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Depth Variation of Tritium and Argon-37 Produced by High-Energy Protons in Iron*

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The H^3 produced by 0.16-, 1.0-, 3.0-, and 6.2-Bev protons and the A^{37} by 0.16-, 1.0-, and 6.2-Bev protons in long iron targets is measured as a function of depth. The maximum effective H^3 cross section is 7.2 mb at 0.16 Bev, 60 mb at 1.0 Bev, 100 mb at 3.0 Bev, and 130 mb at 6.2 Bev. The maximum effective A^{37} cross section is 0.19 mb at 0.16 Bev, 4.7 mb at 1.0 Bev, and 6.7 mb at 6.2 Bev. The depth variation of these isotopes is very energy-dependent. At the higher energies a slight transition effect occurs. At the lower energies there is an exponential decrease with depth. The comparison of these measurements with the depth variation of He^3 in the Carbo meteorite shows that the cosmic rays that produced the He^3 in this material were very similar to the protons with 6-Bev energy. The H^3 to A^{37} ratio is not very energy- or depth-dependent. The ratio is 15 at 1 Bev and 20 at 6.2 Bev. However, for 0.16-Bev protons the H^3 to A^{37} ratio increases from 40 to 1000 in 4-cm depth. The H^3 to A^{37} ratio is compared with the He^3 to A^{36} ratio in four iron meteorites. These are comparable to a remarkable extent with the Bev proton results. The small variation of the He^3 to A^{36} ratio in meteorites is related to the fact that the H^3 to A^{37} ratio is not very energy- or depth-sensitive for protons in the Bev range; however, the He^3 to A^{36} ratio also favors the 6-Bev energy.

I. INTRODUCTION

The first discussion[1] of the production of spallation isotopes in meteorites by cosmic rays suggested that these isotopes should have a depth variation. The existence of spallation isotopes in meteorites is now established by measurements of their high He^3 contents,[2–7] their high He^3 to He^4 ratio,[2–5] the H^3 in recent meteorite falls,[6,7] the anomalous ratio of the neon isotopes,[8] the anomalous A^{36} to A^{38} ratio,[4,5] the proportionality of He^3 to A^{36},[4,5] and the lack of proportionality of He^3 to Li^6.[6,7] However, little has been done on the depth variation of the spallation isotopes. This gives information on the energy of the incident cosmic rays and the ablation of material from the meteorites during their passage through the atmosphere.

The previous measurements of He^3 produced by high-energy protons were done with short targets.[9,10] Previous measurements of A^{37} were done with copper foils.[11] It was necessary to do these measurements in much longer iron targets and to measure the H^3 to A^{37} ratio in the same samples in order to draw conclusions about the energy of the cosmic rays in extraterrestrial space and about the ablation of material from the meteorites. Long target measurements can also be used to gain information about the secondary and shower particles produced in high-energy interactions. There is a calculation[12] of shower effects but there are no target measurements for direct comparison with this calculation.

The depth variation of He^3 in the Carbo meteorite has been measured.[13] The He^3 to A^{36} ratio in five iron meteorites[4,5] has also been measured. These results are combined with our measurements to determine some facts about the energy of the bombarding particles in extraterrestrial space and the distribution of material ablated from the Carbo meteorite.

II. EXPERIMENTAL DISCUSSION

A. Targets—Two iron targets of 9.2-in. length, 1.5-in. height, and 1.0-in. width were irradiated by 1.0-Bev and 3.0-Bev protons in the internal beam of the Brookhaven Cosmotron, one target of 8.2-in. length was irradiated by 6.2-Bev protons in the internal beam of the Berkeley Bevatron, and one target of 2.5-in. length and 0.75-in. width and height was irradiated by 158-Mev protons in the Harvard cyclotron. The length of the targets were limited by the opening to the vacuum chambers. A $\frac{1}{8}$-in. thick Lucite lip projects $\frac{1}{4}$ in. from the rear of the Cosmotron and Bevatron targets; this lip intercepts the proton beam and scatters it more uniformly over the target face on the next traversal. The 6.2-Bev, 3.0-Bev, and 1.0-Bev irradiations were one-hour bombardments. Figure 1 is a drawing of

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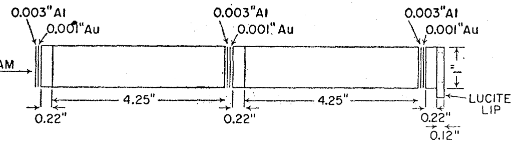

FIG. 1. Cosmotron iron target.

these targets. The 158-Mev target was irradiated for three hours.

