Nuclear Reactions of Copper with Various High-Energy Particles*

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A study of the spallation of copper by 90-Mev neutrons, 90-Mev protons, 190-Mev protons, and 190-Mev deuterons has been made. Radiochemical methods have been employed to determine absolute cross sections for the production of a number of nuclides produced by the interaction of these high-energy particles with copper.

OVER the past several years, the spallation of a number of elements by high-energy particles has been studied.[1–6] However, in almost all cases, the energies of the particles used in producing the spallation reaction have been sufficiently high that the method whereby the struck nucleus is excited prior to spallation is not clear-cut. Charge exchange or other noncapture processes appear to account for the greater part of the excitation, whereas compound nucleus formation is relatively unimportant. A further complicating factor is the appreciable transparency of nuclei to high-energy incident particles. Hence, it was felt that a study should be made of relatively low-energy spallation, where the compound nucleus mechanism plays a more important role in the formation of the "spalling" nucleus.

Unfortunately, the programmatic study of spallation reactions which was originally contemplated could not be carried out; however, a limited research program on the spallation of natural copper (Cu^{63} and Cu^{65}) has been completed. This paper reports on the results of several irradiations which were made on the Berkeley 184-inch cyclotron with 90-Mev neutrons and 90-Mev protons, at which energy the compound nucleus mechanism may be considered more important in the formation of the "spalling" nucleus than is the case at higher energies. To facilitate comparisons between intermediate and high-energy spallation, several additional irradiations of copper were carried out, using 190-Mev protons and 190-Mev deuterons.

After each irradiation the target was dissolved, appropriate carriers were added, and one or more elements were separated by chemical procedures which were, in most cases, similar to those used by Batzel.[7] In all charged-particle bombardments, the Na^{24} produced in aluminum monitor foils was used to determine the absolute beam intensities. In all neutron runs a copper fraction was isolated, and the Cu^{64} was used as an internal monitor to ascertain relative beam intensities. Subsequently, the cross section for the formation of Cu^{64} by 90-Mev neutrons was found by the use of carbon monitor foils, where the $C^{12}(n,2n)C^{11}$ cross section is known. The cross sections used for all monitor reactions are given in Table I.

Activities of beta-emitting nuclides were measured with thin-window halogen-filled GM counters, all of which were cross calibrated. In most cases, disintegration rates were estimated from the measured activities by taking into account self-scattering and self-absorption, counter geometry, counting efficiency of the radiation, and the published data on branching decay.[8] Self-scattering and self-absorption corrections for most of the activities were estimated from curves previously determined for a number of isotopes having a wide range of maximum beta energies.

However, in the cases of the nuclides Cu^{64} and Cu^{61}, all counting corrections were determined by more accurate techniques. A solution containing high specific activities of these two isotopes was assayed by evaporating an aliquot of this solution onto a thin Zapon film and counting the sample in a 4π geometry proportional counter. The solution was then diluted with a solution of inactive copper, and the mixture was used to prepare a series of counting samples with varying weights. The counting data from these samples were subsequently used in the determination of relatively precise self-scattering and self-absorption corrections.

The cross sections measured in this investigation are listed in Table II. The absolute values reported for Cu^{64} and Cu^{61} are accurate to approximately ± 5 percent. The relative values reported for all other nuclides should

TABLE I. Cross sections (in mb) used for monitor reactions.

Reaction	90 Mev	190 Mev	Reference
$C^{12}(n,2n)C^{11}$	22		a
$Al^{27}(p,3pn)Na^{24}$	9.2	9.2	b
$Al^{27}(d,\alpha p)Na^{24}$		21.8	c

[a] E. M. McMillan and H. F. York, Phys. Rev. 73, 262 (1948); Birnbaum, Crandall, Millburn, and Pyle (to be published); Schecter, Crandall, Millburn, and Ise, Phys. Rev. 97, 184 (1955).
[b] Stevenson, Hicks, and Folger, University of California Radiation Laboratory Report UCRL-4371 (to be published).
[c] Batzel, Crane, and O'Kelley, Phys. Rev. 91, 939 (1953).

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[1] D. H. Templeton, Ann. Revs. Nuclear Sci. 2, 93 (1953).
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[6] R. W. Fink and E. O. Wiig, Phys. Rev. 96, 185 (1954).
[7] Batzel, Miller, and Seaborg, Phys. Rev. 84, 671 (1951).
[8] Decay schemes used are those given in Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953).

TABLE II. Cross sections (in mb) for the formation of nuclides in the bombardment of copper.

