understanding of (d,p) widths involve the measurement, over a wide energy range, of (d,p) cross sections as a function of energy.

IV. ACKNOWLEDGMENTS

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Inelastic Proton Scattering from Gold at 6 Mev*

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A thin gold target has been bombarded with 6.0-Mev protons. Inelastically scattered protons, corresponding to Coulomb excitation of the 545-kev, 279-kev, and 268-kev levels in Au^{197}, have been observed in a magnetic spectrograph. The angular distribution of the inelastic groups seems to follow the semiclassical theory.

I. INTRODUCTION

THE detection of the inelastically scattered particles in Coulomb excitation has several advantages compared with detection of the subsequently emitted gamma rays or conversion electrons:

1. Direct information about the excitation energy is obtained independent of the possibility of cascade transitions in the decay of the excited levels.

2. The cross section for excitation of a level can be obtained in a very simple way from the ratio of the intensity of the corresponding inelastic group to that of the elastic group, if one assumes simple Rutherford scattering for the elastic group.

3. The determination of the cross sections does not depend on a knowledge of conversion coefficients and branching ratios.

One of the drawbacks of the method is that the purity requirements of the target material and its support are extreme. Every contamination will give rise to an elastic peak with cross section 10^2 to 10^4 times larger than that of the inelastic groups to be observed. Often these contaminant peaks can be identified by energy or angle shifts, but for heavy masses the differences in shifts become small. In any case, their presence obscures regions of the spectrum.

Another disadvantage compared to gamma-ray measurement is imposed by the necessity of using targets thin to the emitted particles, with consequent loss of intensity.

In view of these considerations, it appeared worthwhile to extend into the region of the heavy elements the inelastic scattering studies undertaken with the broad-range spectrograph[1] associated with the MIT-ONR electrostatic generator.

Preliminary runs with 7.45-Mev protons on a thin gold target showed that it was possible to detect the two well-known states in gold at 279 kev and 545 kev.[2,3] The barrier penetration at 7.5-Mev bombarding energy is low, and the inelastic groups must be due at least in part to Coulomb excitation. Interesting information can be deduced from the cross sections[4] if only Coulomb excitation occurs. To insure that this was the case, it was decided to continue the measurements with 6.00-Mev protons, even though the background is a little higher than at 7.45 Mev. At 6 Mev, the cross section for formation of a compound nucleus[5] is about 0.2 mb compared with a Coulomb excitation cross section of about 0.8 mb.

II. FORMULAS

The elastic scattering of 6-Mev protons from gold is expected to follow the Rutherford scattering law:

$$\frac{d\sigma(\theta)_R}{d\omega}=\frac{e^4Z_1{}^2Z_2{}^2}{16E^2}\left(\frac{1}{\sin^4(\frac{1}{2}\theta)}\right)=1.295Z_1{}^2\left(\frac{Z_2}{E}\right)^2\left(\frac{1}{\sin^4(\frac{1}{2}\theta)}\right)\text{ mb/sterad,}\quad(1)$$

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[1] Buechner, Mazari, and Sperduto, Phys. Rev. **101**, 188 (1956); C. P. Browne and W. W. Buechner, Rev. Sci. Instr. (to be published).

[2] J. W. Mihelich and A. de-Shalit, Phys. Rev. **91**, 78 (1953).

[3] W. I. Goldburg and R. M. Williamson, Phys. Rev. **95**, 767 (1954).

[4] See forthcoming article by Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. (to be published).

[5] J. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

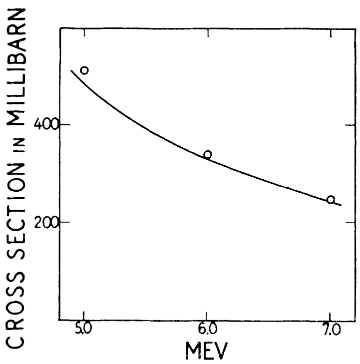

FIG. 1. Elastic proton scattering cross section of gold at 130 degrees. The curve shows the Rutherford scattering law.

where $d\sigma(\theta)_R/d\omega$ is the differential cross section for scattering through the angle θ, Z_1, and Z_2 are the atomic numbers of the incoming particle and the nucleus, respectively, and E is the energy of the incoming particle in Mev.

