kev-*E*2, and 84 kev-*M*1. The proposed energy levels for Ho^{166} are at 54, 84, 375, and 427 kev.

INTRODUCTION

THE species Dy^{166} and Er^{172} are of special interest because they are among the few examples of the decay of an even-even nuclide to the excited levels of an odd-odd nuclide in the region of high-nuclear deformation. Ketelle[1] and Butement,[2] first reported a new 81-hr activity from the high-flux neutron irradiation of dysprosium. Nethaway *et al.*[3] similarly reported a new 49-hr activity from erbium irradiations. These activities were demonstrated to be Dy^{166} and Er^{172} by genetic relationships. More recently the results of experiments carried out concurrently with these have been reported for both of these isotopes.[4–7]

Source Production and Purification

Erbium oxide enriched to 87.3% in Er^{170} was used to produce Er^{172} activity by double neutron capture. The interfering activities also produced were Er^{169}, Er^{171}, Tm^{172} and small amounts of activated contaminants. Tm^{172} and the contaminants were removed using ion-exchange column separation techniques. The 7.5-hr Er^{171} activity, was allowed to decay away before subsequent investigations were begun. Er^{169} is essentially a pure beta emitter except for an 8-kev converted transition, bremsstrahlung and possibly a small percentage of other low-energy radiations. To produce Dy^{166} activity, natural abundance dysprosium was irradiated. The only major contaminant, Ho^{166}, was removed by ion exchange.

The neutron irradiations were carried out in the 5-megawatt reactor of Industrial Reactor Laboratories, Inc., Plainsboro, New Jersey. An "in-core" irradiation facility which has a thermal neutron flux $>1\times10^{14}n/cm^{-2}$ sec was frequently used. The length of the irradiations was about 90 hr.

Experimental Equipment

A 3×3-in. well-type, and a 3×3-in. solid NaI(Tl) crystal, housed in a specially lined lead cave similar to that described by Heath,[8] were used to study the gamma emissions of the isotopes. The 3×3-in. well-type crystal was calibrated for photopeak counting efficiency[9]

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[1] B. H. Ketelle, Phys. Rev. **76**, 1256 (1949).
[2] F. D. S. Butement, Proc. Phys. Soc. (London) **A63**, 532 (1950).
[3] D. R. Nethaway, M. C. Michel, and W. F. Nervik, Phys. Rev. **103**, 147 (1956).
[4] R. G. Helmer and S. B. Burson, Bull. Am. Phys. Soc. **6**, 72 (1961); Argonne National Laboratory Report ANL-6270, 1961 (unpublished), and Phys. Rev. **123**, 992 (1961).
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using 4π and 4π $\beta-\gamma$ coincidence standardization techniques. This facilitated the determination of gamma transition abundances. The high detection efficiency of the crystal frequently produced "sum-peaks" of coincident gamma rays, which were helpful in determining certain decay characteristics. A "fast-slow" coincidence circuit with a resolving time of $2\tau\sim0.2$ μsec was used in conjunction with a single-channel and a multichannel analyzer in the coincidence experiments.

A hollow plastic scintillator similar to that described by Gardner and Meinke[10] was used to obtain beta spectra. The scintillator was tested with beta emitters of known energy and spectral shape, and was found to produce satisfactory Fermi plots down to 100 kev when proper instrument resolution corrections were applied. Non-Gaussian[11] conversion electron profiles were used in making the instrument resolution corrections.

A 123 gauss, 180° uniform-field permanent magnet spectrograph, was used to investigate internal conversion electrons. Sources were prepared by evaporating small aliquots containing the activity on 8-mil platinum wire, or on narrow strips of platinum foil.

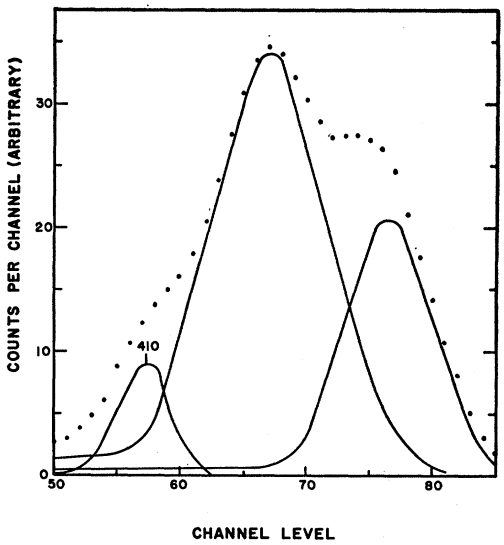

FIG. 2. Spectrum showing the "summing" of two radiations of about 50 kev when the sample was placed in a 3×3-in. well-type NaI(Tl) crystal.

