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ELEMENTARY PARTICLES AND FIELDS
Experiment

Single-Spin Asymmetry of Inclusive Neutral-Pion Production in $pp_\uparrow$ Interactions at 70 GeV in the Region $-0.4 < x_F < -0.1$

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Abstract—For the kinematical region specified by the inequalities $-0.4 < x_F < -0.1$ and $0.9 < p_T < 2.5$ GeV/c, the results are presented that were obtained by experimentally determining the single-spin asymmetry of inclusive neutral-pion production in the reaction $p + p_\uparrow \to \pi^0 + X$ at 70 GeV. According to these results, the asymmetry is close to zero in the region $-0.2 < x_F < -0.1$ and grows in magnitude with decreasing x_F, amounting to $(-10.6 \pm 3.2)\%$ for $-0.4 < x_F < -0.2$. *© 2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

In this article, the single-spin asymmetry A_N in the reaction

$$p + p_\uparrow \to \pi^0 + X \tag{1}$$

at 70 GeV in the Feynman variable region $-0.4 < x_F < -0.1$ is presented according to an analysis of data obtained in 1996 at the U-70 accelerator of the Institute for High Energy Physics (IHEP, Protvino). Previously, the asymmetry A_N of inclusive neutral-pion production was measured in $\pi^- p_\uparrow$ and $pp_\uparrow$ interactions. In $\pi^- p_\uparrow$ interactions, the asymmetry A_N is significant both in the central region [1] and in the region of polarized-target fragmentation [2]. In $pp_\uparrow$ collisions, the asymmetry in the central region is close to zero at energies of 70 GeV [3] and 200 GeV [4], but it is different from zero at 24 GeV [5]; a significant effect was also observed in the region of polarized-proton-beam fragmentation [6].

For the reaction in (1), measurements of A_N in the region of polarized-target fragmentation were performed for the first time. Preliminary data on a raw asymmetry (without investigating systematic errors) were reported previously in [7].

2. DESCRIPTION OF THE EXPERIMENT

Our experiment was conducted at the PROZA-M facility (beamline 14 of the U-70 accelerator complex). The layout of the experimental facility is presented in Fig. 1.

Protons of energy 70 GeV interacted with a transversely polarized frozen-type target, where propanediol ($C_3H_8O_2$) was used for a working substance [8]. In order to take into account unpolarized matter in the target, background measurements were performed with a carbon target.

Photons from neutral-pion decays were recorded by an electromagnetic calorimeter (EMC) that was shaped as a matrix of 12×12 lead-glass counters [9]. The dimensions of a counter were $3.8 \times 3.8 \times 45$ cm^3 (18 radiation-length units along the beam). The calorimeter was arranged at a distance of 2.7 m from the target center, its coverage angle in the horizontal plane being 17° to 26° in the laboratory frame. The trigger used ensured the selection of events where the energy deposition in the calorimeter exceeded 1 GeV.

A detailed description of basic units of the facility was given in [10].

The calibration of the calorimeter was performed by using a beam of 26.6-GeV/c electrons [11]. Upon the subtraction of the beam momentum spread (about 2%), the energy resolution of the calorimeter

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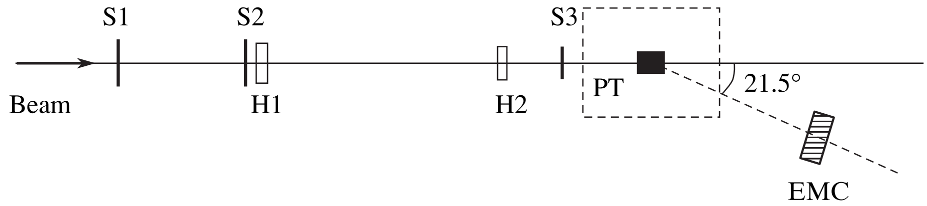

Fig. 1. Layout of the PROZA-M experimental facility: (S1–S3) scintillation counters, (H1, H2) hodoscopes, (PT) polarized target, and (EMC) electromagnetic calorimeter.

at this energy was $\sigma(E)/E \approx 3\%$. The EMC energy scale was additionally calibrated to the neutral-pion mass. The calibration accuracy of 0.1% was attained within five hours of measurements.

