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ABSOLUTE CROSS SECTIONS FOR SECONDARY PARTICLES PRODUCED IN HIGH-ENERGY NUCLEAR BOMBARDMENTS.

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April 20, 1956

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ABSTRACT

Absolute cross sections for the production of charged secondary particles in the bombardments of aluminum, nickel, silver, and gold by 332-Mev protons, 187-Mev deuterons, and 380-Mev alpha particles have been determined. The relative yields of various secondaries from these bombardments were previously reported by Deutsch. Secondaries were produced in thin ribbon targets, were detected in nuclear track plates placed inside the 184-inch synchrocylotron, and were identified through measurement of their curvature in the cyclotron's magnetic field and of their range in nuclear emulsion. To determine absolute yields the targets were monitored for residual beta and gamma activity. These activities were compared with the target activities arising from a known flux of primaries; this flux was determined in a calibration experiment performed in the external cyclotron beam.

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Deutsch[1] has measured the relative yields of charged particles produced at 0° with respect to the 332-Mev proton, 187-Mev deuteron, and 380-Mev alpha-particle beam direction for various elements. This paper reports the absolute cross sections for the production of such secondaries. A knowledge of the cross sections helps to clarify the roles of the cascade and evaporation processes in high-energy nuclear reactions. To obtain a better understanding of the processes involved in these reactions, one would like to learn

(a) the cross sections over a more extensive range of secondary energies,

(b) the cross sections as a function of angle of production, and

(c) the cross sections for the production of neutrons.

Such a program has been carried out at the Radiation Laboratory for 190-Mev proton bombardments of various elements and is to be reported in the near future.[2, 3] The purpose of this paper, however, is to provide absolute cross sections for Deutsch's work, thereby indicating the behavior of the cross section as a function of atomic number, bombarding particle, and beam energy.

The method of secondary-particle detection was identical to that used by Deutsch. Secondaries were produced in thin ribbon targets (1.58 mg/cm^2 aluminum, 8.95 mg/cm^2 nickel, 13.98 mg/cm^2 silver, and 12.00

* This work was performed under the auspices of the United States Atomic Energy Commission.

† Now at Stanford Research Institute, Menlo Park, California.

mg/cm^2 gold) bombarded by the internal cyclotron beam. They were collected by nuclear track plates placed below the plane of the cyclotron beam and were identified by their range in emulsion and their curvature in the cyclotron's magnetic field. For a given bombardment, the cross section was determined for one species of secondary at one secondary energy. This one cross-section measurement is sufficient to calculate absolute yields from the relative yields measured by Deutsch.

The differential cross section is given by

$$\sigma = \frac{A}{N_A B z e v N \rho} J \frac{dn}{d\alpha\, d\beta},$$

where A, is the target's atomic number, N_A is Avogadro's number, B the magnetic field strength, ze the secondaries' charge, v the secondaries' velocity, N the number of primaries through the target, and ρ the areal density of the target respectively. The factor J is calculated from the geometry of the experiment.[4] The quantity $\frac{dn}{d\alpha\, d\beta}$ is the observed density of secondaries in the nuclear track plates.

To determine the number of particles N that went through them, the ribbon targets were counted for residual beta and gamma activity. In addition, two cyclotron runs were made as follows:

(a) a bombardment, at the 79-inch radius of the cyclotron, of a stack made up of groups of three identical foils arranged in the order polyethylene, aluminum, nickel, silver, gold, and polyethylene.

(b) a bombardment by the full-energy external proton beam of three polyethylene foils. For this run the beam was collimated by a 3/4-inch-diameter brass tube, was passed through the foils located 37-inches behind the collimator, and was collected and integrated by a Faraday cup placed 26 inches behind the foils.

The distances between the collimator and foils and between the Faraday cup and foils were each chosen to be large so as to minimize activity caused by secondary neutrons (and charged particles) traversing the foils. Large numbers of these unwanted secondaries originate in the collimator and in the Faraday cup. The foils bombarded in these runs were also

counted for beta and gamma activity. The foils of the two auxiliary runs were bombarded in groups of three so that the outer two served as guard foils. From counting rates measured after these runs, and from published excitation functions for the $C^{12}(x, xn)C^{11}$ reaction,[5] the number of particles through the ribbon targets can be computed.

The largest source of error in this experiment is in the evaluation of N. The principal cause of this uncertainty is in the centering of the foils in the counter, which can introduce an error as high as 10% in each measurement. The foils from the internal stack bombardment were placed in the same position in the counter and had the same distribution of activities. Here one may expect that errors due to poor centering tend to cancel. Other errors in the evaluation of the cross section arise from uncertainties in time measurements (0.5 minute), the C^{11} half life (0.1 minute), the number of counts obtained from the foils (3% or less), the determination of areal densities (1%), the measurements of B (1%), v (1%), J^*(3%) and $\frac{dn}{d\alpha\, d\beta}$ (10% or less). On the basis of the above considerations the uncertainty in the absolute cross section is estimated to be $\gtrsim$25%.

The experimental results are given in Table I. Table II gives the scaling factors that transform Deutsch's relative yields into absolute yields.

I wish to thank Dr. Walter H. Barkas for his help and encouragement and Dr. Robert L. Thornton for his continued interest in this experiment. I am also indebted to Mrs. Jean Spalding for doing most of the scanning necessary for this experiment.

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* To evaluate J one needs to know the height of secondary production above the plane of the nuclear track plates. This height was found by cutting the ribbon targets into 0.25-inch segments and monitoring them for residual activity.

Table I. The differential cross section/ α for the production of the designated secondary of energy E for the various bombardments. The energies are in Mev; the cross sections are in millibarns per steradian per Mev.

Target / Bombardment	Al Secondary	Al E	Al σ	Ni Secondary	Ni E	Ni σ	Ag Secondary	Ag E	Ag σ	Au Secondary	Au E	Au σ
187-Mev deuterons	α	14.8	3.25	α	12.8	5.7	p	6.9	13.6	p	13.5	9.1
375-Mev alpha particles	α	14.8	8.2	α	12.4	5.2	α	16.0	7.0	p	13.5	14.3
332-Mev protons	α	14.8	1.1	α	12.6	2.0	α	16.0	3.3	α	22.5	3.2

Table II. Conversion table. To obtain absolute yields multiply Deutsch's ordinate by the number given in this table (values in millibarns per steradian per Mev).

Target / Figure in Phys. Rev. 97, 1110 / Bombardment	Al	Ni	Ag	Au
	Fig. 6	Fig. 7	Fig. 8	Fig. 9
187-Mev deuterons	1.8	7.5	3.2	2.2
375-Mev alpha particles	3.3	5.0	3.5	2.9
332-Mev protons	0.9	2.0	2.7	1.0

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