has been observed in U^{233} by Pattenden and Harvey[14] and perhaps in Pu^{239} by Vogt[15] is probably manifested also in U^{235}.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. V. L. Sailor for his interest and cooperation, and to Dr. C. R. Hatcher for his assistance with the electronics. The assistance of C. P. Jupiter and P. Lane in setting up the equipment is also acknowledged.

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Alpha Decay Properties of some Holmium Isotopes near the 82-Neutron Closed Shell*

RONALD D. MACFARLANE† AND ROGER D. GRIFFIOEN‡
Lawrence Radiation Laboratory, University of California, Berkeley, California

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Bombardment of Pr^{141} targets with 75- to 137-MeV O^{16} ions has resulted in the identification of new alpha-emitting isotopes of holmium. The results obtained for the alpha-decay properties of these isotopes are:

Nuclide	Alpha-particle energy (MeV)	Half-life
Ho^{151}	4.51±0.02	35.6 ±0.4 sec
Ho^{151m}	4.60±0.02	42 ±4 sec
$Ho^{152g \text{ or } m}$	4.45±0.02	52.3 ±0.5 sec
$Ho^{152g \text{ or } m}$	4.38±0.02	2.36±0.16 min
Ho^{153}	3.92±0.03	9 ±2 min

Excitation functions were obtained for the production of these nuclides and for the production of Dy^{150}, Dy^{151}, and Dy^{152}. Large differences were observed for the energy dependence of the excitation functions of the isomer pairs which were attributed to angular momentum effects. Alpha branching ratios were estimated and used to calculate alpha reduced level widths.

I. INTRODUCTION

ALPHA-DECAY systematics in the rare-earth region show that nuclides containing between 84 and 88 neutrons possess an enhanced alpha-decay energy because of the effect of the extra stability of the 82-neutron configuration. Alpha decay has been observed thus far for isotopes of the rare earth elements from neodymium to dysprosium. Most of these results have been summarized in papers by Toth and Rasmussen[1] and Macfarlane and Kohman.[2] Until the present, no extensive search has been made for the alpha decay of isotopes of the elements above dysprosium which lie near the 82-neutron closed shell although some indications have been reported. Rasmussen, Thompson, and Ghiorso observed a 4.2-min alpha activity which they believed might be due to a holmium alpha emitter[3] and Toth and Rasmussen observed an alpha activity with a half-life of a few hours which they tentatively assigned to an erbium or holmium isotope.[1]

The purpose of this paper is to report some results which were obtained on the alpha-decay properties of the 84 to 86 neutron isotopes of holmium.

II. EXPERIMENTAL PROCEDURE

A detailed description of the experimental techniques has been given in an earlier paper.[4]

A. General Procedure

Holmium isotopes were produced by $Pr^{141}(O^{16},xn)$ reactions using 75- to 137-MeV O^{16} ions from the Berkeley heavy-ion linear accelerator (Hilac). Samples for alpha-particle analysis were prepared by the electrostatic collection of recoils from a target in a helium atmosphere. Alpha-particle spectra were obtained using a Frisch-grid ionization chamber which was calibrated for energy using the alpha particles from Tb^{149}(3.95 MeV)[5] and

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† Present address: Chemistry Department, McMaster University, Hamilton, Ontario, Canada.

‡ Present address: Physics Department, Calvin College, Grand Rapids, Michigan.

[1] K. S. Toth and J. O. Rasmussen, Nucl. Phys. **16**, 474 (1960).

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U^{234}[4.75 MeV (average)].[6] In most cases spectra were obtained within 1 min from the end of the bombardment. The technique of electrostatic collection of recoils from radioactive decay which had been successfully employed previously was also used in this work to establish parent-daughter relationships.[4,7] Experiments to test the usefulness of this technique were performed using thin samples of Dy^{149} and Dy^{150} prepared by the electrostatic collection in helium of recoils from the Ce^{140}+O^{16} reaction. It was found that recoils from the β^+/EC decay of Dy^{149} could be collected on a negatively charged plate in vacuum in sufficient quantity to detect the alpha decay of the daughter, Tb^{149}. It was also possible to obtain a measure of the half-life of the parent by collecting the beta decay recoils from the same sample at different time intervals. No transfer of the primary recoils, which would be detected by the presence of Dy^{150} alpha activity on the beta-recoil collection plates, was observed.