Around 10 million events were recorded over a 10-day run with a polarized target.

3. DATA ANALYSIS

In order to reconstruct photons in the calorimeter, we employed the algorithm that was developed in [12] and which is based on the separation of an electromagnetic shower according to a known shape. Special features of its application to analyzing data that come from the electromagnetic calorimeters of the PROZA-M facility were described in [3].

In order to obtain a physical result, we selected only those photon pairs for which (i) χ^2/NDF for a description in terms of a shower shape was less than 3.0, (ii) the asymmetry of energy satisfied the condition $\alpha < 0.7$ ($\alpha = |E_1 - E_2|/(E_1 + E_2)$, where $E_{1,2}$ are the photon energies), (iii) each photon was at a distance from the detector edges that was not smaller than half the distance from the respective counter to, and (iv) $(E_1 + E_2) > 2$ GeV. In this case, the mean multiplicity in the EMC was about 1.5 photons per event, while the photon energies were in the range between 0.5 and 10 GeV.

The distributions of photon pairs with respect to kinematical variables are displayed in Fig. 2, while the two-dimensional distribution with respect to the variables p_T and $x_{\rm F}$ is given in Fig. 3*a*. In view of a narrow acceptance of the EMC, the variables $x_{\rm F}$ and p_T are correlated.

Figure 3*b* shows a characteristic mass spectrum of photon pairs. In this spectrum, one can see a distinct peak in the region around the neutral-pion mass. In the transverse-momentum range between 0.9 and 2.5 GeV/c, the mass resolution for a neutral pion was 11 to 15 MeV/c^2.

3.1. Calculation of the Asymmetry

The single-spin asymmetry A_N is defined by the expression

$$A_N(x_{\rm F}, p_T) = \frac{1}{P_{\rm targ}}\frac{1}{\langle\cos\phi\rangle} \times \frac{d\sigma^{\rm H}_{\uparrow}(x_{\rm F}, p_T) - d\sigma^{\rm H}_{\downarrow}(x_{\rm F}, p_T)}{d\sigma^{\rm H}_{\uparrow}(x_{\rm F}, p_T) + d\sigma^{\rm H}_{\downarrow}(x_{\rm F}, p_T)}, \quad (2)$$

where $P_{\rm targ}$ is the target polarization, ϕ is the azimuthal angle between the target-polarization vector and the normal to the plane spanned by the beam axis and the momentum of the outgoing neutral pion, and $d\sigma^{\rm H}_{\uparrow}$ and $d\sigma^{\rm H}_{\downarrow}$ are the invariant differential cross sections for neutral-pion production on hydrogen for opposite directions of the target-polarization vector. In our experiment, the azimuthal angle at which we detected neutral pions was in the range $180° \pm 15°$; therefore, we set $\langle\cos\phi\rangle$ to -1. The mean degree of target polarization during data accumulation was $(80 \pm 3)\%$. Since the detection efficiency for neutral pions is identical for the two directions of the target-polarization vector, we find for the detector on the right of the beam that

$$A_N = -\frac{D}{P_{\rm targ}}A_N^{\rm raw} = -\frac{D}{P_{\rm targ}}\frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}}, \quad (3)$$

where $A_N^{\rm raw}$ is the raw asymmetry actually measured in the experiment, D is the target-dilution factor, and $n_{\uparrow}$ and $n_{\downarrow}$ are the normalized (to the monitor) numbers of recorded neutral pions for opposite directions of the target-polarization vector. The procedure used to calculate D was described in detail elsewhere [2]. In order to test our calculations, we employed the results obtained previously in [13] by measuring the dilution factor for the target being investigated. In assessing the asymmetry, we used the calculated values of D without allowance for errors: 8.0, 8.1, 8.2, and 9.2 for p_T from the intervals $0.9 < p_T < 1.4$ GeV/c, $1.4 < p_T < 1.8$ GeV/c, $1.8 < p_T < 2.1$ GeV/c, and $2.1 < p_T < 2.5$ GeV/c, respectively.

