CASCADE TIME OF π^- IN LIQUID HYDROGEN*

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We report herein a measurement of the time taken by negative pions to go from a velocity of $0.01c$ to nuclear capture in liquid hydrogen. The measurement was undertaken in order to provide direct experimental data on the cascade process, which must be understood for the interpretation of experiments concerning π^- and K^- absorptions at rest in liquid hydrogen.

The experimental method[1] utilized the kinematics of $\pi^- \to \mu^-$ decay in flight to permit measurement of the pion velocity at the instant of decay. As Fig. 1 shows, by measuring the muon laboratory angle and the muon range, one can measure pion velocities down to β $(=v/c) = 0.01$ (corresponding to $T = 7$ kev), for muon laboratory angles in the backward hemisphere. By so determining the number of π^- which decay with $\beta < 0.01$, and using the known π^- lifetime, the time taken by the pion to go from this velocity to nuclear absorption was determined.

The experimental procedure consisted of scanning hydrogen bubble chamber pictures of a stopping negative pion beam for $\pi^- \to \mu^- \to e^-$ decays. 80 000 negative pions came to rest in the central volume of a 15-cm bubble chamber in a magnetic field of 9 kilogauss. The pictures were scanned twice, and all $\pi^- \to \mu^- \to e^-$ (i.e., two-kinked) tracks for which the film angle between the directions of the first two tracks exceeded 80° were measured and calculated. Every event for which the space angle between the first two tracks exceeded 90° is shown on Fig. 1 as a dot. The scanning efficiency for events with the muon range exceeding 0.5 cm was found to be > 90%, and was ~ 50% for muon ranges of about 0.1 cm. Typical measuring errors are shown on two points. Also, the muon range straggling, as observed in this chamber for $\pi^+ \to \mu^+$ decays at rest, is shown.

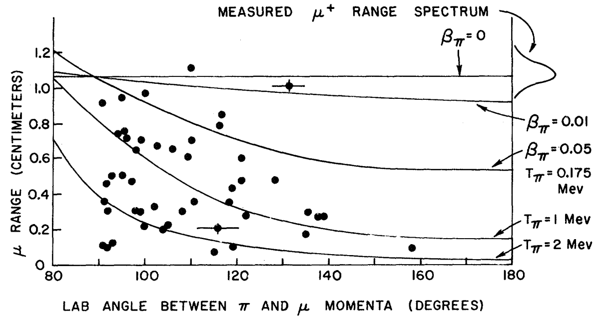

FIG. 1. Kinematics of $\pi \to \mu$ decay in flight. Each dot represents one $\pi \to \mu$ decay found in pictures containing 80 000 π^- stops in liquid hydrogen.

We estimate from Fig. 1 that two $\pi^- \to \mu^-$ decays were observed in the backward hemisphere for which $\beta < 0.01$. This leads to the following expression for the mean time taken by a negative pion in going from $\beta = 0.01$ to nuclear capture:

$$\tau = \left(\frac{2}{80\,000}\right)(2.5 \times 10^{-8}\ \text{sec})(2) = (1.2^{+1.2}_{-0.5}) \times 10^{-12}\ \text{sec}.$$

The quoted statistical error was determined by calculating the relative probability for obtaining two events for various values of the true time τ. Similarly, one concludes from the graph that the time elapsed between $\beta = 0.05$ and $\beta = 0.01$ is about 2×10^{-12} sec.

As a check on the method, a calculation was made, using ordinary stopping power theory, of the number of events expected in the region 1 Mev $> T > 0.175$ Mev, laboratory angle exceeding 90°. The result, 27 events, is to be compared with the observed number of 19. The agreement is probably satisfactory, considering the decrease of scanning efficiency for short muon tracks.

Among the sources of systematic error which have been considered and found to be unimportant are: (1) Coulomb scattering of the pion in its last mm of range, (2) absorption of the negative muon by impurities in the chamber, and (3) false events in which the pion underwent nuclear scattering.

