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Reactions of 370-Mev Protons with Cobalt*†

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The individual cross sections for the formation of 37 different radioactive products that result from the inelastic interaction of 370-Mev protons with cobalt nuclei have been determined. The results are interpreted in the light of a model that emphasizes the importance of the evaporation of particles from an excited nucleus to give the final products of the collision. By the interpolation of the formation cross sections of the undetected product nuclei, an estimation is made of the total inelastic interaction cross section and the differential cross section for the transfer of a given excitation energy to the target nucleus in an inelastic collision.

INTRODUCTION

TWO related questions of interest in the study of the inelastic interaction of high-energy nucleons with nuclei are

(1) the differential cross section for a given energy transfer, and

(2) the subsequent behavior of the struck target nucleus.

Information on these points may be obtained from two different kinds of experiments: those, such as cloud chamber, nuclear emulsion, and counter experiments that focus attention on the particles emitted as a result of an inelastic interaction; and those, such as radiochemical studies, that focus attention on the nuclei remaining after the inelastic interaction. The work to be reported here is concerned with the investigation of the interaction of 370-Mev protons with Co^{59} nuclei by means of the latter method. The information obtained in this manner complements the studies of the emitted particles because it is sensitive to the emission of neutral particles and because it is capable of detecting events that occur in only one in 10^5 or 10^6 inelastic interactions.

Other studies on the formation cross sections of specific radioactive products in high-energy nuclear reactions are discussed in a recent review article.[1] The examination of the nuclear reactions of cobalt with 240-Mev protons has been carried out by Wagner and Wiig.[2]

METHOD

Irradiation

Metallic cobalt targets, prepared by powder metallurgical techniques from Johnson-Matthey spectroscopically pure cobalt sponge, approximately 1 gram per square centimeter thick (*ca* 2 Mev thick), were irradiated in the circulating proton beam of the Nevis cyclotron at a radius corresponding to an energy of 370 Mev. In several of the irradiations, the cobalt target was sandwiched between two sets of three 7-mil aluminum foils; the Na^{24} activity produced in the center member of each set was a measure of the effective beam current during the irradiation.

Chemical Separations

After irradiation, the targets were dissolved in nitric acid to which had been added known quantities of inactive carrier (*ca* 2 mg) for each of the elements which were to be isolated. The elements of interest were then separated from the resulting solution by procedures that entailed some modification of well known schemes of qualitative and quantitative analysis for the elements in this region of the periodic system.[3] The fraction of the inactive carrier that had been recovered was determined by a quantitative analysis of each sample performed after the sample had been counted for a suitable length of time.

Counting Techniques

The isolated chemical fractions were filtered onto disks of filter paper, mounted on cardboard cards, and then counted with suitable detectors under conditions of reproducible geometrical efficiency. In most cases, since the decay was at least partly by particle emission, a helium-organic-quench-filled Geiger tube,[4] with a brass baffle to define geometry, was employed as the detector. In a few rather crucial instances, it was necessary to count x-rays in the 5-kev region with known efficiency. For this purpose, an argon-methane filled proportional counter of the type described by Bernstein, Brewer, and Rubinson,[5] was employed. The pulses from the proportional counter were put through a linear amplifier and pulse-height analyzer so as to provide additional evidence on the radiochemical purity of the sample. The relative efficiencies of the Geiger and proportional counters were determined by counting

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[1] D. H. Templeton, Ann. Rev. Nuc. Sci. 2, 93–104 (1953).

[2] G. Wagner and E. O. Wiig, J. Am. Chem. Soc. 74, 1101 (1952).

[3] Detailed procedures are reported by E. Belmont in Atomic Energy Commission Report NYO-3198 (unpublished).

[4] Nucleonic Corporation of America, Model GM1WAA.

[5] Bernstein, Brewer, and Rubinson, Nucleonics 6, No. 2, 39 (1950).

a sample that has a known branching ratio of positron emission to electron capture, e.g., Mn^{52}, on both tubes.

The relative formation cross sections were obtained by correcting the observed counting rates for absorption by the counter window, absorption and scattering by air, absorption and scattering by sample and mounting structure, the decay scheme of the active sample, decay from end of bombardment, the finite time of irradiation, and the chemical yield in the separation procedure. The scattering and absorption correction factors were either determined experimentally or estimated from literature values.[6] The corrections for the scattering and absorption of the particles, except for weak beta emitters such as Ca^{45}, did not exceed 10 to 15 percent. In nearly all bombardments the time of irradiation was short compared to the half-life of the active species investigated, so that errors due to fluctuation of beam current during the run were held to a minimum.

