Reactions of Cobalt with Protons at 60, 100, 170, and 240 Mev*

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Absolute cross sections are reported for the production of the nuclides Co^{58}, Co^{56}, Co^{55}, Fe^{52}, Mn^{56}, Mn^{52}, Mn^{51}, Cl^{39}, and $Cl^{38,34}$ from bombardment of Co^{59} with protons of energies 60, 100, 170, and 240 Mev. The yields appear to be accounted for at the lower energies by a combination of compound nucleus model, knock-on cascade model and for the production of chlorine isotopes a fission mechanism. A knock-on cascade model together with a fission mechanism may be used to explain the yields at the higher energies.

INTRODUCTION

IN an earlier paper[1] the relative yields were reported for the nuclides produced when spectroscopically pure cobalt was bombarded with 240-Mev protons. The work has been continued for the purpose of determining the absolute cross sections and the excitation functions from 60 to 240 Mev of nine of the product nuclides. Data of the latter type are of interest in connection with current theories[2] of high-energy nucleon-nucleus interactions and there is a paucity of such data. Similar studies of the spallation product yields from 60- to 240-Mev protons on vanadium, yttrium, and cesium have been completed in this laboratory.

Rudstam[3] has reported the yields relative to Cr^{49} of a number of nuclides produced by the reaction of 187-Mev protons on cobalt but none of the nuclides reported here was investigated. Where some of the nuclides were studied earlier by us at 240 Mev, Rudstam's yields compare favorably with ours. Belmont[4] has determined the absolute cross sections at 370 Mev of the nuclides for which we report data to 240 Mev. His values, which have been included in our graphs for the sake of completeness, are in every case consistent with ours.

EXPERIMENTAL

Cobalt sponge powder (spectroscopically pure) wrapped in 1-mil aluminum foil shaped in the form of an envelope $\frac{1}{16}$-in. square in cross section and $1\frac{1}{4}$ in. long was bombarded in the internal beam of the Rochester 130-inch synchrocyclotron at radii corresponding to energies of 60, 100, 170, and 240 Mev. The targets could be considered thin since the expected energy loss was less than 2 Mev. Chemical separations and identification of nuclides have already been described.[1] Samples were counted with end-window, helium-filled, alcohol-quenched Geiger-Müller tubes with thin mica windows (1.5–1.9 mg/cm^2).

The production of Na^{24} by the reaction $Al^{27}(p,3pn)Na^{24}$, the cross section of which has been determined at high energies,[5,6] was selected as the monitor for the proton beam striking the cobalt target. For this purpose four sheets of 1-mil aluminum foil were used, two each placed on the front and back of the target envelope. In the determination of the yield of Na^{24}, only the two inner foils were used in order to insure compensation for recoils[7] out of the foils. In each experiment the yield of the product nuclide Co^{55} was used as an internal standard. It was counted in the same geometry as all other samples, including the monitor foils.

In the calculation of the yields to infinite bombardment time, the following corrections to the observed counting rates were considered: (1) background, (2) coincidence loss, (3) decay of the nuclide after bombardment, (4) percent chemical yield, (5) mode of decay, (6) absorption by air and the counter window, (7) back scattering, (8) scattering from the walls of the counter housing and the air between the sample and the counter window, (9) self-scattering and self-absorption, and (10) counter efficiency for electromagnetic radiation.

The first four of these corrections are easily made. The decay schemes of the nuclides included in this study are well-known with the exception of Co^{56}, where there is an uncertainty of 25 percent in the branching ratio for orbital-electron capture. Correction for air and window absorption was made by the method of Gleason, Taylor, and Tabern.[8]

Since many conditions affect the back scattering of beta-emitters, empirical correction factors were determined for the specific types of mounting and counting used in these experiments. To obtain these factors, standard samples of Na^{22} (positron emitter) and of an equilibrium mixture of Sr^{90}-Y^{90} (negatron emitters) were mounted on thin Zapon films and on disks identical

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

[2] See E. Segrè, editor, *Experimental Nuclear Physics* (John Wiley and Sons, Inc. New York, 1953), Vol. II, p. 141.