The differential cross section for Coulomb excitation has been calculated in classical approximation[6] and can, for electric excitation of multipole order λ, be expressed as

$$\frac{d\sigma(\theta)_C}{d\omega}=\left(\frac{b}{2}\right)^{2-2\lambda}\left(\frac{B_{E\lambda}}{e^2}\right)\left(\frac{Z_1e^2}{\hbar v_i}\right)^2\left(\frac{v_f}{v_i}\right)^{2\lambda-2}f_{E\lambda}(\theta,\xi),$$

$$b=\frac{Z_1Z_2e^2}{\frac{1}{2}mv_i^2},\quad \xi=\frac{Z_1Z_2e^2}{\hbar}\left(\frac{1}{v_f}-\frac{1}{v_i}\right), \tag{2}$$

where v_i and v_f are the initial and final relative velocities of the projectile and m the reduced mass. B is the reduced transition probability of the excitation. The function $f(\theta,\xi)$ has been tabulated by Alder and Winther.

III. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental setup was the same as that described earlier.[7] The gold targets were evaporated onto Formvar from a wolfram wire. Most of the targets used were of thicknesses of the order 150 μg/cm^2; that is, about 7 kev for 6-Mev protons. The beam current during the exposures was around 0.1 μa, with an energy spread of 10 kev or less.

Preliminary to obtaining the inelastic cross section, it was verified that in the energy range near 6 Mev the elastic cross section for protons on gold follows the Rutherford scattering law Eq. (1). For this purpose, a layer of gold was evaporated onto an aluminum support, and the thickness of the layer was determined by weighing. This target was inserted in a Faraday cup, which had a 100-volt positive bias. The current was measured by allowing it to discharge a polystyrene condenser of 0.99$\pm$0.02 μf capacity which was manufactured by the General Radio Company. An electrometer measured the null point. The angle of observation was 130 degrees; the solid angle of the spectrograph was calculated from geometry.

The cross sections measured at 5.0, 6.0, and 7.0 Mev are shown in Fig. 1. These cross sections agree with Eq. (1) within 5%, which is estimated to be the combined error in the measurement.

To obtain the angular distribution of the elastic scattering, a thin gold target evaporated onto a Formvar backing was inserted at an angle of 30 degrees with the beam. In this way, the scattered particles could be examined at angles from 130 to 45 degrees without moving the target. Normalization was accomplished by monitoring the charge collected on a positively biased cup placed several centimeters behind the target. A negatively biased guard ring prevented secondary electrons released from the target from entering the cup. Figure 2 shows angular distribution obtained after a small correction for the variation of the cross section across the angle of acceptance of the spectrograph. The maximum deviation from theory is 7%.

In the following calculations it has been assumed, in accordance with the above-mentioned experiment, that the elastic cross section is given by Eq. (1).

The proton groups scattered at 130 degrees to the beam from a Formvar-backed gold target bombarded by 6.12-Mev protons are shown in Fig. 3. Elastic peaks from gold and from other materials in the target are observed. Also shown are inelastically scattered protons associated with the excitation of the 279-kev and the 545-kev levels in Au. The group at $d=73$ cm has the position expected for a 77-kev state[2] but is considerably broader than the other inelastic groups. It is thought that an elastic group from silver, present as an impurity in the gold, is superimposed. Momentum analyses from the 6.00-Mev angular distribution described below confirm these assignments.