In measuring the asymmetry A_N, there can arise an additional asymmetry caused by trigger-electronics jitter, failures of the monitor counters, beam drift, or some other reasons. This gives rise to a systematic bias of the true asymmetry. A method that can be used to remove this bias and which is based on the fact that the asymmetry of photon pairs off the neutral-pion mass peak is zero is described in detail in [2].

3.2. Analysis of a Spurious Asymmetry

A spurious asymmetry is determined predominantly by the drift of the calorimeter energy scale, this leading to an inaccurate reconstruction of the kinematical parameters of the photon pair. A change of 0.1% in the energy scale gives rise to a raw spurious asymmetry at a level of 0.2% (with allowance for the dilution factor and a target polarization of $D/P_{\rm targ} \sim 10$, this corresponds to 2% in A_N).

In order to estimate the spurious asymmetry, we broke down the total data sample for the "up" direction of the target-polarization vector into two equal subsamples of events and, by convention, assigned one subsample of events a positive sign of the target-polarization vector ("+") and the other subsample a negative sign ("−"), whereupon we determined the asymmetry for them. In the same way, we calculated the asymmetry for the "down" direction of the polarization vector and for a carbon target. For each of these three sets of data, we obtained zero asymmetry in the kinematical region being studied.

Figure 4 shows the total spurious asymmetry [the errors are somewhat less than in A_N (see Fig. 5) owing to additional data accumulated with a carbon target]. By fitting the function $a + bx_{\rm F}$ to the spurious asymmetry, we obtained the following parameter values: $a = (-1.7 \pm 5.9)\%$ and $b = (-3 \pm 32)\%$. One can see that the spurious asymmetry is independent of $x_{\rm F}$ and is equal to zero within the errors. From the approximation of the same data by a constant, we obtained $c = (-1.1 \pm 1.5)\%$. As was indicated above, the spurious asymmetry is due predominantly to the drift of the calorimeter energy scale, this drift being corrected by means of a permanent recalibration to the world-average value of the neutral-pion mass. From the results of our fit, we can infer that, for each value of the observed physical single-spin asymmetry A_N, the absolute systematic error does not exceed 3% upon introducing this correction.

Asymmetry A_N in the reaction $p + p_\uparrow \to \pi^0 + X$ at 70 GeV

$\langle x_{\rm F}\rangle$	$\langle p_T\rangle$, GeV/c	A_N, %
−0.12	0.97	-1.0 ± 4.9
−0.14	1.05	-2.6 ± 4.5
−0.16	1.15	2.1 ± 4.0
−0.18	1.28	-5.8 ± 4.1
−0.22	1.49	-6.3 ± 4.3
−0.25	1.69	-11.6 ± 6.2
−0.29	1.93	-18.8 ± 8.7
−0.34	2.27	-40.0 ± 17.1

4. RESULTS AND THEIR DISCUSSION

The asymmetry A_N, which is a physical observable in our experiment, is shown in Fig. 5 and in the table. The quoted errors are purely statistical. As was indicated above, the absolute systematic error for each value of A_N does not exceed 3% and, in those intervals of $x_{\rm F}$ where A_N is different from zero, is much less than the statistical error. From our estimates, it follows that, for all values of A_N, the relative systematic error associated with the accuracy of determining the dilution factor and the degree of target polarization is within 10%.