B. Excitation Functions

Relative excitation functions were obtained for the holmium isotopes and for Dy^{150}, Dy^{151}, and Dy^{152} which were also observed. These were converted to an absolute basis making use of the Dy^{150} and Dy^{151} cross-section data of Alexander and Simonoff for the Ce^{140}+O^{16} and Pr^{141}+O^{16} reactions.[8] The values of the cross sections where the Dy^{150} and Dy^{151} excitation functions intersect each other were chosen as the points of normalization. The Alexander and Simonoff data give the following values of the cross section and incident energy at the normalization points: 412 mb at 111 MeV for the Ce^{140}+O^{16} reaction and 420 mb at 125 MeV for the Pr^{141}+O^{16} reaction.[8]

For cases where the alpha branching ratio was not known, the product of the absolute cross section and alpha-branching ratio was obtained. The half-lives and alpha branching ratios of the dysprosium isotopes were taken as follows: 7.4-min Dy^{150}, 0.179; 17.9-min Dy^{151}, 0.062; and 2.3-h Dy^{152}, 8.6×10^{-4}. These values have recently been determined with better accuracy than previously reported.[9]

The excitation energies referred to in the discussion of the cross-section results were obtained by subtracting the Q value for compound nucleus formation from the center-of-mass energy of the projectile. Q values were calculated from the semiempirical mass formula of Seeger.[10]

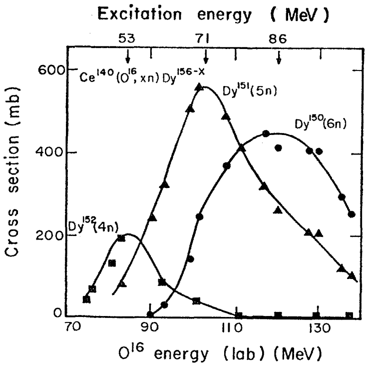

FIG. 1. Excitation function curves for the Ce^{140}(O^{16},xn)Dy^{156-x} reaction.

III. RESULTS

A. Ce^{140}+O^{16}

Alpha-particle spectra of recoil samples collected from O^{16} bombardments of 99.6% Ce^{140} targets showed only known alpha emitters of dysprosium and terbium. These were characterized by alpha-particle energy and half-life. The relative excitation functions for Dy^{150}, Dy^{151}, and Dy^{152} were obtained from the counting data and converted to absolute cross sections in accordance with the procedure outlined in Sec. II B. The Dy^{150} and Dy^{151} cross sections at the energies on either side of the point of normalization were found to be in reasonable agreement with the values obtained by Alexander and Simonoff.[8] As indicated in Fig. 1, the (O^{16},6n), (O^{16},5n,) and (O^{16},4n) cross sections for the Ce^{140}+O^{16} reaction peak at excitation energies of 86, 71, and 53 MeV, respectively.

B. Pr^{141}+O^{16}

The holmium isotopes which were sought, Ho^{151}, Ho^{152}, and Ho^{153}, can be produced from Pr^{141}+O^{16} by the same type reactions that produced Dy^{150}, Dy^{151}, and Dy^{152} from the Ce^{140}+O^{16} bombardments.

Alpha-particle analysis of the recoils which were collected from Pr^{141}+O^{16} bombardments at various incident energies showed the presence of two prominent alpha activities and three weaker groups which were not seen in the alpha spectra of samples from Ce^{140}+O^{16} bombardments. The alpha-particle energies and half-lives of these activities do not correspond to any of the known alpha emitters. Groups resulting from Dy^{150}, Dy^{151}, Dy^{152}, and Tb^{149} alpha decay were also observed. Attempts to establish the identity of the element or elements responsible for these activities by chemical means were unsuccessful primarily because of their short half-lives. However, the fact that these activities were produced by the Pr^{141}+O^{16} reaction and not by the Ce^{140}+O^{16} reaction, which can produce all the nuclides formed by the Pr^{141}+O^{16} reaction with the exception of the isotopes of holmium, was taken as good evidence that they are due to isotopes of holmium.

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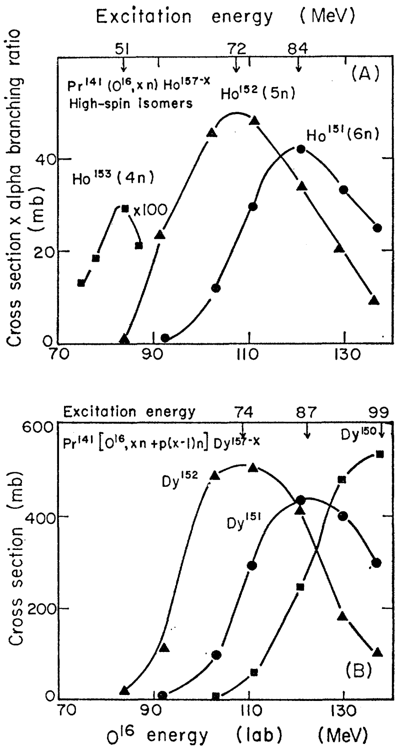

FIG. 2. Excitation function curves for the $Pr^{141}(O^{16},xn)Ho^{157-x}$ reaction leading to (a) the high-spin isomers and (b) Dy^{150}, Dy^{151}, and Dy^{152}.

