Moderation and Absorption Times of Negative Pions in Liquid Hydrogen*

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Among 546 000 negative pions stopping in a liquid hydrogen bubble chamber, 21 events were found corresponding to pion-muon decay in the backward hemisphere from a velocity $\leqslant 0.006c$. Analysis gives $(2.3\pm0.6)\times10^{-12}$ sec as the mean time for a pion to go from this velocity to nuclear capture. Results are also presented for the moderation time of pions between velocities $0.1c$ and $0.006c$.

I. INTRODUCTION

It is experimentally well-known that negative pions, stopping in liquid hydrogen, usually undergo nuclear absorption rather than decay. This was initially predicted by Wightman[1] in his detailed calculations of the times required for the moderation and nuclear absorption of negative mesons. He arrived at an upper limit on the time for the chain of processes leading to absorption and pointed out that this was several orders of magnitude shorter than the mean lifetime of the pion.

The frequency of the rare π^- decay events can be used to determine the mean time required for moderation and capture. Such events can be readily identified in a hydrogen bubble chamber. Furthermore, the bubble chamber affords the possibility of determining kinematically v_π, the velocity of the pion at the instant of decay, for values of $v_\pi \gtrsim \alpha c$ $(=c/137)$.

Such an experiment was first performed by Fields, Yodh, Derrick, and Fetkovich[2] who observed 8×10^4 pion stops and concluded on the basis of two decaying pions with $v_\pi \leqslant 0.01c$ that the total time, $\tau_c(0.01c)$, for a pion to go from this velocity to nuclear capture in liquid hydrogen is $(1.2_{-0.6}^{+1.2})\times10^{-12}$ sec.

This time is about two orders of magnitude shorter than Wightman's estimate; for this reason Day, Snow, and Sucher,[3] Russell and Shaw,[4] and, most recently, Leon and Bethe[5] have reconsidered various aspects of the moderation and absorption process in liquid hydrogen and obtained improved estimates for these rates. The salient difference between Wightman's work and the more recent theoretical studies is that Wightman assumed that nuclear capture would occur principally from the ground state $(1s)$ of the $(\pi^- p)$ atom whereas it was made plausible by Day, Snow, and Sucher that nuclear capture should dominate over atomic cascade processes already for the $n\approx4$ states of this atom. Thus, all other things being equal, the estimate of the time required for capture should be decreased by the time for cascade from $n\approx4$ to $n=0$. The most recent theoretical work[5] leads to an estimate $[\tau_c(0.006c)\approx4\times10^{-12}]$ in fair agreement with the findings of Fields *et al.*[2] The mechanism employed by Day *et al.* and subsequent authors to explain rapid π^- absorption in liquid hydrogen is one proposed by Roberts[6] in a discussion of π^- capture in CH_2.

It is convenient to introduce the following times:

(1) $\tau_\alpha(v_0)$ = mean time required for a pion to be moderated from an initial velocity $v_0>\alpha c$ to a velocity $v=\alpha c$ $(=c/137)$ (this velocity happens to be both the limit of validity of ordinary stopping power theory, and essentially the lowest v experimentally detectable.)

(2) $\tau_n(\alpha)$ = mean time spent by a pion between $v=\alpha c$ and reaching the atomic state $n(\approx4)$ in which nuclear capture predominates.

(3) $\tau_c(n)$ = mean time spent in all states of $n\lesssim4$ before nuclear capture occurs.

(4) $\tau_c(v_0)\equiv$ total mean time spent by a pion between v_0 and nuclear capture $=\tau_\alpha(v_0)+\tau_n(\alpha)+\tau_c(n)$.

Experimentally, one can determine $\tau_\alpha(v_0)$, $\tau_c(v_0)$, and the sum $\tau_c(\alpha)=\tau_n(\alpha)+\tau_c(n)$; by differentiation of $\tau_\alpha(v_0)$ one can, of course, get also $\tau(v_0,v_0+\Delta v_0)$, the mean time spent in an interval Δv_0 about $v_0>\alpha c$. According to present theoretical views, the times (1) through (3) and $\tau_c(\alpha)$ are estimated as follows:

(1) $\tau_\alpha(v_0)$. During this time, the pion loses energy by the usual processes of ionization and excitation. Day[7]

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

[2] T. H. Fields, G. B. Yodh, M. Derrick, and J. G. Fetkovich, Phys. Rev. Letters **5**, 69 (1960).

