The Production of Charged Photomesons from Helium. Hydrogen-Helium Ratios. II

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A study similar to that made by the same authors on hydrogen and deuterium has been made of charged photomesons produced from helium. Measurements were made at the three angles of 45°, 90°, and 135°. π^+ mesons were detected by scintillation counters and delayed coincidence detection. π^+ and π^- mesons were detected with Ilford C2-200μ nuclear emulsions. The π^-/π^+ ratios are 0.99 ± 0.15, 1.07 ± 0.17, and 0.91 ± 0.13 for angles of 45°, 90°, and 135°, respectively. The total cross section for π^+ meson production is $4.8\pm1.0\times10^{-29}$ cm^2 proton^{-1} Q^{-1} for helium as compared to $10.3\pm2.1\times10^{-29}$ for hydrogen. This indicates that a proton in helium is about one half as effective as a free proton for the photoproduction of π^+ mesons. A comparison is made of the π^+ meson production from hydrogen, deuterium, helium, and carbon.

I. INTRODUCTION

PART I[43] presents data for the reactions

$$\gamma+n\rightarrow\pi^-+p \quad (1)$$

$$\gamma+p\rightarrow\pi^++n \quad (2)$$

when the nucleons involved are either free or weakly bound. This paper presents data for reactions (1) and (2) when the production nucleons are strongly bound in the helium nucleus. Experiments on carbon and other elements[1–12,44] have indicated that (1) and (2) decrease as $A^{-\frac{1}{3}}$ for bound nucleons. Experiments on the ratio of (1) to (2) have indicated that the ratio is quite dependent on the nucleus containing the nucleons.[3,8,12,44,45]

The present paper presents the ratio of (1) to (2) for helium as well as the ratios of the cross sections of hydrogen, deuterium, helium, and carbon. The carbon data is that of Peterson, Gilbert, and White.[3]

II. EXPERIMENTAL PROCEDURE

The study was made by bombarding the gas target described in I with the 318±10-Mev bremsstrahlung "spread out" beam from the Berkeley electron synchrotron. The target was filled with helium to a pressure of 140 atmospheres at liquid nitrogen temperature. The density of the gas was calculated from the Beattie-Bridgeman equation of state. The constants in the equation of state have been evaluated by Akin.[46] The error in the number of nuclei/cm^3, as evaluated by this method, is estimated to be less than 5 percent.

The target and collimators were aligned by means of a transit. Photographs of the beam confirmed the fact that the target was aligned. As in the preceding experiment, mesons produced in the gas target were channeled by means of uranium collimators at the nominal angles of 45°, 90°, and 135°. Lead absorbers were used to degrade the energy of the mesons. Those in the proper energy interval stopped and were detected either in nuclear emulsions or in scintillation counters. The emulsions were used to obtain π^-/π^+ ratios, the 45° energy distribution, and the absolute cross sections. The counters were used to obtain the π^+ meson spectra. The minimum meson energy detected was about 30 Mev at 90° and 35 Mev at 135° and 45°. This minimum energy was limited primarily by the energy loss of the mesons in the target.

Operation of the counters has been described in I. The emulsions were exposed and the counter data was taken in one long run. The nuclear emulsions were exposed for 3.8×10^{12} equivalent quanta. The helium-hydrogen ratios were obtained by changing the gasses cyclicly. The cyclic interchange reduced error caused by drift in monitoring and detection.

The uncertainty in the relative photon beam integration is about 2 percent. The absolute beam integration is uncertain to the order of 20 percent.

Bombardment of the empty target indicated that the number of mesons produced by the target chamber and collimator system was negligible. This was verified by the fact that the number of σ endings found in emulsions exposed to hydrogen was less than 2 percent

TABLE I. Minus-plus ratio of π mesons from helium

Angle	π-meson energy (Mev)	Ratio	Ratio (alternate method listed in I)
45°+17°	39±9	1.33±0.33	1.22±0.38
−15°	72±8	0.76±0.18	0.78±0.22
	101±7	1.20±0.34	1.10±0.35
	128±7	0.73±0.30	0.55±0.27
(mean)		0.99±0.15	0.92±0.16
90°±16°	34±10	1.30±0.22	1.36±0.38
	53±8	0.89±0.20	0.99±0.27
(mean)		1.07±0.17	1.21±0.24
135°+15°	57±7	0.90±0.14	0.90±0.17
−17°	72±6	0.93±0.31	0.85±0.34
(mean)		0.91±0.13	0.88±0.14
All angles (mean)		0.98±0.08	0.96±0.10