The small peak at $d=74$ cm in Fig. 3 has the position expected for protons elastically scattered from iodine. This weak peak was not observed in other exposures where lower resolution was used but would have been obscured by the intense gold elastic peak. Since the

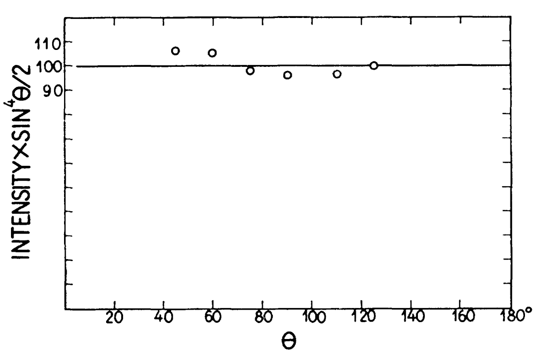

FIG. 2. Angular distribution of elastically scattered protons from gold at 6 Mev.

[6] K. Alder and A. Winther, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 18 (1955); and private communication.

[7] Buechner, Braams, and Sperduto, Phys. Rev. **100**, 1387 (1956).

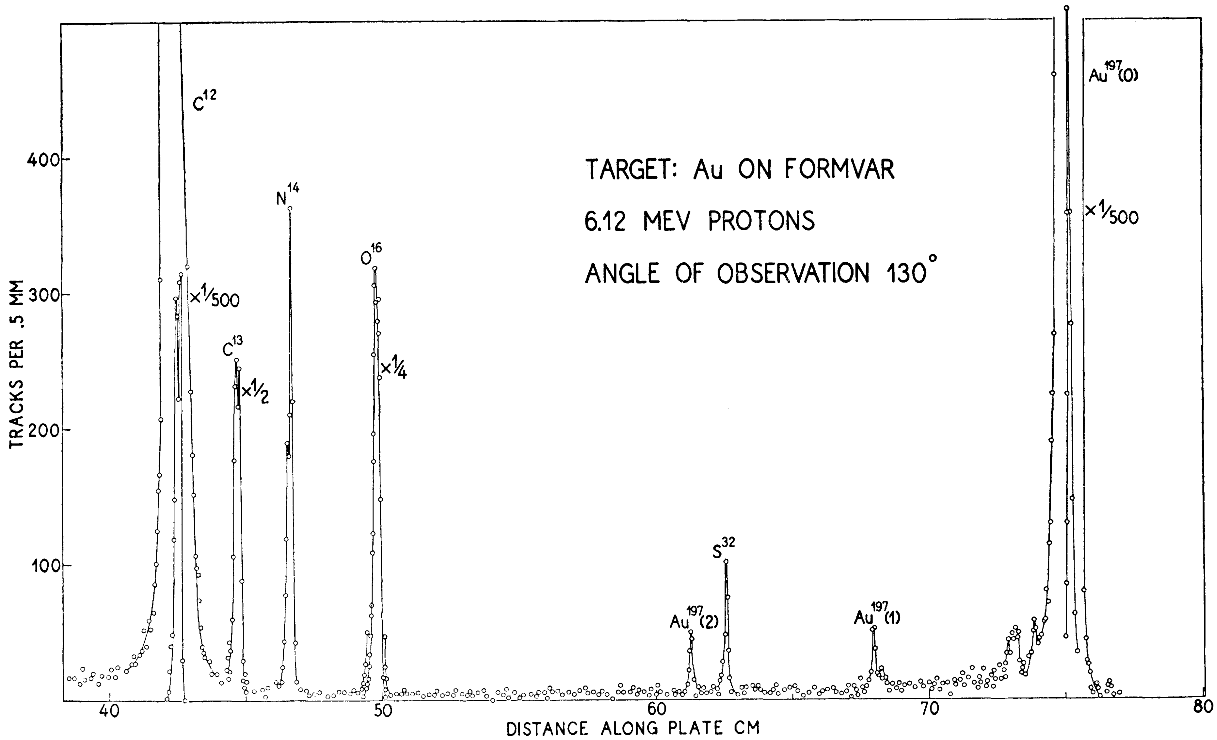

FIG. 3. Proton groups from a gold-Formvar target bombarded with 6-Mev protons. The exposure was 3700 microcoulombs at a magnetic field of 6346 gauss. The peaks labeled (1) and (2) correspond to the 279- and 545-kev levels in gold.

evaporator used in the target preparation was being used concurrently for the evaporation of iodine compounds, the presence of traces of iodine was not unlikely.