B. Flux monitors.—The flux was measured by the Na^{24} produced in 0.003-in. aluminum foils and by the Tb^{149} produced in 0.001-in. gold foils.

The $p+Al^{27}\rightarrow Na^{24}+(3p,n)$ reaction has a 10-mb[14,15] cross section at 1.0, 3.0, and 6.2 Bev and a 9-mb[16] cross section at 158 Mev. Evaporation neutrons also produce Na^{24} from Al.

The $p+Au^{197}\rightarrow Tb^{149}+(15p,34n)$ reaction[17] has a threshold of 0.6 Bev; its cross section rises to a maximum of 1.9 mb for 1.6-Bev protons, decreases to 1.3 mb for 3.0 Bev, and to 1.0 mb for 6.2 Bev. This reaction is not affected by evaporation neutrons.

The proton flux obtained from the Na^{24} activity corrected for the effect of evaporation neutrons (a factor of 0.56 at 6.2 Bev, 0.61 at 3.0 Bev, 0.74 at 1.0 Bev, and 0.94 at 158 Mev) is 3.1×10^{12} protons for the 6.2-Bev irradiation, 4.1×10^{12} protons for the 3.0-Bev irradiation, 3.8×10^{13} protons for the 1.0-Bev irradiation, and 1.1×10^{15} protons for the 158-Mev irradiation. These numbers are slightly smaller than the values obtained from the beam integrator.

The results obtained from the Tb^{149} activity in the gold foil are 3.1×10^{12} protons for the 6.2-Bev irradiation and 4.1×10^{12} protons for the 3.0-Bev irradiation. The distribution of the beam over the target face, middle, and rear is obtained by counting eight sections of each foil.

C. H^3 *and* A^{37} *measurements.*—Samples of about 8 g mass are taken from different depths along the beam direction. Care is taken to prevent heating of the iron in cutting. The sample is placed in a water-cooled Vycor furnace. The sample is melted by an induction heater with 2 cc STP of carrier hydrogen and 2 cc STP of carrier argon. The melted sample remains with the carrier gas for ten minutes; the gas is then pumped from the furnace and hot sample for twenty minutes. The gas is then forced into a palladium unit where the hydrogen is extracted by its passage through the palladium. The hydrogen is put into a Geiger counter and counted. The H^3 activity in the counter is high so that no shielding is necessary. The counter volume is 17 cc and its counting efficiency is 83%. For good counting characteristics 20 cm pressure of a standard argon ethyl-acetate filling is added to the hydrogen. To test if any tritium remained in the sample, furnace, or palladium, all samples are melted a second time with the same extraction procedure. The second run gives about 10% of the activity of the first run. No additional tritium is found after cracking the gas over a hot tungsten filament.

The gas that does not pass through the palladium is put into a calcium furnace at 600°C; the calcium cools in contact with the gas. This procedure removed everything except the noble gases. To insure that all traces of tritium and hydrogen are removed, the gas is put into a CuO furnace at 450°C with a connected liquid-air trap. The argon is absorbed on charcoal at liquid-air temperature and then put into the Geiger counter with a standard filling. The tritium and argon measurements were done about five months after the 6.2-Bev irradiation, and one month after the 1.0-Bev and 158-Mev irradiations. The argon activity exhibited a 35-day half-life. The measurements on the 3-Bev target were done 15 months after the irradiation. Only the tritium was measured since the A^{37} had disappeared; it would be interesting to measure the A^{39} activity in this target.

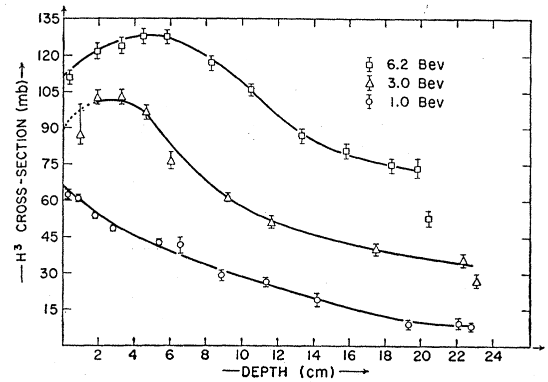

FIG. 2. Depth variation of tritium.

The tritium production cross sections as a function of depth for 1.0, 3.0, and 6.2 Bev are plotted in Fig. 2. The 1.0-Bev curve shows a smooth exponential decrease with depth. The 3.0-Bev curve shows a slight initial rise and smooth exponential decrease after 4-cm depth. The 6.2-Bev curve decreases after 7-cm depth. The maximum effective cross section increases from 65 mb at 1 Bev to 128 mb at 6.2 Bev. The tritium cross section for 158 Mev decreases rapidly with depth from an initial value of 7.2 mb to 0.63 mb at 3.8 cm.

