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ELEMENTARY PARTICLES AND FIELDS
Experiment

Single-Spin Asymmetry of Inclusive π^0-Meson Production in 40-GeV Pion Interactions with a Polarized Target in the Target-Fragmentation Region

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Abstract—Data on the single-spin asymmetry (A_N) of inclusive π^0 production in 40-GeV pion interactions with a polarized target, $\pi^- + p_\uparrow \to \pi^0 + X$, are presented for the target-fragmentation region. The result is $A_N = (-13.8 \pm 3.8)\%$ for $-0.8 < x_\mathrm{F} < -0.4$ and $1 < p_T < 2$ GeV/c and is compatible with zero for $-0.4 < x_\mathrm{F} < -0.1$ and $0.5 < p_T < 1.5$ GeV/c. At a π^0 momentum of about 1.7 GeV/c in the c.m. frame, the asymmetry becomes nonzero both in the central and in the target-fragmentation region. The behavior of the asymmetry is similar to that observed in the beam-fragmentation region of the E-704 (FNAL, 200 GeV) and STAR (BNL, 20 TeV) experiments, which employed a polarized proton beam.

INTRODUCTION

The spin is one of the fundamental properties of elementary particles. Since the advent of polarized targets and polarized beams, investigation into spin effects has become one of the most important fields in high-energy physics.

Within perturbative QCD (pQCD), transverse single-spin effects tend to zero in the limit of high energies and high momentum transfers. However, even the first experiments with polarized targets yielded results contradicting these expectations. A significant asymmetry was revealed in elastic and charge-exchange reactions. Experiments in the region of polarized-beam fragmentation at the Argonne National Laboratory (ANL) disclosed considerable effects in $p_\uparrow + p \to \pi^\pm + X$ reactions at beam energies of 6 and about 12 GeV [1, 2]. In 1990, a detailed study of the asymmetry was performed by the E-704 experiment in a 200-GeV beam at the Fermi National Accelerator Laboratory (FNAL). The E-704 Collaboration reported a substantial value of the π-meson asymmetry in the beam-fragmentation region [3]. The absolute value of the asymmetry of inclusive charged-pion production was 40% in the E-925 experiment performed in a 22-GeV polarized-proton beam at the Brookhaven National Laboratory (BNL) in the late 1990s [4].

The main purpose of the PROZA-2 experiment [5] was to measure the asymmetry in question in the region of polarized-target fragmentation. No experiments were performed in this kinematical region previously. A feature peculiar to the PROZA-2 experiment is that, in contrast to all previous experiments, which sought the asymmetry of inclusive π^0-meson production either in the fragmentation region at high longitudinal momenta ($x_\mathrm{F} \gg x_T$, where $x_\mathrm{F} \approx 2p_L/\sqrt{s}$ is the Feynman variable and $x_T = 2p_T/\sqrt{s}$, p_L and p_T being, respectively, the longitudinal and the transverse secondary-particle momentum) or in the central region ($x_\mathrm{F} \approx 0$), the contributions of both the

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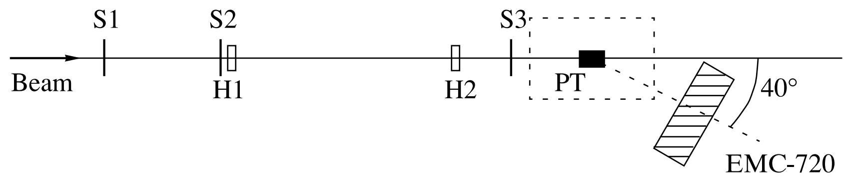

Fig. 1. Layout of the PROZA-2 experimental setup: (S1–S3) scintillation counters of the total flux, (H1, H2) hodoscopes, (PT) polarized target, and (EMC-720) electromagnetic calorimeter placed at an angle of 40° or 30° with respect to the beam axis.

longitudinal and the transverse momentum components are significant here.