Ho^{151} ($E_\alpha = 4.51$ MeV)

Measurements on one of the two promient new alpha activities that was formed from the $Pr^{141}+O^{16}$ reaction gave as values of the half life and alpha-particle energy 35.6±0.4 sec and 4.51 MeV, respectively. The energy dependence of the excitation function was found to correspond to that expected for an $(O^{16},6n)$ reaction which would produce Ho^{151}. As shown in Fig. 1 the peak of the excitation function for the $Ce^{140}(O^{16},6n)$ reaction occurs at excitation energy of ~86 MeV while the peak of the excitation function for this activity falls at ~84 MeV [Fig. 2(a)]. Alpha-particle spectra which contain this alpha group are shown in Fig. 3.

A parent-daughter relationship was established between this activity and Dy^{151} by making use of the technique of the electrostatic collection of beta decay recoils referred to in Sec. II. Recoils from the β^+/EC decay of this activity were electrostatically collected in vacuum on a plate for a one-minute period and then on another plate for a similar length of time. The alpha-particle spectra of the two plates (Fig. 4) clearly showed the presence of Dy^{151} alpha activity with the level of activity four times higher on the first plate than on the second. This indicates that the parent, Ho^{151}, has a half-life of approximately 30 sec which is consistent with the value obtained for the 4.51-MeV group. Some Dy^{150} alpha activity was also observed on the plates, which is undoubtedly the result of Ho^{150} decay. From the level of Dy^{150} activity on the two plates, Ho^{150} appears to have a half-life of approximately 20 sec.

An alpha-branching ratio of 0.20±0.05 was obtained for the 4.51-MeV Ho^{151} by measuring the growth of Dy^{151} and comparing it with the decay of the 4.51-MeV Ho^{151} alpha group. This was done using a different target assembly which made it possible to obtain alpha particle spectra within a few seconds after the end of bombardment. The details of this assembly will be described in a future paper.

Ho^{151} ($E_\alpha = 4.60$ MeV)

A weak alpha group decaying with a half-life of 42±4 sec was observed at an alpha-particle energy of 4.60 MeV. This group can be seen in the alpha-particle spectrum shown in Fig. 3(b). The cross section for the production of this activity [Fig. 5(a)] peaks at an excitation energy of 70 MeV which corresponds to that expected for the $(O^{16},5n)$ reaction (Fig. 1). However, the asymmetric shape of the excitation function [Fig. 5(a)] which rises sharply on the low-energy side and falls more gradually on the high-energy side suggests something peculiar about the mode of formation. Another feature of the excitation function is the low peak cross section–alpha-branching ratio product. This may be the result of a highly hindered alpha decay, a small peak cross section, or a combination of both. A similar asymmetry was observed with the excitation function for the $La^{139}(O^{16},6n)Tb^{149}$ reaction in which the low-spin isomer is formed. The peak cross section for the low-spin Tb^{149} was found to have a very small value and also to fall at an energy 15 MeV lower than the peak of the excitation function for the high-spin isomer.[4,11] These differ-

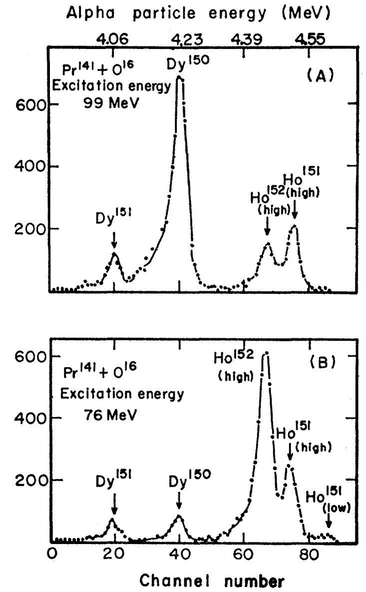

FIG. 3. Alpha-particle spectra of nuclides produced by the $Pr^{141}+O^{16}$ reaction at (a) 99-MeV excitation energy and (b) 76-MeV excitation energy. Bombarding time was 30 sec and samples were counted for a 1-min period at a time 1.5 min after bombardment.

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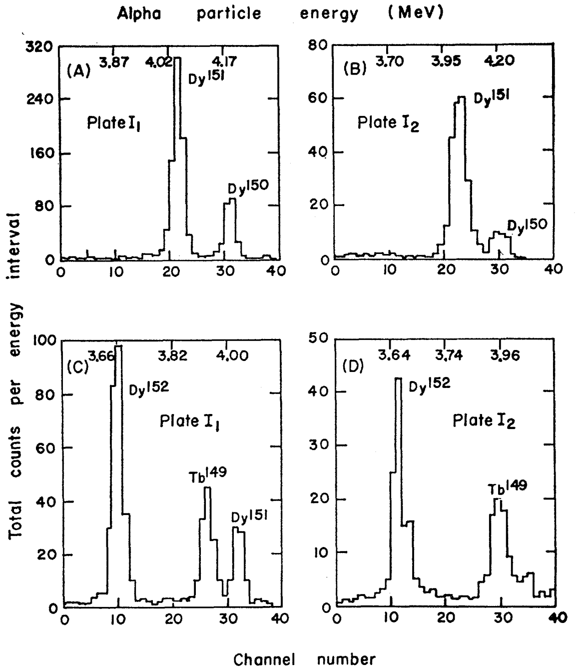

