Inelastic Proton Scattering on Holmium-165 and Gadolinium-156*

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Elastic and inelastic scattering of 17.5-MeV protons by the low-lying rotational levels of holmium-165 and gadolinium-156 has been studied using a telescopic array of solid-state detectors with a resolution of about 60 keV. Angular distributions were obtained for the ground state ($7/2^-$), first excited state ($9/2^-$), and second excited state ($11/2^-$) of holmium-165, and the ground state (0^+), first excited state (2^+), and second excited state (4^+) of gadolinium-156. The cross section for the first excited state of Ho^{165} is an order of magnitude below that of the ground state. The ratio of the first excited state of Ho^{165} to that of the second does not agree with the prediction given by first-order direct reaction theory. There is some evidence that the third excited state of Gd^{156} (6^+) is weakly excited by 17.5-MeV protons.

I. INTRODUCTION

In recent years a great deal of interest has been focused on the understanding of the elastic and inelastic scattering of medium-energy particles from nuclei. Distorted-wave theory[1–3] has been quite successful in fitting a wide variety of inelastic scattering reactions.[4–9] The simpler inelastic diffraction model,[10,11] which makes use of the Fraunhofer approximation, has enjoyed equivalent success in describing (α,α') reactions, but has been less applicable to (p,p') reactions.[12]

Because of resolution difficulties, most experimental investigations have been limited to light or medium-A nuclei, where the discussion of nuclear transitions in terms of a collective model is not necessarily justified. However, some recent work in the $A=60$ region has been extremely well explained in terms of a simple collective model.[13–15] With the advent of high resolution surface-barrier detectors capable of stopping 18-MeV protons, it is now possible to investigate the inelastic scattering of protons from high-A nuclei which are well known to be nonspherical rotors. Using a newly designed beam analyzing system in conjunction with high resolution detectors it has been possible to attain a total resolution of approximately 60 keV which is sufficient to resolve the low-lying excited states of rare-earth nuclei. In addition to obtaining angular distributions and cross sections for the inelastic states, we are also able to obtain elastic differential cross sections which are free from excited state contamination. These measurements then serve as a check on the survey elastic scattering data which had been used in optical-model analysis.[16]

II. EXPERIMENTAL PROCEDURE

The experiment was performed using the 17.5-MeV proton beam of the Princeton FM cyclotron.[17] The external beam system is shown in Fig. 1. The beam was first focused on a $\frac{1}{16}$-in. graphite slit with a quadrupole set and a steering magnet. A feedback system between this slit system and the steering magnet insured that the maximum intensity of the beam profile passed through the slit. This slit served as an object for a double focusing spectrometer magnet whose dispersion made it possible to analyze the beam to better than 35 keV using $\frac{1}{16}$-in. collimators. Beam currents were typically $2-3\times10^{-9}$ A. The experiment was carried out in a 20-in.-i.d. scattering chamber which was designed expressly for use with solid-state detectors, and which will be described elsewhere.[18] The beam was monitored and integrated using a model A310B Elcor integrator. A pressure of better than 10^{-5} mm Hg in the region of the scattering chamber insured accurate charge collection. Elastic cross sections for O^{16} have checked within 5% with measurements made by other experimentalists in a separate experimental setup.[19]

A sectional view of the detector used in this investigation is shown in Fig. 2. It consists of a telescope composed of two solid-state surface barrier detectors. The first detector is a fully depleted 1000-μ transmission mounted detector whose active area is $\frac{1}{4}$-in. diameter.[20] The second detector is a 1400-μ detector whose active