[3] T. B. Day, G. A. Snow, and J. Sucher, Phys. Rev. Letters **3**, 61 (1959); and Phys. Rev. **118**, 864 (1960). See also reference 6.

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

[5] M. Leon and H. A. Bethe, Phys. Rev. **127**, 676 (1962).

[6] A. Roberts, in *Proceedings of the Third Annual Rochester Conference on High-Energy Nuclear Physics*, edited by H. P. Noyes, M. Camac, and W. D. Walker (University of Rochester Press, Rochester, New York, 1952), pp. 93–4.

[7] T. B. Day, Bull. Am. Phys. Soc. **5**, 225 (1960); and University of Maryland, Physics Department Technical Report No. 175, 1960 (unpublished).

computes $\tau_\alpha(v_0=0.05c)\approx 2.8\times 10^{-12}$ sec using the Born approximation.

(2) $\tau_n(\alpha)$. According to Day,[7] it takes a pion with $v=\alpha c$ about 1.2×10^{-12} sec to reach an $n=15$ level of the $(\pi^- p)$ atom losing energy by elastic Coulomb collisions with protons and ionization of H_2 molecules and then by dissociation of H_2 molecules. The $n\leqslant 4$ levels, from which nuclear capture occurs, are then reached by collisional Auger processes with hydrogen molecules in $\lesssim 1\times 10^{-12}$ sec.[7]

(3) $\tau_c(n=4)$. In the absence of external fields a pion arriving in a level of principal quantum number n cannot be captured from that level if it is initially in any of the various degenerate sublevels $(s,p,d,f,\cdots)$ other than $l=0$ (s). Since values of $l>0$ are statistically favored, the pion in an isolated $(\pi^- p)$ atom will seldom be captured until it has had time to reach the 1s state.

In liquid hydrogen, on the other hand, the small neutral $(\pi^- p)$ atom is frequently exposed to an external electric field as it collides with and penetrates into a neighboring hydrogen molecule. In such a field, the Stark effect mixes angular momentum sublevels of opposite parity. Thus, for example, a pion in the $4p$ state before a collision may go to the $4s$ state from which it may be captured by the proton. As pointed out by Day, Snow, and Sucher,[3] this mechanism greatly reduces the mean time for nuclear capture since it increases the probability of capture while the pion is still in states of $n>1$. Russell and Shaw[4] have estimated that for $n\lesssim 4$ nuclear absorption is more probable than de-excitation. They estimate an absorption time for these n levels of $\lesssim 10^{-12}$ sec. Leon and Bethe,[5] in their more detailed study, calculate that the total time from $n=15$ to nuclear capture, which takes place mostly from the $4s$ and $3s$ levels, is $(2.3_{-0.7}^{+1.4})\times 10^{-12}$ sec for pions in liquid hydrogen of density 4.3×10^{22} atoms/cm^3.

(4) $\tau_c(v_0=\alpha c)$. A predicted value for the measureable quantity $\tau_c(\alpha)$ may now be found by adding the estimates for $\tau_n(\alpha)$ and $\tau_c(n)$. We obtain the value $\tau_c(\alpha)\approx 3.2\times 10^{-12}$ sec using references 4 and 7 and $\tau_c(\alpha)\approx 4\times 10^{-12}$ sec using references 5 and 7 (see Table I).

Since a determination of these times is the most direct experimental measure of the atomic interactions involved in the capture of negative particles by light nuclei, we have redetermined them with improved statistics and resolution.

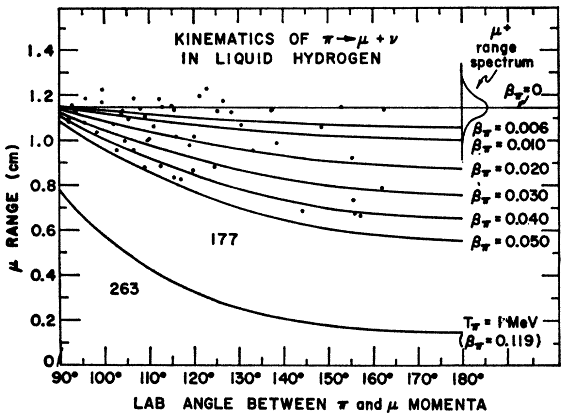

FIG. 1. Kinematics of π^-–μ^- decay in flight in liquid hydrogen of density 5.65×10^{-2} g/cm^3. Each dot represents one decay found in pictures containing 546 000 stops. The total numbers of events in two lower regions are indicated. Also shown is a μ^+ range spectrum determined from measurements of 700 positive muons emitted by positive pions decaying at rest.