The A^{37} production cross section as a function of depth for 1.0 and 6.2 Bev is plotted in Fig. 3. The A^{37} cross section curves are similar to the tritium curves. At 158 Mev, however, the A^{37} decreases much more rapidly with depth than the H^3. The initial A^{37} cross section is 0.19 mb and at 3.8 cm it is 0.66×10^{-3} mb. At 6.2 Bev the H^3 to A^{37} ratio is 20 except for the first

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two cm where it rises to 30. At 1.0 Bev the H^3 to A^{37} ratio is 15 and practically constant with depth. At 158 Mev the H^3 to A^{37} ratio starts at 40 and rises rapidly to 950 at 3.8-cm depth.

The statistical counting errors are given by the lines through the points. The distribution of Na^{24} and Tb^{149} activity in the front, middle, and rear foils indicates that the targets were well aligned with the beam direction and that the spreading out of the beam with depth is small. The proton-beam monitors have an uncertainty of 20% which could affect the absolute magnitude of the cross section and the relative heights of the curves but not the shape of the curves.

There have been two previous experiments[9,10] on the tritium production by high-energy protons on iron. One was done with a 4.5-cm target consisting of a stack of 8 sheets each 0.57-cm thick. The other was done with a 0.22 cm and 0.62 cm target at 2.05 Bev and a 0.05 cm target at 450 Mev. There is good agreement with the previous results.

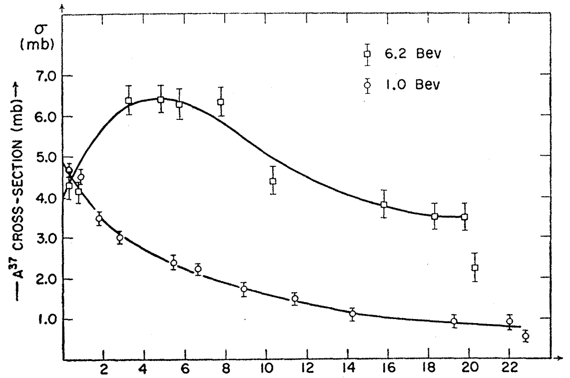

FIG. 3. Depth variation of argon-37.

There is a drop in activity in the last section of the targets. This effect increased with energy and may be partly due to the loss of secondary particles.

III. APPLICATIONS

The measurements give the depth variation of H^3 and A^{37} in a one-dimensional situation. If the lateral shower spread is small as the measurements indicate, then the target results can be integrated for an omnidirectional flux striking a solid iron body. This integration was done for spheres of 11.5-cm and 30-cm radius. Figure 4 shows the tritium distribution in these spheres for 1.0-, 3.0-, and 6.2-Bev protons. If meteorites in extraterrestrial space were spheres, the contours of constant He^3 would be concentric spheres. The minimum He^3 content would be at the center for large spheres (greater than 15-cm radius). For smaller spheres the He^3 content at the center is either a maximum or a minimum depending upon the energy distribution of the bombarding particles. If meteorites in extraterrestrial space were of irregular shape, the contours of constant He^3 would also be irregular following somewhat the shape of the meteorite.

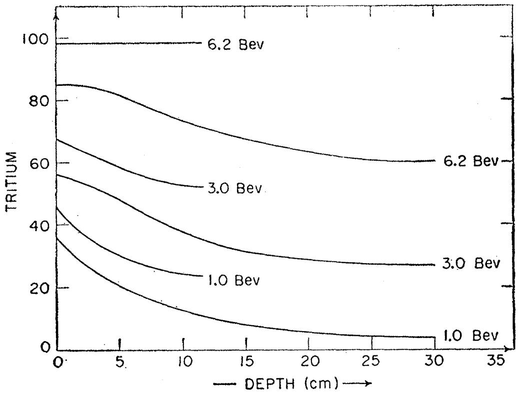

FIG. 4. Tritium produced in spheres of 11.5- and 30-cm radius.