1. EXPERIMENTAL SETUP

Our experiment was conducted with the aid of the PROZA-2 setup installed in the beamline 14 of the U-70 accelerator complex. In a 40-GeV beam, we measured the asymmetry of inclusive π^0-meson production in the reaction

$$\pi^- + p_\uparrow \to \pi^0 + X. \quad (1)$$

The setup consisted of beam detectors, a polarized target, and an electromagnetic calorimeter. Figure 1 shows the layout of the experimental setup, which was described in detail elsewhere [6].

1.1. Beam Formation and Beam Detectors

The beam of negatively charged particles produced in the internal target was deflected into beamline 14 by the magnetic field of the accelerator. The system of three magnets and eight lenses permitted us to select particles of specific energy and to focus the resulting beam onto the polarized target of the setup. The beam formed in this way contained π^- mesons, K^- mesons, and antiprotons (about 98, 1.8, and 0.3%, respectively), the beam intensity being 10^6 particles per spill. The spread in particle momenta was about 2% and was determined by the acceptance of a pulsed collimator.

The beam foci in the horizontal and vertical planes were close to the target center. The beam dimensions at the target were $\sigma_x \simeq \sigma_y \simeq 3.5$ mm. More than 97% of beam particles hit the target, which was 18 mm in diameter.

The number of particles incident on the target was determined by three scintillation counters, S1–S3; the first two of them were 10 cm in diameter, while the last one, located near the target, was 1.8 cm in diameter.

The coordinates of beam particles incident on the target were determined by two hodoscopes, H1 and H2, placed at distances of, respectively, 8.7 and 3.2 m from the target center. The hodoscope H1 comprised two planes, each containing 16 counters of size $5 \times 5 \times 85$ mm; the hodoscope H2 had two planes with 12 counters per plane, each of them being of size $2 \times 5 \times 40$ mm (the 2-mm side was oriented along the direction transverse to the beam).

1.1.1. Polarized target

A frozen polarized-proton target based on propanediol ($C_3H_8O_2$) was used in the experiment [7]. The mean polarization of hydrogen nuclei there was 80% during the accumulation of data. The pumping of the polarization, with its simultaneous reverse, took about four hours. On average, it was performed once every 48 hours. A special compact magnet ensuring a field of high uniformity (up to 10^{-4}) was designed for the polarized target at the Institute for High Energy Physics (IHEP, Protvino) [8].

A thin-walled horizontal cryostat was used in the target. Low-energy secondary particles could be recorded owing to thin side walls of the cryostat. This property was of special importance for measurements of the asymmetry in the target-fragmentation region.

We note that the mass of hydrogen nuclei was about 1/10 of the entire target material. In calculating the asymmetry, it is therefore necessary to take into account the target-dilution factor D, which is defined as the ratio of the total number of beam interactions with the target to the number of interactions with hydrogen nuclei.

1.1.2. Electromagnetic calorimeter

Photons from π^0-meson decay were recorded by a total-absorption electromagnetic calorimeter. The calorimeter comprised 720 counters (EMC-720) from TF1-00 lead glass [9]. It was shaped as a rectangular matrix containing 30 column of 24 counters. The calorimeter was placed at a distance of about 2.3 m from the target. The counters were of size $38 \times 38 \times 450$ mm (18 radiation-length units); they were wrapped with an aluminized Mylar film 20 μm thick. Cherenkov light produced by electromagnetic showers in the glass was recorded by a 12-dynode

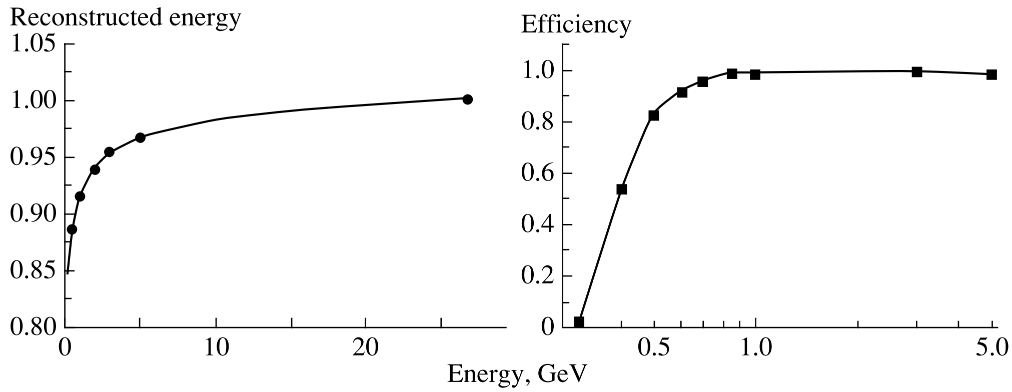

Fig. 2. Energy fraction recorded by the calorimeter (left panel) and efficiency of electromagnetic-shower reconstruction in the detector (right panel) versus the true photon energy in a simulation.

