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Brief Reports

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Elastic pion Compton scattering

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We present evidence for elastic pion Compton scattering as observed via the Primakoff process on nuclear targets. We find production cross sections for $\pi^- A \rightarrow \pi^- \gamma A$ on lead and copper of 0.249 ± 0.027 and 0.029 ± 0.006 mb, respectively, in agreement with the values expected from the one-photon-exchange mechanism of 0.268 ± 0.018 and 0.035 ± 0.004 mb in the region of our experimental acceptance. This reaction provides a clean test of the Primakoff formalism.

I. INTRODUCTION

Quantum electrodynamics provides a starting point for studying elastic pion Compton scattering. The process is similar to classical electron Compton scattering. The relevant Feynman diagrams are shown in Fig. 1.[1] The first two diagrams are the same as the ones that arise in the Compton scattering of fermions. The third diagram, however, is unique to the boson case. It arises because, in contrast to the Dirac equation which describes the electron, the Klein-Gordon equation for the pion is quadratic in the derivatives. Thus, when the standard substitutions $\partial_\mu \rightarrow \partial_\mu + ieA_\mu$ is made, the $A_\mu A^\mu$ term which corresponds to the third graph contributes in the case of $\pi\gamma \rightarrow \pi\gamma$.

The cross section for pion Compton scattering in the $\pi\gamma$ center of mass, averaged over the incident-photon polarizations, is given by[1]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} = \frac{\alpha^2}{s}\,\frac{(s^2+m^4)(1+\cos^2\theta)+2(s^2-m^4)\cos\theta}{[s+m^2+(s-m^2)\cos\theta]^2}\,, \tag{1}$$

where m is the pion mass, α is the fine-structure constant, $\sqrt{s}$ is the mass of the π-γ system, and θ is the angle between the incident and scattered pion. Integrating over θ, we obtain

$$\sigma_{\pi\gamma}(s) = \frac{4\alpha^2\pi(s+m^2)}{s(s-m^2)^3}\,[s^2-m^4+2sm^2\ln(m^2/s)]\ . \tag{2}$$

The data to study the Compton process were obtained at

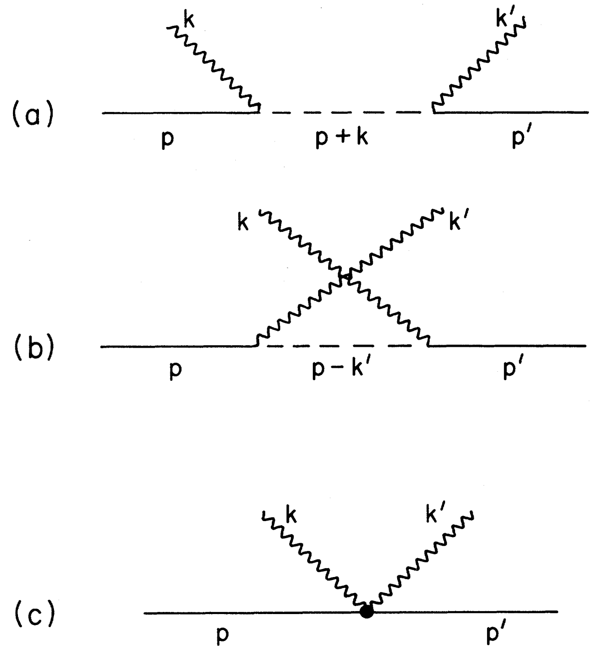

FIG. 1. Feynman diagrams for (a) direct term, (b) crossed term, and (c) point term (bosons only) in Compton scattering. The primed quantities represent the final-state four-vectors of the photon (k) and pion (p).

Fermilab as part of experiment E272, which was designed for measuring radiative decay widths of mesons.[2] A 156-GeV/c pion beam was incident on several nuclear targets (A), providing the possibility of investigating electromagnetic (Primakoff) production of hadrons.[3] The specific reaction studied was

$$\pi^- A \rightarrow \pi^- \gamma A \ . \tag{3}$$

In the Primakoff effect, the incoming charged particle interacts with the nuclear Coulomb field through single-photon exchange, thereby mediating reactions of the type $a+\gamma \rightarrow a^*$, where a^* is the produced state (not necessarily resonant) and a is the incident particle. The reaction is coherent (i.e., the nucleus does not break apart) and therefore the scattering is highly peripheral. Thus there is very little momentum transferred in the collisions, which means that the exchanged photon is essentially real. The cross section for Coulomb (Primakoff) production of $\pi^-\gamma$ systems in the reaction $\pi^- Z \rightarrow \pi^- \gamma Z$ can be written as[4]

$$\frac{d\sigma_c}{dt\,ds} = \frac{Z^2\alpha}{\pi}\frac{\sigma_{\pi\gamma}(s)}{s-m^2}\frac{t-t_0}{t^2}|F_{\mathrm{EM}}(t)|^2 \ , \tag{4}$$