Previous measurements[2] indicate the existence of a level at 268 kev in Au. In an attempt to resolve such a group from the more intense 279-kev peak, the target used for the exposure shown in Fig. 3 was particularly thin (about 3 kev, estimated from its yield). The spectrograph acceptance angle was narrowed to 3 degrees, and the incident energy spread was reduced to about 5 kev. The data in the region of the 279-kev level are shown on an expanded scale in Fig. 4. While the number of tracks recorded is too low to define the shape of the distribution, the data clearly indicate the presence of more than one group of protons in this region. The solid line in Fig. 4 is an attempt to fit the data with reasonable line shapes in a manner consistent with the existence of states at 279 and 268 kev.

For the angular-distribution measurements, momentum spectra were obtained at 60, 95, 110, and 130 degrees for an incident energy of 6.00 Mev. It was not possible to go to smaller angles because of the rapid increase of the background, presumably caused by scattering of particles in the beam from the defining slit system in the analyzer. The background followed closely the $\sin^{-4}(\theta/2)$ law. The positions of the inelastic peaks were calculated before each exposure to make sure that no coincidences would occur with the elastic groups from the target support and various contaminations.

The exposure for each angle was about 2000 μcoul. In addition to this long exposure, a short exposure of about 5 μcoul was taken to obtain a countable elastic peak. The intensity of the elastic peak in the long exposure was then calculated from the ratio between the two exposures. The uncertainty in this procedure was only a few percent, much less than the statistics on the inelastic peaks that contained only a few hundred tracks each.

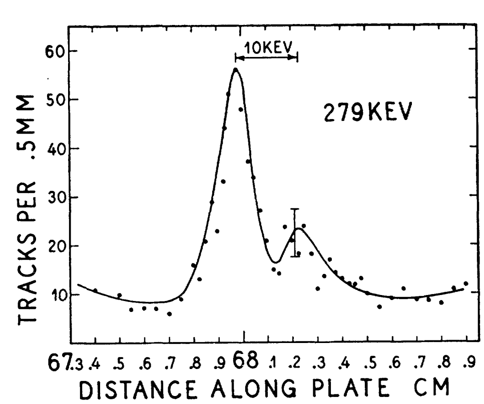

FIG. 4. Proton momentum spectrum corresponding to the 268- and 279-kev levels in gold.