INTERPRETATION OF DECAY DATA

The determination of cross sections from the counting data of each chemical fraction requires analysis of a composite decay curve into its component parts, and correction of the activity of each component for the sensitivity of the detector to the radiation emitted by that component. In most cases, because of a convenient spread in half-life, the decay curve analysis presented no problem. Also, in most cases, the decay scheme, which must be known for the detection efficiency correction, has been examined and the data made available in recent compilations.[7] In a few cases, however, because of an unfortunate combination of half lives, or because of an unknown decay scheme, it was necessary to introduce some arbitrary assumptions into the analysis of the data. These assumptions will be presented in the following paragraphs of this section.

Cobalt Fraction

The similarity of the half-lives of Co^{56} and Co^{58} makes it impossible to differentiate between the two by decay curve analysis. Owing to the substantial difference in the energy of the particles from these two isotopes, however, an estimate of their relative activities, good to about 50 percent, can be made by means of an aluminum absorption curve. Further difficulties arise from the unknown, but obviously complicated, decay scheme of Co^{56}. In the results reported here, Co^{56} was taken to decay 25 percent by positron emission.[8]

Scandium Fraction

It was not possible to distinguish Sc^{43} from Sc^{44} by decay-curve analysis or by absorption experiments since these two isotopes have identical half-lives and rather similar particle energies. In this report, therefore, we will give only the sum of these two yields without any correction for electron capture contribution.

Chlorine Fraction

No attempt was made to distinguish between 33.2-minute Cl^{34} and 37.3-minute Cl^{38}; the sum of the two yields is reported.

Unknown Branching Ratios

The small contribution of electron capture to the decay of Fe^{53}, Mn^{51}, Cr^{49}, V^{47}, Ti^{45}, K^{38}, F^{18}, and C^{11} was estimated by the method of Feenberg and Trigg[9] under the assumption that they are all allowed transitions.

RESULTS AND DISCUSSION

The cross sections in millibarns for the formation of 37 different product nuclei that result from the inelastic interaction of 370-Mev protons with the Co^{59} nucleus are listed in Table I. The precision estimate is either based upon multiple determinations, or in the event of a single determination, it is based upon a precision estimate of each factor involved in the cross-section determination. These cross sections are all based upon a cross section of 44 millibarns for the $C^{12}(p,pn)C^{11}$ reaction interpolated from the data of Warshaw, Swanson, and Rosenfeld.[10,11] These data are also presented in summary form in Figs. 1 and 2.[12] In Fig. 1, the sum of the cross sections for the formation of products of a given atomic number is plotted against the atomic number. In Fig. 2, the sum of the cross sections for a given mass number is plotted against the mass number.

The evaluation of the total inelastic cross section, and of the complete distribution of product nuclei that results from an inelastic collision, requires the interpolation of the unmeasured formation cross sections of the

[6] L. Zumwalt, Atomic Energy Commission Report MDDC-1346, 1947 (unpublished); B. Burtt, Nucleonics **5**, No. 2, 38 (1949). Engelkemeir, Seiler, Steinberg, and Winsberg, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, New York, 1951), Paper No. 4, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV.

[7] *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950). Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1951).

[8] King, Dismuke, and Way, Oak Ridge National Laboratory Report ORNL-1450 (unpublished).

[9] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 402 (1950).

[10] Warshaw, Swanson, and Rosenfeld, Phys. Rev. **95**, 649(A) (1954).

[11] Because of the short half-life of C^{11}, the $C^{12}(p,pn)$ reaction was not directly used as a beam monitor in these runs; but rather, the cross section for the $Al^{27}(p,3pn)Na^{24}$ reaction was determined relative to the carbon cross section, and the aluminum reaction was then employed to monitor the beam. Unfortunately, the cross section for the formation of Na^{24} from aluminum determined in this manner gave a value of 15.5 millibarns; a result that is in disagreement both with the value of 10.8 millibarns determined absolutely by Marquez [L. Marquez, Phys. Rev. **86**, 405 (1952)] and an unpublished value of approximately 10-11 millibarn by R. Folger and P. Stevenson.

[12] The result for mass number 58 is not included in these figures.