photomultiplier tube (PMT-84/3), the photocathode being 34 mm in diameter.

The coefficients used to convert the pulse from each detector cell to the energy deposited inside this cell were determined by means of a detector calibration with a 26.6-GeV electron beam [10]. The calorimeter design permitted moving the detector in the horizontal and vertical directions orthogonal to the beam in such a way that the electron beam could irradiate all of the calorimeter cells. The calorimeter resolution was $\sigma(E)/E = 2.5\%$ at the energy value used (the beam-momentum spread of 2% was subtracted).

A monitoring system based on photodiodes [11] was used to test the calorimeter stability with time. The energy scale was monitored by means of an additional calibration against the π^0-meson mass to a precision of 0.1% in the course of five-hour measurements.

The EMC-720 central counters were arranged in the horizontal plane at a viewing angle of 30° with respect to the target center in the run of 1999 for measurements in the range $-0.4 < x_{\mathrm{F}} < -0.1$ and at an angle of 40° in two runs of 2000 for measurements in the range $-0.8 < x_{\mathrm{F}} < -0.3$.

1.2. Electronic System and Transverse-Energy Trigger

The electronic system consisted of unified nanosecond-electronics modules, circuits of pulse-height converters, rescaling circuits, registers, and other additional systems manufactured in the SUMMA standard [12].

The coincidence of signals from three scintillation counters S1–S3 was a zero-level trigger for an incident particle. In addition, a response from each plane of the hodoscopes was required. The trigger was formed within a 60-ns gate if another particle did not pass within this time gate.

A level-1 trigger within a 350-ns gate was developed on the basis of an analysis of the total transverse energy deposition in the calorimeter. A fraction of the pulse from each counter (about 5%) was fed into an analogous adder, the angle at which this counter was viewed from the target being taken into account. To introduce angular corrections, use was made of shunting resistors whose resistances were proportional to $\sin\theta$, where θ was the mean angle corresponding to a given column. Thus, the total signal was proportional to the transverse energy $E_T = E\sin\theta$ recorded by the detector. The detector trigger was adjusted at a level of 1.1 GeV in the run of 1999 and at a level of 1.4 GeV in the runs of 2000.

For electronics of the pulse-height analysis, we used 12-bit analog-to-digital converters (P-267) [13]. The data were read out by a computer based on the MC68030 processor and controlled by the OS-9 real-time operating system and were then transferred by a local network to an individual computer in order to perform on-line processing and to log them on a magnetic tape. With allowance for the efficiency of the data-acquisition system, about 300 events were recorded per accelerator cycle. In all, about 100 million events were obtained over 30 days of data accumulation.

2. DATA ANALYSIS AND RESULTS

Analyzing our experimental data, we selected, among all of the recorded photons, those whose energy ranged between 0.5 and 3.5 GeV. The mean multiplicity of recorded photons was about 1.3.

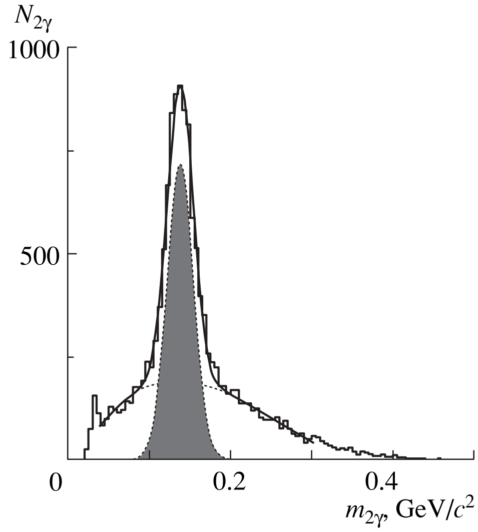

Fig. 3. Mass distribution of photon pairs recorded in the EMC-720 electromagnetic calorimeter. The distribution is approximated by a Gaussian and a polynomial of third degree (solid curve). The dotted curve represents the background in the region of the π^0-meson mass peak, while the shaded area corresponds to the Gaussian function describing the π^0 mass distribution.

