Production of He^6 by High-Energy Protons*

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Excitation functions have been obtained for the production of He^6 in the interactions of high-energy protons with various targets. The cross sections rise with increasing energy and increasing Z, varying between 0.5 mb for C at 1.0 Bev and 29 mb for Pb at 3.0 Bev.

INTRODUCTION

HIGH-ENERGY protons interacting with various targets create few readily-measured radioactive isotopes with $Z<5$. Cross sections have been obtained for H^3 and Be^7 production, from several target elements.[1–7] The excitation functions of He^6 formation by protons of 1 to 3 Bev have been measured for five target elements in order to extend the information on low-Z products of such reactions. The cross sections have been measured by a new technique based on nuclear recoil, which obviates the difficulties introduced by the 0.82-sec half-life.

EXPERIMENTAL

The principal experimental problem in measuring the yield of He^6 in high-energy bombardments is the necessity for separation and purification of the isotope, and introduction into a counter within approximately one second. These steps have been accomplished by using a target composed of alternating plates of the target element and gas spaces filled with a "catcher" gas. The proton beam passed through both the plates and gas spaces, and the recoil energy of the isotopes produced in the plates carried some of each species into the gas. Immediately after production of the radioactivity, the gas was allowed to flow through a liquid nitrogen trap into a nearby evacuated counter chamber and the decay was followed with a scaler and Brush recorder. This counter chamber was specially designed to hold 400 cm^3 of gas in the center space of a sandwich arrangement, where it was counted with good efficiency by the two outer spaces operating as proportional counters.

Under typical conditions, with helium as the catcher gas, the decay curves were readily analyzed into He^6 and one or more long-lived components. The identity of the latter was not always clear, but often contained 19.1-second C^{10} (presumably as CO) and the neon isotopes Ne^{19} and Ne^{23}. In every case, the He^6 decay stood out clearly, enabling an accurate measurement of its activity. The counting rate of He^6 varied from 1 to 3 orders of magnitude higher than the background. The background activity showed a negligible decay over a period of one minute following a pulse. A more detailed description of the target and counter, and a discussion of the method have been given elsewhere.[8]

The activity due to He^6 (and to any other isotopes present) was determined for targets made of graphite, aluminum, copper, silver, and lead, at several energies from 1.0 to 3.0 Bev. For most measurements helium was used as the catcher gas, although hydrogen, propane, and nitrogen were also used in certain experiments. For each target material at each energy, several measurements were made at various pressures in the target from 5 to 150 lb/in^2. The reproducibility of duplicate runs was about $\pm 5\%$.

CALCULATION OF CROSS SECTIONS FROM RECOIL YIELDS

Conversion of the measured He^6 activities into cross sections requires a knowledge of the relative stopping powers of helium and the target material for helium ions. In addition, some relationship is needed for the variation in yield of He^6 *versus* pressure of stopping gas. Such a relationship may be greatly simplified if the recoil range of the isotope is long compared to the layer of stopping gas, but short compared to the thickness of target material. In that case, the He^6 activity measured in the gas should increase linearly with pressure, and the cross section can be directly calculated from the formula:

$$R \times N = \sigma f n, \tag{1}$$

in which N = number of atoms of product isotope formed per unit time (unit time being short compared to half-life), σ = cross section in cm^2, f = number of impinging particles per unit time, n = number of catcher gas atoms/cm^2, and

$$R = \frac{\text{atomic stopping power of target atoms}}{\text{atomic stopping power of catcher gas atoms}}.$$

Deviations from linearity could be observed if either (a) the value of R changes sharply with the energy of

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the recoiling particle, or (b) the recoil range of the particle was not long compared to the path length in the gas.

Experimentally, the plots of He^6 activity *versus* pressure always gave a straight line as shown in Fig. 1, implying the absence of these causes of deviation within the experimental errors involved. The activity of He^6 does not go to zero for zero pressure on these plots because of diffusion of He^6 from the target plates into the gas spaces before opening of the solenoid and release of the stopping gas.[8] The cross sections listed in Table II have been calculated on the basis of the slope of the linear plots, as representative of the portion of the yield due to actual stopping by the gas.

Atomic stopping powers, of course, show large variations for different energies of incident ions, and these changes do not necessarily cancel out in calculating a ratio of atomic stopping powers for two different elements. However, the value of R which is desired for formula (1) is actually a complex average ratio of atomic stopping powers. The ions recoiling into and out of a catcher gas will do so at all angles relative to the surface of the target material. The angular distribution of these recoil paths relative to the surface will then depend on the angular distribution of the initial recoil emission, as well as subsequent scattering events both in the target and in the catcher gas. As a result, the energy expenditure for ions stopping in a catcher gas will show a wide distribution, including energies above that necessary to penetrate the minimum gas path length, and most of the variations in ratio will be averaged out.

We have calculated values of R which appear to be appropriate for these experiments from available range-energy data,[9–12] and an assumption of isotropic emission of recoils. These are collected in Table I. The tenfold increase of pressure shown in the figures requires that this average ratio be calculated for steadily increasing average energy losses of the stopped ions. A monotonic change of R with average energy loss would very likely be concealed in a linear plot of the type shown in Fig. 1. However, our calculations indicate that any such changes in R would be quite small compared to other errors involved in the He^6 cross sections.

