very high energy necessary to account for such a narrow collimation.

A more detailed account of this event will be published later when a more careful discussion of possible causes can be undertaken. It should be noted, however, that this event has very remarkable features in that it consists of about 20 photons with no electrons present. Such a phenomenon would appear to be incompatible with the production of these photons by any conventional electromagnetic process. Nuclear collisions can also be ruled out, since even if one had the extreme improbability of no charged particles created in the event, but only neutral pions, the high collimation of the tracks would be totally incompatible with energies of the order of 1 Bev as observed for several of the pairs. No process known to the authors at the present time seems to explain all the features of the event. One possibility, however, which has been considered in an effort to account for it, is that it may be produced by an annihilation process in flight at very high energy. In such a case the event occurs in a center-of-mass system moving with such a high velocity that any very low-energy photons which might be emitted could receive rather high energies in the laboratory system. If the particles which receive practically all of the energy in the center-of-mass system are also neutral, for instance photons, then they might be missed and an event of the kind described here would be produced. It is of special interest to note that the event occurred under only 12 g/cm^2 of air, which means that at the zenith angle of the event only $\frac{1}{3}$ of a nuclear mean free path was traversed. It is thus improbable that the event could be the result of two successive collisions, so that if the event is due to an antiparticle it is probably not produced in the atmosphere, but enters from outside as an extremely high-energy particle ($E>10^{13}$ ev). Production of antiparticles at these energies by cosmic-ray particles outside the atmosphere would be predicted by Fermi's theory.[1]

The authors wish to thank the U. S. Office of Naval Research for arranging the launching of the balloon and Mrs. E. Goodman, who located the event.

---

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] E. Fermi, Progr. Theoret. Phys. (Japan) 5, 570 (1950).

Photopion *S* Wave Near Threshold and the Pion Nucleon Coupling Constant

G. Bernardini and E. L. Goldwasser
Department of Physics, University of Illinois, Urbana, Illinois

(Received June 14, 1954)

In a previous letter,[1] the authors presented results of investigations of π^+ photoproduction from hydrogen near threshold. New data have been added for a center-of-mass angle of about 90° and all the data for this angle, together with the experimental curve, are presented in Fig. 1. The pellicle data have been corrected for nuclear absorption and scanning efficiency. The maximum correction is 15 percent (for the high-energy point) and the corrections themselves are believed to be accurate to within 30 percent. Errors in the abscissas have been propagated into the indicated errors. Possible errors in the photon flux calibration are not included. They are believed to be less than 3 percent.[2]

In terms of the S-matrix formulation, the 90° cross section for photoproduction of positive and negative pions may be expressed, quite generally, as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)^{\pm}_{\text{c.m.}}=\frac{k}{\nu E_i E_f \omega}|\mathcal{H}^{\pm}|^2\left(1+\frac{\nu}{E_i}\right)^{-1}\left(\frac{1}{\omega}+\frac{1}{E_f}\right)^{-1}. \quad (1)$$

Here $k, \omega=$ final meson momentum, energy; $\nu=$ photon momentum (or energy); E_i, $E_f=$ initial and final nucleon energies; and $\mathcal{H}^{\pm}$ are the matrix elements for the production of positive and negative pions. All quantities are in the center-of-mass system and in units $\hbar=c=1$.

The two factors in parentheses represent dynamical corrections to the incident photon flux and final available phase space, respectively, arising from the motion of a nucleon of finite mass. Near threshold $E_i\simeq E_f\simeq M$, the nucleon rest energy (or inverse Compton wavelength of nucleon), and (1) may be written

$$\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)^{\pm}_{\text{c.m.}}&=\left(\frac{1}{M}\right)^2|\mathcal{H}^{\pm}|^2\chi;\\ \chi&=\frac{k}{\nu}\left(1+\frac{\omega}{M}\right)^{-1}\left(1+\frac{\nu}{M}\right)^{-1}.\end{aligned} \quad (2)$$

The matrix element $|\mathcal{H}^{\pm}|$ is not known, but its square can almost certainly be expressed as follows:

$$\left(\frac{1}{M}\right)^2|\mathcal{H}^{\pm}|^2=\{A_0^{\pm}+A_2^{\pm}\eta^2+\cdots \text{higher-order terms}\}, \quad (3)$$

where $\eta=(k/\mu c)$, μ is the meson rest mass, and the A coefficients depend upon the sign of the pion. The absence of the first power term can be shown to follow from the disappearance of interference effects at 90°. Exploring the possibility that the higher-order terms in k may be negligible within the scope and accuracy of this work, the experimental values of $(d\sigma/d\Omega)/\chi$ have been plotted *versus* η^2 (Fig. 2). Within the indicated errors a straight line seems to be a very good fit to the experimental points up to $\eta\simeq1$ ($E_\gamma\simeq2.30$ Mev). Three points, which represent the averages of several counter experiments,[3] have been also added to show more clearly the trend of the curve at energies over 200 Mev and the point of deviation from a straight line.