The asymmetry is $(-2.5 \pm 2.0)\%$ in the region $-0.2 < x_{\rm F} < -0.1$ ($\langle p_T\rangle \approx 1.1$ GeV/c) and $(-10.6 \pm 3.2)\%$ in the region $-0.4 < x_{\rm F} < -0.2$ ($\langle p_T\rangle \approx 1.7$ GeV/c). The value of $x_{\rm F} \approx -0.2$ is the threshold point for the emergence of A_N. It was indicated in [14] that, in the majority of experiments, the asymmetry of inclusive neutral-pion production is compatible with zero up to the c.m. pion energy of $E_{\rm c.m.} = E_0 \approx 1.5$–$2.0$ GeV, whereupon it grows in magnitude. The asymmetry measured in our experiment is shown in Fig. 6 as a function of $E_{\rm c.m.}$.

By fitting the function

$$A_N = \begin{cases} 0 \quad \text{for} \quad E_{\rm c.m.} < E_0 \\ k \cdot (E_{\rm c.m.} - E_0) \quad \text{for} \quad E_{\rm c.m.} \geq E_0 \end{cases} \tag{4}$$

to our data on A_N, we obtained the value of $E_0 = 1.5 \pm 0.1$ GeV, which is in good agreement with the results reported in [14]. The fitted value of the slope parameter k is -15 ± 4.

In Fig. 7, our result (the sign of A_N is reversed for a comparison to be more convenient) is given along with data of previous experiments devoted to measuring the single-spin asymmetry of inclusive neutral-pion production in the region of polarized-proton fragmentation. One can see that, within the errors, the values of A_N in $pp_\uparrow$ interactions at 70 GeV are identical to their counterparts in $\pi^- p_\uparrow$ interactions at 40 GeV, but that, at 200 GeV, the growth of the asymmetry with increasing neutral-pion energy is slower.

As is well known, large single-spin effects cannot be explained within perturbative QCD, which is the

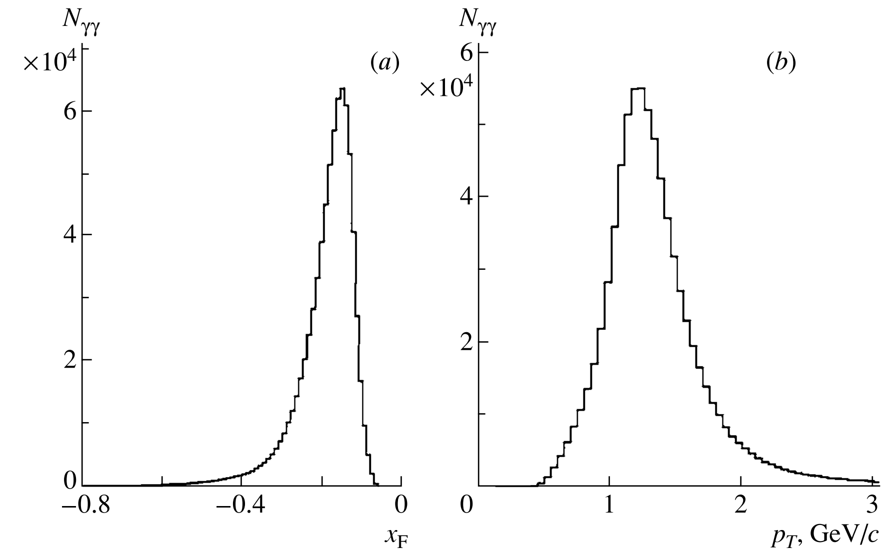

Fig. 2. Distribution of photon pairs with respect to (a) the Feynman variable and (b) the transverse momentum.