2.1. Simulation of an Electromagnetic Shower in the Calorimeter

To test the algorithm for reconstructing photons and π^0 mesons, the development of electromagnetic showers in lead glass was simulated on the basis of the GEANT 3.21 code [14]. In the simulation of Cherenkov light, we took into account the effects caused by its propagation through matter and its reflection from the surface of the crystal wrapped with a Mylar film, as well as the quantum properties of PMT-84/3 photomultiplier tubes. The number of photoelectrons was about 1000 GeV^{-1}, which corresponds to experimental data obtained for this type of glass [15].

The simulation revealed that a substantial fraction of energy (up to 20%) was lost in recording low-energy photons mainly because of the detection threshold of the electronics. Figure 2 shows the ratio of the recorded energy to the true energy. It can also be seen from this figure that the efficiency of electromagnetic-shower reconstruction in the calorimeter without the background is close to 100% for energies above 0.8 GeV and exceeds 80% at an energy of 0.5 GeV.

2.2. Properties of Reconstructed Neutral Pions

Corrections to the shower energy that were obtained in the simulation permitted us to take into account the energy losses and to reconstruct the energy and the mass of π^0 mesons correctly. Figure 3 shows the mass distribution of a photon pair, its width σ_m being about 15 MeV/c^2.

The chosen geometry and trigger made it possible to record π^0 mesons in the target-fragmentation region for transverse momenta in excess of 0.5 GeV/c. Figure 4 shows the distribution of photon pairs in the region of the π^0-meson mass versus some kinematical variables. The correlation between p_T and $x_{\rm F}$ is clearly seen in this figure.

2.3. Algorithm for Calculating Single-Spin Asymmetry

The single-spin asymmetry A_N observed physically is defined as

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

where $P_{\rm targ}$ is the target polarization, $\cos\phi$ is the cosine of 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 π^0 meson, and $\sigma_\uparrow^{\rm H}$ and $\sigma_\downarrow^{\rm H}$ are the cross sections for π^0-meson production on hydrogen for opposite directions of the target polarization. In our case, π^0 mesons were recorded at an azimuthal angle in the range $180° \pm 15°$; therefore, $\cos\phi$ was set to -1.

The raw asymmetry $A_N^{\rm raw}$ actually measured in our experiment for the detector placed to the right of the beam axis is related to A_N by the equation

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

where D is the target-dilution factor and $n_\downarrow$ and $n_\uparrow$ are the normalized (to the monitor) numbers of π^0 mesons produced on the propanediol target for opposite directions of the polarization vector.

The number of particles that traversed the setup target was used as a monitor with allowance for the efficiency of the hodoscopes—that is, with allowance for the number of triggers T_0 formed upon a simultaneous actuation of the telescope consisting of three scintillation counters and each plane of the hodoscopes.

In measuring the asymmetry, there can arise an additional instrumental asymmetry caused by trigger-electronics jitter, failures of the monitor counters, and other reasons. As a consequence, the