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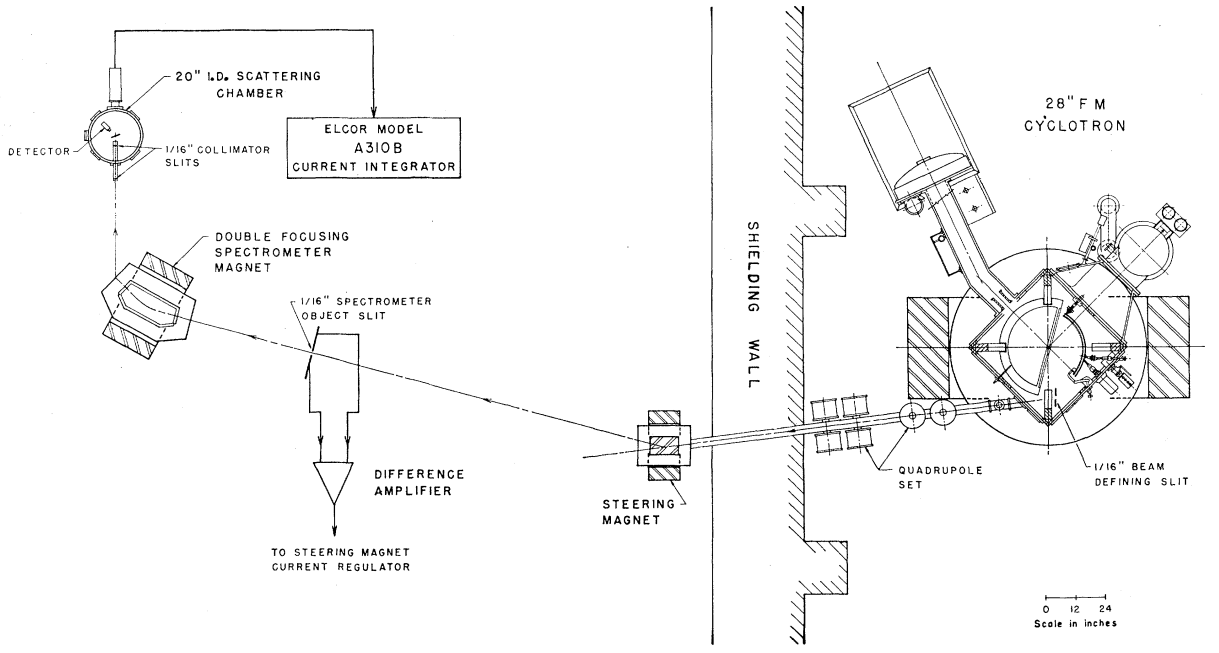

FIG. 1. Plan view of the external beam system of the Princeton FM cyclotron. The beam is collimated inside the cyclotron, focused on a graphite slit system and analyzed to better than 35 keV by a double focusing spectrometer magnet.

area is $\frac{5}{8}$-in. diameter.[21] In order to lower noise levels in these detectors the system was cooled using two thermoelectric diodes. These diodes are capable of maintaining a no load differential of 55°C between their plates, and in this configuration cooled the detectors to approximately −20°C. The collimators were constructed of nickel because of its low (p,n) cross section. They were tapered slightly to lower slit scattering and to remove