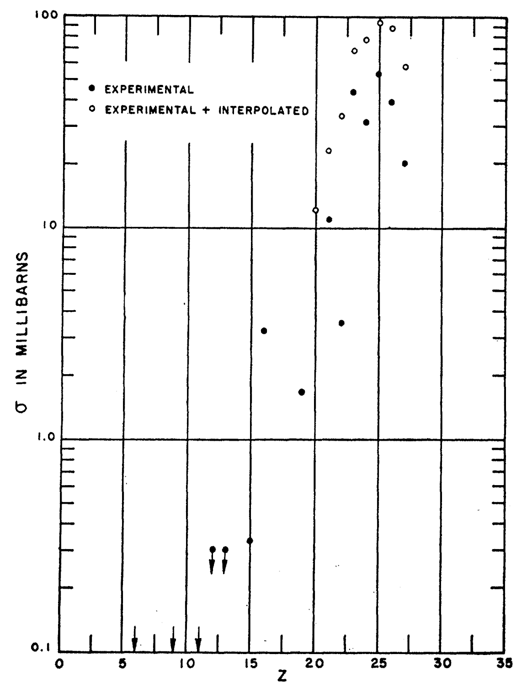

FIG. 1. Cross section in millibarns for the formation of given atomic-number products from the bombardment of cobalt with 370-Mev protons. The solid circles represent experimental values; the open circles give the sum of experimental and interpolated values.

stable, very short-lived, and very long-lived products. Since it is not possible at this time to make that interpolation in a satisfyingly unambiguous manner, we shall first examine some of the gross features of high-energy reactions that can be derived from the experimental results, and then attempt to infer the unmeasured cross sections.

General Features

Figures 1 and 2 indicate that the measured cross sections, within the fluctuations to be expected because of the contribution of stable and long-lived products, do not diminish appreciably within four atomic numbers or ten mass numbers of the target. We may conclude that an inelastic interaction has essentially equal probability of ejecting up to at least ten nucleons from the struck nucleus.

Figure 3, where the cross sections for the formation of a product nucleus of given atomic number is plotted against mass number, illustrates a second attribute of these reactions: the strong correlation between the number of neutrons and protons lost from a struck nucleus. For example, the loss of one proton and three neutrons (excluding the incident proton) is 130 times more probable than the loss of one proton and five neutrons; this factor, on the other hand, would be approximately 2.5 if random emission of neutrons and protons occurred. A more satisfying demonstration of this point would be afforded by a comparison of the relative yields within an isobaric set of products; the usefulness of that comparison in this work, though, is lessened since we were unable to measure more than two cross sections in any isobaric set. If, however, the most probable charge, Z_A, for a given mass number product is chosen, and if the cross sections for the various products are plotted against the displacement from this most probable atomic number as is done in Fig. 4 for odd mass-number products, then the correlation in the relative number of neutrons and protons emitted is seen more clearly. Further, this plot suggests that the atomic

TABLE I. Cross sections for the formation of nuclides from the bombardment of cobalt with 370-Mev protons.

Nuclide Z		A	Cross section in millibarns
28	Ni	57	0.34± 0.08
27	Co	58	121 ±60
		56	15.2 ± 3.8
		55	5.2 ± 1.3
26	Fe	55	37.0 ± 9.0
		53	1.7 ± 0.6
		52	0.28± 0.07
32	Mn	56	3.8 ± 1.0
		54	25.4 ± 7.0
		52	14.1 ± 3.5
		52*m*	5.6 ± 2.2
		51	4.1 ± 1.4
24	Cr	51	27.5 ± 2.0
		49	4.1 ± 1.0
23	V	49	31.1 ± 9.0
		48	10.6 ± 2.8
		47	2.1 ± 1.0
22	Ti	45	3.5 ± 0.9
21	Sc	46	2.2 ± 0.3
		44*m*	3.5 ± 1.4
		43+44	5.0 ± 1.7
20	Ca	47	0.06± 0.03
		45	0.66± 0.33
19	K	43	0.50± 0.23
		42	0.85± 0.28
		38	0.31± 0.14
17	Cl	39	0.50± 0.40
		38+34	2.8 ± 1.4
15	p	33	0.03± 0.02
		32	0.30± 0.1
13	Al	29	<0.30
12	Mg	27	<0.30
11	Na	24	0.07± 0.03
9	F	18	0.07± 0.03
6	C	11	0.05
	Total		330 ±65