TABLE I. Comparison of π^- moderation and absorption times (units of 10^{-12} sec).

Interval	Experiment: This paper	Experiment: Fields *et al.*[a]	Theory	
$\beta_\pi=0.006$ ($\approx\alpha$) to nuclear capture	2.3 ± 0.6	$\cdots$	$\leqslant 3.2$[b]	~ 4[c]
$\beta_\pi=0.01$ to nuclear capture	2.5 ± 0.6	$1.2_{-0.5}^{+1.2}$	$\cdots$	$\cdots$
$\beta_\pi=0.05$ to $\beta_\pi=0.006$	3.3 ± 0.6	$\cdots$	~ 2.8[d]	$\cdots$
$\beta_\pi=0.05$ to 0.01	3.1 ± 0.6	~ 2	$\cdots$	$\cdots$
$\beta_\pi=0.119$ (1 MeV) to $\beta_\pi=0.05$	25 ± 3	$\cdots$	$\cdots$	23.5[e]

[a] See reference 2. These results are for hydrogen 7% denser than ours. If the time is approximately inversely proportional to the density, as the theoretical models indicate, then the effect of this 7% difference is negligible compared to the experimental error.
[b] We have used Day's calculation (see reference 7) for the time from $\beta_0=0.006$ to $n\approx 4$, $\lesssim 2.2\times 10^{-12}$ sec, added to the estimate of Russell and Shaw (see reference 4) for the time for nuclear absorption from $n\approx 4$, $\lesssim 10^{-12}$ sec.
[c] We have used Day's calculation (see reference 7) of $\sim 1.2\times 10^{-12}$ sec for the time for the pion to go from $\beta_0=0.006$ to $n\sim 15$, and the figure of Leon and Bethe (see reference 5), $(2.3_{-0.7}^{+1.4})\times 10^{-12}$ sec, for the time for the pion to go from $n=15$ to nuclear capture. The latter number was calculated for hydrogen of density 4.3×10^{22} atoms/cm^3; our experiment was done in hydrogen of density 3.4×10^{22} atoms/cm^3. This difference has been taken into account in obtaining the value $\sim 4\times 10^{-12}$ sec for the total time.
[d] See reference 7.
[e] Calculated from normal stopping power theory (for example, see reference 1, thesis).

II. EXPERIMENT

We followed the method used by Fields *et al.*[2] for determining the velocity of negative pions at the instant of decay. For an event in which the muon is emitted by the pion in the backward hemisphere, the pion velocity is uniquely determined by the muon range and its angle relative to the pion direction. Using the distribution of these pion velocities at decay, the total number of captured pions, and the known pion lifetime one may calculate the mean time for pions to go from a velocity v_0 to nuclear capture. Since the angular distribution of muons in the pion rest system must be isotropic, this time, $\tau_c(v_0)$, is given by

$$\tau_c(v_0)=(2kn/N)\tau_\pi \quad \text{for} \quad \tau_c\ll\tau_\pi,$$

where n = the number of pions which decay with a laboratory π-μ angle $\geqslant 90°$ at a velocity $\leqslant v_0$, N = the number of pions captured in the chamber = 546 000. τ_π = the mean lifetime of the pion = 2.56×10^{-8} sec,[8] and k = a correction for the fact that the backward hemisphere in the laboratory corresponds to less than a

[8] J. Ashkin, T. Fazzini, G. Fidecaro, Y. Goldschmidt-Clermont, N. H. Lipman, A. W. Merrison, and H. Paul, Nuovo Cimento **16**, 490 (1960).

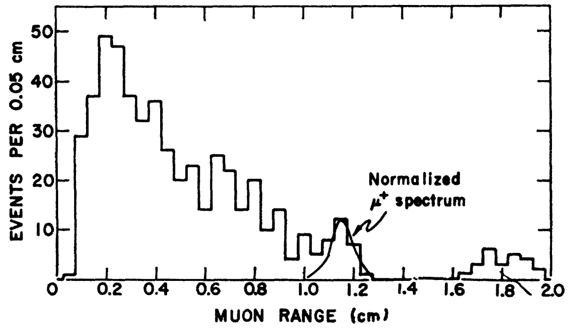

FIG. 2. Range spectrum of muons from $\pi^- - \mu^- - e^-$ events with $\pi - \mu$ laboratory angles $>90°$. The normalized muon spectrum from $\pi^+ - \mu^+ - e^+$ is superimposed.

hemisphere in the pion rest system. Values of k range from 1.01 for $v_\pi = 0.006c$ to 1.30 for $v_\pi = 0.10c$.