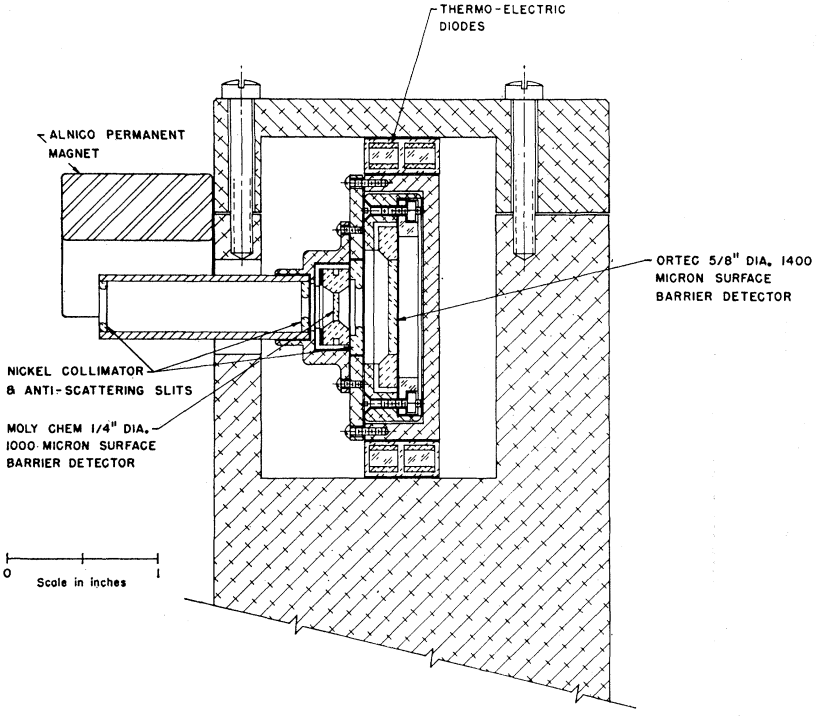

FIG. 2. Sectional view of the tandem solid-state telescope. The detectors are cooled by two thermoelectric diodes placed above and below the detector assembly. The outer aluminum body serves as a heat sink. Nickel collimators are employed to define the detectors solid angle and eliminate scattering because of their low (p,n) cross section.

[21] Kindly lent for evaluation by Oak Ridge Technical Enterprises, Incorporated, Oak Ridge, Tennessee.

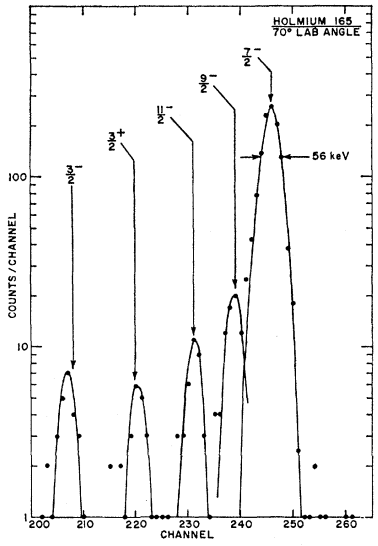

FIG. 3. Typical holmium-165 spectrum taken at 70°.

tails on the elastic peaks. A permanent Alnico magnet was used in front of the detector to sweep electrons away.

The signals derived from these two solid-state detectors were added and fed into a model 101-201 Ortec amplifier system. The data were displayed on a RIDL 400-channel analyzer. Typical resolution for the Ho^{165} target was 56-keV full width at half-maximum, while the resolution was 65-keV full width at half-maximum for the Gd^{156} target.

The discrepancy in resolutions for Ho^{165} and Gd^{156} spectra is due to the type of target used. The holmium target was prepared by evaporating the metal onto a 0.25-mil Polyethylene backing. Natural holmium is isotopically pure. The gadolinium target was prepared by evaporating an aqueous slurry of Gd_2O_3 on a 0.25-mil Polyethylene backing. Thus this target contained a known amount of oxygen which could serve as a check on cross sections and also serve as an aid in normalization. The Gd^{156} was obtained from Oak Ridge National Laboratories as a separated isotope. A spectral analysis of this sample showed it to be 97% Gd^{156}. The most abundant other isotope of gadolinium was Gd^{157} (1.2%) and the largest trace of other rare earths was that of cerium (0.5%).

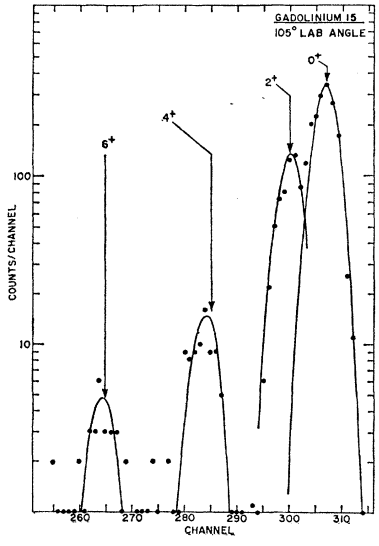

FIG. 4. Typical gadolinium-156 spectrum taken at 105°.