FIG. 4. Alpha-particle spectra of recoils collected from the β^+/EC decay of Ho^{150}, Ho^{151}, Ho^{152} and $Ho^{149}-Dy^{149}$; (a) recoils collected for 1 min and (b) recoils collected for the following minute from the same source. Counting time for both samples was 10 min. The spectra shown in (c) and (d) were obtained with the same samples used for (a) and (b) after a lapsed time of 1 h. Counting time was 5.5 h.

ences between the isomer excitation functions are thought to be due to the effect of competition of gamma-ray emission with nucleon evaporation in the decay of high angular momentum states of the excited compound nucleus.[4,8,12–15] In view of the similarity of some of these results with those obtained for the Tb^{149} isomer pair, it would appear that the 4.60-MeV holmium alpha activity might be due to a low-spin isomer. The most logical mass number would be 151 because of the position of the excitation function relative to that for the 4.51-MeV Ho^{151} activity discussed above.

When a low-spin isomer is made by an (HI,*xn*) reaction, where HI means heavy ion, it appears that the peak cross section is much smaller than that for the high-spin isomer and the excitation function is shifted to a significantly lower energy. If, however, the low-spin isomer can be produced as a radioactive decay product of a nuclide which is formed by an (HI,*xn*) reaction involving most or all of the angular momentum distribution of compound nuclei, then the contribution of this mode of formation to the total excitation function of the low-spin isomer will reflect properties of the excitation function of the parent and no energy shifts caused by angular momentum effects would be observed. If, then, the 4.60-MeV holmium activity is due to a low-spin isomeric state in Ho^{151}, it may be possible to identify this activity with the β^+/EC decay of Er^{151} by this technique.

The isotope, Er^{151}, can be made by the reaction $Nd^{142}(O^{16},7n)Er^{151}$. The cross section for this reaction should peak at an excitation energy of approximately 100 MeV according to results obtained for the $Pr^{141}(O^{16},7n)Ho^{150}-Dy^{150}$ reaction [Fig. 2(b)]. Bombardments were made with O^{16} ions on a neodymium target enriched in Nd^{142} to 93.9%. The results obtained indeed show that the cross section for the 4.60-MeV holmium alpha-activity peaks at an excitation energy of 98 MeV [Fig. 5(b)], an energy which is close to that expected for the peak of the Er^{151} excitation function.

The 4.51-MeV Ho^{151} excitation function was also found to peak at 98-MeV excitation energy. This excitation function is probably a composite of the $Nd^{142}(O^{16},7n)Er^{151}$ reaction followed by the decay of Er^{151} and the $Nd^{142}(O^{16},p6n)Ho^{151}$ reaction leading to the high spin isomer. Both of these reactions are expected to peak at approximately the same excitation energy. This is based on a consideration of the Q values for each of the reactions and an estimate of the average amount of kinetic energy carried off by neutrons and protons.[8] The latter reaction is expected to have an appreciable cross section because of the large neutron binding energies of the erbium isotopes in this region.[10]

Apparently that part of the cross section for the low-

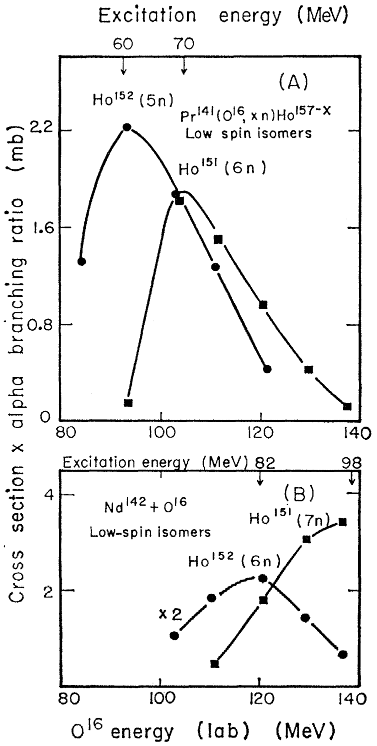

FIG. 5. Excitation functions of the Ho^{151} and Ho^{152} low-spin isomers produced by the (a) $Pr^{141}+O^{16}$ reaction and (b) $Nd^{142}+O^{16}$ reaction.

