Tritium Production by 2.2-Bev Protons on Iron and Its Relation to Cosmic Radiation*

E. L. FIREMAN
Brookhaven National Laboratory, Upton, New York
(Received November 19, 1954)

The cross section for tritium production by 2.2-Bev protons on iron is measured to be 62±7 mb. This tritium cross section indicates that $(1.4\pm0.4)\times10^{-3}$ tritons/g sec would be produced in small iron meteorites (a few inches in radius) in space by cosmic rays of the intensity of those striking the earth's polar regions. In 4×10^9 years, $(6\pm2)\times10^{-6}$ cc of He^3 per gram of iron results from this cosmic-ray tritium. Mount Ayliff meteorite contains 11.5×10^{-6} cc of He^3 per gram, indicating its bombardment by a cosmic-ray flux at least as intense as is presently striking the earth. The variation of tritium with target depth is also measured and indicates a decrease less rapid than an attenuation due to geometric cross section.

INTRODUCTION AND SUMMARY

THE proposal[1] that cosmic rays produce appreciable helium in meteorites has led to the discovery[2] of meteoritic He^3 and the investigation of the variation of this helium with depth.[3]

The measurement of the tritium production by high-energy protons in meteoritic materials is a related problem.[4] The tritium cross section for 2.2-Bev protons on iron is measured to be 62±7 mb; the corresponding cross sections for oxygen and nitrogen[5] are 33±4 mb and 28±4 mb. For these three elements the tritium production cross sections are approximately 10 percent of the geometric cross sections. If meteorites in space are bombarded by an omnidirectional cosmic-ray flux of the character of the cosmic-ray primaries striking the earth above 55°N latitude[6] and if the tritium production cross section is the same for each bombarding nucleon, then $(1.4\pm0.4)\times10^{-3}$ tritons/g sec are produced in small iron meteorites. During the course of time, which is taken as 4×10^9 years, $(6\pm2)\times10^{-6}$ cc of He^3 per g iron would result. A smaller quantity[7] of additional He^3 is produced directly.

The measurement[2] of He^3 in iron meteorites gives 11.5×10^{-6} cc/g for the Mount Ayliff meteorite and lower values for four other iron meteorites. The Mount Ayliff He^3 is just consistent with its bombardment for 4×10^9 years by cosmic rays equivalent to those presently striking the earth's polar regions. Any loss of He^3 from the meteorite or shielding by ablated material would require a more intense bombardment of this meteorite in the course of its travels. The smaller He^3 content[2] in the four other meteorites can be explained in terms of either the shielding by ablated material, the loss of He^3, a younger age, or their bombardment by less intense cosmic rays.

The stony meteorites[8] (chondrites) are composed primarily of oxygen (35 percent), iron (25 percent), silicon (18 percent), and magnesium (14.5 percent). If the measured tritium cross sections are used for oxygen and iron and tritium cross sections 10 percent of geometric are used for other elements, then the cosmic-ray tritium production in a gram of chondrite is 30 percent greater than in a gram of iron.

The variation of tritium yield with target depth in iron is given in Fig. 1. This yield appears to decrease less rapidly than an attenuation of the proton beam due to an interaction of geometric cross section. Since the total thickness of the target used is only 1.80 in., an extrapolation is necessary for the estimation of the shielding by larger thicknesses of iron. The measurement[3] of the variation of helium content with meteoritic depth has been done for several meteorites. It is difficult to say whether the results are in agreement because the reported measurements[3] are on the total helium content and because of our target size. A comparison of the variation with depth in iron with that in oxygen[5] indicates that the tritium yield decreases less rapidly with depth in iron than in oxygen.

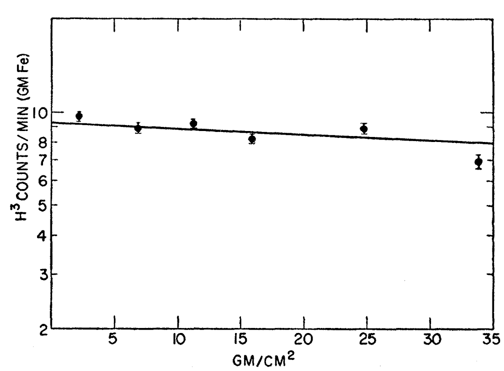

FIG. 1. Variation of tritium with target depth. The errors shown are standard deviations in the counting.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] C. A. Bauer, Phys. Rev. **72**, 354 (1947); **74**, 225 and 501 (1948); H. E. Huntley, Nature **161**, 356 (1948).

[2] Mayne, Reasbeck, and Paneth, Geochim. et Cosmochim. Acta **2**, 300 (1952).

[3] Chacketts, Reasbeck, and Wilson, Geochim. et Cosmochim. Acta **3**, 261 (1953).