The spectra were plotted and Gaussians fitted to the peaks as an aid in peak separation. Typical spectra for holmium and gadolinium appear in Figs. 3 and 4, respectively. The oxygen ground state did not interfere with the region of interest for scattering angles greater than 35°, due to kinematics. In general, background subtractions for angles greater than 45° were unnecessary. It is felt that the largest source of error in determination of the cross sections for the excited states of holmium and gadolinium stems from unfolding the peaks.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Holmium-165

Angular distributions for the ground state ($7/2^-$), first excited state ($9/2^-$), and second excited state ($11/2^-$) are shown in Fig. 5. Even though there is an indication of excited states up to the $3/2^-$ level in holmium in Fig. 3, the levels beyond the $11/2^-$ state were generally too weakly excited for angular distributions to be obtained. The error bars in Fig. 5 reflect the statistical uncertainties as well as a liberal allowance for errors incurred in unfolding the peaks. The function of the curves drawn in is to merely delineate the peaks.

One noteworthy feature of the angular distributions is that they all peak in the forward direction. Another is that the excited states have cross sections an order of magnitude below that for the ground state. Because of the difficulties in unfolding the first excited state from that of the ground state it would probably be unwise to attach too much significance to the structure of this distribution. However, according to first-order direct reaction theory it can be shown that the ratio of the cross section of the first excited state to that of the second is given by

$$\frac{d\sigma(\rightarrow 9/2^-)}{d\sigma(\rightarrow 11/2^-)}=\left[\frac{(\frac{7}{2},\frac{7}{2},2,0|\frac{9}{2},\frac{7}{2})}{(\frac{7}{2},\frac{7}{2},2,0|11/2,\frac{7}{2})}\right]^2=35/9. \quad (1)$$

This ratio assumes only that the first two levels are members of the ground state $K=\frac{7}{2}$ rotational band and is independent of the distortion. It is clear from the data that the observed ratio is more nearly 2. The difference between the observed and predicted ratio may be due to another unresolved level enhancing the cross section of the second excited state which is generally acknowledged

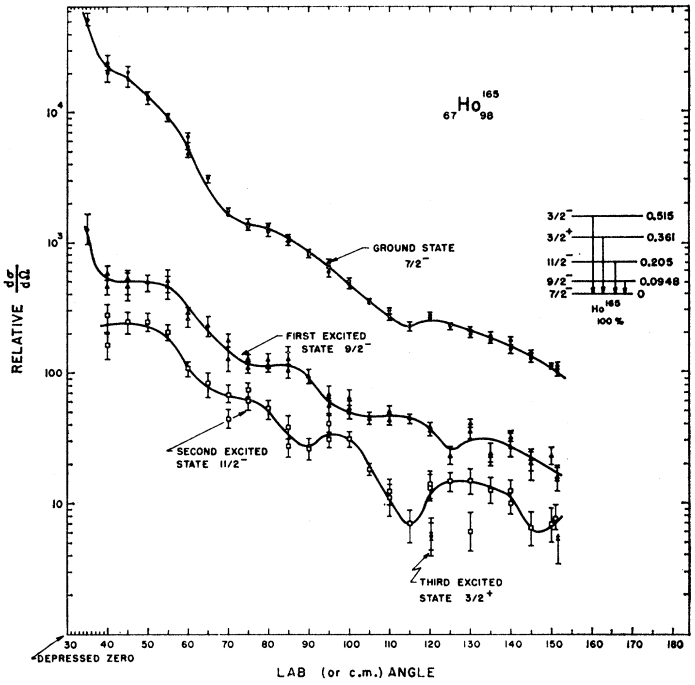

FIG. 5. Angular distributions for the ground state and first two excited states of holmium 165.