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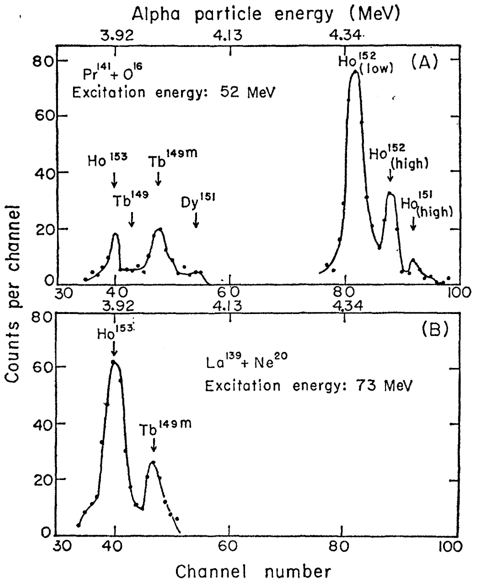

FIG. 6. Alpha-particle spectra showing the presence of the Ho^{152} low-spin isomer and Ho^{153} alpha activities. The spectrum shown in (a) is the result of a 5-min bombardment of $Pr^{141}+O^{16}$ at an excitation energy of 52 MeV. The spectrum was obtained over a period of 10 min after a lapsed time of 3 min from the end of bombardment. The spectrum shown in (b) is from a 10-min bombardment of $La^{139}+Ne^{20}$ at an excitation energy of 73 MeV. The spectrum was obtained over a period of 8 min after a lapsed time of 3 min from the end of the bombardment.

spin Ho^{151} isomer which is a result of the β^+/EC decay of Er^{151} is much larger than the contribution from direct formation by an (O^{16},$p6n$) reaction. The cross section for this reaction should peak at an excitation energy of ~85 MeV if angular momentum effects for the (O^{16},$p6n$) reaction are similar to those affecting the position of the peak of the isomer excitation functions of the (O^{16},$6n$) reaction.

Ho^{152} ($E_\alpha=4.45$ MeV)

The second prominent holmium alpha activity that was observed has an alpha-particle energy of 4.45 MeV and decays with a half-life of 52.3±0.5 sec. This alpha group can be seen in the alpha-particle spectra shown in Fig. 3 and Fig. 6(a). The cross section for this activity when produced by the $Pr^{141}+O^{16}$ reaction peaks at an excitation energy of 72 MeV [Fig. 2(a)] which is close to the value observed for the $Ce^{140}(O^{16},5n)Dy^{151}$ reaction. These results suggest that the activity is due to Ho^{152}.

This mass assignment was substantiated by the "recoil-milking" experiment which provided the results establishing the $Ho^{151}-Dy^{151}$ relationship. Using the same recoil collection plates, the more intense Dy^{151} and Dy^{150} alpha activities were allowed to decay away and a search was made for Dy^{152} alpha activity. As shown in Fig. 4, the Dy^{152} alpha group was observed and the ratio of Dy^{152} activity on the two plates was found to be 2:1. This means that the parent, Ho^{152}, has a half-life of approximately 1 min, a value which is consistent with the measured half-life of the 4.45-MeV alpha group.

Ho^{152} ($E_\alpha=4.38$ MeV)

Alpha-particle spectra obtained after most of the prominent Ho^{151} and Ho^{152} activity produced in $Pr^{141}+O^{16}$ bombardments had decayed revealed the presence of an additional alpha group which has a half-life of 2.36±0.16 min and an alpha-particle energy of 4.38 MeV. This group can be seen in the alpha spectrum shown in Fig. 6(a). The excitation function, which is shown in Fig. 5(a), has the same asymmetric shape that was observed with the Ho^{151} low-spin isomer. If this activity is also due to a low-spin holmium isomer, then the excitation function will probably exhibit a downward shift in energy compared to the excitation function of the high-spin member of the isomer pair. The peak cross section for the 4.45-MeV Ho^{152} alpha group, as discussed above, was found to occur at an excitation energy of 72 MeV. If a low-spin isomer of Ho^{152} exists, its peak cross section would be expected to fall 12 to 15 MeV lower in energy as was observed with the Tb^{149} and Ho^{151} isomer pairs. The peak of the excitation function for the 4.38-MeV alpha group falls at 61-MeV excitation energy which is a value consistent with that expected if it were a low-spin Ho^{152} isomer.

The same type of experiment used in the study of the low-spin Ho^{151} isomer was carried out to see if this activity could be associated with the β^+/EC decay of Er^{152} when produced by the $Nd^{142}+O^{16}$ reaction. The $Nd^{142}(O^{16},6n)Er^{152}$ and $Nd^{142}(O^{16},p5n)Ho^{152}$ (high-spin) reaction cross sections are both expected to peak at an excitation energy of approximately 84 MeV while the (O^{16},$p5n$) reaction cross section in which a low-spin isomer is formed should peak 12 to 15 MeV lower. The results obtained show that the cross section for the 4.38-MeV holmium alpha activity when produced by the $Nd^{142}+O^{16}$ reaction peaks at an excitation energy of 82 MeV [Fig. 5(b)]. The excitation function of the 4.45-MeV Ho^{152} also peaks at the same energy. These results were taken as good evidence that the 4.38-MeV alpha group is a decay product of the β^+/EC branch of the Er^{152} decay. The cross section for direct formation by the (O^{16},$p5n$) reaction which should peak at an excitation energy of approximately 70 MeV is apparently much smaller than the contribution from the β^+/EC decay of Er^{152}. The nuclide Er^{152} is the 84-neutron erbium isotope and exhibits a measurable alpha decay branch.[16] This may be a reason why the relative peak cross section of the low-spin Ho^{152} isomer is much lower than that for the low-spin Ho^{151} isomer compared with the results obtained when these activities were produced by the $Pr^{141}+O^{16}$ reaction.