ERBIUM 172

Experimental Results

After an ion-exchange column separation of the erbium activities, Tm^{172} activity was found to grow in, at a rate consistent with the decay of the prominent radiations of the activity being investigated. The mass assignment of 172 to the new activity was confirmed by an experiment in which three different Er^{168}/Er^{170} composition ratios were irradiated. These ratios of percent abundances were 76.9/8.3, 27.1/14.9 (natural erbium) and 87.3/9.0. The activity ratios of Er^{169}/Er^{172} were consistent with the abundance ratios.

The decay of the 610 kev gamma intensity was followed with a 3×3-in. well-type NaI(Tl) scintillation detector for 5 half-lives. The resulting half-life of Er^{172} was found to be 48.7±0.5 hr.

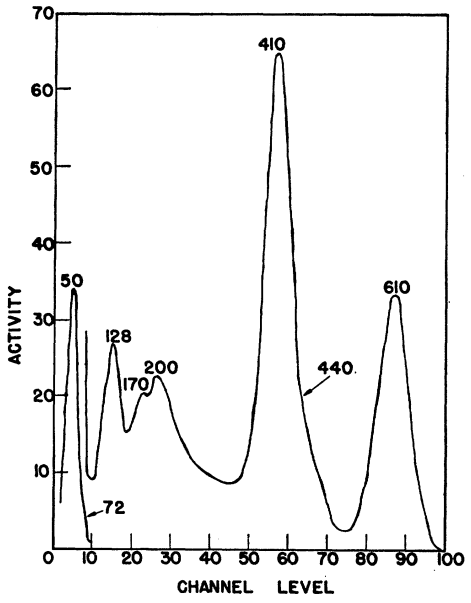

FIG. 1. Er^{172} gamma-ray spectrum.

Scintillation Studies

The scintillation spectrum of Er^{172} is shown in Fig. 1. Low-energy radiations arising from Er^{169} have been subtracted out. When the sample was placed in the 3×3-in. well-type crystal, the resulting spectrum showed a "summing" of two 50-kev radiations with the 410-kev gamma ray (see Fig. 2). These results are in agreement with the $\gamma-\gamma$ coincidence studies. Analysis of the single and double summing of the 50-kev radiations indicated that one of the radiations was about equal in intensity to the 410-kev gamma, and the other was about 50% as intense.

Absolute intensity measurements of the gamma rays were accomplished as follows: A solution containing Tm^{172} was assayed using a 4π beta-proportional counter. This solution was then placed in the 3×3-in. well-type crystal and the counting efficiency of an arbitrary, but known portion of the Tm^{172} high-energy gamma spectrum (>610 kev) was determined. After an Er^{172}-Tm^{172} ion exchange separation, the growth of Tm^{172} content in a sample could be accurately determined, and the Er^{172} disintegration rate could be calculated. Since the 3×3-in. well-type crystal was calibrated for photopeak

[10] D. G. Gardner and W. W. Meinke, J. Appl. Rad. and Isotopes 3, 232 (1958).
[11] M. S. Freedman, T. B. Novey, F. T. Porter, and F. Wagner, Jr., Rev. Sci. Instr. 27, 716 (1956).

TABLE I. Er^{172} Gamma-ray energies (kev) and intensities (%).

Energy (kev)	Intensity (%)
50	55±5
72	~5
128	1.85±0.2
170	0.83±0.3
200	1.6±0.3
410	44±1
440	···
610	40±1

detection efficiency, the gamma-ray abundance was also easily determined. The gamma-ray energies and their abundances are tabulated in Table I.