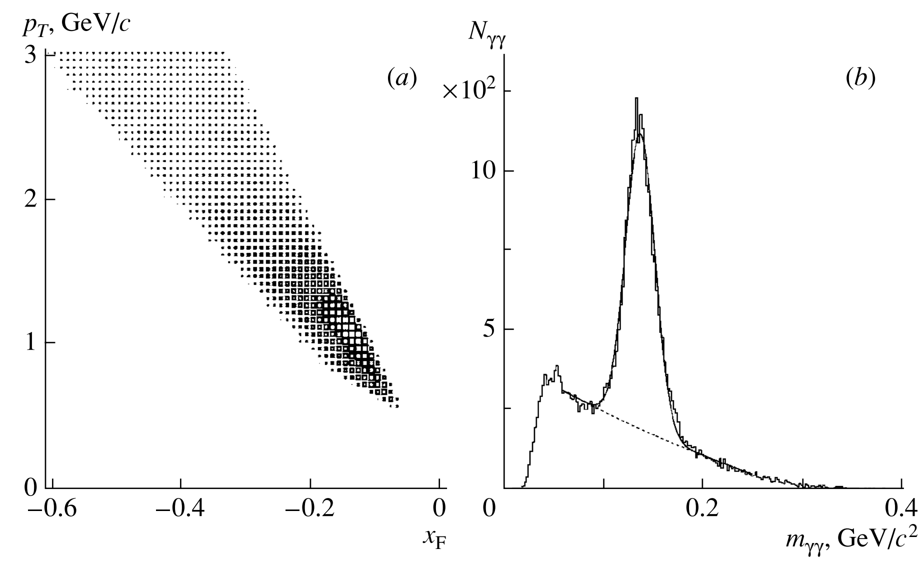

Fig. 3. (a) Two-dimensional distribution of photon pairs with respect to the transverse momentum (p_T) and the Feynman variable x_F and (b) mass spectrum of photon pairs in the region $-0.3 < x_F < -0.2$ (summation over p_T was performed). In Fig. 3b, the solid curve is an approximation by the sum of a Gaussian distribution and a third-degree polynomial, while the dotted curve represents the contribution of a combinatorial background.

generally accepted theory of hard interactions. For the reaction $p + p \to \pi^0 + X$, it follows from the factorization theorem that

$$d\sigma = \sum_{a,b,c} f_{a/p} \otimes f_{b/p} \otimes d\sigma(ab \to c \ldots) \otimes D_{\pi/c}, \quad (5)$$

where $f_{a/p}$ and $f_{b/p}$ are the parton distributions in colliding protons, $d\sigma(ab \to c \ldots)$ is the elementary-process cross section, and $D_{\pi/c}$ is the parton-to-pion fragmentation function. For the asymmetry $A_N \sim (d\sigma_\uparrow - d\sigma_\downarrow)$, the helicity-conservation law yields

$$A_N \sim \frac{m_q}{\sqrt{s}} \alpha_s \sim 0. \quad (6)$$

A number of models based on generalizations of the factorization theorem were proposed after the discovery of significant values of A_N in some experiments. These models assume the presence of (i) higher twist correlation functions in the distribution functions (for example, twist-3 correlation functions in the Qui–Sterman [15] and Efremov–Korotkiyan–

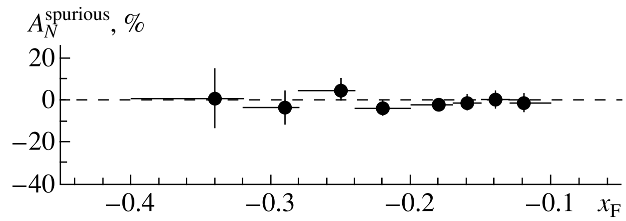

Fig. 4. Spurious asymmetry as a function of x_F. The horizontal straight-line segments show x_F intervals, while the points correspond to the average value of x_F in a given interval (summation over p_T was performed).

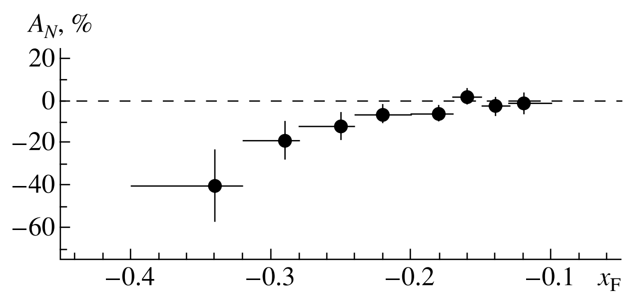

Fig. 5. Asymmetry A_N as a function of x_F.