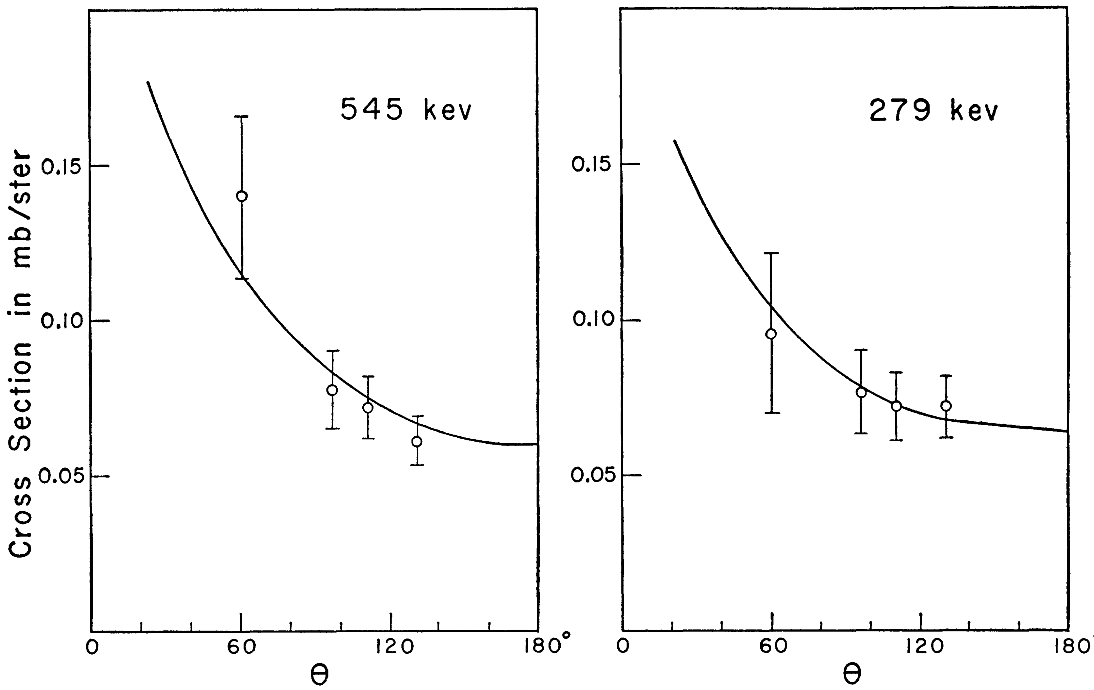

FIG. 5. Differential cross section for Coulomb excitation of the 545-kev and 279-kev levels in gold by 6-Mev protons. The solid lines show the theoretical cross section calculated with the mean B values from Table I.

The exposures all showed the levels at 279 and 545 kev. The 279-kev level had a composite structure which was ascribed to excitation of the 268-kev level, also seen in other Coulomb excitation experiments on gold.[3,8,9] As a mean of the exposures at 130, 110, and 95 degrees, the intensity was determined to be 18% of the yield of the 279-kev+268-kev groups.

Accurate information about the 77-kev level was not obtained in this experiment. However, a group which is attributed to this level was seen at 95 degrees, an angle at which the contamination peaks had moved. Because of the high background, the cross section determined here is not very reliable.

An average of eight measurements yields 279±5 kev and 546±8 kev for the excitation energies corresponding to the prominent inelastic groups from gold. Two measurements give 75±4 kev for the position of the first level.

The peak intensities were calculated by adding across the peak the number of tracks in the $\frac{1}{2}$-mm strips in which the plates were counted. The background was determined by counting a number of strips on each side of the peak. From the ratio of the intensity of the inelastic peak to that of the elastic peak, the differential inelastic cross section was calculated using Eq. (1). This procedure assumes that there was no contaminant elastic peak merged with the gold elastic group. Care was taken to evaporate the gold at as low a temperature as was practical; this was much lower than the melting point of the wolfram wire used as a boat. As a direct check for the presence of wolfram, one of the targets used was bombarded with 6.5-Mev He^+ ions accelerated in the generator. Use of the heavier He ions allowed a better separation of elastic groups than was obtainable with protons. The profile of the scattered particles gave no indication of wolfram; the exposure obtained set an upper limit of 10% on the amount of wolfram impurity.

The results for the four different angles are shown in Fig. 5, together with the theoretical angular dependence for quadrupole excitation calculated from Eq. (2) using the mean B values obtained in this experiment. The B values calculated from the individual points using the classical $f(\theta,\xi)$ are given in Table I.

The agreement with theory is satisfactory. It will take more accurate experiments to find possible deviations from the semiclassical theory. At the moment, the exact quantum mechanical angular distribution has not been worked out. It is known that the distribution in the extreme quantum mechanical case ($\eta=Z_1Z_2/\hbar v=0$) is isotropic. The B values determined are in reasonable agreement with the values of Stelson and McGowan.[8] This is a further evidence that the semiclassical $f(\theta,\xi)$ function is a good approximation. For the ratio $B(E2)_{268}$:$B(E2)_{279}$, Bernstein and Lewis[9] obtain 0.40±0.13, somewhat larger than the presently measured ratio of 0.22 ±0.07. For the ratio $B(E2)_{279}$:$B(E2)_{77}$, these authors give 1.83±0.4, compared with the value of 1.4±0.4

[8] P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112, 127 (1955).