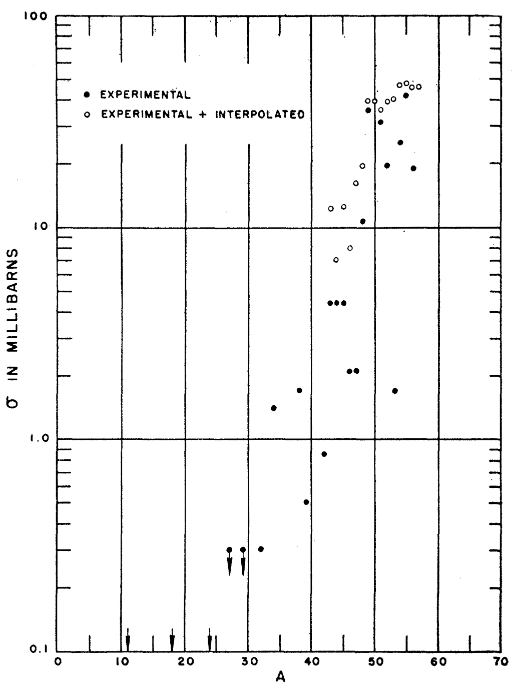

FIG. 2. Cross section in millibarns for the formation of given mass-number products from the bombardment of cobalt with 370-Mev protons. The solid circles represent experimental values; the open circles give the sum of experimental and interpolated values.

number distribution function for a given odd mass-number product is nearly independent of mass number in the region of mass number 49 to 55, except, of course, for a linear shift in the peak position. If this is the case, then we would again conclude that the formation cross sections for mass numbers 55, 51, and 49 are essentially the same.

Comparison with Nucleon-Induced Stars in Photographic Emulsion

Bernardini, Booth, and Lindenbaum[13] found equal probabilities for one, two, or three black prongs from stars induced by 300–350 Mev protons incident upon the nuclei in photographic emulsion; they also observed that these numbers of black prongs are usually accompanied by one sparse black or gray prong ($E \geqslant 30$ Mev). From their work, it is also seen that the probability of stars with more than three black prongs falls off rather rapidly with increasing prong number until it has effectively vanished for about eight or nine black prongs. If it is assumed that about $\frac{1}{4}$ of the observed black prongs are alpha particles, and that $\frac{3}{4}$ of them are protons,[14,15] the star data correspond to an equal probability for the loss of from one to about four charges from the target nucleus; a conclusion that is consistent with the data illustrated in Fig. 1.

Model for High-Energy Reactions

The results of this experiment are in agreement with the consequences of the model set forth by Serber[16] for high-energy reactions: the interaction of a high-energy nucleon with a nucleus is best described as a series of interactions of the incident nucleon with individual nucleons in the nucleus; a nucleonic cascade is generated and a variable fraction of the incident energy is deposited in the struck nucleus. This model has been given quantitative treatment by means of the Monte Carlo formalism by Goldberger[17] and by Bernardini, Booth, and Lindenbaum.[15] In both of these treatments, the notion of nucleon-nucleon interactions was extended down to include the low-energy components of the nucleonic cascade; and, with the increasing assistance of the exclusion principle, they both thus reproduce the observed asymmetry in the angular distribution of the black prongs in nucleon-induced emulsion stars. The results described here can throw some light on the relative importance of "knock-on," as opposed to "evaporated," low-energy particle emission. The data demonstrate the decisive importance of the final evaporation phase of the process in giving the

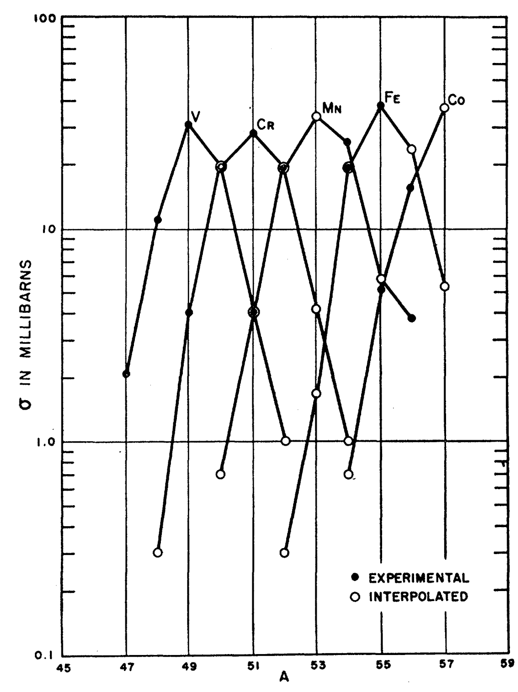

FIG. 3. The variation of the cross section for the formation of a given atomic-number product with mass number. The points for a given atomic-number product are connected by tie lines. The solid circles represent experimental values, and the open circles give the interpolated values.