For muons with range $\geqslant 0.6$ cm, our uncertainty in the π-μ angle is $\leqslant 2°$. The precision of the muon range measurement is determined by the measured range spectrum for positive muons from the decay of positive pions. The kinematics of the $\pi^- \rightarrow \mu^-$ decay and the experimental μ^+ spectrum based on 700 $\pi^+ \rightarrow \mu^+$ decays are shown in Fig. 1. Together they indicate that determination of pion velocities down to $v_\pi \approx 0.006c$ is possible.

In this experiment, a 68-MeV/c negative pion beam from the University of Chicago cyclotron was stopped in the Chicago 9-liter bubble chamber containing liquid hydrogen of density 5.65×10^{-2} g/cm^3. The chamber was operated in a magnetic field of 25 kG. 546 000 pions stopped in the central volume of the chamber, a region with boundaries at least 1.5 cm from the chamber walls.

The scanning criteria for acceptable pion decays required that (1) the angle between the pion and muon momenta was greater than 70°, (2) the muon range was greater than 0.1 cm, and (3) the muon had a decay electron. All photos were scanned twice; the over-all scanning efficiency was $>99\%$, for muon ranges $\geqslant 0.5$ cm, and $>97\%$ for shorter ranges. Measurement of accepted events was done on a conventional digital measuring machine.

For each event the angle between the two tracks, the range of the muon, and the position in the chamber of the pion-muon vertex were calculated. The events in the backward hemisphere, with vertex in the central volume of the chamber, corresponding to $v_\pi \leqslant 0.05c$ have been plotted in Fig. 1. Figure 2 shows the μ^- range spectrum in the backward direction, disregarding β_π $(=v_\pi/c)$; the normalized μ^+ range spectrum is superimposed. This shows a sharp cutoff at the muon range corresponding to a pion decay at rest.

The second peak in Fig. 2, near 1.8 cm, is attributed to muons which enter the chamber, are mistaken for pions, and catalyze the fusion reaction,[9] $p + d\mu \rightarrow He^3 + \mu$, from which the "rejuvenated" muon is emitted with an energy of 5.4 MeV.

III. RESULTS

Our results are presented in Figs. 3 and 4 and in Table I. Figure 3 gives the mean time for a negative pion to go from velocity v_0 $(=\beta_0 c)$ to nuclear capture in liquid hydrogen of density 5.65×10^{-2} g/cm^3. Figure 4 gives these results in differential form for β $(=v_0/c)$ between 0.01 and 0.10, showing the mean time for the pion to decrease β by 0.01. The experimental uncertainty indicated in these figures is the combination of (1) the uncertainty in the value of β for an event, due to the uncertainty in muon range; and (2) the statistical uncertainty in the number of pions found with β in a

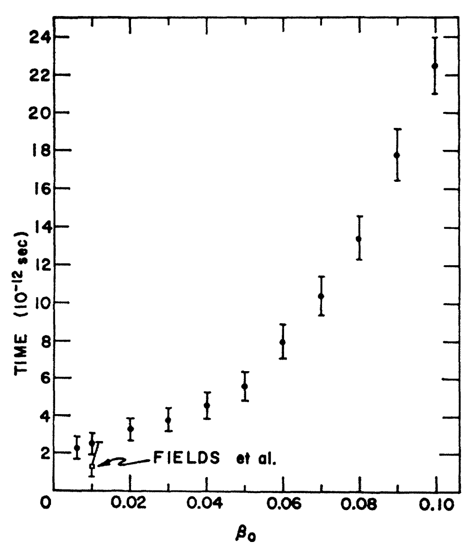

FIG. 3. Mean time for a negative pion to go from β_0 $(=v_0/c)$ to nuclear capture in liquid hydrogen of density 5.65×10^{-2} g/cm^3.

