effect persists into the high-energy region with only relatively small changes in the simple formulas we have derived.

It is clear from these results that the possibility of deuteron formation can be expected to increase very markedly the near-threshold production of mesons at high multiplicities. The additional effects of other "final-state interactions" cannot be expected to be small; these will be discussed in a paper now in preparation.

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Nuclear Reactions of Copper with 2.2-Bev Protons*

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The circulating proton beam of the Brookhaven Cosmotron has been used to determine the cross sections for the formation of about 50 radioactive nuclides in the bombardment of copper with 2.2-Bev protons. Target foils between 40 and 1200 mg/cm^2 thick were irradiated in one of the straight sections of the machine for periods ranging from a few minutes to several hours. To avoid irradiation of the targets with stray protons of less than the desired energy, the foils were in a shielded position except during the final 200 milliseconds of each acceleration cycle; during that time they were propelled, by means of an air-driven ram, to a location at a slightly smaller radius than the equilibrium proton orbit. When the rf acceleration was turned off at the end of the cycle, the protons spiralled in towards the target. Activity levels were found to be practically independent of target thickness, which indicates that, for the range of thicknesses used, the number of beam traversals through a target foil is about inversely proportional to the foil thickness. With beam intensities of the order of 10^{11} protons per minute, saturation activities in the range of 10^5 to 10^7 disintegrations per minute were found for practically all the products investigated.

After each irradiation the target was dissolved, appropriate carriers were added and one or more elements were separated by fairly standard radiochemical procedures. In most runs a manganese fraction was isolated, and the Mn^{52} yield was used as a measure of the relative beam intensity. In some other cases the Na^{24} activity induced in an aluminum monitor foil[1] was used for this purpose. Activities of beta-emitting nuclides were measured with thin-window G-M or proportional counters; the x-rays from nuclides decaying mostly by K-electron capture were measured with a large proportional counter and pulse-height analyzer. Scintillation gamma-ray detectors were used for Be^7 and Cr^{51}. All counters were appropriately intercalibrated, and the measured counting rates were converted to disintegration rates by means of factors for counter geometry and efficiency and for branching decay.[2] Corrections for self-absorption, backscattering, and window absorption of beta rays were made for beta groups with $E_{max} \leq 0.4$ Mev, according to published data.[3] Conversion of the relative yield values for the various products to absolute cross sections was based on the value 9.0 mb[4] for the cross section of the reaction $Al^{27}(p,3pn)Na^{24}$.

The measured cross sections are listed in Table I. Their relative values are believed to be good to ± 20 percent except where otherwise stated. To show the very striking differences between these results and the corresponding cross sections measured[5–7] with proton energies of 340 and 370 Mev, the ratio of high-energy to low-energy cross section is plotted against product mass number in Fig. 1. Only experimentally determined cross sections are included. It is evident that deposition of small amounts of excitation energy, leading to products within a few mass numbers of the target, has become relatively less important at the higher energy, while loss of 15 or more nucleons is much more probable. In fact, interpolation of cross sections for undetected product nuclides on the basis of approximate evaporation calculations leads to the conclusion that the total cross section for a given product mass number peaks

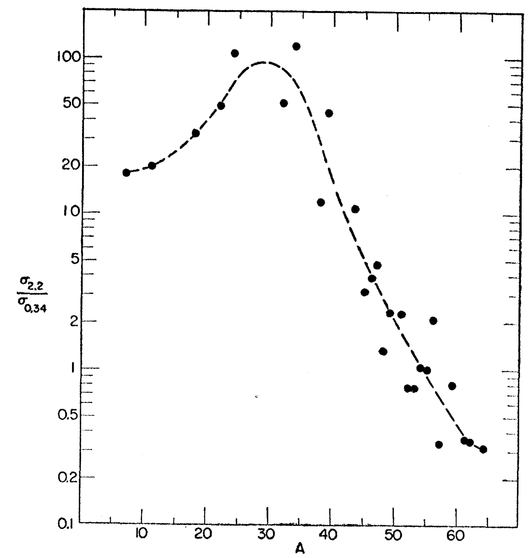

Fig. 1. Ratios of formation cross sections at 2.2-Bev proton energy to those at 340 Mev. The low-energy data are taken from references 5, 6, and 7. The points at $A=11$, 18, and 42 were obtained at 370 rather than 340 Mev (see reference 7).