[3] S. G. Rudstam, Phil. Mag. 44, 1131 (1953).

[4] E. Belmont, U. S. Atomic Energy Commission Report NYO 3198, 1952 (unpublished).

[5] L. Marquez and I. Perlman, Phys. Rev. 81, 953 (1951); L. Marquez, Phys. Rev. 86, 405 (1952).

[6] N. M. Hintz and N. F. Ramsey, Phys. Rev. 88, 19 (1952).

[7] S-C. Fung and I. Perlman, Phys. Rev. 87, 623 (1952).

[8] Gleason, Taylor, and Tabern, Nucleonics 8, No. 5, 12 (1951).

with those used in other experiments. All counting of samples was done with a half-inch stainless steel block backing under the disks, i.e., under conditions of saturation back scattering. The observed counting ratios checked favorably with the literature values except that the difference for positron and negatron sources was of the order of 3 percent, rather than 10 percent as reported by Seliger.[9]

No correction for wall scattering of β rays was used, since the change in the counting rate with and without housing was within that expected for the error in the corresponding sample to window distances. Burtt[10] observed a change in counting rate of the order of 1 percent for a similar counter housing. Interpolation of the data of Nervik and Stevenson[11] was used to obtain the correction for self-scattering and self-absorption for the beta emitters studied.

For γ rays the usual counter efficiency of 1 percent was used. In the case of capture processes with little or no electron conversion and accompanied by γ emission, as for Co^{55}, an efficiency of 5 percent was taken for the type of counter used. This value was compatible with the ratio of counting rates due to beta emission to the total counting rate of the sample as observed in aluminum absorption curves for nuclides of known branching ratio.

For each nuclide the error in the counting rate at infinite bombardment was obtained from the square root of the sums of the squares of the estimated errors in each of the correction factors just discussed and that caused by irreproducibility of area of the sample used for counting. The probable errors in the values of the absolute cross sections given in Table I were then obtained from the square root of the sum of the squares of the error just calculated for a given nuclide and for Co^{55} (the internal monitor) and the error in the cross section for Co^{55} (which takes account of the errors in the counting rate of Na^{24}).

TABLE I. Experimental values of the cross sections in millibarns.

Nuclide	Energy 240 Mev	170 Mev	100 Mev	60 Mev
Co^{58}	140±70	180±90	310±155	960±480
	110±55	190±95	450±225	770±385
	110±55		330±165	
Co^{56}	26±13	29±15	75±38	130±65
	20±10	31±16	110±55	110±55
	20±10		81±41	
Co^{55}	6.6±1.3	9.4±1.9	21±4	5.7±1.1
		9.3±1.9		
Fe^{52}	0.67±0.20	0.65±0.19	0.47±0.14	0.0006±0.0003
	0.59±0.18	0.65±0.19	0.62±0.19	0.0012±0.0006
			0.58±0.18	
Mn^{56}	16±4	11±3	14±3	15±3.8
	16±4	12±3	14±3	8.6±2.3
	9.0±2.3		14±3	
Mn^{52}	42±10	31±8	36±9	1.2±0.3
	39±10	31±8	40±10	1.5±0.4
	23±6		31±8	
Mn^{51}	18±6	4.9±1.7	6±3	...
	14±5	6.7±2.3		
Cl^{39}	0.07±0.05	0.011±0.008		
	0.23±0.16	0.003±0.002	...	...
$Cl^{38,34}$	0.15±0.08	0.018±0.009	0.11±0.06	0.006±0.003
	0.22±0.11	0.018±0.009	0.03±0.02	0.004±0.002
Na^{24}	11.7[a]	13.2[a]	15.2[b]	14.0[b]

[a] Interpolated values.
[b] Values given by Hintz and Ramsey. (See reference 6)