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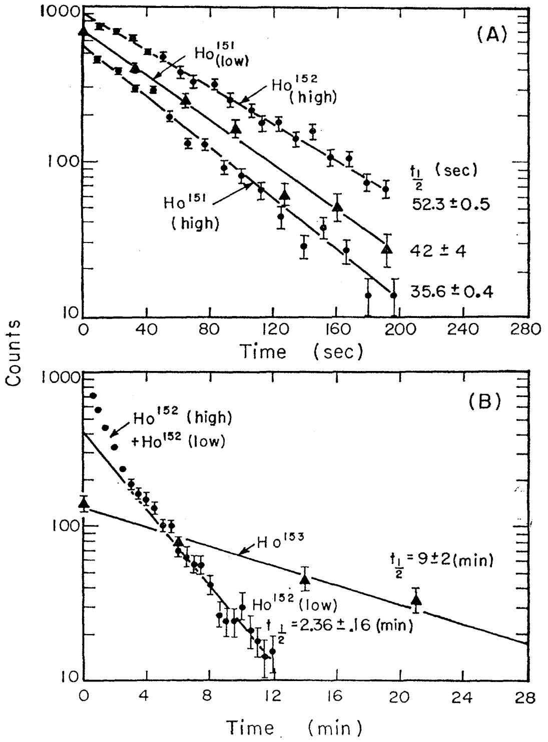

FIG. 7. Alpha-decay curves of the holmium alpha emitters.

Ho^{153}

A search was made for evidence of Ho^{153} alpha activity by looking at products of the Pr^{141}+O^{16} reaction at incident energies in the range of 70 to 90 MeV. At these low energies a small peak was observed at an alpha-particle energy of 3.92 MeV [Fig. 6(a)] which was found to decay with a half-life of 9 min. The cross-section peaks at an excitation energy of 51 MeV [Fig. 2(a)]. The Ce^{140}(O^{16},4*n*)Dy^{152} reaction cross section (Fig. 1) peaks at an excitation energy of 53 MeV so that the excitation function for this activity is consistent with that expected for the Pr^{141}(O^{16},4*n*)Ho^{153} reaction. It was not possible to establish a parent-daughter relationship by the recoil-milking method because of the difficulty in detecting Dy^{153} alpha decay which has a very low alpha branch.[1] Attempts to detect the alpha-decay daughter, Tb^{149}, proved to be unsuccessful, probably because of the low alpha counting rate of the parent. The mass assignment can only be made on the basis of the excitation function results.

The (O^{16},4*n*) peak cross section has a low value for the Pr^{141}+O^{16} reaction because of Coulomb barrier effects which reduce the cross section for compound nucleus formation at energies close to the barrier. This effect can be seen with the Dy^{152} excitation function for the Ce^{140}+O^{16} reaction (Fig. 1). A higher level of this holmium activity was seen when produced by the La^{139}+Ne^{20} reaction [Fig. 6(b)], where the isotope Ho^{153} is produced by the La^{139}(Ne^{20},6*n*)Ho^{153} reaction. The peak cross section for this reaction occurs at a higher incident bombarding energy compared to the Coulomb barrier than the corresponding Pr^{141}(O^{16},4*n*)-Ho^{153} reaction. The Tb^{149m} group seen in the alpha spectrum [Fig. 6(b)] is probably the product of the (Ne^{20},α6*n*) reaction.

The decay curves which were obtained for the holmium activities are shown in Fig. 7.

C. Ho^{151} and Ho^{152} Isomers

It has been reasonably well established from the results described above that the 4.60-MeV Ho^{151} and 4.38-MeV Ho^{152} alpha activities are low-spin isomers. The 4.51-MeV Ho^{151} and 4.45-MeV Ho^{152} alpha activities must, therefore, be associated with states of higher spin. From the experimental results described above it was not possible to clearly determine which of these activities are associated with the ground states of Ho^{151} and Ho^{152}. In order to obtain some additional information on the assignment of the metastable and ground states of the Ho^{151} isomer pair, the alpha-particle spectrum of the Ho^{151} alpha decay was studied further. Alpha-particle spectra were recorded at different time intervals under conditions where the initial level of the 4.60-MeV Ho^{151} alpha group was extremely small in order to determine whether there might be a detectable buildup of this activity by an isomeric transition from the state responsible for the 4.51-MeV alpha activity. None was observed. A search was made for evidence of higher energy groups associated with the alpha decay of the high-spin Ho^{151} isomer but none was observed. Evidence was obtained from a resolution check that the 4.51-MeV group associated with the Ho^{151} high-spin isomer may actually be composed of a doublet. The full width at half-maximum of the 4.51-MeV group was found to be 45 keV while that for Dy^{150} in the same spectrum was 35 keV.