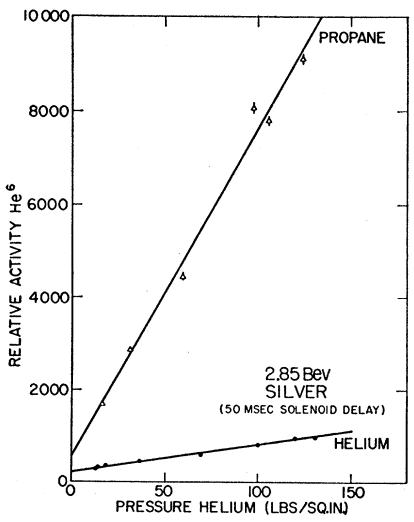

FIG. 1. He^6 recoil yield from silver at 2.85 Bev as a function of helium and propane catcher gas pressure.

RESULTS AND DISCUSSION

The observed cross sections for He^6 production are given in Table II. All cross sections are measured relative to the cross section of the $Al^{27}(p,5p5n)F^{18}$ monitor reaction and related through that reaction to an absolute cross section of 10.8 mb for $Al^{27}(p,3pn)Na^{24}$ in the energy region 1.0–3.0 Bev.[13–16] Possible errors are thus introduced in the ratios He^6/F^{18} and F^{18}/Na^{24}. There is also an uncertainty in the efficiency to be used for the large counter for two reasons: the counter efficiency has been accurately calibrated at 38% for pile produced A^{41}, but not for the higher energy beta particle of He^6; and not all of the gas from the target eventually reaches the counter. We have assumed that the efficiency is the same for He^6 as for A^{41} and that the activity is distributed uniformly through the gas after the solenoid is opened.

TABLE I. Relative atomic stopping powers of targets for He^6.

Target	R (Relative stopping power per atom; He = 1.0)	Number of mg/cm² equivalent to 1 cm Hg at 15°C, 1 atmos
C	2.2	0.23
Al	3.6	0.32
Cu	6.0	0.45
Ag	7.6	0.60
Pb	8.8	1.00

The estimated limit of error for the absolute cross sections in Table II, based on these possible errors, is ±50%. The errors in counting efficiency will cancel out and the uncertainties from the monitor reaction will be greatly reduced in relative cross sections. The comparison of cross sections for different elements at the same energies reflects linearly any error made in the values of R assumed in Table I. This uncertainty is larger for high Z, where it might be as high as 25%. Errors in the shape of the excitation function for any given

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element will depend primarily on possible errors in the monitoring reactions. These relative cross sections are estimated to be good to about ±15%.

The cross section for H^3 production in high-energy reactions is roughly proportional to the geometric cross section for targets of $Z=6$ to 82,[5–7] and increases with increasing bombarding energy. At 2.2 Bev, the tritium production cross section is about 10% of geometric.[7] In all targets from Al to Au, the excitation functions for Be^7 production also rise with increasing energy.[1–4] The Be^7 cross sections are from 1–10 mb at 2.2 Bev for all of these elements.[3] The results in Table II show that the He^6 cross sections are comparable to or larger than the corresponding Be^7 cross sections for Al and heavier targets. The ratio H^3/He^6 appears to be approximately constant (at ~15) in all cases.

The major production process for all three isotopes from medium to heavy target nuclides is assumed to be evaporation from the excited nucleus left following the initial high-energy events. Monte Carlo calculations, based on the evaporation model and using excitation energies from Monte Carlo calculations of the high-energy processes,[17] account for the observed yields within the rather wide limits of error of both experiment and calculation.[18]

The cross section for Be^7 production from carbon is 10–12 mb at all energies in the range 0.34–3.0 Bev, and it has been suggested that the Be^7 is produced as a residue of the high-energy process, rather than by ejection as an entity.[1,3] The cross sections for production of He^6 from carbon are lower than those for Be^7 production by a factor of 20, and also do not change radically with bombarding energy. This lower cross section is plausible since production of He^6 as a residue of reactions such as $C^{12}(p,p2He^3)He^6$ or $C^{12}(p,3p\alpha)He^6$ is much less likely than the production of Be^7 in a reaction such as $C^{12}(p,p\alpha n)Be^7$.

TABLE II. Cross sections (in millibarns) for He^6 production in high-energy proton bombardments.

Target \ Energy (Bev)	1.0	1.9	2.85
C	0.5	···	0.6
Al	1.1	1.3	···
Cu	2	4	4
Ag	4	7	12
Pb	10	21	29

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Interaction of 1.5-Bev Negative π Mesons with Emulsion Nuclei*†

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The energy spectrum of charged pion secondaries, produced from emulsion nuclei by bombardment with 1.5-Bev negative pions, has been measured. The spectrum was observed to be sharply peaked for pions of laboratory energies from 100 to 150 Mev. The mean pion energy was 148 Mev, and 75% of the pions were in the energy range from 50 to 150 Mev. The observed number of charged pions per star was 0.66. Half of the emulsion stars had no meson track, 36% had a single meson, 12% two mesons, and 2% more than two mesons. The experimental results have been compared with Monte Carlo nuclear cascade calculations.

INTRODUCTION

FOR the most part, investigations of fundamental pion-nucleon interactions at high energies have now been performed. One might then ask whether this information can be used to describe the interaction of high-energy pions with nucleon complexes, such as nuclei. Can one assume, as has been done successfully in analyzing interactions of high-energy nucleons with nuclei, that individual pion-nucleon processes can be followed within nuclei as nuclear cascades?

Investigations of moderately high-energy pions (0.5–0.75 Bev) with nuclei, however, have shown that there are features of the inelastic processes which are difficult to understand on the basis of individual pion-nucleon

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