Measurement of the Analyzing Power in the Primakoff Process with a High-Energy Polarized Proton Beam

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The analyzing power (spin-dependent azimuthal symmetry) has been observed for the first time in the nuclear Coulomb coherent production process, the "Primakoff process," with the use of the newly constructed 185-GeV/c Fermilab polarized proton beam. We have observed a large asymmetry of this process in the regions of $|t'| < 0.001$ (GeV/c)^2 and $1.36 < M(\pi^0 p) < 1.52$ GeV/c^2, where the Coulomb process is predominant. The measured asymmetry is consistent with the analyzing power of the existing low-energy $\gamma + p \rightarrow \pi^0 + p$ data.

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As was first suggested by Primakoff and co-workers[1] the radiative decay width of hadron resonances can be related to the cross section for resonance production for hadrons interacting in the Coulomb field of a nucleus.[2,3] The photoproduction of π^0 is related to the Coulomb coherent production by a proton incident on a high-Z nucleus, $p + Z \rightarrow \Delta/N^* + Z \rightarrow \pi^0 + p + Z$. The general formula for this relationship, including spin observables, has been described by Margolis and Thomas.[4] The differential cross section with an incident polarized proton beam can be described in terms of the low-energy photoproduction cross section with a polarized target as

$$\frac{d\sigma}{dM^2 dt d\phi} = \frac{\alpha Z^2}{\pi} \frac{|F(t)|^2}{M^2 - m^2} \frac{t'}{t^2} d\sigma(\gamma p^\uparrow \rightarrow \pi^0 p) \times [1 + T(\theta) P_B \cos\phi] , \qquad (1)$$

where M is the invariant mass of the π^0-p system, m is the proton mass, t is the square of the momentum transfer carried by the virtual photon, $t' = t - (M^2 - m^2)^2/4P_L^2$, $F(t)$ is a form factor for the target nucleus, $T(\theta)$ is the analyzing power (target azimuthal asymmetry) for photoproduction of π^0 from a polarized proton target at c.m. polar angle θ, ϕ is the azimuthal angle, and P_B and P_L are the transverse polarization and the momentum of the incident protons, respectively. The photoproduction of π^0 from a polarized target has been studied at low energies.[5] The observed asymmetry varies with both photon energy and scattering angle. It is almost zero at the $\Delta(1232)$ resonance, but rises to -90% in the photon energies ranging between 500 and 800 MeV. This kinematic region corresponds to a π^0-p invariant-mass region between 1.36 and 1.52 GeV. According to Eq. (1), the asymmetry seen in photoproduction due to the interference between Δ and N^* is expected in coherent Coulomb π^0 production by polarized protons, using the same region of the π^0-p invariant mass. Therefore this process may be used to measure the polarization of the proton at high energies.[6] Until now, there has been no measurement of the asymmetry in the nuclear coherent process.

The cross section for the Coulomb coherent process (1) has a sharp peak at $t' \sim 10^{-5}$ $(\text{GeV}/c)^2$ and decreases rapidly as t'/t^2. The "width" of the Coulomb peak is determined by the detector resolution. Diffractive dissociation due to the strong interaction is also present, but it has a much slower t' dependence.

We have measured the analyzing power (azimuthal asymmetry) of nuclear Coulomb coherent production from a Pb target by using the newly constructed 185-GeV/c Fermilab polarized proton beam.[7] The beam polarization is 45% and this is further described in Ref. 7. To reduce certain systematic errors, the spin direction of the incident proton was flipped every 10 min using a spin-rotator system.[7]

The setup of the experiment is shown in Fig. 1. The apparatus consists of a 3-mm-thick Pb target surrounded by veto counters, a lead-glass calorimeter for π^0 detection, and a magnetic spectrometer for the scattered protons. The scattered-proton momentum resolution is measured to be 1.1% (rms) at 135 GeV/c. The overall resolution of the scattering angle is about 0.08 mrad, with the predominant contribution due to multiple scattering in the Pb target. Helium bags were placed along the scattered proton trajectory to reduce multiple scattering in air.