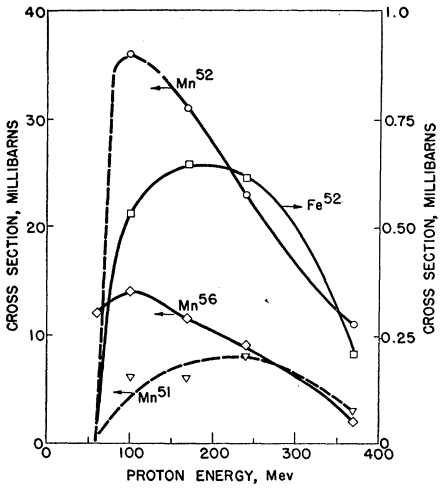

FIG. 1. Yields of Mn isotopes and Fe^{52} from Co^{59} as a function of proton energy. The arrows on each curve point to the appropriate ordinate scale.

RESULTS AND DISCUSSION

The experimental cross sections obtained for nine nuclides at energies of 60, 100, 170, and 240 Mev are presented in Table I. The first two values for Mn^{52} and Mn^{56} in the table appear to be about twice the actual value. The third values given agree closely with the relative yields obtained in the first studies[1] at 240 Mev. There appears to be some experimental error associated with the manganese fractions for these two runs. The source of this difficulty is not completely understood but appears to be associated with the chemical yield for these fractions. The lower values for these isotopes are shown in Fig. 1. In addition, the values for Mn^{51}, both obtained from the same chemical fractions which gave the larger values for the other two isotopes, were reduced by the same factor before plotting the data in Fig. 1. These values are all consistent with Belmont's values[4] at 370 Mev.

From the table it is seen that the yield of Co^{58} is largest at all energies, while that of Co^{56}, which is second largest at 60 and 100 Mev, is surpassed at the higher energies by the (Z-2) nuclide Mn^{52}. The yields of the latter are minimum values since the isomer, Mn^{52m}, has not been included. Similar relative yields as a function of energy are in general observed in

[9] H. N. Seliger, Phys. Rev. **78**, 491 (1950).
[10] B. P. Burtt, Nucleonics **5**, No. 2, 28 (1949).
[11] W. E. Nervik and P. C. Stevenson, Nucleonics **10**, No. 3, 18 (1952).

the spallation studies of vanadium,[12] yttrium,[13] and cesium,[14] except that the cross section for Cs^{131} is almost 8 times that of Cs^{132} at 240 Mev. Because of lack of data for stable and long-lived nuclides it is difficult to draw general conclusions.

The *observed* total cross sections are 92, 49, 25, and 20 percent of the geometric cross section at 60, 100, 170, and 240 Mev, respectively. The sharp drop from 60 to 100 Mev would appear to be associated with the change from compound nucleus formation followed by evaporation of nucleons at lower energies to a knock-on cascade model at higher energies. In the spallation of yttrium,[13] a similar pronounced change from about 100 to 43 percent occurs in the same energy range. The observed yields of products from protons on cesium[14] are 92, 100, and 87 percent of the geometrical cross section at 60, 80 and 100 Mev, respectively, dropping to 53 percent at 150 Mev. The results with cesium may reflect the influence of the larger size of the nucleus.

Cobalt Yields

The cross sections for Co^{58}, Co^{56}, and Co^{55} as a function of proton energy are shown in Fig. 2. The yields of Co^{58} and Co^{56} decrease continuously with proton energy while that of Co^{55} exhibits a maximum value in the region of 100 Mev. The threshold for the reaction $Co^{59}(p,p4n)Co^{55}$ is less than the lowest energy, 60 Mev, available in this study. The yields of Co^{55} are always smaller than those for Co^{56}, as might be expected.

The excitation function for Co^{58} beyond 60 Mev is in general the same as that for C^{11} from C^{12}, which has been studied[15] up to 340 Mev, except that the cross section for Co^{58} is of the order of ten times as great as that for C^{11}. Qualitatively, the high yield of Co^{58} in the lower-energy range is understandable in view of the possible contributions from (1) the charge exchange process to form Ni^{59} followed by evaporation of a proton, (2) the contribution of the pickup process[2] with the emission of a deuteron, and (3) the favorable competition of the (p,pn) process over the $(p,2n)$ owing to the greater level density of the odd-odd product nucleus of the former process as compared to the even-even product nucleus of the latter. Ghoshal[16] has shown this for reaction of low-energy protons on Cu^{63} to produce Cu^{62} and Zn^{62}.