[4] S. F. Singer, Nature **170**, 728 (1952); Phys. Rev. **90**, 168 (1953).

[5] E. L. Fireman and F. S. Rowland, Phys. Rev. **97**, 780 (1955).

[6] Data taken from Table II of Winkler, Stix, Dwight, and Salwin, Phys. Rev. **79**, 656 (1950).

[7] Martin, Thomson, and Wardle, Phil. Mag. **452**, 410 (1954).

[8] H. C. Urey and H. Craig, Geochim. et Cosmochim. Acta **2**, 36 (1953).

Table I. Summary of experimental data. The errors given are standard deviations in the counting.

Position No.	Average sample depth g/cm^2	Sample[a] weight g	H^3 counts/min	No. Tritons $\times 10^{-8}$	(No. H^3/No. Fe) $\times 10^{15}$	σ(mb)[b]
1	2.24	4.38	42.4±1.2	5.2±0.5	11.0±1.1	69±7
2	6.72	8.09	71.7±1.5	8.7±0.8	10.1±0.9	64±6
3	11.20	8.09	74.6±1.5	9.1±0.8	10.5±0.9	66±6
4	15.68	8.00	65.5±1.5	8.0±0.8	9.3±0.9	59±6
6	24.64	7.91	70.5±1.5	8.6±0.8	10.1±0.9	64±6
8	33.60	7.99	56.0±1.5	6.9±0.7	8.0±0.9	50±5
Calibration		···	36.2±1.0	4.4±0.3		

[a] All samples 4.48 g/cm^2 thick.
[b] No. protons/cm^2 $=1.6\times 10^{11}$.

Theoretical calculations[1,4,9] of a depth effect have been attempted; the most quantitative of these[9] does not appear to be in good agreement with our measurements.

EXPERIMENTAL DISCUSSION AND RESULTS

A. Target.—The target consists of a stack of 8 sheets of hot-rolled steel, 0.225 in. thick with 1 in.×4 in. faces, which are irradiated for 20 minutes in the internal beam of the Brookhaven Cosmotron. The beam strikes the 1 in.×4 in. face and passes through the 8 sheets of steel. A $\frac{1}{8}$ in. lip of Lucite projects $\frac{1}{4}$ in. from the target; this lip intercepts the beam and scatters it more uniformly over the face of the target on the next traversal.

B. Tritium Assay.—Samples of about 8 g are cut from the center of each steel sheet of target. Care is taken to prevent heating of the steel in cutting. The samples are heated to about 1800°C by an induction heater in an atmosphere (1.0-cm Hg pressure) of carrier hydrogen. In the first minutes of heating CO, N_2, and H_2 are released from the iron, raising the pressure in the furnace to about 15 cm Hg. During the next hour, the CO reacts with the molten iron and the pressure falls to 3 cm Hg. With the sample at 1800°C, the gas is pumped from the furnace. By three hours of pumping all the gas is extracted from the furnace; during the pumping about $\frac{1}{4}$ g of iron evaporates to the furnace walls. To test the completeness of the tritium extraction, several samples were subjected a second time to this procedure with negative results.

[9] G. R. Martin, Geochim. et Cosmochim. Acta **3**, 288 (1953).

The hydrogen is removed from this gas by its passage through palladium. A 16-cc Geiger counter is filled to 10–18 cm pressure with this hydrogen; 2.5 cm of ethyl acetate is added to the counter for quenching. The counting is done in a low-level counting facility[10] which reduces the background of this counter to 1.20±0.10 counts/min. The data are given in Table I. The tritium yield is about 1.0×10^8 tritons/gram of iron with the front sample giving a somewhat higher yield and the rear sample a somewhat lower yield. Figure 1 shows the variation of tritium activity with target depth. The decrease appears to be somewhat less than would be given by an attenuation of the incident beam by an interaction of geometric cross section. The average value of the tritium production cross section in our target is 62±7 mb.

C. Proton Monitor.—The proton flux is measured by the Na^{24} production in 0.003-in. aluminum monitor foils on the front and back of the target. The cross section for this reaction[11] is 9.0 mb for 2.2-Bev protons. The errors given do not include any errors in this measurement, but represent errors relative to this cross section. A 20 percent correction to the front foil and 50 percent to the rear foil is necessary because of the Na^{24} produced by secondary neutrons from the target by the (n,α) reaction on aluminum. This monitor indicates that 1.6×10^{11} protons/cm^2 strike the center of the target during the 20-minute irradiation. The total number of protons striking the target is 1.5×10^{12}.

The author is indebted to Mr. Donald Schwarzer who assisted in all phases of the experiment and to the Cosmotron staff for the irradiation.

[10] The author wishes to thank Dr. R. Davis for the use of this facility.
[11] A. Turkevich, Phys. Rev. **94**, 775 (1954).