[13] Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 826 (1952); **88**, 1017 (1952).
[14] R. J. Le Couteur, Proc. Phys. Soc. (London) **A63**, 259 (1950).
[15] R. W. Deutsch, University of California Radiation Laboratory Report UCRL-2258 (unpublished).
[16] R. Serber, Phys. Rev. **72**, 1114 (1947).
[17] M. Goldberger, Phys. Rev. **74**, 1269 (1948).

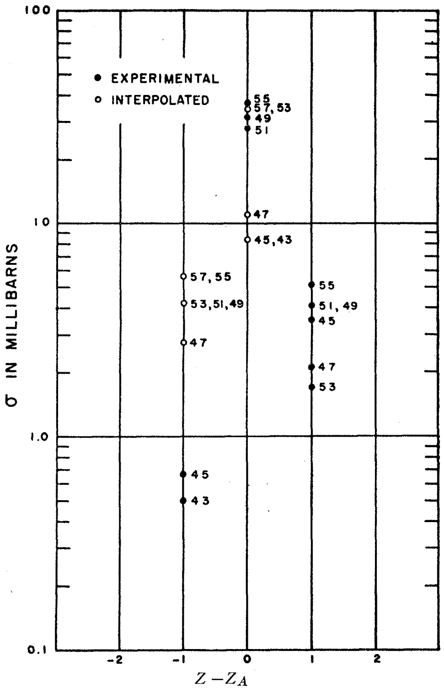

FIG. 4. Cross section for the formation of a given odd mass-number product, A, plotted against the difference between the atomic number of that product, Z, and the atomic number, Z_A, of the most probable product of that mass number. The solid circles are experimental values, and the open circles give interpolated values.

observed specificity in the distribution of products, and therefore suggest a simplified model that ignores the contribution of "knock-on" processes to the emission of black prongs. This model would be applied to the formation of all products more than one mass number removed from the target; products one unit lighter than the target probably correspond to events in which two fast nucleons are emitted from the struck nucleus by a "knock-on" process. We may, therefore, try the following phenomenological model for the nuclear reactions that result from an inelastic collision of a high-energy nucleon with a nucleus:

(a) The incident particle with kinetic energy E_i, in traversing the struck nucleus, deposits a portion of its energy, U, in the nucleus and emerges with kinetic energy $E_f = E_i - U$ and

(b) The excitation energy, U, is randomly distributed among the nucleons in the struck nucleus, and the subsequent behavior of the system can be described by evaporation theory.

This model leads to the following expression for the formation cross section of a product nucleus characterized by mass number A and atomic number Z:

$$\sigma_{A,Z} = \int_0^\infty \frac{d\sigma}{dU}\eta(U;A,Z)dU,$$

where $d\sigma/dU$ is the differential cross section for the deposition of excitation energy U in the struck nucleus, and $\eta(U;A,Z)$ is the probability that a nucleus of charge Z and mass number A remains after the target nucleus has expended the excitation U in the emission of particles and photons. A discussion of $d\sigma/dU$ and $\eta(U;A,Z)$ will be presented in a subsequent paper; at this time, however, it will be necessary to anticipate a few of the properties of the $\eta(U;A,Z)$ distribution so that a guide will be available for the interpolation of the unmeasured formation cross sections of long-lived and stable products.

The distribution of products that results from the evaporation of several particles from an excited nucleus can be easily approximated under the following assumptions:

(1) Only nucleons are evaporated,

(2) each nucleon evaporated from an excited nucleus of mass number 45 to 60 carries away from 15 to 20 Mev of excitation,

(3) the probabilities of either proton or neutron emission at each step in the evaporation cascade may be calculated from the Weisskopf formalism,[18] and

(4) the density of energy levels of a nucleus excited to U Mev above the ground state is given by $C\exp[2a^{\frac{1}{2}}(U+d)^{\frac{1}{2}}]$, where C and a are constants, and d has the value of 1.5 Mev for odd-odd nuclei, 0 Mev for odd-even or even-odd nuclei, and -1.5 Mev for even-even nuclei. The quantity d is a correction applied to the simple level density formula in a manner suggested by Hurwitz and Bethe,[19] and arises from their analysis of the effect upon neutron capture cross sections of the oddness or evenness of neutron and proton number of the target nucleus.

As an indication of the predictive value of this approximate method for the analysis of an evaporation cascade, we may compare the ratio of peak cross sections for the $Cu^{63}(p,pn)Cu^{62}$ and the $Cu^{63}(p,2n)Zn^{62}$ reactions calculated by this approximate method with the ratio observed by Ghoshal:[20] the computed ratio is 3.6, and the observed ratio is 4.0. If a correction is not made for the difference in level densities of odd-odd and even-even nuclei, the calculated value decreases to 0.7; this symmetry correction, as was pointed out by Ghoshal, improves matters considerably.