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43 White, Jakobson, and Schulz, Phys. Rev. **88**, 836 (1952); hereafter referred to as I. *Note*: Reference numbers 1 through 42 refer to references listed in Part I.
44 R. M. Littauer and D. Walker, Phys. Rev. **86**, 838 (1952).
45 J. C. Carrothers, Ph.D. thesis, University of California, 1952 (unpublished).
46 S. W. Akin, Trans. Am. Soc. Mech. Engrs. **72**, 751 (1950).

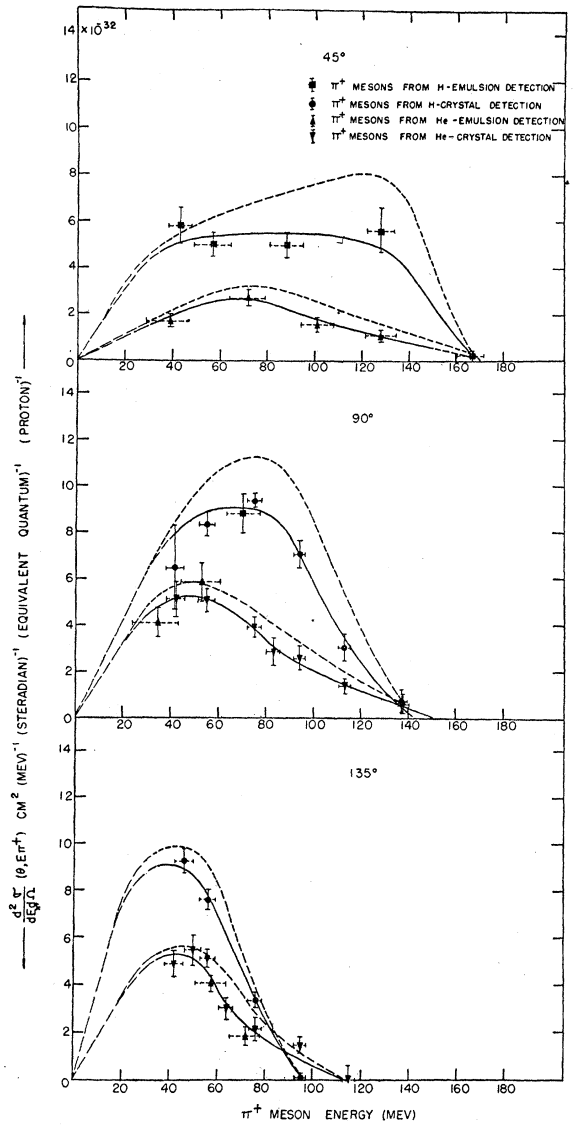

FIG. 1. Energy spectra in the laboratory system for π^+ mesons from helium and hydrogen. The extrapolation to zero meson energy is for the purpose of integration. The dashed curves include the correction for nuclear interaction in the absorbers. Standard deviations are indicated.

of the π-μ endings. The total volume of emulsion scanned for helium was 0.5 cm³. Cross checks indicated that the efficiency of the scanners was better than 90 percent. (See I.)

Corrections were applied to the data for (1) multiple scattering of the mesons in the absorbers, (2) decays in flight, (3) penetration of the collimating edges, and (4) absorption and scattering of the mesons in the target and absorbers. A plot of these correction factors is given in I. Figures 1, 2, 3, and 4 show the data before and after the correction is included for nuclear interaction.

III. RESULTS OF THE EXPERIMENT

A. π^-/π^+ Ratios

The ratio of π^- to π^+ mesons produced in the target can be expressed in terms of the σ stars and π-μ decays observed in the emulsions. From the data of Adelman and Jones,[35] the number of σ stars observed is 73 percent of the number of π^- mesons stopping in the emulsion. The number of π-μ decays observed is equal to the number of π^+-mesons stopping in the emulsion.[47] By assuming that equal numbers of π^- and π^+ mesons are lost in transit from the target to the emulsions by decay[48] and interaction,[37,49] the π^-/π^+ ratio is simply $[\pi^-/\pi^+]=[1.37\sigma]/[\pi\text{-}\mu]$.