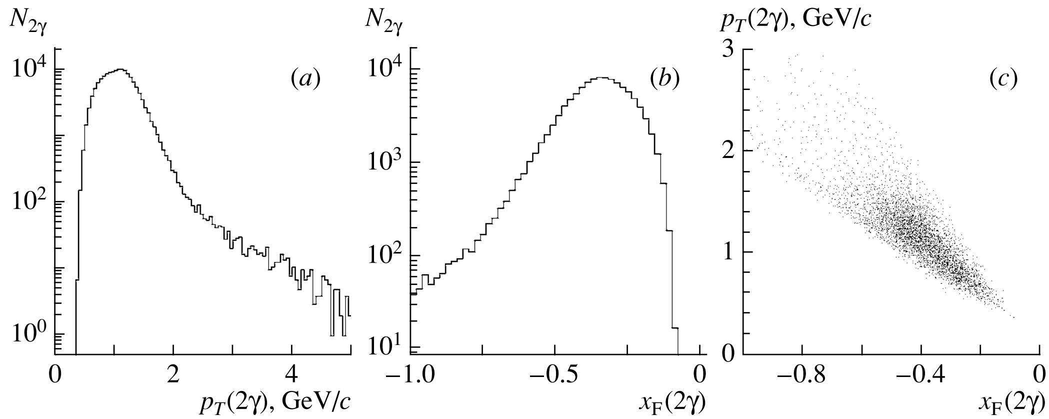

Fig. 4. (a) Transverse-momentum (p_T) and (b) x_F distributions of photon pairs and (c) p_T as a function of x_F in the region of the π^0 meson mass according to measurements with EMC-720 during the run in the fall of 2000. The efficiency of π^0-meson reconstruction is not taken into account in the displayed distributions.

measured asymmetry is a sum of the real and the instrumental asymmetry (A_{backgr}); that is,

$$A_{2\gamma}^{\mathrm{meas}} = kA_{\pi^0}^{\mathrm{real}} + A_{\mathrm{backgr}}, \qquad (4)$$

where k is the relative number of π^0 mesons, which depends on the photon-pair mass. In order to remove this systematic bias of the asymmetry, we developed a method based on the assumption that the background asymmetry is zero. By the background asymmetry A_{backgr}, we mean the asymmetry of photon pairs off the region of the π^0-meson mass peak. This assumption is based on the results of the PROZA-M and E-704 experiments performed previously. The asymmetry A_N for photon pairs off the π^0-meson mass region was $A_N = (-1.0 \pm 0.8)\%$ in the E704 experiment [16] and $(0.04 \pm 0.4)\%$ in the raw data of the PROZA-M experiment, where it was averaged over the range $1.8 < p_T < 3.2$ GeV/c. In our calculation, we set the background asymmetry to zero, disregarding the uncertainty in the measurements.

In order to suppress systematic uncertainties associated with the instability of electronics operation, the data from counters that were actuated much more often, on average, than neighboring ones at least in one of the event sets (hot counters) were excluded from the analysis of the whole statistics. Hot counters were tested over three-hour intervals. In all, two groups of 16 counters, each corresponding to two analog-to-digital converters and nine separate counters were discarded. It should also be noted that we selected only clusters described by an electromagnetic shower of shape known from the experimental data.

Figure 5 shows an example illustrating the calculation of the asymmetry $A_{\pi^0}^{\mathrm{raw}}$. The asymmetry is derived as the ratio of the difference of the normalized numbers of photon pairs as a function of their mass for two opposite directions of the target polarization vector to the sum of these numbers, $\dfrac{n_\downarrow - n_\uparrow}{n_\downarrow + n_\uparrow}$. The background asymmetry A_{backgr} is fitted off the region of the mass peak. The resulting value is subtracted, at each point, from the measured asymmetry $A_{2\gamma}^{\mathrm{meas}}$. In this way, we obtained the raw asymmetry $A_N^{\mathrm{raw}}(2\gamma)$ as a function of mass. The resulting distribution was fitted with allowance for the weight factor k for π^0 mesons at each point of the mass spectrum.

The systematic error of this method is determined primarily by the statistics of photon pairs off the region of the π^0-meson mass and, for different intervals of x_F, is 50 to 100% of the statistical uncertainty in assessing the number of π^0 mesons. In the results presented in this article, we took into account both the statistical and the systematic uncertainty.