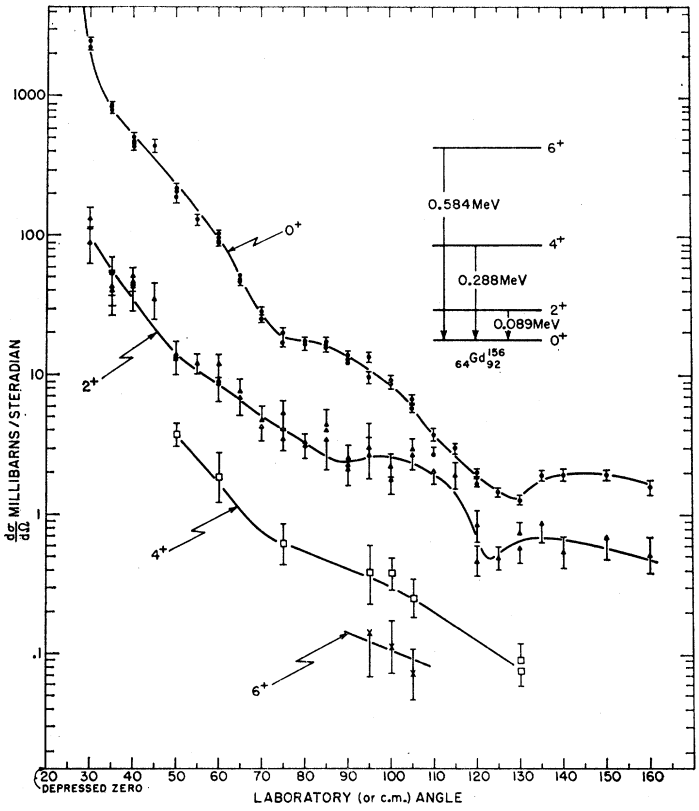

FIG. 6. Angular distributions for the ground state and first two excited states of gadolinium 156.

to be 205 keV.[22] This unresolved level might be that reported to be at 277 keV by Hashizume *et al.*[23]

B. Gadolinium-156

A spectrum for Gd^{156} is shown in Fig. 4. In this and other runs there is evidence that the 6^+ level is weakly excited by 17.5-MeV incident protons. Angular distributions for the ground state and first two excited states are shown in Fig. 6. The error bars reflect statistical uncertainties as well as errors in peak separation. In each run the elastic oxygen peak and the elastic carbon peaks were displayed and used as a cross-section check. The angular distributions taken for oxygen elastics agreed within 5% with those taken previously in this laboratory.[19] The amount of oxygen in the target was accurately known from the composition of the oxide Gd_2O_3. It is felt that the error in determination of the gadolinium ground-state cross sections is less than 10%.

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Disintegration of the Deuteron in a Coulomb Field

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The Coulomb disintegration of the deuteron is treated by means of perturbation theory. The breakup cross section is determined in the electric-dipole approximation. Total cross sections have been calculated for deuteron laboratory energies below 25 MeV and for target nuclei in the range $4 \leq Z \leq 92$. The results of these calculations are compared with earlier theoretical estimates and recent experimental measurements.

INTRODUCTION

IN low-energy deuteron reactions there may exist processes which compete favorably with direct nuclear stripping. A complete analysis of such reactions may then comprise contributions due to electric breakup, nuclear disintegration, and evaporation from compound nucleus formation. The electric breakup aspects of this problem have been considered by Dancoff[1] for 200-MeV deuterons, by Mullin and Guth[2] for 15-MeV deuterons, and for lower energy deuterons by Landau and Lifshitz.[3] A critical review of much of this work has been given by Breit.[4] Disintegration due to nuclear potential as well as Coulomb disintegration has been theoretically investigated by Akhieser and Sitenko.[5]

More recently, Hamburger *et al.*[6] have adopted a semiclassical breakup model to fit experimental results obtained with 15-MeV deuterons. However, due to an error,[7] the calculated values of the angle of maximum intensity are incorrect. It now appears that the simple semiclassical model of deuteron breakup does not satisfactorily account for the observed angle of maximum intensity of the continuum protons. An integral of this continuum for[6] $E_p \leq E_D - 2.2$ MeV yields total cross sections much larger than that calculated for either electric[2] or nuclear[5] breakup. This implies a serious disagreement with theoretical estimates assuming negligible contributions from compound nucleus and direct stripping processes.

Recently, Anderson and Bauer[8] have attempted to

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$$q = (Ze^2/2E_p)(1+\csc\theta_p) = (Ze^2/2E_d)(1+\csc\theta_d).$$
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