An upper limit for the π^-/π^+ ratio for hydrogen of two percent can be obtained from the fact that 5σ and 301π-μ events were observed in emulsions exposed to hydrogen. It is most probable that these σ events are due to π^- production in the target walls or the collimation system.

250σ, 351π-μ, and 485ρ events were observed in the total volume of emulsion scanned for helium. Table I lists the ratios for the individual angles and energies. The uncertainties listed here and in subsequent data are standard deviations. Within statistics, the ratio is independent of the meson angle and energy. A ratio of approximately one is in agreement with experimental ratios for deuterium, carbon, and other low Z nuclei with equal numbers of neutrons and protons.[3,44,45]

Theoretical calculations have been made for the ratio of the free nucleon reactions (1) and (2) by Brueckner[36] and Watson.[50] In order to make a comparison with helium, the free nucleon calculations would have to be modified for coulombic effects and nuclear binding. These effects can be assumed small, since the π^-/π^+ ratios for deuterium and helium agree within experimental error. Theories which neglect the recoil nucleon current lead to a minus-plus ratio of about one.[50] The fact that the π^-/π^+ ratios for deuterium and carbon are approximately one indicates this is to some extent justified and the interaction of the photon is primarily through the meson currents. As a consequence of this, one would expect $d\sigma(\gamma+p\rightarrow\pi^0+p')=d\sigma(\gamma+n\rightarrow\pi^0+n')$. Recent experimental evidence indicates this is the case.[51]

B. Cross Sections for Helium

1. *Energy Distribution*

The energy distribution for π^+ mesons per equivalent quantum Q are plotted in Fig. 1 for the three production

[47] F. M. Smith, Phys. Rev. **81**, 897 (1951). H. L. Friedman and J. Rainwater, Phys. Rev. **84**, 684 (1951).

[48] Durbin, Loar, and Havens, Phys. Rev. **88**, 179 (1952).

[49] Martin, Anderson, and Yodh, Phys. Rev. **85**, 486 (1952). K. J. Button, Phys. Rev. **88**, 956 (1952). D. Stork, Bull. Am. Phys. Soc. **27**, No. 6, 16 (1952).

[50] K. M. Watson, Phys. Rev. **85**, 852 (1952).

[51] G. Cocconi and A. Silverman, Phys. Rev. **88**, 1230 (1952).

angles of 45°, 90°, and 135°. Data are shown for both helium and hydrogen. The hydrogen cross sections, although published in I, are included to provide a standard for comparison. Figure 2 presents the π^- distribution from helium at 45°. Smooth curves have been drawn through the data and extrapolated to zero meson energy for the purpose of integration. As indicated in I, the angular resolution is about $\pm 16°$. The tails at higher meson energies which indicate mesons of energies higher than those permitted by conservation of energy and momentum for hydrogen at an angle $\bar{\theta}$ are due to mesons allowed through the collimating systems from angles smaller than $\bar{\theta}$.

2. *Differential and Total Cross Sections*

The differential cross sections for helium and hydrogen are presented in Fig. 3. The cross sections were obtained by numerical integration of the data of Fig. 1 and are dependent upon the extrapolation to zero meson energy. The data indicates the peak of the angular distribution lies between 45° and 135°.

The total cross section per proton of helium per Q was obtained from the curves in Fig. 3 by integrating over angles. This requires an extrapolation over angles not measured. Since the solid angle becomes zero at 0° and 180°, the error resulting from this extrapolation should be small. The total cross section for helium for

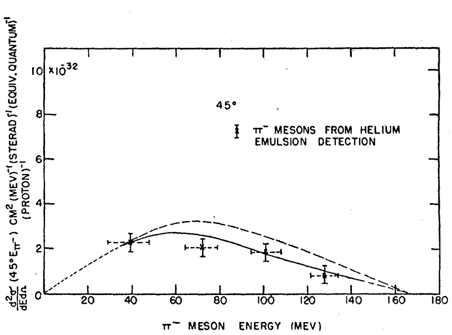

FIG. 2. π^- energy spectra from helium. Standard deviations are indicated.