The two photons from the π^0 decay are detected with a finely segmented lead-glass calorimeter. The calorimeter consists of 156 lead-glass blocks arranged as shown in Fig. 1. A square hole in the center allows the scattered protons and noninteracting beam particles to pass through. Each rectangular block has a cross section of 3.8×3.8 cm^2 and a depth of 45 cm, corresponding to 19.1 radiation lengths. The stability of the calorimeter is

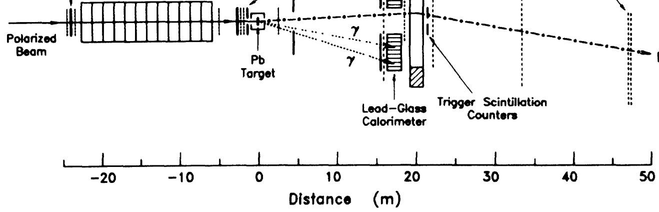

FIG. 1. Schematic view of the experimental setup. The dimensions transverse to the beam are not scale.

monitored to a 1% accuracy with a xenon-flash-tube system. A 30-GeV positron beam was used to calibrate the calorimeter. The measured energy resolution is 3% (rms) at 30 GeV and the position resolution is 2 mm (rms). The measured π^0 energies in this experiment ranged from 25 to 75 GeV.

A set of thin plastic scintillation counters (TP1) is placed downstream of the magnet and provides the trigger for the scattered protons. The set consists of four counters arranged to distinguish protons scattered to the left, right, up, and down. The calorimeter also has left, right, up, and down sections, and signals from each section are summed for the trigger. In the coherent process where t' is almost zero, the π^0 and scattered protons are coplanar. Thus the trigger logic is such that the energy deposit is larger than 25 GeV in the left half of the calorimeter, less than 5 GeV in the right half, and a proton hits the right segment of TP1. There are four such combinations to cover the whole range of azimuthal angles. To reject the events which have any extra particle besides a proton and π^0, veto counters are included in the trigger logic.

The data were taken at an intensity of 10^7 protons per 20-s spill, integrated to a total number of 1.8×10^{10} protons on the Pb target. Some data were taken with carbon and copper targets to study the A dependence of the diffractive process. Data were also taken without a target in place, in order to estimate the background events mainly due to scattering from the air around the target position.

In the analysis, a proton track is reconstructed to evaluate its scattering angle and momentum. The energy and position of a photon are reconstructed into a π^0 with the use of a shower table obtained from the positron calibration data. The measured mass resolution of the reconstructed π^0's is 8.4 MeV/c^2 (rms), which is consistent with the results of a Monte Carlo simulation.[8]

Since the Coulomb coherent process has only one proton and one π^0 in the final state, the following criteria are applied for the event selection: (a) There is a single proton track with momentum from 100 to 160 GeV/c; (b) the interaction point is within 50 cm for the target; (c) there is no electromagnetic energy in the calorimeter other than the π^0; and (d) the sum of the longitudinal momenta of proton and π^0 is equal to the beam momentum within ± 10 GeV/c.

The measured invariant-mass distribution for the p-π^0 system at $|t'| < 10^{-3}$ $(\text{GeV}/c)^2$ is shown in Fig. 2. The prominent peak is the $\Delta^+(1232)$ resonance and the second bump is due to the $N^*(1520)$ resonance. Both resonances have rather large radiative decay widths. The selected region of the momentum transfer is $|t'| < 10^{-3}$ $(\text{GeV}/c)^2$, since the expected t' resolution by Monte Carlo simulation is about 4×10^{-4} $(\text{GeV}/c)^2$ and most of the Coulomb process is included in this region. Even at such a small region of t', the contribution

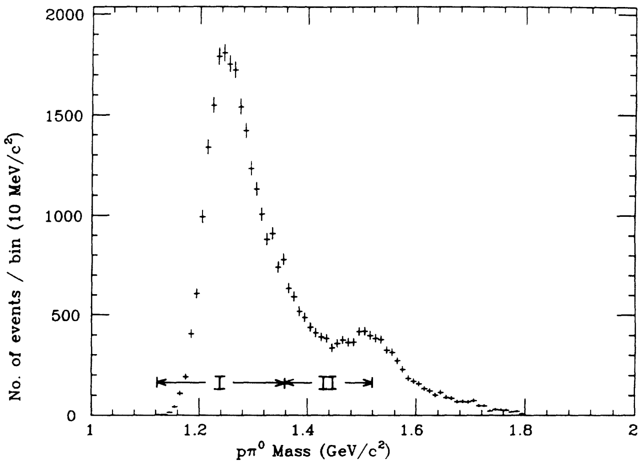

FIG. 2. The invariant-mass spectrum of the π^0-p system in $p+\mathrm{Pb}\to\pi^0+p+\mathrm{Pb}$ for $|t'|<1\times10^{-3}$ $(\mathrm{GeV}/c)^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.