The depth variation of He^3 in the Carbo meteorite[13] has been measured in two perpendicular holes. The He^3 in hole *A* varies from 4.93×10^{-6} cc/g at 0.5 cm to 4.12×10^{-6} cc/g at 9.5-cm depth. The slow gradient of He^3 indicates that cosmic-ray particles give an effect similar to what would be obtained from 6-Bev protons. Hole *A* is surrounded by a considerable amount of material in the other directions so that the slow decrease of He^3 in the 9.5 cm could not be due to side effects. At 17 and 28.5-cm depth the He^3 is 3.76×10^{-6} cc/g and 3.65×10^{-6} cc/g. In this region hole *A* passes within 3 cm of a side surface so that there must have been additional shielding material on this side surface that was ablated or broken away. The shape of Carbo during its cosmic-ray bombardment seems to have been quite different than its present shape. In hole *B* the He^3 has been measured at only four depths and is 4.29×10^{-6} cc/g at 0.5 cm, 4.53×10^{-6} cc/g at 3 cm, 4.17×10^{-6} cc/g at 12 cm, and 3.84×10^{-6} cc/g at 19.5 cm depth. The indication of a transition effect in the first 3 cm of hole *B* is inconsistent because the first 3 cm of hole *A* has higher He^3 values and no transition effect. The small variation of the He^3 with depth in hole *B* also favors the high energy of the bombarding particles but further measurements should be done to resolve the inconsistency. Additional measurements on the Carbo meteorite are planned in order to get more information on its original shape and on the nature of the bombarding particles.

The ratio of H^3 to A^{37} as a function of depth and energy in the iron targets is another source of information. The ratio[4,5] of He^3 to A^{36} for Henbury is 25:1, Cerros de Buei Muerto is 20:1, Toluca is 23:1, and the iron phase of Imilac is 24:1. The A^{37} production rate should be less than the A^{36} production rate which includes the Cl^{36} decays. We shall take the A^{37} production to be one-half the A^{36} production. The He^3 in meteorites is the sum of the H^3 and direct He^3 production. The ratio of directly produced He^3 to H^3 for 340-Mev protons on iron[18] is 0.6. This ratio increases with energy but cannot exceed 1.0. We shall use 0.8 at 1 Bev and 1.0 at 6 Bev. The He^3 to A^{36} ratio is then 0.9 H^3/A^{37} at 1 Bev and equal to the H^3/A^{37} ratio at 6 Bev. With this correction factor the He^3/A^{36} in meteorites for 1-Bev particles should be about 14 and for 6-Bev particles should be about 30 for small depths and decrease to 20 at about 20 cm depth. The measured He^3/A^{36} ratios for the four iron meteorites favor the 6-Bev irradiation.

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Interaction of K^+ Mesons in the Interval 30–65 Mev*

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A systematic study of the scattering of 1173 definitely identified K_L mesons and 279 τ (including τ') mesons has been made in the energy interval 30–65 Mev using photoemulsion exposed to the Berkeley K^+ meson beam. All scatterings of K^+ mesons having a projected angle greater than 2° on the emulsion plane were recorded and analyzed. The results of analysis are the following: (1) the interaction properties of the K_L and τ mesons are essentially indistinguishable; (2) the coherent nuclear scattering of K^+ mesons interferes constructively with the Coulomb scattering; (3) in terms of the optical model, the best fit for coherent scattering corresponds to a real potential of $\sim+15$ Mev, and the inelastic scattering gives an imaginary potential of ~3.6 Mev; (4) charge exchange is rare in this energy region: σ(charge exchange)/σ(incoherent) $<\frac{1}{10}$. A tentative interpretation of the results in terms of states of isotopic spin $T=0$ and $T=1$ is presented. A discussion is also given on the characteristic features of K^+ stars.

I. INTRODUCTION

IN the past two years a large amount of experimental data on K^+ mesons has been obtained by different laboratories utilizing artificially produced K^+ mesons. The data have been related to the intrinsic properties of the K^+ mesons, such as mass, lifetime, spin, and parity. However, the present status of our knowledge about the nuclear interaction properties of these particles is still incomplete. With the advent of the hydrogen bubble chamber, it is now possible to attempt a direct investigation of the K^+-p interaction, and yet, at the present stage, in lieu of any K^+-d investigations, information relevant to the K^+-n interaction can only be obtained through a study of K^+ nuclei interactions. An experimental tool quite useful for this purpose is nuclear emulsion.

A general survey on the properties of the interactions of K^+ mesons has been presented at the Sixth Rochester Conference by Goldhaber and Dallaporta.[1] Since then, a considerable wealth of new data has been accumulated by different groups working with artificially produced K^+ mesons: Bologna,[2] Bristol,[3] Göttingen,[4] Padova,[5] Berkeley,[6] M.I.T. and Harvard,[7] Brookhaven,[8] and Rochester.[9]

The difficult problem which is posed in the use of photoemulsion for the investigation of the K^+ inter-

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