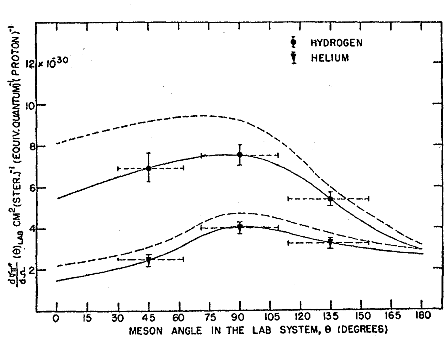

FIG. 3. Differential sections per Q per proton in the laboratory system for π^+ mesons from helium and hydrogen. The smooth curve was drawn for the purpose of integration. The dashed curves include the correction for nuclear interaction in the absorbers. Standard deviations are indicated.

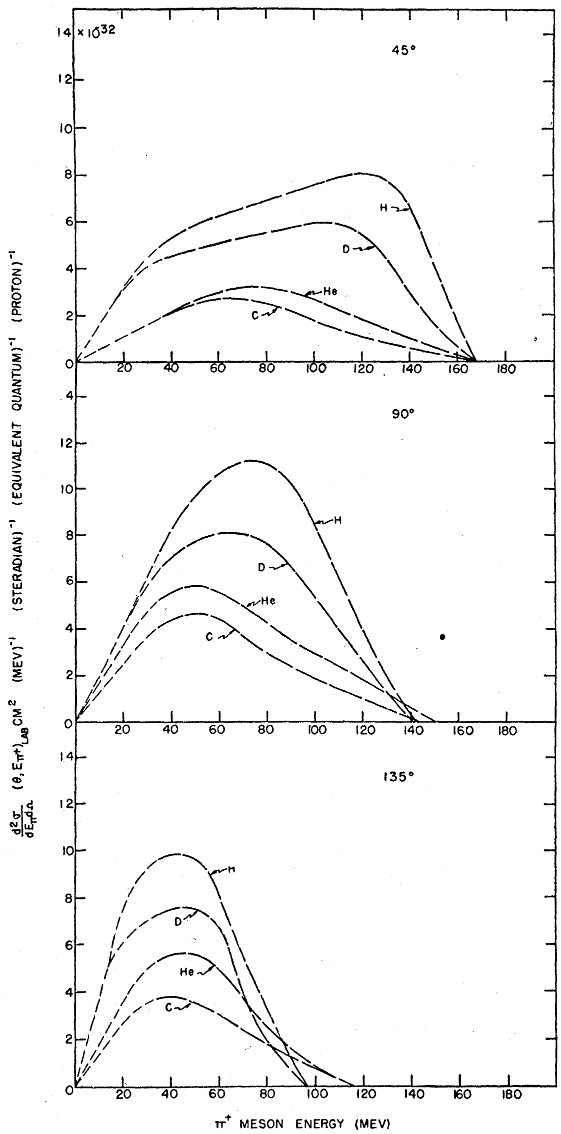

FIG. 4. A plot of the π^+ energy spectra for hydrogen, deuterium, helium, and carbon. The carbon data is from Peterson, Gilbert, and White (see reference 3). The correction for nuclear interaction in the absorbers has been included. The extrapolation to zero meson energy is for the purpose of integration.

π^+ production is

$$\sigma = 4.8 \pm 1.0 \times 10^{-29} \text{ cm}^2 \text{ proton}^{-1} Q^{-1}.$$

This includes a correction of 20 percent for nuclear interaction in the absorbers. The uncertainty listed is that of the absolute beam integration.

C. Comparison of π^+ Production from Hydrogen, Deuterium, Helium, and Carbon

The π^+ energy spectra for hydrogen, deuterium, helium, and carbon are presented in Fig. 4. The cross sections plotted are per proton. The carbon data is from Peterson, Gilbert, and White.[3] The spectra for

TABLE II. π^+ meson cross sections for hydrogen, deuterium, helium, and carbon.[a,b]

