contraction of the region of diffuseness, the independent-particle model levels will separate. This is as experimental observations suggest. Such a coupling is analogous to that which occurs in the Bohr collective model of the nucleus through the intermediary of aspherical surface distortions.[15]

If one wishes to compare the diffuseness parameters arrived at here with the diffuseness corresponding to other shapes, the 0.9 to 0.1 fall-off distance for a fixed distance to the 0.5 point might serve as a reasonable basis for comparison. Let us suppose, for a heavy element, that the distance to the 0.5 point is $R=6.7$ (in units of 10^{-13} cm). Then $\delta=0.2$ corresponds to a fall-off distance of 2.6. This is only slightly more diffuse than the experimentally determined fall-off length (2.2) for the nuclear charge distribution in lead,[16] but appreciably less diffuse than Swiatecki's recent theoretical determination ($3.1\rightarrow4.3$) based upon surface energies.[17]

In closing, it might be remarked that practically all of the evidence relating to nuclear shell structure comes from phenomena originating in the outermost regions of the nucleus. In view of the sensitivity of particle binding energies to the diffuseness parameter, one might well hope that many of the quantitative difficulties with the independent particle model might be removed by the use of nuclear potentials with appropriate degrees of diffuseness.

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[15] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selsbab, Mat.-fys. Medd. **27**, (16) (1953).
[16] Hill, Freeman, and Ford, Bull. Am. Phys. Soc. **30**, No. 3, 49 (1955).
[17] W. J. Swiatecki, Phys. Rev. **98**, 204 (1955).

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Neutron-Deficient Activities of Terbium

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A survey was made of the neutron-deficient activities of terbium produced by proton bombardment of enriched isotopes of gadolinium. Half-lives and mass assignments are made for Tb^{156} and Tb^{154}, and the limits of half-lives for Tb^{158}, Tb^{157}, and Tb^{155} are defined. Data were obtained on the gamma-ray spectrum of Tb^{156}.

A SURVEY has been completed of the neutron-deficient activities of terbium which were produced by proton bombardment of enriched stable isotopes of gadolinium. The stable gadolinium isotopes of masses 152 through 158, in the form of oxides, were bombarded with protons in the Oak Ridge National Laboratory 86-inch cyclotron. After bombardment, ion exchange methods[1] were used to separate the products. The energy of the incident proton beam was controlled with appropriate aluminum absorbers. In separate runs, beam energies of 9.5, 14.0, and 22.4 Mev were used in order to insure that the reaction was chiefly (p,n), $(p,2n)$, or $(p,3n)$. Following separation, the terbium fraction was investigated for nuclear properties, such as half-lives and radiations, by the use of absorption and decay data, scintillation spectrometers, and alpha and beta counters. Assignment of mass numbers is based on excitation functions as determined experimentally and on enrichment factors of the stable gadolinium isotopes, Table I. Limits for the half-lives of some mass numbers are based on the relative production of the 5.2-day activity assigned to Tb^{156}. By assuming equal counting efficiencies and with corrections for length of bombardment, decay, chemical yields, and mass analysis of the stable isotopes, it is possible to calculate the minimum half-life of the longer lived activities. Because of these assumptions, these half-lives may be in error by as much as an order of magnitude. By using shorter bombardment times (2 or 3 minutes) and without attempting any separations, upper limits for half-lives are assigned to several mass numbers. This upper limit was controlled by the time required to get the

Table I. Analyses of enriched gadolinium isotopes.

Isotope	Isotopic analyses (%) 152	154	155	156	157	158	160
152	*14.96*	9.75	27.26	19.32	10.08	11.67	6.97
154	0.32	*33.17*	38.57	15.92	5.49	4.50	2.05
155	0.46	1.23	*72.28*	17.72	4.60	2.86	0.81
156	···	0.25	4.34	*80.22*	10.02	4.30	0.86
157	0.04	0.11	1.23	7.31	*69.68*	19.90	1.74
158	···	*t*	0.30	0.84	3.15	*92.87*	2.84

[1] B. H. Ketelle and G. E. Boyd, J. Am. Chem. Soc. **69**, 2800 (1947).

TABLE II. Nuclear properties of terbium nuclides.