[9] E. M. Bernstein and H. W. Lewis, Phys. Rev. **100**, 1345 (1955).

obtained from the one measurement here. The measurements of Sunyar[10] indicate that $B(E2)_{77}=0.10$.

The 279-kev ($5/2^+$) and the 545-kev ($7/2^+$) levels could be members of the ground-state rotational family.[4] The 77-kev ($1/2^+$) and 268-kev ($3/2^+$) levels are then supposed to be members of a second rotational family. It should be possible to excite the next rotational state ($5/2^+$, about 700 kev[11]) of this family. No indication of such a level was seen, in agreement with the expected intensity of the excitation.

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One of us (B. E.) wishes to thank the MIT Foreign Student Summer Project for making his stay at MIT possible and the Fulbright Foundation for a travel grant.

[10] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).
[11] A. Kerman and B. M. Mottelson (private communication).

TABLE I. Values of B/e^2 in units of 10^{-48} cm^4 calculated by use of classical $f(\theta,\xi)$ function. The cross section used for the 268-kev excitation was calculated as 18% of the cross section for the composite (268+279)-kev line.

Angle	Coulomb excitation of levels in Au at: 545 kev	279 kev	268 kev	77 kev
60°	0.47	0.29		
95°	0.40	0.30		0.22
110°	0.41	0.30		
130°	0.39	0.32		
Mean	0.42	0.30	0.066	0.22
(a)	0.470	0.334	0.088	<0.20

[a] See reference 8.

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Neutron Resonance Structure of Uranium-238*

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Modifications in the Argonne fast-neutron chopper and its installation at the reactor *CP*-5 are described. With this system, neutron transmissions of very pure samples of U^{238} were measured. Parameters for the resonances observed were obtained by a refined wing shape analysis as well as by the conventional area analysis. A previously unobserved level having a smaller reduced neutron width than any heretofore reported was detected at 10.2 ev; it is interpreted as being a p-wave resonance. Average parameters of significance to nuclear theory are deduced. For reactor application, the resonance capture integral is calculated from the parameters and is found to be in excellent agreement with the directly measured value.

I. INTRODUCTION

A DESCRIPTION of the Argonne fast-neutron velocity selector and its use at the original heavy water moderated pile *CP*-3′, was given in a previous paper.[1] After modification of all of its major components, the velocity selector was installed at the new pile *CP*-5 in the summer of 1954. The present paper lists these modifications and presents the first data obtained with the improved system.

II. APPARATUS

The great increase in the neutron flux available from *CP*-5 as compared to *CP*-3′ (about a factor of 20) made it possible to improve almost every characteristic of the velocity selector; resolution was improved, counting rates and signal-to-background ratios were increased, a second order effect was almost eliminated, and the minimum sample size was decreased.

The most important changes were made in the chopper rotor. The second order effect, an overlapping of neutron bursts, was essentially eliminated by blocking 4 of the original 6 slits. Fast-neutron leakage through the 16-inch steel rotor was greatly diminished by replacing 3 inches of the steel by Monel metal. With these changes it was feasible to use a neutron flight path of almost 60 meters (58.7), giving a resolution of 0.08 μsec/meter.

The detector used, a boron-loaded liquid scintillator, has been described elsewhere.[2] Its important improvement, as compared with the counter of reference 1, is an enlarged area, namely 37 in.^{2}

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Now at Operations Research Office, The Johns Hopkins University, Chevy Chase, Maryland.
[1] Bollinger, Dahlberg, Palmer, and Thomas, Phys. Rev. **100**, 126 (1955).
[2] L. M. Bollinger, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 47.