In the energy range beyond 100 Mev, where the knock-on cascade model would be expected to apply, the yields of Co^{58} relative to other nuclides produced appear high but are consistent with the yields of the analogous $(A\text{-}1)$ nuclides produced at high energies from C^{12}, Y^{89},[13] Cs^{133},[14] and Cu^{63}.[17] These Co^{58} cross sections are also consistent with that of Belmont[4] at 340 Mev.

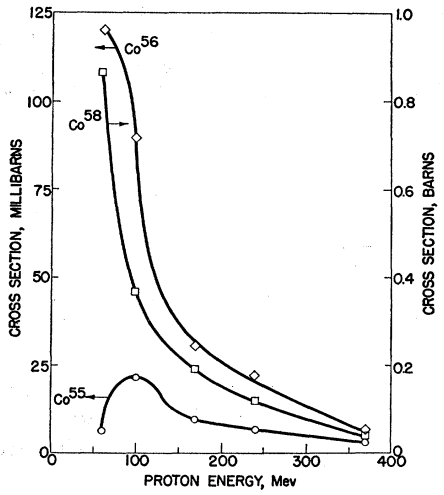

FIG. 2. Yields of Co isotopes from Co^{59} as a function of proton energy. The arrows on each curve point to the appropriate ordinate scale.

Iron and Manganese Yields

The cross sections for the formation of Mn isotopes and Fe^{52} are shown in Fig. 1. The relatively high yield of Mn^{56} at 60 Mev would seem to indicate compound nucleus formation and the reaction $Co^{59}(p,pHe^3)Mn^{56}$ or a similar reaction. This process together with contribution from the knock-on model may account for roughly the same yields at 100 to 170 Mev.

The yields of Co^{56}, Co^{55}, and Mn^{52} at 100 Mev are roughly of the same order of magnitude (21–89 mb) and again at 170 Mev (9–31 mb). This would seem to suggest that an excited Co^{58} or Co^{57}, rather than an excited iron nucleus, remains as a result of the initial nuclear collision and cascade process. Subsequent evaporation of neutrons to form Co isotopes or an alpha-particle and neutrons to form Mn^{52} readily accounts for these nuclides. Evaporation of neutrons from an excited Fe^{58} or Fe^{57} would favor formation of stable iron isotopes or Fe^{55}. Facilities for detection of the latter were not available at the time this work was performed. This shielding of Fe^{52} by stable Fe^{54}, Fe^{56}, Fe^{57} and long-lived Fe^{55}, and the favored emission of alpha particles from an excited Co nucleus may serve to account for the high yield of Mn^{52} relative to Fe^{52}. Also, evaporation of neutrons from excited iron nuclei to form Fe^{52} would necessarily involve Fe^{53} as one step. Since the latter is neutron-deficient the "governor" factor[2,18] which reduces departure from the region of stable nuclei in the cooling process, would be operative. Loss of a proton would be energetically less

[12] C. G. Heininger, Jr., Ph.D. thesis, University of Rochester, 1954 (unpublished).
[13] A. A. Caretto, Jr., Ph.D. thesis, University of Rochester, 1953 (unpublished).
[14] R. W. Fink and E. O. Wiig, Phys. Rev. **96**, 185 (1954).
[15] Aamodt, Peterson, and Phillips, Phys. Rev. **88**, 739 (1952).
[16] S. N. Ghoshal, Phys. Rev. **80**, 939 (1950).
[17] Batzel, Miller, and Seaborg, Phys. Rev. **84**, 671 (1951).
[18] K. S. LeCouteur, Proc. Phys. Soc. (London) **A63**, 259 (1950).

difficult than loss of an additional neutron and Mn^{52} would result, rather than Fe^{52}.