The application of this calculation to the relative yields of the odd mass-number isobars resulting from evaporation of nucleons from an excited Co^{59} nucleus indicate that for each mass number, the peak does indeed occur at the Z_A value used in Fig. 4, and that the cross section for the formation of odd mass-number isobaric products two atomic numbers on either side of the peak contribute, at most, only a few percent to

[18] J. Blatt and V. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[19] H. Hurwitz and H. Bethe, Phys. Rev. **81**, 898 (1951).
[20] S. N. Ghoshal, Phys. Rev. **80**, 939 (1950).

the total cross section of that mass number. The estimation of the relative yields of even mass-number isobaric products does not give a peak, but rather there are two nearly equal "peak yields" that arise because of the symmetry effect on the density of nuclear energy levels. The double peak corresponds to the Group II products of Rudstam, Stevenson, and Folger.[21] These conclusions will be incorporated into the next section where an attempt will be made to evaluate the total inelastic interaction cross section.

Absorption Cross Section

The values for some of the unmeasured cross sections, interpolated and extrapolated from the experimental results under the guidance of the approximate evaporation cascade calculations described in the previous section, are presented in Table II and Figs. 1 to 4.[22] The sole exception to this method of interpolation and extrapolation occurs at mass number 58; there, in view of the finite probability for the emission of two fast ($E \geqslant 50$ Mev) particles observed in photographic emulsion studies,[13] it was assumed that the distribution of products was governed by "knock-on" rather than "evaporation" processes.

No attempt was made to estimate the unmeasured yields of products with mass number less than 43 because of the sparsity of measured cross sections in that mass number region, the probable inadequacy of the assumed model in explaining the production of light nuclei, and finally because it seems that only a small fraction of the inelastic interactions produce these light products and therefore this omission will have but little consequence upon the estimation of the absorption cross section.

The sum of the measured and estimated cross sections listed in Tables I and II gives 700±155 millibarns as an estimate of the absorption cross section of the cobalt nucleus for 370-Mev protons. Since only about half of this figure is made up of experimental values, and since there are some doubts about the absolute value upon which it is based, it would be surprising if this value were not in considerable error. It is clear that this is a rather unsatisfactory method for determining an absorption cross section; it is of interest, nevertheless, to compare this estimate with similar values obtained in other ways in order to provide some external check on the approximate validity of the interpolated values so that they may be employed in an estimation of $d\sigma/dU$.

The total cross section for 410-Mev neutrons on copper, as measured by Nedzel,[23] has been found to be 1187 millibarns. If the inelastic contribution to this cross section is still at least one-half, as it was at 270 Mev,[24] then the absorption cross section would be at least 593 millibarns. Ball[25] has found an inelastic interaction cross section of 755 millibarns for 300-Mev neutrons on copper by a "poor geometry" attenuation experiment; a value that is in excellent agreement with the 700-millibarn absorption cross section for 340-Mev protons on copper determined by Batzel, Miller, and Seaborg[26] through a radiochemical study similar to the one described in this paper. Also employing the radiochemical technique, Rudstam, Stevenson, and Folger[21] estimate an inelastic cross section of 350 millibarns for 340-Mev protons on iron, which is a much lower result than any of the others quoted and which seems to be based upon a 10–11 millibarn cross section for the $Al^{27}(p,3pn)Na^{24}$ reaction, although the value employed is not explicitly stated in their paper.

The expected value of the absorption cross section may also be computed from the "optical model,"[27]

TABLE II. Interpolated cross sections for the formation of nuclides from the bombardment of cobalt with 370-Mev protons.