Beta-Ray Spectra

The gross beta spectrum of an Er^{172} sample revealed only a trace, if any, of higher energy beta components (<5% of total decay). No low-energy spectra could be directly obtained because of the large excess of Er^{169} activity which was present. Consequently, β-γ coincidence techniques were used to determine the maximum beta energies of the transitions, coincident with the 410- and 610-kev gamma rays. Fermi plots of the resulting beta spectra are shown in Fig. 3. When gating on the photopeak of the 410-kev gamma ray, a portion due to the 610-kev Compton spectrum is also included. This effect on the 410-kev β-γ coincidence spectrum has been subtracted out in Fig. 3. The end point of the beta spectrum coincident with the 610-kev transition is 278±5 kev. It was also found, that the beta end points for the two spectra differ by 78 kev, indicating that the 410-kev level is not primarily populated by a direct beta transition. This is supported by coincidence studies which show that several low-energy transitions accompany the 410-kev transition.

γ-γ Coincidence Spectra

Gamma radiations could not be found which were in prompt coincidence with the 610-kev gamma transition. Gamma rays which were observed to be in coincidence with each other are (in kev):

50–50; 50–410; 72–128(?); 72–410;
128–410; 200–410; 170–440.

It is interesting to note, that the 410-kev gamma radiation was simultaneously coincident with two abundant 50-kev radiations which are x rays of highly converted transitions and/or direct gamma transitions of ~50 kev energy. This fact was shown not only by the "summing" phenomenon observed when the sample was placed in the "well" of a scintillation crystal, but also by observing a 100–105 kev sum-peak, in coincidence with the 410-kev gamma ray, when the source was in close proximity to the detecting crystal.

The 50-kev radiation in coincidence with the 410-kev gamma, also displayed some "tailing" on the high-energy side. This was attributed to a 60–70 kev radiation.

The 410-kev gamma is also coincident with a 128- and a 200-kev transition, (see Fig. 4). This spectrum also shows that a 170-kev gamma became pronounced, when gating on the 430–480 kev region of the gamma spectrum. The absence of a 170–240-kev coincidence

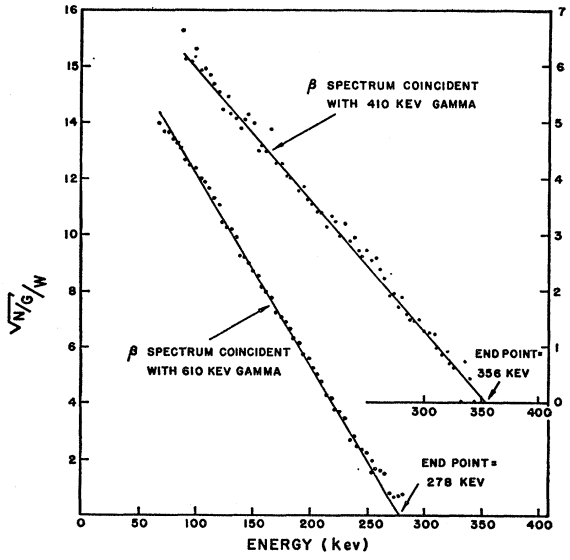

FIG. 3. Fermi plots of Er^{172} beta spectra ($G=pF/W$).

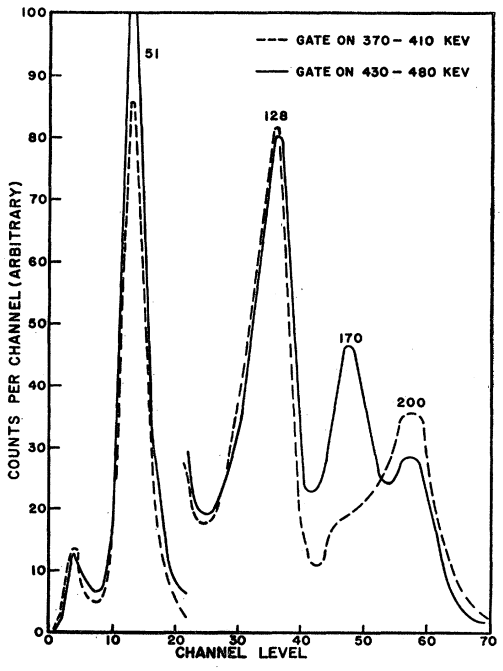

FIG. 4. Spectra of gamma rays coincident with the 410- and 440-kev regions.

indicates that the 170-kev gamma probably involves a transition from the 610-kev level, to a 440-kev level.