somewhere in the region of $A=45$ to 50. This behavior may well be connected with a mechanism for energy deposition which involves production and reabsorption of mesons. Adding up all the measured and interpolated cross sections one arrives at an inelastic cross section for Cu of about 0.8 barn, in reasonable agreement with the value of 0.75 barn measured[8] with neutrons of average energy 1.4 Bev. This may be taken as evidence that the absolute cross sections reported here have probably somewhat smaller errors than the ± 50 percent quoted by Turkevich[4] for the $Al(p,3pn)Na^{24}$ cross section.

Table I. Cross sections (in mb) for the formation of nuclides in the bombardment of copper with 2.2-Bev protons.

Zn^{63}	0.4 –0.8[a]	Mn^{56}	2.3	Sc^{49}	<0.8[b,c]	S^{35}	0.95
Zn^{62}	0.16–0.6[a]	Mn^{54}	12[c]	Sc^{48}	2.4[c,d]	P^{33}	0.9[c]
Cu^{64}	7.2[c]	Mn^{52}	5.4	Sc^{47}	3.5[c,d]	P^{32}	6.4
Cu^{62}	17[c]	Mn^{52m}	1.6[c]	Sc^{46}	6.5[c]	Mg^{28}	0.41
Cu^{61}	6.5[c]	Mn^{51}	1.4	Sc^{44m}	5.0[c,d]	Na^{24}	3.2
Cu^{60}	1.8[c]	Cr^{51}	19	Sc^{43+44}	9.7[c]	Na^{22}	1.8[c]
Ni^{57}	0.6	Cr^{49}	2.2	Ca^{47}	0.10	F^{18}	1.0[c]
Co^{61}	3.6[c]	Cr^{48}	0.5	Ca^{45}	1.1	C^{11}	$\geq$0.65[e]
Co^{55}	1.5	V^{53}	<0.05[b]	K^{43}	1.3	Be^7	10
Fe^{59}	0.6	V^{49}	27	K^{42}	3.7		
Fe^{55}	12	V^{48}	9.6	Cl^{39}	0.40		
Fe^{53}	1.3[c]	V^{47}	2.7	Cl^{38}	0.67[d]		
Fe^{52}	0.19	Ti^{45}	2.5	Cl^{34}	0.89[d]		

[a] The Zn yields varied with target thickness, indicating that low-energy secondaries contribute to the production of these activities.
[b] These nuclides were not detected.
[c] Based on single run.
[d] Large uncertainty because of difficult decay curve analysis.
[e] $\sigma(C^{11})$ was found to be variable, depending on the chemical procedure used; the value given is the highest obtained. In this run the target was dissolved in a mixture of H_2SO_4, H_3PO_4, and CrO_3; and CO_2 was distilled out.

It may be noted that relative yields of members of isobaric pairs are not drastically different from those observed at lower bombarding energies; however, the contribution of the neutron-richer member of any pair is found to be consistently higher in the present work than in other spallation studies. Another striking feature is the large cross section for Be^7 formation, which almost certainly indicates a high probability for direct ejection of light nuclei.

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Gallium, Germanium, and Arsenic Nuclides Produced in the Bombardment of Copper with 2.2-Bev Protons*

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ALPHA particles and nuclei with charges greater than two have been shown[1] to be emitted in the bombardment of medium-weight nuclei with particles of energy greater than 100 Mev. Some of these ejected particles may be energetic enough to produce transtarget species by secondary nuclear reactions inside the bombarded target.[2,3] This communication reports on such nuclear reactions in copper bombarded with 2.2-Bev protons at the Brookhaven Cosmotron identified by the radiochemical isolation of isotopes of gallium, germanium, and arsenic.