	90-Mev neutrons	90-Mev protons	90-Mev protons[a]	190-Mev protons	190-Mev deuterons	190-Mev deuterons[b,c]	340-Mev protons[b]	370-Mev neutrons[d]
Zn^{63}		9[e]	12	2	21[e]	1.4	1.1	
Zn^{62}		7[e]	7.$_5$	2[e]	14[e]	1.0	0.8	
Cu^{64}	98	39	55	24	40	37	23	58.6
Cu^{62}	135	98[e]	120	42[e]	83	69	48	37.1
Cu^{61}	50	56.$_5$	65	30	46	~30[f]	23	15.4
Cu^{60}	5	6[e]		8[e]	10	9		
Ni^{65}	2				0.4[e]	1.2		0.88
Ni^{57}	0.3	0.8		1.3[e]	1.3[e]	2.6	1.8	0.54
Co^{62}	2							
Co^{61}	15	2		2[e]	7.$_5$[e]	4	5	3.78
Co^{55}	0.5	0.6$_5$		1.4	2.6[e]	1.0	2.3	0.415
Fe^{53}	0.16	0.30[e]		0.16[e]	0.30[e]	2.2	1.7	1.24
Fe^{52}	0.003	0.007		0.10	0.11	0.1	0.2	0.134
Mn^{56}	3	0.8		1.6	2.5	5	2.5	2.81
Mn^{52}	0.14[g]	0.1[e,g]		0.4[e,g]	0.8[g]	4	7	4.68
Mn^{51}	0.03			0.3[e]	0.6	1.3	1.6	0.76
Cr^{49}	0.006	0.01[e]		0.7[e]	0.9[e]	0.5	0.9	0.35
V^{48}	0.1[e]	0.02[e]		2.6[e]	2.9[e]	1.6	0.7	

[a] Calculated from results given in reference 2.
[b] Calculated from results given in reference 7.
[c] Cross sections in this column were recalculated by the authors.
[d] From reference 9.
[e] Based on a single run.
[f] Reported by W. H. Hutchin as 38 mb (see reference 7).
[g] Cross section for Mn^{52m} only.

be accurate to ±25 percent; however, those cases in which only one determination was made have been noted. Some results obtained by Meadows,[2] Batzel, Miller, and Seaborg[7] and Marquez[9] are also listed to provide a reasonably complete picture of copper spallation studies below 400 Mev. It should be noted that the cross section quoted by Miller for the formation of Cu^{61} in the 190-Mev deuteron bombardment of copper was only a rough estimate. Since all spallation product yields reported by him were expressed relative to this isotope, the authors arbitrarily used the production cross section for Cu^{61} determined in the present work to recalculate Miller's results. Inasmuch as Meadows did not apply backscattering corrections to his data, the agreement between his cross sections and those reported in this paper is satisfactory.

It can be seen that the cross sections of most of the proton-initiated spallation reactions are quite similar at 190 Mev and 340 Mev. Apparently, the excitation of the target nucleus is not greatly enhanced by increasing the energy of the incident protons above 190 Mev. However, reduction of the particle energy to 90 Mev produces the expected decrease in the production of the lighter spallation products. This effect is shown by both neutrons and protons, thereby indicating that the nature of the impinging nucleon is of only secondary importance. It is to be noted that the cross section for the production of Cu^{64} is appreciably higher in 90-Mev neutron spallation than it is in 90-Mev proton spallation. Although this effect may reflect a real difference in the $(n,2n)$ and (p,pn) reaction cross sections on Cu^{65}, it is possible that in the case of neutron spallation a small background of low-energy neutrons could produce an appreciable amount of Cu^{64} by means of the $Cu^{63}(n,\gamma)$ reaction. A comparison between the production of Cu^{64} in the spallation of copper with 340-Mev protons and 370-Mev neutrons indicates that a somewhat similar situation exists in this energy region.

In a comparison of the spallation produced by 190-Mev protons and 190-Mev deuterons, the smaller average energy per nucleon and hence the smaller transparency of the struck nucleus to deuterons should be manifested by an increased production of those nuclides which are formed predominantly in spallation induced by 90-Mev particles. This expected effect is markedly displayed by the data given in Table II.

A more detailed analysis of the results reported in this paper does not appear to be warranted because of the incomplete nature of these results. A further complication in the interpretation of experimental data lies in the lack of uniqueness in the method of production of any given spallation product; i.e., in almost all cases the nuclide may have resulted from the interaction of a bombarding particle with either Cu^{63} or Cu^{65}.

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[9] L. Marquez, Phys. Rev. **88**, 225 (1952).