Nuclide Z		A	Cross section in millibarns
27	Co	57	37
		54	1.7
26	Fe	58	120
		57	6.7
		56	24
		54	20
25	Mn	55	6
		53	34
		50	1.7
24	Cr	54	1
		53	4
		52	20
		50	20
		48	0.3
23	V	52	1
		51	4
		50	20
22	Ti	50	1
		49	4
		48	9
		47	11
		46	6
21	Sc	48	0.5
		47	2.8
		46	6.0
		45	8.5
20	Ca	46	0.1
		44	2.8
		43	8.5
Total			375±140

[21] Rudstam, Stevenson, and Folger, Phys. Rev. **87**, 358 (1952).
[22] The estimated error assumes a variance for each interpolated value that is equal to the square of the interpolated value.
[23] V. A. Nedzel, Phys. Rev. **94**, 174 (1954).
[24] J. De Juren, Phys. Rev. **80**, 27 (1950).
[25] W. P. Ball, University of California Radiation Laboratory Report UCRL-1938 (unpublished).
[26] Batzel, Seaborg, and Miller, Phys. Rev. **84**, 671 (1951).
[27] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

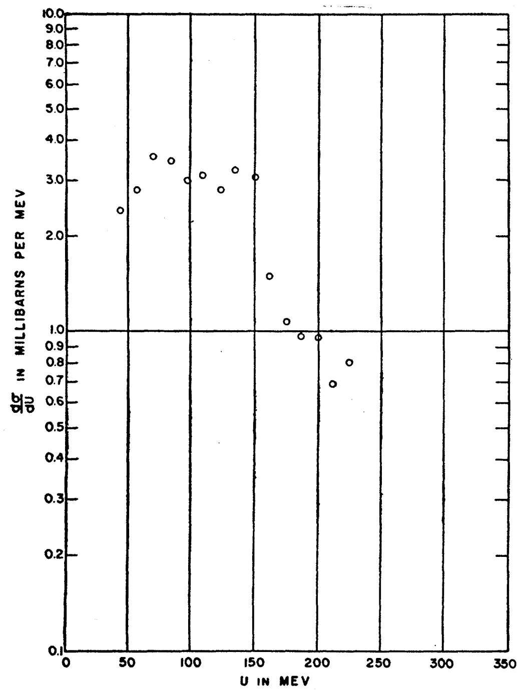

FIG. 5. Differential cross section for the deposition of excitation energy U in the inelastic interaction of 370-Mev protons with cobalt.

which gives

$$\sigma_a = \pi R^2 \left[1 - \frac{1-(1+2KR)\exp -2KR}{2K^2R^2} \right],$$

where K is the absorption coefficient for protons in nuclear matter and R is the nuclear radius. If the values of $K = 0.485\times 10^{13}$ cm^{-1} and $R = 1.23\times 10^{-13}$ $A^{\frac{1}{3}}$ cm, found by Nedzel[23] to give the best fit to the 410-Mev neutron total cross sections, are used, then $\sigma_a = 650$ millibarns for Co^{59}. The parameter K may also be evaluated from the free-nucleon total cross section if the impulse approximation is used:

$$K = 3[Z^a\alpha(r_0)\sigma_{pp} + N\beta(r_0)\sigma_{pn}]/4\pi r_0^3 A,$$

where $\alpha(r_0)$ and $\beta(r_0)$ serve to correct the free-nucleon cross sections, σ_{pp} and σ_{pn}, for scatterings into inaccessible states.[17] If σ_{pp} is taken as 27 millibarns, σ_{pn} as 34 millibarns,[23] $\alpha(r_0)$ evaluated for a Fermi gas model

TABLE III. The absorption cross section of cobalt for 370-Mev protons calculated by means of the optical model as a function of r_0.

$r_0\times 10^{13}$ cm	$\frac{\sigma_a}{\pi r_0^2 \times 10^{-26} A^{\frac{2}{3}}}$	$\sigma_a \times 10^{24}$ cm^2
1.0	0.89	0.42
1.1	0.86	0.49
1.2	0.83	0.56
1.3	0.78	0.62
1.4	0.75	0.69
1.5	0.72	0.77
1.6	0.68	0.84

and for p-p scattering spherically symmetric in the center-of-mass system, and $\beta(r_0)$ approximated under the assumption that the p-n scattering angular distribution is roughly the same at 400 Mev as it is at 270 Mev,[28] then the dependence of σ_a upon r_0 for Co^{59} is as presented in Table III. It is seen that the σ_a estimated from the present work corresponds to an $r_0 = 1.44\times 10^{-13}$ cm.

From these various comparisons we may conclude that the interpolated cross sections are sufficiently reliable to be used in the estimate of the relative formation cross section of each mass-number product as will be done in the following section.