where Z is the nuclear charge, m is the mass of the incident particle (π), $\sqrt{s}$ is the mass of the produced system a^*, $\sigma_{\pi\gamma}$ is the cross section given in Eq. (2), $t \equiv |q|^2$ is the square of the four-momentum transfer to the nucleus, t_0 is the square of the minimum momentum transfer required to produce the mass $\sqrt{s}$, and $F_{\mathrm{EM}}(t)$ is the nuclear form factor. $|F_{\mathrm{EM}}(t)|^2 \simeq e^{-400t}$ for Pb, and $\simeq e^{-200t}$ for Cu; for the t values we will consider, typically $\lesssim 10^{-5}$ GeV^2, these factors essentially equal unity. The strong peaking at such low values of t [Eq. (4)] is characteristic of Coulomb production. Because we have abundant confidence in the predictions of QED for low-energy processes such as pion Compton scattering, where pion structure and form factors can be ignored, our results provide a good experimental check on the validity of the Primakoff formula, which is used in extracting radiative decay widths of mesons.

II. EXPERIMENTAL TECHNIQUE AND DATA ANALYSIS

A description of the experimental setup used for this study can be found elsewhere.[2] Multiwire proportional chambers and drift chambers that comprised the charged-particle spectrometer provided an angular resolution of ±0.04 mrad. A liquid-argon calorimeter (LAC), located ~24 m downstream of the target, was used to detect photons and had an energy resolution of $\sim 15\%/\sqrt{E}$,[5] where E is in GeV. To discriminate against noise, hadronic interactions in the LAC, and other backgrounds at the trigger stage, we required that at least 6 GeV of energy were deposited in the LAC. During reconstruction, events with the charged track within 2 cm of the photon were eliminated from consideration to avert energy reconstruction ambiguities.

In our off-line analysis we imposed the following requirements: (1) The reconstructed event had to have one photon and one charged track. (2) The total energy had to be consistent with the resolution (in the range 152 to 164 GeV). (3) The t value in the event had to be less than 0.002 GeV^2. (4) The interaction vertex had to reconstruct to within ±100 cm of the target. (5) The photon energy had to be in the range $10 < E_\gamma < 130$ GeV. (6) The vertical (y) position of the charged track at the LAC had to be at least 2.5 cm away from the nominal beam center. These restrictions were imposed for the following reasons.

The requirement that there be one photon and one charged track is obvious. However, this cut did not eliminate background events such as $\pi^- A \rightarrow A\rho^- \rightarrow A\pi^-\pi^0$, wherein one of the photons from the $\pi^0 \rightarrow \gamma\gamma$ decay escaped detection (primarily through coalescence of the two photons into a single shower), or such as beam $K^- \rightarrow \pi^-\pi^0$, where, in addition, a K^- was misidentified as a π^- in the beam Cherenkov counters. The requirement that the photon energy be less than 130 GeV eliminated most of this background. The vertex cut eliminated K^- decays, because kaons in the beam decay uniformly along the beam line, and only a small fraction decay in the target area. Bremsstrahlung events caused by electrons in the beam were eliminated by the total-energy requirement. Because pions could interact in the LAC and deposit the minimum amount of energy required to form a trigger, elastic $\pi^- A$ scattering events posed a serious background at the trigger stage. To minimize this background it was necessary to require that the charged tracks in the upper half of the scattering plane ($y > 0$) be accompanied by energy deposition in the lower half plane ($y < 0$) of the LAC and vice versa. This made the efficiency near $y = 0$ very sensitive to the Monte Carlo model. Consequently, to eliminate from the

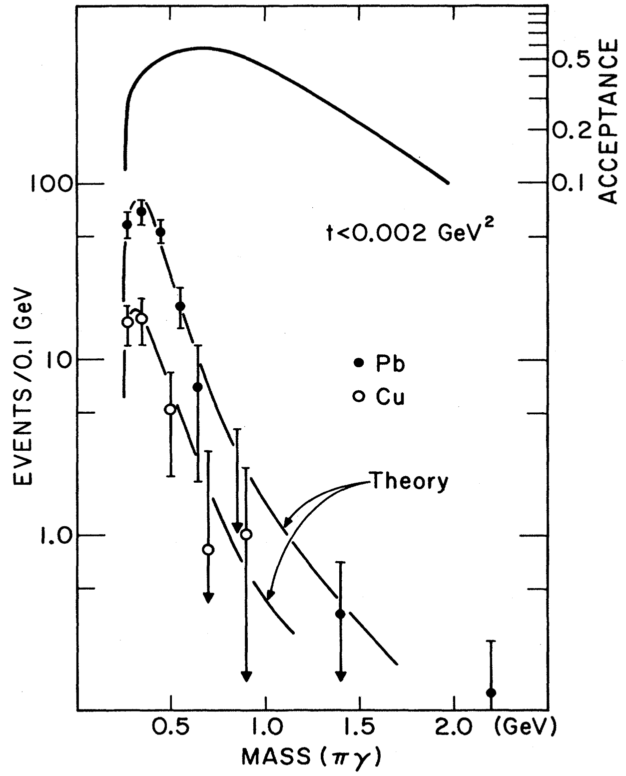

FIG. 2. At the top is the geometric acceptance as a function of the mass of the $\pi^-\gamma$ system; at the bottom are the $\pi^-\gamma$ mass distributions on Pb and Cu targets. Smooth curves are predictions for the shapes from the Monte Carlo.