IV. DISCUSSION

A. Proposed Alpha-Decay Scheme of the Ho^{151} Isomers

The appearance of nuclear isomerism among the spherical terbium isotopes is thought to be due to the beginning of the filling of an $h_{11/2}$ proton shell by the 65th proton which, in the case of Tb^{149}, results in the appearance of an $h_{11/2}$ level lying close to a $d_{5/2}$ ground state.[4] Apparently these levels are still close together in Ho^{151} as evidenced by the existence of the isomer pair. If the high-spin state of Ho^{151} is $h_{11/2}$ and the low-spin state $d_{5/2}$, this would give rise to an $E3$ isomer similar to that proposed for Tb^{149}. If one assumes that this is the case, it is possible to obtain an alpha-decay scheme which is consistent with the experimental results. The features of the proposed alpha-decay scheme are as follows: the $h_{11/2}$ state of Ho^{151} is the ground state and the $d_{5/2}$ level, a metastable state lying at a low undetermined energy above the ground state. The ground state of the daughter, Tb^{147}, is $d_{5/2}$ and the $h_{11/2}$ level lies at a small undetermined energy above the ground state. Alpha decay from the $h_{11/2}$ ground state of Ho^{151} populates predominantly the $h_{11/2}$ metastable state of Tb^{147} but there is also a weak transition to the ground state. The alpha particles associated with these transitions give rise to the 4.51-MeV alpha group for which there is evidence of an unresolved doublet (Sec. IIIC). The alpha decay of the $d_{5/2}$ metastable state of Ho^{151} proceeds mainly to the $d_{5/2}$ Tb^{147} ground state and is responsible for the 4.60-MeV group. With this scheme the difference in alpha-decay energies between these isomers (90 keV) represents the sum of the spacing between the $h_{11/2}$ and $d_{5/2}$ levels of Ho^{151} and Tb^{147}. The spacing between the two isomeric states of Tb^{149} was found to be 40 keV.[4]

All of the other possible combinations of the $h_{11/2}$ and $d_{5/2}$ states of the parent and daughter result in levels which are too widely spaced for an $E3$ isomer with a half-life as long as 35 sec, or give alpha-decay energies for the high- and low-spin isomers which are different from the observed values, or predict the existence of higher energy alpha groups which were not observed.

B. The Ho^{152} Isomers

The isotope, Ho^{152}, is the first example of an odd-odd alpha emitting nuclide in the rare-earth region. Another odd-odd rare-earth nuclide, Tb^{150}, should also exhibit a measurable alpha decay, but it has not yet been observed. If an $h_{11/2}$ proton and an $f_{7/2}$ neutron, as predicted by the shell model, are the odd nucleons in Ho^{152}, these could couple to give a spin state as high as 9 at or near the ground state of Ho^{152}. There is no way of determining from the experimental results whether the high-spin or low-spin isomer is the ground state of Ho^{152}.

C. Holmium Alpha Emitters with $A>153$

In a preliminary report of this work,[17] results were given for the alpha-decay properties of Ho^{153}, Ho^{154}, and Ho^{155}. These results have since been found to be in error. Also, the values of the alpha-particle energy, half-life, and alpha-branching ratio which were given in that report have been remeasured in this work with greater accuracy using improved techniques.

The 4-min holmium activity reported by Rasmussen, Thompson, and Ghiorso was not found.[3] The similarity of the half-life and alpha energy of this activity with that of the Tb^{149} high-spin isomer[4] suggests that they may have seen this nuclide rather than a holmium isotope.

A search was made for holmium alpha emitters above $A=153$ by looking at the products of $Nd^{148}+N^{14}$ bombardments. An isotopically enriched Nd^{148} target was used but it also contained some small amounts of the lighter neodymium isotopes. These lighter isotopes produced enough Dy^{150} and Dy^{151} to make it difficult to detect any weak alpha activities at energies below these alpha groups. The experiment did establish that the intensity of the alpha decay of the heavier holmium isotopes is at least three orders of magnitude smaller than for Ho^{151} and Ho^{152}.

D. Alpha Branching Ratios

The alpha branching ratio of the high-spin Ho^{151} isomer was experimentally determined to be 0.20 ± 0.05. In order to obtain the alpha-branching ratio of the other holmium activities, it was necessary to estimate the expected relative peak cross sections from other cross-section data and infer the alpha-branching ratio. The ratios of the peak cross sections for Dy^{151} and Dy^{152} to the peak cross section for Dy^{150} were found to be 1.22 and 0.444, respectively, for the $Ce^{140}+O^{16}$ reaction. If these ratios are assumed to be the same for Ho^{152}/Ho^{151} and Ho^{153}/Ho^{151} for the $Pr^{141}+O^{16}$ reaction, the alpha-branching ratio which is obtained for the high-spin Ho^{152} isomer is 0.19 ± 0.05 and for Ho^{153} $(3\pm2)\times10^{-3}$.

