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PHOTOPRODUCTION OF CHARGED PIONS FROM BERYLLIUM IN THE BeV RANGE*

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This Letter reports preliminary measurements carried out at the Cambridge Electron Accelerator of the photoproduction of charged pions at laboratory angles of 1° to 11° in the energy range from 2 to 6 BeV. The peripheral model has met with a large measure of success in understanding experiments involving strongly interacting particles, and Drell has applied it to photoproduction.[1-3] This experiment covers the range of validity of the model, and the results indicate that a one-pion exchange diagram roughly describes the major features of the pion photoproduction.[4]

In Drell's calculation a photon with a laboratory energy k produces a pair of charged pions by an electromagnetic interaction. One of the pions emerges directly at a laboratory angle θ with a total energy ω, momentum p, velocity βc, and four-momentum q. The virtual member of the pair interacts with the target particle (beryllium nucleus) leading to an undetected final state; this interaction is approximated by the experimental total π-Be cross section at energy $k-\omega$. This is expected to be valid when the virtual pion is near the mass shell; that is, when $\Delta/\mu \lesssim 1$, where μ is the pion mass and $\Delta^2=(k-q)^2$ is the invariant four-momentum transfer. In this approximation the photoproduction cross section for $\pi^\pm$ is[1]

$$\frac{d^2\sigma^\pm}{d\Omega dp}=\frac{\alpha}{8\pi^2}\left(\frac{\sin\theta}{1-\beta\cos\theta}\right)^2\frac{p(k-\omega)}{k^3}\sigma_{\pi^\pm\text{-Be}}(k-\omega). \quad (1)$$

For a spectrum of gamma rays the cross section per equivalent quantum is

$$\frac{d^2\sigma}{Qdpd\Omega}=\frac{\alpha}{8\pi^2}\left(\frac{\sin\theta}{1-\beta\cos\theta}\right)^2 p \times\int_{\omega+\mu}^{k_{\max}} f(k)dk\frac{k-\omega}{k^3}\sigma(k-\omega), \quad (2)$$

where $f(k)$ is the thin-target photon spectrum. The integral was done numerically using the available experimental π-Be cross sections up to 1 BeV and interpolating with the optical-model calculation of Sternheimer.[5,6] The lower limit $(\omega+\mu)$ is the minimum photon energy and implies that the recoiling, unobserved, final state carries off no kinetic energy.

In another approximate final state, the recoil momentum is carried by a "particle" with the mass of a nucleon plus one pion; then the lower limit is a function of p and θ, and the yield is reduced significantly at large values of p and θ.

The experimental arrangement is shown in Fig. 1. A bremsstrahlung beam from a 0.1-radiation length target in the synchrotron was collimated, passed through a clearing magnet, and allowed to impinge upon a 0.5-inch thick beryllium target. Charged particles emerging from the target at an angle θ with respect to the incident beam were deflected by a bending magnet through an angle of approximately 9° and then vertically focused by a quadrupole spectrometer

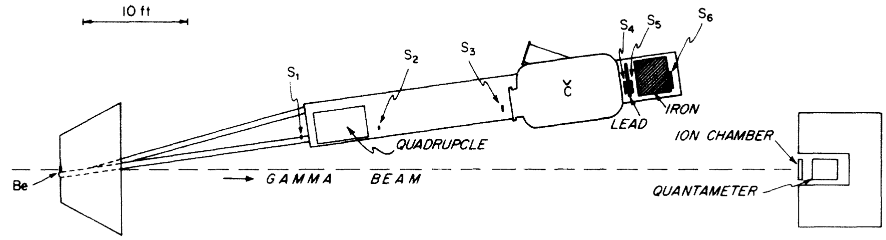

FIG. 1. Top view of the experimental apparatus.

onto a momentum-defining counter, S_3. The quadrupole magnet and all of the counters were mounted on a rolling platform so that the production angle could be varied easily. The momentum resolution was ±5%, and the spectrometer acceptance $\int(dp/p)d\Omega$ was calculated to be 4.85×10^{-6} sr. The angular acceptance was defined by S_1 to be $\pm\frac{1}{4}°$ in both the horizontal and vertical planes. The total energy of the bremsstrahlung beam was measured with a quantameter whose calibration was known to better than ±8%. The synchrotron energy was known to approximately ±1%.