Element	$(d\sigma/d\Omega)$ cm^2(steradian)$^{-1}Q^{-1}$(proton)$^{-1}$ 45°+17° −15°	90°±16°	135°+15° −17°	σ_T cm$^2Q^{-1}$(proton)$^{-1}$
Hydrogen[c]	$9.2\pm0.9\times10^{-30}$	$9.3\pm0.6\times10^{-30}$	$6.0\pm0.4\times10^{-30}$	$10.3\pm0.3\times10^{-29}$
Deuterium[c]	6.7 ± 0.7	7.1 ± 0.5	4.6 ± 0.3	7.7 ± 0.3
Helium[c]	3.1 ± 0.3	4.7 ± 0.4	3.8 ± 0.3	4.8 ± 0.2
Carbon[c]	2.6 ± 0.4[a]	3.5 ± 0.3[a]	2.5 ± 0.3[a]	3.8 ± 0.3[a]
Ratio D/H	0.73 ± 0.08	0.76 ± 0.05	0.76 ± 0.06	0.75 ± 0.03
Ratio He/H	0.34 ± 0.05	0.51 ± 0.05	0.63 ± 0.06	0.47 ± 0.04
Ratio C/H	0.28 ± 0.11	0.38 ± 0.15	0.42 ± 0.16	0.36 ± 0.14

[a] Carbon data from Peterson, Gilbert, and White, Phys. Rev. **81**, 1003 (1951).
[b] All data are corrected for nuclear interaction in the absorbers.
[c] In addition to the above standard deviations (except for the ratios), there is an uncertainty of 20 percent in the absolute values of H, D, and He and an uncertainty of 40 percent for C due to beam monitoring.

H, D, and He were obtained with identical geometry. The carbon spectra were obtained with a geometry constructed about a small spherical source with an angular resolution of the detectors of about $\pm7°$.

The ratios of the cross sections for π^+ production, D/H, He/H, and C/H, as obtained from the energy spectra, are tabulated in Table II. The ratios D/H and He/H are dependent only on the relative beam monitoring which has been checked to be accurate to ±2 percent over short periods of time. The ratio C/H is uncertain because of relative beam monitoring over a long period of time. As a check that the beam monitoring had remained fairly constant, the C/H ratios obtained by Mozley[7] were compared with appropriate ratios from the spectra of Fig. 4 and found to be in agreement. A comparison with the C/H data of Steinberger and Bishop[4] gave similar agreement.

It is apparent from the spectra of Fig. 4 that the peaks of the energy distributions of He and C are shifted slightly to lower meson energies relative to the peak of hydrogen. The He/H and C/H ratios listed in Table II indicate the cross sections are reduced more at the angle 45° than at the angle 135°.

The principle reduction in cross sections from the free nucleon reactions (1) and (2) for bound nucleons is due to (a) nuclear binding, (b) exclusion effects, and (c) meson reabsorption. D/H ratios have been considered by a number of authors.[13–19,52] As indicated in I, the D/H ratio is in qualitative agreement with the phenomenological theory.

In He and C the effect of (a) and (b) is to reduce the phase space available for the nucleons in the final state. This reduction is more pronounced when a large portion of the photon momentum is carried away by the meson, leaving the nucleons with little momentum. This then would reduce the cross sections more at small meson angles than at large angles, as is observed. At a given angle, the effect of nuclear binding would be to shift the peak of the meson energy distribution from He and C to a lower energy relative to the meson spectra from free nucleons. At a low Z such as helium, the meson reabsorption (c) should be small compared to the effect of (a) and (b).

[52] H. Feshbach and M. Lax, Phys. Rev. **88**, 509 (1952).

IV. CONCLUSIONS

The most important conclusions of this experiment are:

(1) The minus-plus ratio for helium is close to unity and, within statistics, independent of the angle and energy of the π mesons. This, combined with the fact that the ratio for deuterium is very similar, provides evidence that the recoil nucleon current does not contribute appreciably to photomeson production.

(2) The upper limit for the π^- production cross section from hydrogen is 2 percent of the π^+ cross section.

(3) A proton in helium is essentially one half as effective as a free proton for the photoproduction of π^+ mesons.

(4) The reduction in cross sections for the bound nucleons of helium and carbon is less at backward angles. The peaks of the π^+ energy spectra produced from He and C by 318-Mev bremsstrahlung are shifted to lower energies with respect to the free proton case.

(5) The total cross sections for π^+ production from H, D, He, and C all follow an approximate $A^{\frac{2}{3}}$ dependence. Agreement of the D/H ratios with the phenomenological theory indicate that this dependence is not due to reabsorption of mesons but is due principally to the binding energy and exclusion effects which provide a reduction in cross section such as to approximate an $A^{\frac{2}{3}}$ curve per nucleus for low Z.

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