The best least-squares fit straight line has been passed through the experimental points, yielding

$$A_0^+ = (1.51\pm0.14)\times10^{-29};\quad A_2^+ = (1.12\pm0.31)\times10^{-29}.$$

The errors are determined by a weighted propagation of the errors of the individual observations. Consideration of the external consistency of the points leads to the same estimated errors. The value of A_0^+ gives directly the following total cross section for S-wave photoproduction at threshold:

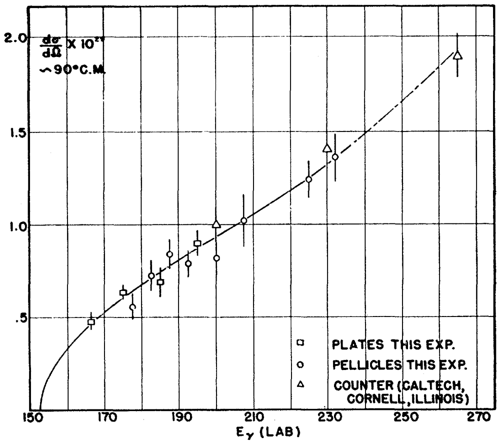

FIG. 1. The 90° c.m. cross section for photoproduction of pions in hydrogen *versus* photon energies in the laboratory frame. The solid curve was obtained by transformation of the straight line of Fig. 2.

$$_{\text{c.m.}}\sigma^{+S\text{ wave}} = (1.90\pm0.18)\times10^{-28}\chi. \tag{4}$$

A theorem due to Kroll and Ruderman[4] proves, for a relativistic covariant meson theory, that at threshold,[5]

$$A_0^\pm = \frac{e^2g^2}{2M^2}\left\{1\pm\frac{\mu}{M}C+\left(\frac{\mu}{M}\right)^2 D\left(\frac{\mu}{M}\right)^\pm+\cdots\right\}, \tag{5}$$

where $e^2=1/137$, g is the renormalized symmetric coupling constant, $\mu/M=$ ratio of pion mass to nucleon mass, C is a constant, and $D^\pm$ are functions of μ/M. Thus if the assumption is made that $(\mu/M)^2D$ is negligible, it is found that

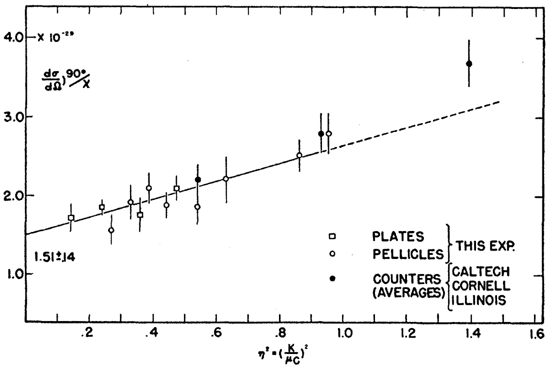

FIG. 2. Plot of $(d\sigma/d\Omega)/\chi$ (see text) *versus* the square of pion momentum in the c.m. frame. The straight line represents the least-squares fit of the points of *this* experiment.

$$e^2g^2/2M^2=\tfrac{1}{2}(A_0^++A_0^-)=\tfrac{1}{2}A_0^+(1+A_0^-/A_0^+). \tag{6}$$

The ratio A_0^-/A_0^+ is simply the limiting value at threshold of the ratio $d\sigma(\pi^-)/d\sigma(\pi^+)$ from free nucleons. Available experimental data[6] indicate that this ratio in deuterium is 1.51 ± 0.1. This value requires some correction for the effects of the difference of the final states (alternatively two protons or two neutrons for the negative or positive pion case), but it is felt that the corrections will be no larger than the indicated limit of error.

Using this value for A_0^-/A_0^+, it is found that $g^2=11.8\pm0.14$.

Similarly the Chew cut-off theory gives, at threshold,

$$A_0^\pm=\frac{2e^2f^2}{\mu^2}\left(1\pm\frac{\mu}{M}C'\right),$$

where f is the coupling constant for this theory. The value obtained is $f^2=0.066\pm0.008$.

We wish to express our deep appreciation to Professor A. O. Hanson for the continuous interest and invaluable help he has lent us throughout this work, and to Professor G. F. Chew and Professor F. Low for numerous enlightening discussions.

[1] G. Bernardini and E. L. Goldwasser, Phys. Rev. **94**, 729 (1954).

[2] P. D. Edwards and D. W. Kerst, Rev. Sci. Instr. **24**, 490 (1953).

[3] Jenkins, Luckey, Palfrey, and Wilson, Phys. Rev. (to be published); J. E. Leiss and C. S. Robinson (private communication); Bacher, Peterson, Tollestrup, and Walker (private communication).

[4] N. M. Kroll and M. A. Ruderman, Phys. Rev. **93**, 239 (1954).

[5] Here the authors have assumed that the kinematical correction factors introduced in (1) are applicable to the Kroll-Ruderman theorem for the case $\mu/M\neq0$.

[6] Beneventano, Lee, and Stoppini, Nuovo cimento (to be published); Sands, Teasdale, and Walker, Phys. Rev. (to be published).

Decay Curve of *K* Particles*

L. MEZZETTI† AND J. W. KEUFFEL‡
Palmer Physical Laboratory, Princeton University,
Princeton, New Jersey

(Received June 14, 1954)

We have measured the decay curve of stopped unstable cosmic-ray particles with liquid scintillators and directional Čerenkov counters.[1] Auxiliary information is provided by Geiger counters connected to an 80-channel hodoscope. The apparatus is shown in Fig. 1. Each Čerenkov counter is a hollow Lucite box filled with water, painted black on the bottom, and viewed from above by an RCA C7157 photomultiplier. The measured efficiency is 90 percent for fast μ mesons traveling *towards* the photomultiplier end, and 0.4 percent for particles traversing the counter in the