Isotope	Type of decay	Half-life	Energies of particles Mev	Energies of gamma transitions (Mev)
Tb^{158}		<10 min or >5 years		
Tb^{157} [a]		<10 min or >25 years		
Tb^{156}	E.C., β^-?	5.2 days	0.6 0.2	2.0, 1.8, 1.4, 1.2, 0.76, 0.54, 0.36, 0.26, 0.21, 0.10
Tb^{156m}	β^-	5.5 hours	0.14	
Tb^{155}		<10 min or >5 years		
Tb^{154}	E.C., β^+?	17.5 hours		
Tb^{154}	E.C., β^+?	~7.5 hours		
Tb^{152}		<10 min or >5 years		
Tb^{151}	Previously reported 19-hour α activity not observed.			

[a] See also reference 4.

sample into a counter after completion of bombardment.

It was planned originally to make an exhaustive study of these activities but, due to a shutdown of the cyclotron for changes in design, this was impossible. Results obtained are presented at this time with the hope that they may be of value to others who may wish to continue the work. Table II is a summary of the results. As noted in the table, there are a number of disagreements with previous work.

TERBIUM-158

Tabulated nuclear data[2] make no activity assignment to Tb^{158}. The terbium fraction produced by bombardment of enriched Gd^{157} with 9.5-Mev protons was found to contain only 73-day Tb^{160}, decay of which was followed for two half-lives. Bombardment with 14.0-Mev protons yielded 5.2-day and 5.5-hour activities, and a very small amount of 73-day Tb^{160}. The 5.2-day and 5.5-hour activities are assigned to Tb^{156} (see below), and are produced by $(p,2n)$ on the 3% abundant Gd^{157}. Bombardment with 22.4-Mev protons yielded the 5.2-day and 5.5-hour activities and a very small amount of a longer-lived component. Based on production of the 5.2-day activity and the amount of long-lived activity present, limits of <10 min or >5 years were placed on the half-life of Tb^{158}. The upper limit was ascertained by short bombardments with no attempt to separate products.

TERBIUM-157

Other workers[3] have assigned a 4.7-day activity to this mass. Later work[4] indicates a much longer half-life; the present work is in agreement with the latter.

Following bombardment of enriched Gd^{157} with 9.5- and 14.0-Mev protons, the terbium fraction was found to contain the 5.2-day and 5.5-hour Tb^{156} activities with a longer-lived component only about twice background. Bombardment with 22.4-Mev protons yielded 5.2-day, 5.5-hour, and 17.5-hour activities. The 17.5-hour activity is assigned to Tb^{154} (see below) and is formed by the $(p,3n)$ reaction on the 7.3% abundant Gd^{156}. By methods previously described, calculated limits of <10 min or >25 years were placed on the half-life of Tb^{157}. This agrees with previously reported results obtained by bombarding terbium.[4] If some of the long-lived activity is due to Tb^{160} produced by the (p,n) reaction on 1.74% abundant Gd^{160}, then the limits on the half-life must be greater.

TERBIUM-156

Wilkinson and Hicks[3] have assigned a 5.0-hour activity to this mass. In the present work, bombardment of enriched Gd^{156} with a 9.5-Mev protons yielded 5.2-day and 5.5-hour activities and a small fraction of longer-lived component. The 5.5-hour component was not observed when the decay of an aliquot was followed by counting through a 10-mil aluminum absorber. The ratio of the beta counting rates of the 5.5-hour component to the 5.2-day component was observed to remain the same for bombardments of varying lengths, after corrections for time of bombardment and decay had been made. The ratio of 80 to 1 (5.5-hour to 5.2-day) was observed from G-M counting and was independent of either enrichment or particle energy. Thus, it appears the two activities are isomeric. They are assigned to Tb^{156} because they are produced by 22.4-Mev protons on Gd^{158} and by 9.5-Mev protons on Gd^{157} which contains 7.31% Gd^{156}. Aluminum absorption data show the 5.5-hour component to decay by negatron emission with a single beta group of 0.14-Mev energy.

Aluminum absorption data obtained after the 5.5-hour activity had decayed out indicated the beta activity of the 5.2-day activity to consist of two beta groups with maximum energies of 0.6 and 0.2 Mev. The gamma-ray spectrum of the 5.2-day activity showed the presence of a number of gamma rays as well as a large amount of K x-rays from gadolinium (Table II). It appears, therefore, that the 5.2-day activity decays to Dy^{156} by beta emission and to Gd^{156} by K-electron capture. The ratio K/β^- is believed to be large. The amount of β^+ branching in the latter case must be small since no 0.51-Mev annihilation radiation was seen in the gamma-ray spectrum.