The cascade time observed in this experiment is about two orders of magnitude smaller than that which would be required for radiative de-excitation of the $\pi^- p$ atom to the $n = 1$ state.[2] Day, Snow, and Sucher[3] have recently shown that such an effect could arise from Stark effect mixing of various l levels during a collision of the $\pi^- p$ atom with a hydrogen atom, which can lead to rapid nuclear absorption of the pion from s states with $n \approx 4$. In particular, Day[4] has made calculations which yield the following picture for the sequence of events taking place[2]: The pion slows from $\beta = 0.05$ to $\beta = 0.01$ by inelastic collisions with atomic electrons in $\approx 2.8 \times 10^{-12}$ sec. Then the pion, through further inelastic collisions, is captured from the continuum in about 0.9×10^{-12} sec. A $\pi^- p$ atom with $n \approx 30$ is formed, and de-excites to $n \approx 15$ by collisions in which H_2 molecules are dissociated, in $\approx 0.2 \times 10^{-12}$ sec. At $n \approx 15$, the predominant mode of energy loss becomes Auger transitions in collisions, which can de-excite the $\pi^- p$ atom to $n \approx 4$ in $\approx 1.0 \times 10^{-12}$ sec. At this point the Stark effect mixing and consequent nuclear capture from s states happens[5] in $< \approx 10^{-12}$ sec, a much shorter time than would be required for further de-excitation via Auger collisions or via radiation.

The present data are in reasonable agreement with the above picture[6] of pion absorption from s states via Stark effect mixing. They therefore imply the absence of mesonic x rays from low-lying levels of the $\pi^- p$ atom.

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[1] T. Fields, G. B. Yodh, M. Derrick, and J. Fetkovich, Bull. Am. Phys. Soc. 4, 401 (1959).

[2] A. S. Wightman, Phys. Rev. 77, 521 (1950); and Princeton University thesis, 1949 (unpublished).

[3] T. B. Day, G. A. Snow, and J. Sucher, Phys. Rev. Letters 3, 61 (1959).

[4] T. B. Day, invited paper at 1960 American Physical Society Washington Meeting, and University of Maryland Physics Department Report No. 175 (unpublished).

[5] J. E. Russell and G. L. Shaw, Phys. Rev. Letters 4, 369 (1960).

[6] A crucial part of the above picture is the rapid de-excitation of the $\pi^- p$ atom to $n \approx 4$. Wightman's (reference 2) original upper limit for the de-excitation time was 5×10^{-11} sec. An investigation of the implications of this value in view of the present experimental result was reported by T. B. Day, G. A. Snow, and J. Sucher, Phys. Rev. 118, 864 (1960). However, the rapid de-excitation (1.2×10^{-12} sec) calculated in reference 4 seems to allow fairly good agreement with this experiment without invoking other absorption mechanisms.

EFFECTIVE-RANGE FORMULA FOR PHOTOPION PRODUCTION FROM PIONS*

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In the Chew-Mandelstam[1] approach to the strong-interaction problem at low energies, the amplitude for $\gamma + \pi \rightarrow 2\pi$ plays a central role in any phenomena involving photons. Recently, Ball[2] has found that this process produces an additive correction to the formulas of Chew et al.[3] for photopion production from nucleons. Compton scattering by pions and by nucleons also involves the $\gamma + \pi \rightarrow 2\pi$ reaction. A simple and reasonably accurate formula for the $\gamma + \pi \rightarrow 2\pi$ amplitude which can be used in any of these applications is given here.

We assume that the simple invariant transition amplitude, $M(s,t,u)$, has the Mandelstam representation[4]

$$M(s,t,u) = \frac{1}{\pi^2} \int_4^\infty \int_4^\infty \rho(x,y) \left[\frac{1}{(x-s)(y-t)} + \frac{1}{(x-t)(y-u)} + \frac{1}{(x-u)(y-s)} \right] dx\, dy. \tag{1}$$

It is defined through the relation,

$$T_{fi} = \frac{i(2\pi)^4 \delta^4(K + p_1 - p_2 - p_3) \sum [(-i/\sqrt{2}) \epsilon_{\alpha\beta\gamma} \epsilon_{\lambda\sigma\mu\nu} (p_1)_\lambda (p_2)_\sigma K_\mu \epsilon_\nu] M(s,t,u)}{(16 p_{10} p_{20} p_{30} K)^{1/2}}, \tag{2}$$

where α, β, and γ are the isotopic indices of the pions, and $\epsilon_{\alpha\beta\gamma}$ and $\epsilon_{\lambda\sigma\mu\nu}$ are the conventional antisymmetric tensors of third and fourth rank, respectively, Here s, t, and u are defined[5] as (see Fig. 1)

$$s = -(K + p_1)^2,$$
$$t = -(K - p_2)^2,$$
$$u = -(K - p_3)^2, \tag{3}$$

and are related by the condition

$$s + t + u = 3.$$