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.