DISCUSSION AND INTERPRETATION OF DATA FOR Er^{172}

The proposed decay scheme for Er^{172} is given in Fig. 5. The 610-kev transition, presumably populates the ground state of Tm^{172}, since no radiations were observed to be in coincidence with it.

The 410-kev gamma radiation could either indicate a transition between the 610-kev level and a 200-kev level, or could originate directly from a 410-kev energy level. The latter energy sequence appears to be the correct one, because (1) there is a 78-kev difference in the end points of the beta transitions coincident with the 610- and 410-kev gamma radiations, and (2) the 200-kev gamma coincident with the 410-kev gamma is much lower in intensity.

The fact that there were several low-energy gamma rays coincident with the 410-kev transition necessitates the placing of several energy levels between the 410- and 610-kev levels. The exact position and sequence of these levels cannot be fixed precisely from the present data, but the sequence presented in Fig. 5 is thought to be the one most consistent with the data, and is in substantial agreement with that proposed by Helmer and Burson.[4]

One additional level was found in an experiment which revealed a 170–440 kev coincidence. It was first thought that the 440-kev gamma originated at the 610-kev level and populated a 170-kev level. A 240-kev transition from the 410-kev level to such a 170-kev level was sought, but results were negative. It is therefore believed that the sequence should be inverted, placing an energy level at 440 kev.

Energy Level Spin Assignments

Er^{172} is an even-even nuclide and is therefore assumed to have a ground-state spin of zero with positive parity. The ground state of the odd-odd Tm^{172} daughter of Er^{172} presumably has a spin and parity of 2−. This follows from a study of the odd-even and even-odd neighbors of Tm^{172} and also from Mottelson and Nilsson[12] energy level diagrams for highly deformed nuclei. The asymptotic quantum numbers assigned to the odd proton and odd neutron were $\frac{1}{2}+[411]$ and $\frac{5}{2}-[512]$ respectively. The beta transition between the ground state of Er^{172} and Tm^{172} would therefore be quite highly forbidden. This is confirmed by the fact that the observed transition between ground states is small.

The logft values assigned to the beta transitions populating the 610- and 538-kev levels indicate allowed transitions. The spin assignments therefore must be 0 or 1 with positive parity. No detectable amount of 538-kev radiation was observed, whereas the 610-kev gamma is quite prominent. This would seem to indicate that the 538-kev level is 0+ while the 610-kev level is 1+.

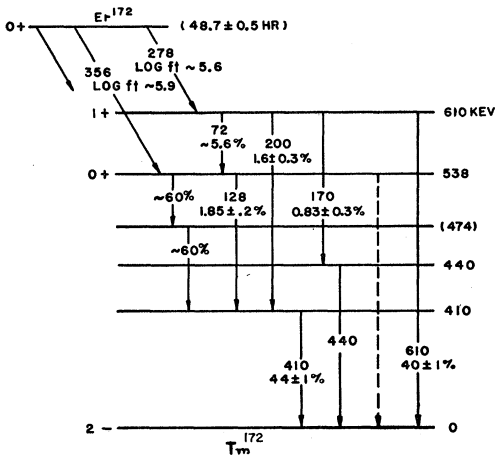

FIG. 5. Proposed decay scheme for Er^{172}. Percentages are absolute gamma-ray intensities.

DYSPROSIUM 166

Experimental Results

Just as the present study of Dy^{166} was being completed, two other independent studies of the decay of this isotope were reported.[5,6] Since our work agrees substantially with these reports, the present results pertaining to the decay of Dy^{166} are only summarized.

The half-life of Dy^{166} determined by observing the decay of the Dy^{166}-Ho^{166} equilibrium mixture through 13 half-lives, was found to be 81.8±0.2 hr.

Gamma spectra of the separated Dy^{166} activity are shown in Fig. 6. These spectra show the presence of

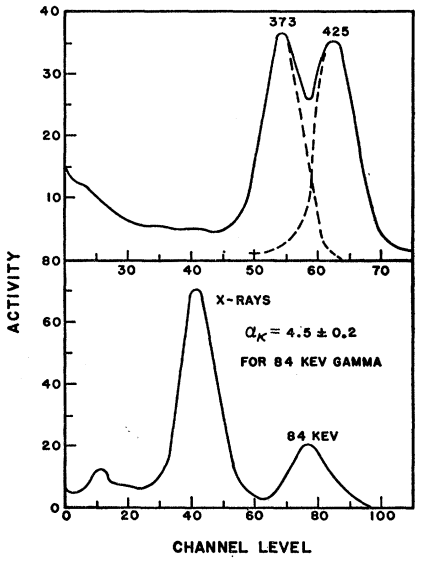

FIG. 6. Low- and high-energy gamma spectra of Dy^{166}.