A charged particle traversing the system was indicated by a fourfold coincidence (12-nanosecond resolving time) between the scintillation counters $S_1S_2S_3S_4$. Counters C, S_5, and S_6 together with the coincidence pulse were displayed on a fast oscilloscope and photographed whenever $(S_1S_2S_3S_4)$ occurred. Counter C was a propane-filled, threshold gas Cherenkov counter set below muon threshold so that nominally it responded only to electrons. Scintillator S_5 was preceded by a radiator consisting of one radiation length of steel and three radiation lengths of lead; nominally electrons showered and gave large pulses whereas pions and muons gave modest pulses. Scintillator S_6 was placed behind 30 inches of iron that absorbed electrons and pions so that, in principle, only muons were counted. Particle identification consisted mainly in distinguishing pions and electrons. An $(S_1S_2S_3S_4)$ coincidence with large pulses in C and S_5 was called an electron. If C were small or zero and S_5 were greater than a minimum value, the coincidence was called a pion. All other coincidences (about 10 to 20%) were rejected. About 7% of the "pions" and very few (<1%) of the "electrons" had pulses in S_6. A Cherenkov counter pressure curve indicated that only about 30% of the S_6 counts were due to muons. In the final analysis the information from S_6 was not used.

The measurements were made with the spectrometer momentum set approximately 850 MeV/c below the end point of the bremsstrahlung spectrum. With this arrangement the accepted particles had a small range of momentum transfer, Δ. The maximum gamma-ray energies were chosen to be 2.91, 3.88, 4.85, and 5.82 BeV and at each energy data were taken at various angles from 1° through 11°. Figure 2 summarizes the pion results. A small correction was

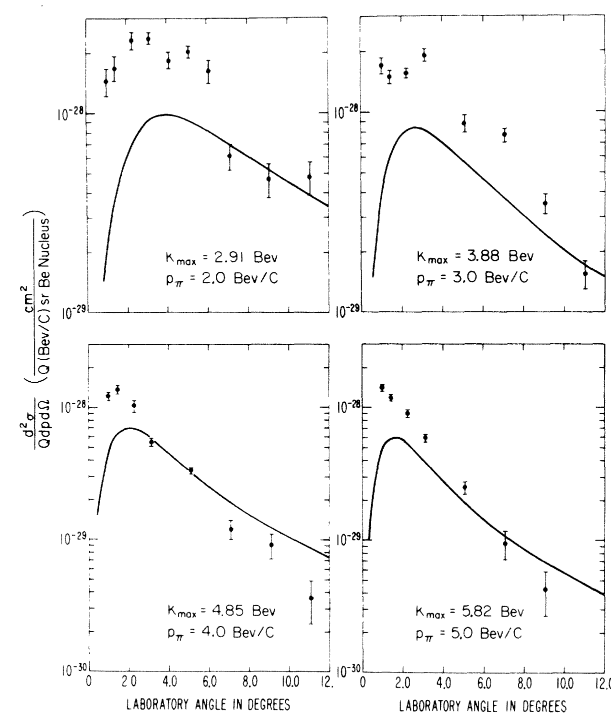

FIG. 2. Experimental and theoretical photoproduction cross sections for negative pions. The cross sections are expressed in terms of the number of equivalent quanta rather than the number of gamma rays. The solid curve is the theoretical yield calculated using Eq. (2). The vertical bars on the experimental points are standard deviations and they are based on counting statistics only. The numbers on each graph give the endpoint energy of the gamma-ray beam and the momentum of the pions.

made for π-μ decay ahead of the quadrupole; the errors shown were derived from counting statistics only. Systematic uncertainties in the spectrometer acceptance, the monitoring of the bremsstrahlung beam, and the counter efficiency (assumed to be unity) are less than 20%. The solid lines in Fig. 2 are the pion yields computed using Eq. (2). Inspection of Fig. 2 suggests that Eq. (1) predicts the general magnitude of the observations but that the measured yields are generally greater than the predicted ones, especially at small angles.

Figure 3 shows the ratio, R, of the measured yields to the calculated yields as a function of momentum transfer; for clarity the error bars are not all shown. Inspection suggests that R is insensitive to k_{max} and p and that R may be a function of Δ only. Fermi motion does not explain the rise at small angles which may be due in part to nuclear rescattering of the detected pion inside the nucleus in which it was made. Since the smaller angle points require better electron rejection, some of the rise in R at small angles may be due to poor electron rejection. Multiple Coulomb scattering effects are small, and we have neglected them.

Most of the measurements were made with negative pions but some were made with positive pions. The yields for positives and negatives were equal within statistics in agreement with Eq. (1). At one setting of (k_{max}, p, θ) we measured the pion yields from targets of C, Al, and Cu, as well as Be. The experimental yields varied as A^{δ}, where $\delta = 1.0 \pm 0.1$, in agreement with the predictions of the optical model.[6] At one setting of (k_{max}, p, θ), data were also taken with S_1 reduced in area by a factor of 3.5, and the pion yields were consistent with the calculated change in the spectrometer acceptance. Various settings of (k_{max}, p, θ) were remeasured during the experiment and subsequently combined. On the basis of 44 remeasurements distributed among 15 settings, a chi-square analysis yielded a Pearson probability of about 15%; this suggests that the counting errors alone account satisfactorily for the observed variation of the points.