The irradiations were carried out with a pulsed target[4] consisting of a copper foil which was usually at least 10 mil thick, with aluminum monitors in front and back. Gallium, germanium, and arsenic were isolated from an acid solution of the irradiated copper by standard procedures.[5] The radioactivity of each element was assigned to a particular isotope on the basis of the decay period. Consideration of the effect of possible impurities in the copper indicates that perhaps 10 percent of the arsenic radioactivity, but much less of the germanium or gallium, can have such an origin.

Table I summarizes the results on the nuclides found and the effective cross sections for their production in thick targets. For comparison, the yields reported in the 340-Mev bombardment of copper[2] are also given. It is seen that the gallium yields at 2.2 Bev are four times higher than those at 340 Mev, and that the germanium yields have increased by a factor of ten. Arsenic had not previously been reported as a result of such reactions. In the bombardment of tin with 350-Mev protons,[3] isotopes of iodine, of atomic number three larger than tin, were observed with cross sections of about 0.005 millibarn. These cross sections are anomalously high as compared to the analogous cross sections from copper even at the higher energy of 2.2 Bev.

One irradiation of a bare copper foil, 10.7 mg/cm² thick, gave an effective cross section for Ga^{66} 83 percent lower than that found in the thicker foil. Similarly, the cross section for Ge^{69} was 64 percent lower, but less than a 15 percent change was observed for As^{71} and As^{72}.

These gallium, germanium, and arsenic nuclides are interpreted as being formed by reactions of the type $Cu(Z,xn)$ with Z a helium, lithium, or beryllium nucleus formed by the primary interaction of the 2.2-Bev protons with copper, and x the number of emitted neutrons. The decreased production in the thin foil can be used to estimate the reaction distances of these fragments if it is assumed that they are formed isotropically in the target. The number of such reacting fragments produced per proton interacting with copper can then be calculated if some assumption is made about the cross section to give an observed product. For the $Cu(\alpha,n)$ reaction, Ghoshal's[6] cross-section curve for $Ni^{60}(\alpha,n)Zn^{63}$ was assumed. The yields of the $Cu(\alpha,xn)$ reactions were consistent with this analysis. For the lithium and beryllium reactions, cross sections to produce each observed product were assumed to be about 300 millibarns. Table I also lists the results of the calculations on the number and energy of the He, Li, and Be nuclei responsible for the reactions yielding Ga, Ge, and As nuclides, respectively. The calculated cross sections for production of the lithium and beryllium nuclei reacting are about 10 millibarns, amounting to about one percent of the proton interaction cross section. These high yields support the direct radiochemical evidence[4] of a marked increase in the production of mass numbers just above four at Cosmotron energies.

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TABLE I. Formation of transtarget nuclides in the bombardment of copper with 2.2-bev protons.

Nuclide	Half-life	Thick-target cross sections, millibarns 340 Mev	Thick-target cross sections, millibarns 2.2 Bev[a]	Interaction distance in copper, mg/cm²	Secondary particle assumed	Energy of secondary particle, Mev	Yield of reacting secondaries, millibarns
Ga^{66}	9.45 hr	0.01	0.04 }	136	$_2He$	35	~300
Ga^{67}	67 hr	0.006	0.06[b] }				
Ga^{68}	68 min	0.01	0.04				
Ge^{66}	2.5 hr	~0.0001	<0.000035				
Ge^{67}	21 min	~0.0001	<0.0018[c]				
Ge^{69}	40 hr	~0.0001	0.0011	41	$_3Li$	40	~10
As^{70}	52 min	...	<0.000063[c]				
As^{71}	60 hr	...	0.00021[c] }	<6	$_4Be$	<30	~10
As^{72}	26 hr	...	0.00020[c] }				

[a] These cross sections are based on a cross section of 6.0 millibarns for Cu^{64}, and 9.0 millibarns for Na^{24} from aluminum [Hudis, Wolfgang, Sugarman and Friedlander, Phys. Rev. **94**, 775 (1954)].
[b] The counting efficiency of this K-capture nuclide is particularly hard to estimate.
[c] Decay assumed to be entirely by positron emission.