of the diffractive dissociation process is not negligible. The analyzing power of this process is expected to be zero, because the single Pomeron exchange with diagrams known as the Deck effect[9] dominates the process. The observed ϕ-angle dependence of the coherent π^0 production process may be expressed as $1+[fT(\theta)P_B]\cos\phi$, where the parameter f is a dilution factor due to the diffractive dissociation. The raw asymmetry at ϕ is given as

$$A(\phi)=[N^\uparrow(\phi)-N^\downarrow(\phi)]/[N^\uparrow(\phi)+N^\downarrow(\phi)]$$
$$=fT(\theta)P_B\cos\phi=\epsilon\cos\phi\,, \qquad (2)$$

where $N^\uparrow(\phi)$ and $N^\downarrow(\phi)$ are the number of events at ϕ for the up and down spin directions of the incident proton, respectively.

The asymmetry parameter ϵ is obtained by fitting the observed values of $A(\phi)$ with the functional form $A(\phi)=\epsilon\cos\phi$. The fit was made for two regions of the π^0-p mass: (I) Δ region, $m<1.36$ GeV/c^2 and (II) interference region, $1.36<m<1.52$ GeV/c^2. The asymmetry in region I was found to be -0.005 ± 0.017, and is consistent with $T(\theta)$ almost zero in this region. In region II, we obtained $\epsilon=-0.14\pm0.03$, with a χ^2 per degree of freedom of 0.83.

In order to confirm that the observed asymmetry is due to the Coulomb coherent process, the following two checks were made. First, the asymmetry of the same mass region at $2.5\times10^{-3}<|t'|<5\times10^{-3}$ $(\mathrm{GeV}/c)^2$, where the diffractive process is dominant, was measured to be 0.012 ± 0.028. This result is consistent with the assumption that the diffractive-dissociation process has no polarization asymmetry. Second, the asymmetry in region II was measured to be -0.002 ± 0.022 with an unpolarized proton beam. These two null results confirm that the present asymmetry result is free from systematic bias within the errors quoted above.

The dilution factor f in Eq. (2) is estimated by fitting the t' distribution of the events, assuming the observed cross section is a sum of the Coulomb process and the diffractive process, as smeared by the detector resolution. The t' distribution is the sum of two cross sections, $d\sigma/dt=d\sigma_C/dt+d\sigma_D/dt$, where $d\sigma_C/dt$ and $d\sigma_D/dt$ are the Coulomb and diffractive cross sections, respectively, plus a possible interference term which should be small due to the approximate 90° relative phase. By including the t resolution of the detector $(\Delta t'=\Delta P_t^2)$, the observable distribution is calculated numerically from a convolution integral,

$$N_{\mathrm{obs}}(t')=\int\frac{1}{2\pi\Delta P_t^2}\exp\left(-\frac{(P_t-\bar{P}_t)^2}{2\Delta P_t^2}\right)\left(C\frac{d\sigma_C}{dt'}+D\frac{d\sigma_D}{dt'}\right)d^2\bar{P}_t\,, \qquad (3)$$