Most of the data at small angles were taken with the Cherenkov counter in anticoincidence in order to reduce the number of scope pictures of electrons. However, in a few cases the elec-

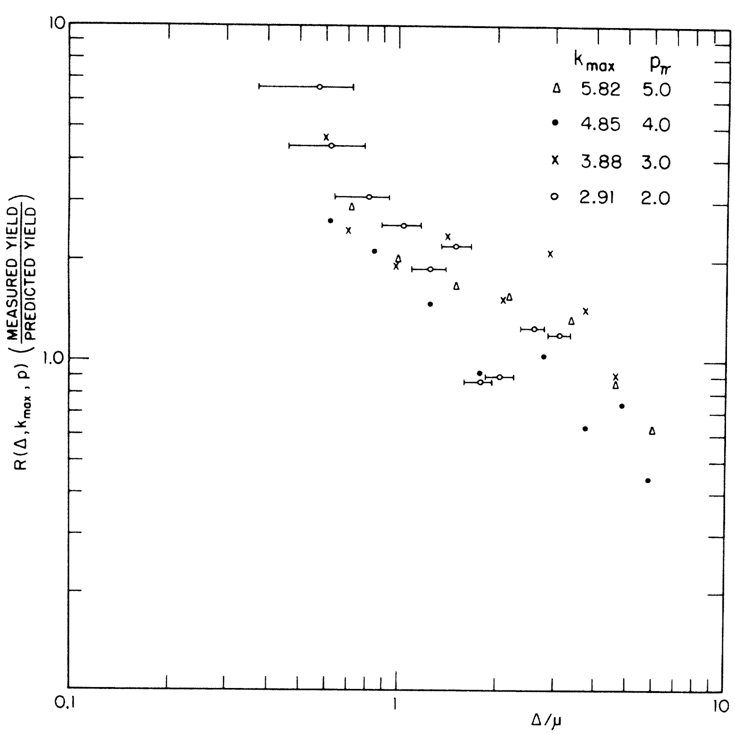

FIG. 3. Ratio of the measured pion yields to the calculated pion yields as a function of the four-momentum transfer, Δ; μ is the pion mass. The horizontal error bars on the 2-BeV/c pion measurements give the range of momentum transfer due to the unknown energy of the gamma ray which initiated the reaction. The range of momentum transfer is smaller for the higher energy measurements.

tron yields were also measured. The principal contributions to the calculated yields are wide-angle pair production directly at an angle θ,[7] and small-angle pair production followed by scattering to an angle θ.[8] For the 0.5-inch Be target the former contributes about half as much as the latter. The observed yields at 1° were always significantly smaller than calculated and they increased too slowly with target thickness; at larger angles for the 0.5-inch target, the yield became increasingly greater than calculated. However, since the pion data satisfactorily met all tests and checks and since great care was not taken to obtain the correct electron yields but instead to provide electron rejection, we believe the pion yields support a large one-pion exchange contribution to high-energy pion photoproduction.

The motivation for making these pion measurements arose in discussions with Professor K. Crowe. We would like to thank the staff of the Harvard cyclotron for their aid in building and setting up the apparatus. We thank the staff of the Cambridge Electron Accelerator for their many services and their patience during the difficult days of the first experiments on a new accelerator. We wish to thank Paul F. Cooper, Jr., for general aid and advice, Dr. H. Butler for doing the magnet calculations, Dr. M. Thiebaux for various yield calculations, Dr. R. A. Schluter and Mr. A. Tamosaitis of Argonne National Laboratory for the use of a differential Cherenkov counter, and Professor S. D. Drell and Professor S. M. Berman for several illuminating discussions of the theory.

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ELASTIC p-p CROSS SECTIONS AT HIGH MOMENTUM TRANSFERS*

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A series of measurements of p-p elastic scattering at high energies and large angles has been made at the Brookhaven Alternating Gradient Synchrotron (AGS). Eighteen differential cross sections have been measured in the energy region $T_{\text{lab}} = 10$ to 30 BeV and momentum transfer region $-t = 2.3$ to 19.6 $(\text{BeV}/c)^2$, where $-t = q^2$ is the invariant four-momentum transfer squared. In units of inverse fermi squared, our highest value of $-t$ is 505 F^{-2}, which is about a factor of four higher than previously measured values of t. In units of reciprocal square-root inverse fermi squared, this is 0.044 or an interaction distance of $\hbar/q = 4.4\times10^{-15}$ cm. These new results show several striking features: (1) The energy dependence or "shrinkage" at constant momentum transfer becomes more pronounced the higher the momentum transfer; (2) with increasing momentum transfer the cross sections decrease less rapidly than would be expected from the trend of the previous data taken at lower momentum transfer[1]; and (3) the shapes of the observed