2.4. Analysis of the Spurious Asymmetry

The spurious asymmetry is caused by a drift of the calorimeter-energy scale and by the respective inaccuracy in reconstructing the kinematical parameters of the photon pair. The cross section for the inclusive production of π^0 mesons depends greatly on p_T. Therefore, a 1% difference in the energy scale of the detector between the data for positive and negative target polarizations leads to a spurious raw asymmetry on the order of 2%—that is, to a spurious asymmetry of 20% upon taking into account the dilution factor. In our case, the instability of the calorimeter energy scale was below 0.1%. Thus, the spurious asymmetry caused by the instability of the energy scale was below 0.2% for the raw asymmetry and

Table 1. Dilution factor versus the transverse momentum

p_T [GeV/c]	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.8
D from [17]	8.0 ± 1.0	8.1 ± 1.2	8.1 ± 0.7	8.2 ± 0.9	8.8 ± 1.3	9.2 ± 1.6	9.5 ± 2.0	10.1 ± 2.5

2% for the quantity under study (the dilution factor and target polarization $D/P_{\rm targ} \sim 10$ were taken into account).

In order to estimate the spurious asymmetry, the total data set obtained for the same direction of the target polarization vector was broken down into two equal subsets, and the asymmetry for these subsets was determined (opposite signs of target polarization were arbitrarily assigned to these subsets). Figure 6 shows the result calculated for the spurious asymmetry in one of the three experimental runs. The spurious asymmetry is zero within the errors. The same result was obtained for the other experimental runs as well; however, the uncertainties are rather large. In order to be sure that the data obtained in the different measurements are consistent, we compared the results on the asymmetry from the three experimental runs performed in different periods. The results are in agreement within the errors.

2.5. Determination of the Dilution Factor

In order to calculate the physically observed asymmetry A_N on the basis of Eq. (3), it is necessary to determine the target-dilution factor. For this, we must know the composition of the target material (in percent). Interactions can also occur on the target iron walls 0.3 mm thick. The cross section for the production of charged π mesons is proportional to A^α, with α lying in the range between 0.85 and 1.2 for $p_T > 1$ GeV/c [18]. According to our calculations, the dilution-factor value must range between about 8 and about 10.5 if the transverse momentum p_T varies between 1 and 3 GeV/c. To test the calculations, we used the results of dedicated measurements from previous runs [17] with an empty target and with a carbon equivalent of our target. The effect for an unpolarized propanediol target was determined as the mean effect for two orientations of the target polarization vector. Table 1 summarizes the data from these measurements. It should be noted that our study is performed with the same polarized target from the same material. In 1996, we also measured the dilution factor, but on the basis of scarcer statistics. The results were $D = 8.4 \pm 1.2$ and $D = 9.2 \pm 1.5$ at $p_T \sim 1.8$ GeV/c and $p_T \sim 2.1$ GeV/c, respectively, these values being in agreement with previous results. We adopted the value of $D = 8.1$ for our calculations.

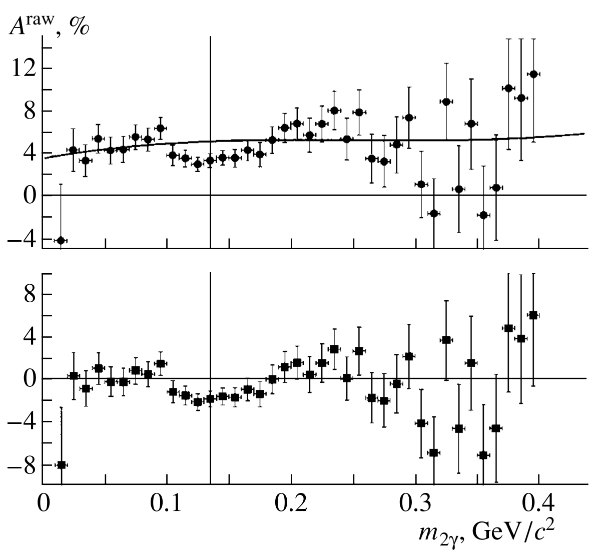

Fig. 5. Raw asymmetry $A^{\rm raw}$ as a function of the photon-pair mass (upper panel) and result obtained upon subtracting the background asymmetry (lower panel). The curve represents a fit to the background asymmetry—that is, for photon pairs off the π^0-meson mass peak.

2.6. Measurements of the Asymmetry

Figure 7 and Table 2 display the ultimate results with allowance for the dilution factor and the target polarization. In the calculation of the physically observed asymmetry A_N, the uncertainties in the dilution factor D and in the target polarization (about 10%) were disregarded.