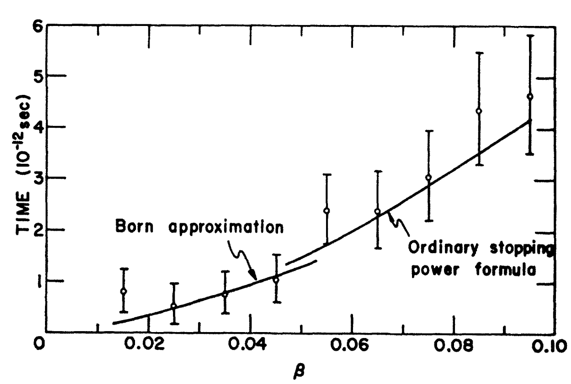

FIG. 4. Mean time for negative pions to go from $(\beta + 0.005)$ to $(\beta - 0.005)$ in liquid hydrogen of density 5.65×10^{-2} g/cm^3. Curves predicted on the basis of the normal stopping power formula and the Born approximation are also given.

[9] L. W. Alvarez, H. Bradner, F. S. Crawford, Jr., J. A. Crawford, P. Falk-Vairant, M. L. Good, J. D. Gow, A. H. Rosenfeld, F. Solmitz, M. L. Stevenson, H. K. Ticho, and R. D. Tripp, Phys. Rev. **105**, 1127 (1957).

given interval. Corrections in these integrated times due to events lost in scanning were calculated to be $<2\%$ in all cases. In the differential plot these corrections were negligible for $\beta_0 \leqslant 0.05$ and reached about 4% in the interval of β between 0.09 and 0.10. The number of events corresponding to $\beta_\pi \leqslant 0.006$ has been corrected for events with β_π really $\leqslant 0.006$, which, near 90°, are thrown into intervals corresponding to higher β_π as a result of the muon range uncertainty. This correction was determined by plotting 177 positive pion decay events on a figure similar to Fig. 1. Of these, 155 appeared to correspond to $\beta_\pi \leqslant 0.006$, 14 to β_π between 0.006 and 0.01, 6 to β_π between 0.01 and 0.02, and 2 to β_π between 0.02 and 0.05. From this it was inferred that the number of negative pion decays with $\beta_\pi \leqslant 0.006$ should be corrected from 21, as indicated in Fig. 1, to 24; the number with β_π between 0.006 and 0.01 should be corrected from 4 to 2; and the number with β_π between 0.01 and 0.02 from 9 to 8.

As an internal check, we deduced the time, $\tau_c(v_0)$, for a negative pion to go from $v_0 = 0.006c$ to nuclear capture, taking various values of the minimum π-μ laboratory angle, $\theta_{\min}$, in addition to 90°. The time was found to be independent of $\theta_{\min}$ (see Fig. 5).

Among the sources of systematic error which have been considered and found to be negligible are: (1) pion and muon scattering, (2) nuclear capture of the decay muon by hydrogen or impurities, (3) decay of the muon in flight, and (4) nuclear capture of the pion by impurities.

Figure 4 and Table I compare our results with those of theory and earlier experiment. The experimental and theoretical values for $\tau_c(\alpha)$ shown in the first row of Table I seem to be in satisfactory agreement; however, the theoretical estimates involve errors (often not given—see footnotes to Table I) which are larger than the experimental errors. In Fig. 4, our moderation times are compared with predictions based on the work of Wightman.[1] These were calculated using normal stopping power, valid for $\beta_0 \gg \alpha c$ and the Born approximation valid for $\beta_0 \approx \alpha$.

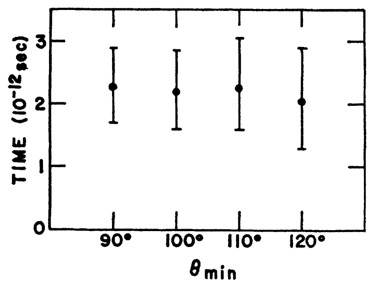

FIG. 5. Mean time for a negative pion to go from $\beta_0 = 0.006$ to nuclear capture, as calculated using only decay events for which the laboratory angle between the pion and muon momenta was $>\theta_{\min}$.

In conclusion, we emphasize that the observed moderation and absorption time, $\tau_c(\alpha) = (2.3 \pm 0.6) \times 10^{-12}$ sec, is more than an order of magnitude shorter than would be expected if the capture occurred principally from the 1*s* state of the $(\pi^- p)$ atom. We suppose that other strongly interacting particles are also absorbed faster than would be expected allowing for cascade to the *k* shell. The mechanism invoked by Day, Snow, and Sucher[3] to explain rapid π-absorption, i.e., capture from *s* states of $n > 1$ due to Stark-effect mixing of angular momentum substates (see Sec. I), is expected to hold for any strongly interacting negative particles stopping in liquid hydrogen or liquid deuterium.

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