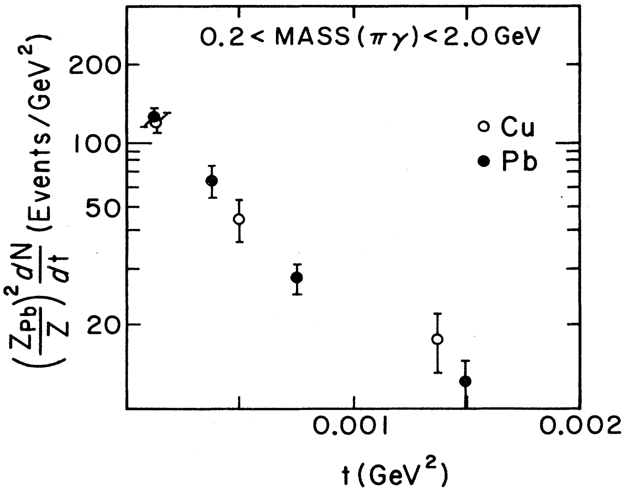

FIG. 3. The t distributions on Pb and Cu targets scaled by Z^2. At the smallest values of t ($\lesssim 0.0005$ GeV^2) the shapes are dominated by the resolution.

data and from the Monte Carlo that region where the acceptance is very dependent on the details of the Monte Carlo, we required that $|y| > 2.5$ cm for the charged track. The requirement that t be small was made to insure that the $\pi\gamma$ events were produced electromagnetically (events produced through other mechanisms, such as diffractive production, typically have larger t values).

The geometric acceptance of the apparatus, which was determined by the Monte Carlo, is shown as a function of $\pi\gamma$ mass in Fig. 2. The acceptance was only a weak function of target material.[2] The data for the various targets have been corrected for acceptance and other target-dependent inefficiencies, subtracted for empty-target background, and normalized to the measured yield of $K^- \rightarrow \pi^-\pi^0$ decays of kaons in the beam. A small ($\sim 15\%$) subtraction was performed for contamination of the $\pi^-\gamma$ samples from the known background from $\pi^-\pi^0$ events,[2] where one of the photons from the π^0 was not properly reconstructed or it missed the detector entirely.

III. RESULTS AND CONCLUSIONS

As will be borne out by the agreement between the predicted and the observed spectra and the integrated cross sections, our data provide clear evidence for pion Compton scattering. The steep t distributions, shown in Fig. 3, suggest that we are indeeed observing Coulomb production. The scaling between targets is consistent with Z^2.

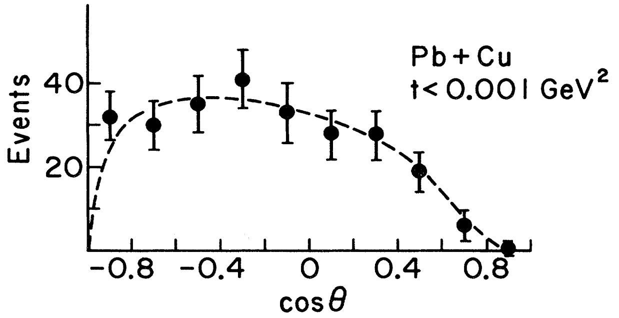

FIG. 4. The Gottfried-Jackson decay-angle distribution (angle between incident and scattered π^- in the $\pi^-\gamma$ center-of-mass frame) for $t < 0.001$ GeV^2. The smooth curve is the prediction of the Monte Carlo. The lead and copper data have been combined for improving statistics. The more restrictive cut on t was used to reduce background from $\pi^-\pi^0$ events in the data.

The $\pi^-\gamma$ mass distributions for lead and copper targets are compared with shapes expected from the prediction of Eq. (4), where for $\sigma_{\pi\gamma}$ we used expression (1), integrated over our acceptance in θ. The agreement is excellent. The angular distribution of the π^- in the $\pi^-\gamma$ rest frame (the Gottfried-Jackson angle of the π^-), shown in Fig. 4, indicates essential agreement with the expectations of the Monte Carlo based on Eqs. (4) and (1). Deviations in this distribution would indicate the presence of pion-structure effects, such as a possible pion polarizability.[6] At the present level of statistics, our data are completely consistent with a pointlike behavior of the pion.

Integrating the cross sections for the data and for the model between $\sqrt{s} = 0.3$ GeV and $\sqrt{s} = 2.0$ GeV, we obtain experimental production cross sections on lead and on copper of 0.249 ± 0.027 and 0.029 ± 0.006 mb, respectively, in agreement with the values expected from the one-photon-exchange mechanism of 0.268 ± 0.018 and 0.035 ± 0.004 mb in the region of our acceptance. The agreement between these cross sections is good to better than 10% accuracy, which is essentially our experimental uncertainty (dominated by statistical error). We conclude, therefore, that we have observed $\pi^-\gamma$ elastic Compton scattering, and that the Primakoff formalism is reliable to an accuracy of at least 20%, at an 85% confidence level.

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