[12] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8 (1959).

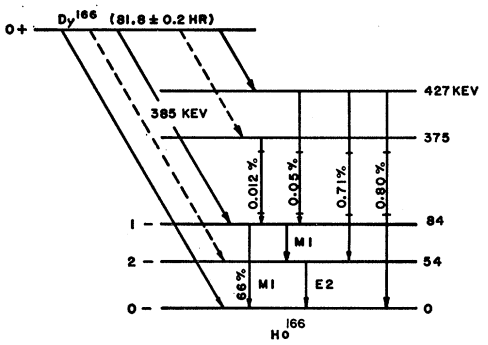

FIG. 7. Proposed decay scheme of Dy^{166}. Percentages are absolute gamma-ray intensities except for the 84 kev transition which includes conversion intensities.

radiations of the following energies: 50, 84, 373, and 427 kev. When scintillation studies were made to find radiations coincident with the 84-kev gamma ray, two additional low intensity radiations of 291 and 343 kev were found to be present. No other γ-γ coincidences were observed although the 373-kev transition is presumably coincident with the 54-kev level transition which was observed in permanent magnet spectrographic studies. The coincidence could not be observed, due to the high electron conversion probability of this low-energy state.

The beta spectrum coincident with the 84-kev radiation was studied using the previously described hollow plastic scintillator. The maximum beta energy leading to this state, was found to be 385±10 kev. The total energy therefore between the Dy^{166} and Ho^{166} ground states is 469±15 kev.

Permanent-magnet studies revealed the presence of two highly converted transitions which could not be seen in the gamma spectrum. Their approximate energies are 30 and 54 kev. The converted 84-kev transition was also present. Relative intensities of the L_1, L_2, and L_3 conversion lines, indicated the following multipolarity changes predominate in these transitions: 30 kev—$M1$, 54 kev—$E2$, and 84 kev—$M1$.

A decay scheme consistent with the data is given in Fig. 7. Except for minor transition intensity differences, the decay scheme is in substantial agreement with that which has recently been reported elsewhere.[5,6]

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New Isotope Indium-106†

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A new isotope, In^{106}, has been produced by proton bombardment of cadmium. Mass and atomic number assignment have been made on the basis of the excitation function and chemical separations, and by using a target enriched in Cd^{106}. Two positron energy end points of this 5.3-min activity have been measured at 4.85 and 3.1 Mev. Gamma rays at 1.65 and 1.85 Mev have been resolved from a complex high-energy spectrum.

IN cadmium targets irradiated with protons from the UCLA cyclotron, a 5.3-min activity emitting high-energy gamma rays has been observed. This activity has been assigned to In^{106} on the basis of the following evidence.

Measurements were made with a $1\frac{1}{2}$- ×2-in. NaI(Tl) scintillation detector coupled to an integral discriminator followed by a scalar. The discriminator was set to accept only pulses corresponding to gamma-ray energies greater than 1.8 Mev. Using this method, two easily separable half-lives were present in the decay of the cadmium target, one of 5.3 min and another of about one hour.

A cadmium foil 6 mg/cm² thick with Cd^{106} enriched from its natural abundance of 1.21 to 77.9% was obtained from Isotopes Division of Oak Ridge National Laboratory. A portion of this enriched foil was superimposed on a natural cadmium foil 10 mg/cm² thick of the same area and bombarded with 14-Mev protons. The yields of the 5.3-min activity from the foils, corrected to the same foil thickness, was found, within experimental error, to be in the same ratio as the isotopic abundance of Cd^{106}. This proved that the target isotope responsible for the activity was Cd^{106}.

A chemical separation of the target into indium, cadmium, and silver fractions showed the 5.3-min activity to be from an isotope of indium.

Measurements on the yield of gamma rays above 1.8 Mev as a function of proton energy indicated the 5.3-min activity to be the result of a p,n reaction and placed an upper limit on its threshold of 8 Mev. With the above information this activity can definitely be assigned to

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