By use of a krypton-methane-filled x-ray propor-

[2] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[3] G. Wilkinson and H. G. Hicks, Phys. Rev. **79**, 815 (1950).

[4] T. H. Handley and E. L. Olson, Phys. Rev. **90**, 500 (1953).

tional counter spectrometer equipped with a linear amplifier and a differential and integral pulse-height selector, the L x-ray region ($\sim$6 kev) was studied for sources of both activities. L x-rays from dysprosium were observed with the 5.5-hour activity which indicates the presence of a highly converted weak gamma ray. Polystyrene absorption data obtained by using a beta proportional windowless methane flow-type counter showed the presence of weak conversion electrons in the short-lived activity. Decay of the L x-ray peak was followed and the observed half-life was 5.5 hours. As the 5.5-hour activity decayed, however, the energy of the L x-ray shifted until the peak leveled off into a a half-life of 5.2 days and the energy of the L x-ray corresponded to that of x-rays of gadolinium.

The integral gamma counting rate was followed by using a NaI gamma scintillation counter. These data showed a small increase of gamma activity reaching a maximum approximately 18 hours after separation. Attempts to find which of the several gammas observed are responsible were unsuccessful.

TERBIUM-155

Others[3] have assigned a 190-day activity to this mass. In the present work bombardment of enriched Gd^{155} (isotopic analysis Table I) with 9.5-Mev protons yielded only 5.2-day and 5.5-hour activities in the terbium fraction. These have been assigned to Tb^{156} and were produced in this bombardment by the (p,n) reaction on the 17.72% Gd^{156} remaining in the enriched Gd^{155}. By using methods previously described, calculated limits of <10 minutes or >5 years are placed on the half-life of Tb^{155}.

TERBIUM-154

Tb^{154} has been reported[3] as a 17.2-hour activity. In the present work, bombardment of enriched Gd^{155} with 14.5-Mev protons yielded 5.2-day, 17.5-hour, and 7.5-hour components. The 7.5-hour activity was observed by counting through a thick absorber; thus, it is not the same activity (5.5-hour) observed in previous bombardments of heavier gadolinium isotopes. Also the ratio of the 7.5-hour to the 5.2-day activity was 500 to 1. Previously it was shown that the ratio of the 5.5-hour to the 5.2-day was consistantly 80 to 1. Bombardment with 22.4-Mev protons gave essentially the same results. Therefore, the 7.5-hour activity is assigned to Tb^{154}; it cannot be assigned to any mass higher than 154, since it was not produced by 9.5-Mev protons on the enriched Gd^{155} sample. Similarly, the assignment of the 17.5-hour activity can be made to mass 154 or lower since it was produced in the same manner as the 7.5-hour activity and was also not produced by 9.5-Mev protons on enriched Gd^{155}. In addition, bombardment of enriched Gd^{154} with 9.5-Mev protons yielded, in the Tb fraction, 5.2-day, 17.5-hour, and 7.5-hour activities. Since the 9.5-Mev protons produce only a (p,n) reaction, the possibility of either of these two activities being Tb^{153} is small. Thus, the activities seem logically to fall only to the 154 mass assignment.

If these activities are Tb^{152}, they would have been formed by the (p,n) reaction on Gd^{152}. In the enriched Gd^{155} sample, there was 44% more Gd^{152} than in the Gd^{154} sample. However, no 17.5-hour or 7.5-hour activities were produced by 9.5-Mev protons on Gd^{155}, but a large amount was observed in terbium fraction from the $Gd^{154}(p,n)$ reaction. Consequently, the assignment of both the 17.5-hour and 7.5-hour activities is made to Tb^{154}.

Further study of these nuclides was interrupted by the shutdown of the 86-inch cyclotron.

TERBIUM-152

Tabulated nuclear data[2] make no activity assignment to Tb^{152}. Bombardment of Gd^{152} did not yield any new activities. However, since the enriched Gd^{152} contains appreciable amounts of the other isotopes, it is somewhat difficult to analyze the decay curve. There could be some new activity present with a half-life nearly the same as one already identified.

TERBIUM-151

The 19-hour α activity previously reported[5] was not observed by bombarding Gd^{152} with 14.0- or 22.4-Mev protons. No α activities were observed in any of the terbium fractions, in which heavier gadolinium isotopes were bombarded.

[5] Rasmussen, Thompson, and Ghiorso, Phys. Rev. **89**, 33 (1953).