$d\sigma/dU$: Although the absolute values of the measured cross sections are in some doubt owing to the conflicting results for the only observed activation cross sections measured in this energy region that might be used in beam monitoring, the relative values of the cross sections listed in Tables I and II are clearly unaffected by this dilemma and may be used, in the spirit of the proposed model, to infer the probability of an inelastic interaction resulting in a given energy transfer. To accomplish this, we must estimate how much excitation energy each product represents. For this purpose we can employ the extensive calculations made by Le Couteur[29] on the number and kind of particles emitted from an excited nucleus as a function of its excitation energy, with approximate corrections to make the results applicable to an excited Co^{59} nucleus. The results of this analysis, which indicate an excitation of from 14 to 17 Mev per mass number lost from the target, is presented in Fig. 5 where the differential cross section per unit of excitation energy in millibarns per Mev is plotted against the excitation in Mev.

The results for mass number 58 are not included in this analysis since that product, as has been previously stated, is undoubtedly largely formed by a "knock-on" process and represents an energy transfer that is certainly greater than that required to evaporate one nucleon from a cobalt nucleus.

CONCLUSIONS

The distribution of products resulting from the inelastic interaction of 370-Mev protons with cobalt nuclei demonstrates the decisive importance of the evaporation process in dissipating the energy transferred to the struck nucleus. The data, interpreted in the light of product formation through evaporation processes, indicate a rather uniform (within 30 percent) differential cross section for transferring up to about 40 percent of the incident energy of the proton to the target nucleus as a whole. The cross section shows a rapid drop for energy transfers in excess of about one half of the incident energy.

[28] Kelley, Leith, Segrè, and Wiegand, Phys. Rev. **79**, 96 (1950).
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Absorption of Negative Pions in Deuterium: Parity of the Pion*

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The reaction $\pi^-+d\rightarrow 2n$ has been observed by detecting the two neutrons in coincidence with slow negative mesons incident on a liquid deuterium target. The observed angular correlation of the two neutrons confirms the identification of the process. The process is therefore not forbidden, and this fact may be used to establish the odd relative parity of the pion and the nucleon.

I. INTRODUCTION

IT was first pointed out by Ferretti[1] that the capture in deuterium of negative mesons at rest might furnish a means of distinguishing between scalar and pseudoscalar pions. The reaction,

$$\pi^-+d\rightarrow 2n, \quad (1)$$

is forbidden for scalar mesons in S states since requirements of angular momentum and parity conservation and the Pauli principle cannot simultaneously be satisfied. The argument is independent of the theoretical model for the process. If the reaction is observed, then to rule out scalar parity for the pion, it is only necessary to show that the reaction proceeds indeed from an S state. Brueckner, Serber, and Watson[2] have shown, using the measured cross section for the process $\pi^++d\rightarrow 2p$, extrapolated to lower energy, that capture from the excited states of the meson-deuteron atom does not compete favorably with electromagnetic de-excitation. At most, one in thirty mesons is expected to be captured before reaching the ground state. Therefore, if more than one-thirtieth of the stopped mesons are captured according to process (1), the meson cannot be scalar. Since it has already been shown that the pion has zero spin,[3,4] the pion is then pseudoscalar.

The only previous evidence for reaction (1) is furnished by the experiments of Panofsky, Aamodt, and Hadley.[5] In these experiments measurements were made on the energy spectra of γ rays from hydrogen and deuterium gases at 3000 lb/sq. in. pressure and 78°K in which mesons had come to rest. All reactions in hydrogen give γ rays, either directly or through π^0 decay. The γ-ray yield from deuterium was lower and left 70 percent of the capture processes unaccounted for. This was interpreted to mean that 70 percent of the captures proceed through reaction (1).

In view of the important consequences of this result, we have performed an experiment in which the two neutrons are observed in coincidence and in coincidence with incident mesons some of which come to rest in a container of liquid deuterium. This provides a direct observation of the process (1) and confirms the conclusions of Panofsky *et al.*

II. EXPERIMENTAL ARRANGEMENT

Negative mesons produced at the internal target of the Columbia University 390-Mev cyclotron are collimated in a channel of the 8-foot iron shielding wall and further analyzed by a double focusing magnet and the beam defining counters No. 1 and No. 2. (See Fig. 1.) Counter No. 1 is a liquid scintillator $4\frac{1}{2}$ inches in diameter and $\frac{5}{8}$ inch thick; counter No. 2 is a stilbene crystal $2\frac{1}{4}$ inches horizontally, $2\frac{3}{4}$ inches vertically, and $\frac{1}{8}$ inch in thickness. Between counters No. 1 and No. 2 a 2 g/cm² carbon absorber is inserted, with 5 g/cm² of LiH and 2.7 g/cm² of polyethylene between counter No. 2 and the deuterium target. The absorber thickness is chosen to maximize the number of mesons which stop in the deuterium; the type of material to minimize Coulomb scattering, consistent with convenience.

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