where $\bar{P}_t$ and P_t are the exact and smeared momentum transfers, respectively, and C and D are normalization coefficients. The observed t' distribution, $N_{\mathrm{obs}}(t')$, behaves as $\exp(-bt')$ for $|t'|<1\times10^{-3}$ $(\mathrm{GeV}/c)^2$; this is due almost entirely to detector resolution. Above $|t'|$ of 3×10^{-3} $(\mathrm{GeV}/c)^2$, the Coulomb part $N_C(t')$ of $N_{\mathrm{obs}}(t')$ behaves approximately as $|F(t)|^2/|t|$. The diffraction part, $N_D(t')$, alone may be expressed as $N_D(t')=D\exp(-b_D't')$, where $b_D'=(1/b_D+2\Delta P_t^2)^{-1}$, and b_D is the slope parameter of the diffractive process. After subtracting the background events due to air by using the data taken without a target in place, the t' distribution of the events for the Pb target was fitted with the form $N(t')$, where the free parameters are ΔP_t, b_D, C, and D. During fitting we allowed an interference term with the amplitudes of the two processes and variable phase. No significant change in fit quality due to interference was found within experimental errors. The t' distributions of the events together with the best-fit values for both $N_C(t')$ and $N_D(t')$ are given in Fig. 3. The values obtained for the fit parameters for the region of $M_{\pi^0p}=1.36$–1.52 GeV/c^2 are the following: $\Delta P_t=18.4\pm2.4$ MeV/c^2, $b_D=503^{+73}_{-123}$ $(\mathrm{GeV}/c)^2$, and $f=0.55^{+0.20}_{-0.17}$ for $|t'|<1\times10^{-3}$ $(\mathrm{GeV}/c)^2$, with $\chi^2/N_{\mathrm{DF}}=0.7$.

The value found for ΔP_t is consistent with the simulation calculations. The slope parameter of the diffractive process depends on the mass of the π^0p system and on the nuclear radius.[10] Empirically it is expressed as $b_D=R_{\mathrm{eff}}^2/4$, where R_{eff} is the sum of the interaction radius of the elementary process from a nucleon target and the rms radius of a nucleus. The value obtained for b_D is slightly larger than the value calculated by the empirical formula. The t' distributions were obtained using carbon and copper targets and were also fitted in the same way.

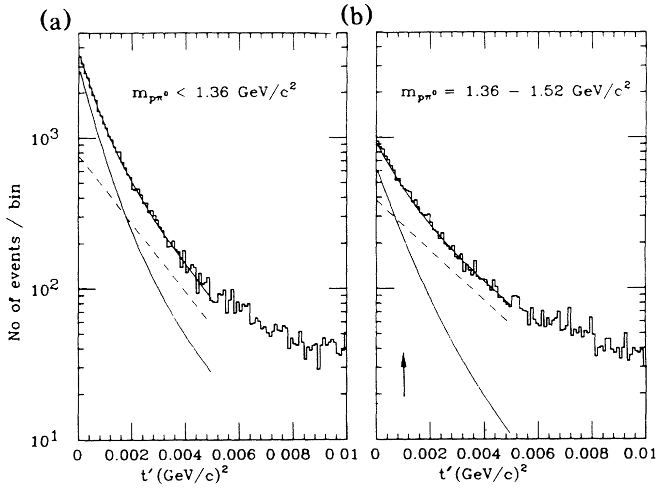

FIG. 3. The t' distribution of the $p+\mathrm{Pb}\rightarrow p+\pi^0+\mathrm{Pb}$, at (a) $M_{p\pi^0}<1.36$ GeV/c^2 and (b) $M_{p\pi^0}=1.36$–1.52 GeV/c^2. The curves are obtained by fitting the data. The dashed and dotted lines show the diffractive process and the amount of background events, respectively, and the solid curve represents the Coulomb process. The arrow indicates the position of the t' cut.

The values of b_D at the same mass region are 77.7 ± 6 and 172 ± 48 $(\mathrm{GeV}/c)^{-2}$ for carbon and copper, respectively, and they are consistent with the calculation. We conclude that the fit is adequate to deduce the Coulomb process within the statistical accuracy of the measurements.

The analyzing power $T(\theta)$ of the Coulomb coherent process is -0.57 ± 0.12(statistical)$^{+0.21}_{-0.18}$(scale error due to the dilution factor) in the π^0-p mass region of 1.36–1.52 GeV/c^2 and $\theta_{\pi^0 p}=60°$–$120°$. The analyzing power of π^0 photoproduction average over the same kinematical region is -0.65 ± 0.04. These results are consistent with each other within the accuracy of the measurements, and provide empirical evidence that the relationship [see Eq. (1)] between the low-energy photoproduction and the nuclear Coulomb coherent production at high energy can be applied in the case of polarized protons. Because of the invariance of the electromagnetic interaction under charge conjugation, the same magnitude of analyzing power is expected in the Coulomb coherent production by polarized antiprotons. We therefore have established a method to measure the polarization of protons and of antiprotons at high energies.

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