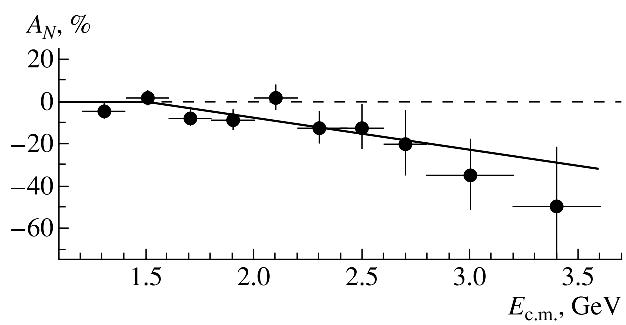

Fig. 6. Asymmetry A_N as a function of the neutral-pion energy in the c.m. frame. The solid line represents an approximation by the function in (4).

Teryaev [16] models), (ii) an intrinsic transverse momentum k_T and a spin dependence of the distribution functions (Sivers model [17]), or (iii) an intrinsic transverse momentum k_T and a spin dependence of the fragmentation function (Collins model [18]).

Also, so-called semiclassical models were developed on the basis of introducing a quark orbital angular momentum [19, 20]. Proposing various mechanisms for explaining the emergence of single-spin asymmetries, these models do not present a universal spin theory, but they describe experimental data satisfactorily.

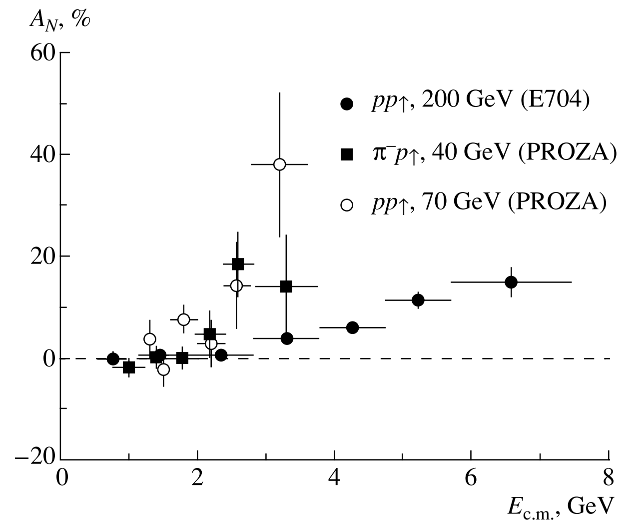

Fig. 7. Asymmetry A_N in the reaction $hp_\uparrow \to \pi^0 X$ as a function of the interaction energy for various hadron types h (π^- or p).

5. CONCLUSION

The single-spin asymmetry of inclusive neutral-pion production in the reaction $p + p_\uparrow \to \pi^0 + X$ at 70 GeV has been measured over the kinematical region specified by the inequalities $-0.4 < x_F < -0.1$ and $0.9 < p_T < 2.5$ GeV/c. The asymmetry is equal to zero for $-0.2 < x_F < -0.1$ within the errors, but it grows in magnitude as x_F decreases beyond this region, amounting to $(-10.6 \pm 3.2)\%$ in the region $-0.4 < x_F < -0.2$.

In $pp_\uparrow$ interactions, the asymmetry A_N begins deviating from zero at a c.m. neutral-pion energy of about 1.5 GeV.

In contrast to what we have in the central region, the asymmetry of inclusive neutral-pion production in the region of polarized-proton fragmentation takes the same value within the experimental errors in $\pi^- p_\uparrow$ and in $pp_\uparrow$ interactions.

Our result is compatible with the predictions of theoretical models describing spin effects in $hp_\uparrow$ interactions.

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