LeCouteur[18] has calculated the probability of alpha-particle emission from an excited nucleus by using the evaporation model. By basing the calculations on a nucleus of mass 98, the ratio of the probability of alpha emission to that for proton emission was found to vary from 0.3 to 0.5 for excitation energies from 30 to 400 Mev. Hodgson[19] in a study of stars produced in photographic emulsions by 50–125 Mev protons on silver and bromine found strong evidence that alpha particles take part. The proportion of alpha particles among all the particles emitted showed no significant variation with energy. About 25 percent of the cascade particles were found to be alpha particles and there was no significant difference in yield between evaporation and cascade alpha particles. If the excited nucleus were iron, then neither Mn^{52} nor Fe^{52} could be formed by an alpha process. In the event where charge exchange occurred between the incident proton and a neutron in the nucleus, leaving an excited Ni nucleus, Fe^{52} could be formed by evaporation of an alpha particle whereas Mn^{52} would require an alpha particle and a proton. Since the yield of Mn^{52} is so very much greater than that of Fe^{52}, either this process is unimportant or Fe^{52} formation is blocked by the formation of stable iron isotopes.

Chlorine Yields

Some activity was observed in all chlorine fractions, even those from targets bombarded at 60 Mev. At the lower energies all this activity appeared to have a half-life consistent with the presence of Cl^{38} and/or Cl^{34}. Because of the difficulty in resolving the decay curve, it was not possible to rule out the presence of Cl^{39} at these energies and the cutoff for the formation of this nuclide, shown in Fig. 3 to be at some energy greater than 100 Mev, may be merely the reflection of experimental difficulties.

The formation of chlorine isotopes requires a large loss of nucleons from the target nucleus. Bernardini *et al.*[20] have found that the cutoff for charged particle emission, as observed in photographic plates, appears to be at eight particles for incident proton energies of 350–400 Mev. From an examination of the angular distribution of the particles, they found that about

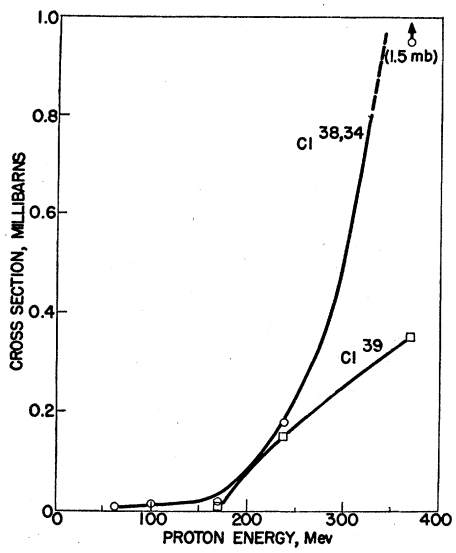

FIG. 3. Yields of Cl isotopes from Co^{59} as a function of proton energy.

40 percent were the result of a knock-on process, i.e., associated with the nucleonic cascade, and about 60 percent were evaporation nucleons. Assuming the maximum energy for such evaporation particles, about 30 Mev, such an eight particle event corresponds to a transfer of about 150 Mev of excitation energy to be dissipated by evaporation. Since such an event would be expected to be accompanied by evaporation of a large number of neutrons not observable in an emulsion, this energy estimate is conservative. Thus, it is not difficult to imagine how chlorine could be formed from a cobalt target nucleus with protons of high energy, particularly if aggregates of nucleons, such as alpha particles, are taken into consideration.

For protons in the 60- to 100-Mev range, it is difficult to imagine such formation on the basis of loss of individual nucleons. At these energies an event in which the nucleus undergoes a type of fission is a more reasonable picture, since the energy requirements for such a process are less than for the former.[21] It is probable that both processes contribute to the yield of chlorine isotopes in the higher energy range.

We wish to thank Professor S. W. Barnes and the crew of the Rochester 130-in. cyclotron for their cooperation in making this study possible.

[19] P. E. Hodgson, Phil. Mag. **45**, 190 (1954).

[20] Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 826 (1952).

[21] R. E. Batzel and G. T. Seaborg, Phys. Rev. **79**, 528 (1950).