The alpha-branching ratios of the Ho^{151} and Ho^{152} low-spin isomers were estimated assuming that the ratio of the peak cross section of the high-spin isomer to the low-spin isomer is 33. This value was obtained from the data of Alexander and Winsberg[11] for the peak cross section of the $La^{139}(O^{16},6n)Tb^{149}$ reaction leading to the low-spin isomer (15 mb) and the peak cross section for the $Ce^{140}(O^{16},6n)Dy^{150}$ reaction (500 mb) which was measured by Simonoff and Alexander.[8] The assumption was made that this cross section is approximately the same as that for the $La^{139}(O^{16},6n)Tb^{149}$ reaction leading to the high-spin isomer of Tb^{149}. The alpha-branching ratios which were obtained are 0.28 for Ho^{151} and 0.30 for Ho^{152}. Because of the several assumptions which were involved in the method of obtaining these alpha branches, they are probably only good to within a factor of 2.

E. Reduced Level Widths

Using the alpha-branching ratios obtained above, alpha-decay half-lives were calculated for each of the holmium activities. From these values, reduced level widths (δ^2) were obtained using the procedure of Rasmussen for calculating barrier penetrabilities.[18] The reduced level width δ^2 is defined by the expression

$$\lambda=\delta^2P/h, \tag{1}$$

where λ is the alpha-decay constant, P is the barrier penetrability, and h is Planck's constant. The nuclear potential used in the calculation of P is the sum of the Coulomb potential, the centrifugal potential, and the

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TABLE I. Summary of results

Nuclide	Q_α (MeV)	Half-life	Alpha branching ratio	Reduced width, δ^2 (MeV)	Remarks
Ho^{151}	4.63±0.02	35.6 ±0.4 sec	0.20±0.05	0.065	high-spin isomer, probably the ground state
Ho^{151}	4.73±0.02	42 ±4 sec	0.28 (within factor of 2)	0.025	low-spin iosmer, probably the metastable state
Ho^{152}	4.57±0.02	52.3 ±0.5 sec	0.19±0.05	0.087	high-spin isomer
Ho^{152}	4.50±0.02	2.36±0.16 min	0.30 (within factor of 2)	0.12	low-spin isomer
Ho^{153}	4.03±0.03	9 ±2 min	$(3\pm2)\times10^{-3}$	0.22	

real part of the alpha-nuclear potential given by[19]

$$V(r) = -1100 \exp\{-[(r-1.17A^{1/3})/0.574]\}\text{MeV}. \quad (2)$$

The alpha-particle energy used in the calculation was the experimentally determined value plus an additional small correction to account for electron screening effects.[20]

Because of the lack of knowledge of the spin assignments of the parent and daughter, values of the reduced width were calculated for $l=0$ alpha waves only. The calculated values are given in Table I. The reduced widths for those dysprosium and gadolinium alpha emitters whose alpha decay properties are known with reasonable accuracy fall in the range of 0.05 to 0.1 MeV.[1] The reduced widths for the high-spin Ho^{151} and Ho^{152} isomers are 0.065 and 0.087 so they compare rather favorably with the dysprosium and gadolinium values. The reduced widths for the other holmium alpha emitters are only approximate values but none of them indicate a significant hindrance associated with their decay. This would be reflected by a low value for the reduced width. In contrast, the terbium alpha emitters, Tb^{149} and Tb^{151}, exhibit a significantly hindered alpha decay. This difference between the terbium and holmium alpha emitters can be qualitatively explained by a consideration of the nature of the initial and final states. If the spherical terbium and holmium isotopes are filling the same $h_{11/2}$ proton shell, the initial and final state wave functions of terbium and holmium may be quite similar (at least as far as the alpha decay process is concerned) and this would result in a favorable overlap. However, for the terbium isotopes decaying to spherical europium daughters, the initial state may involve some significant $h_{11/2}$ proton configuration: e.g., $(d_{5/2})^5\ (h_{11/2})^2$ while the final state may have the form $(d_{5/2})^5$. The overlap between these two states would probably be considerably less than in the transition $(d_{5/2})^6(h_{11/2})^3 \rightarrow (d_{5/2})^6(h_{11/2})^1$ which may be involved in the alpha decay of the high-spin Ho^{151} isomer. The order of filling of the proton levels in this discussion is assumed to be that given by Mottelson and Nilsson for the case of zero deformation.[21] According to their scheme, the filling of the proton levels above $Z=50$ is $g_{7/2}$, $d_{5/2}$, $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$.

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