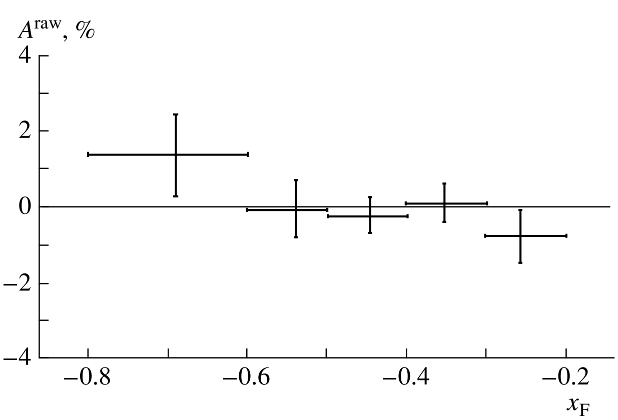

Fig. 6. Spurious asymmetry as a function of $x_{\rm F}$ in the spring run of 2000.

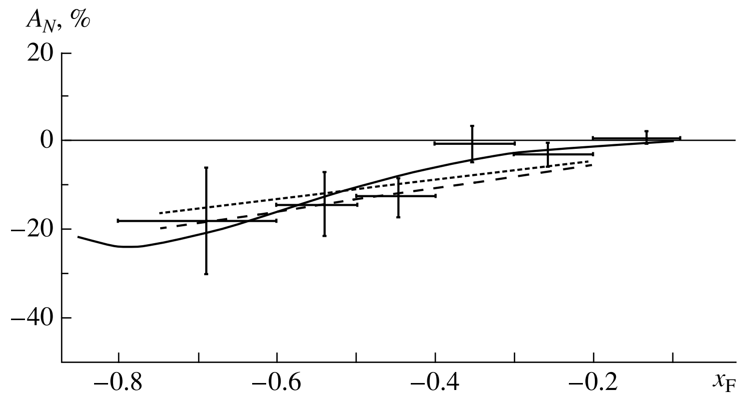

Fig. 7. Asymmetry A_N of π^0-meson production in the target-fragmentation region as a function of x_F. The resolution in x_F varies from 0.03 for $-0.3 < x_F < -0.1$ to 0.07 for $-0.8 < x_F < -0.6$. The solid curve represents the prediction obtained in [23] on the basis of the Collins model; the dotted and dashed curves are the predictions of the U-matrix quark model at various values of $\langle L_{\{\bar{q}q\}}\rangle$ ($\langle L_{\{\bar{q}q\}}\rangle$ is the mean angular momentum of current quarks inside the constituent quark) [30].

The asymmetry proves to be $A_N = (-13.8 \pm 3.8)\%$ in the range $-0.8 < x_F < -0.4$ and is close to zero in the range $-0.4 < x_F < -0.1$.

3. DISCUSSION

3.1. Comparison with Other Experimental Data

The asymmetry of inclusive π^0 production in the polarized-particle-fragmentation region was also measured in experiments at FNAL (E-704) and BNL [19] at, respectively, 200 GeV and 20 TeV in the target rest frame (the latter energy value was rescaled from the c.m. energy of two 100-GeV beams of the RHIC collider to the beam energy in the laboratory frame). Table 3 summarizes the results of the three experiments in the polarized-particle-fragmentation region.

In all of the experiments, the absolute value of the asymmetry grows with increasing $|x_F|$, reaching a value of 10 to 15% at high values of $|x_F|$. Therefore, we can conclude that the asymmetry of inclusive π^0-meson production in the polarized-proton-fragmentation region is virtually independent of energy in the range 40–20 000 GeV in the laboratory frame. The measured analyzing power is rather high in the reaction being studied (10–15%), and the cross section for π^0 production is quite large. Thus, this reaction can be used to measure the polarization of proton beams.

The asymmetry A_N in the central π^0-production region of the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ was previously measured with the PROZA-M setup at 40 GeV/c [17]. In that case, the asymmetry grew in magnitude with increasing p_T, reaching a value of −30%. If the asymmetry was approximated by a linear function, it intersected the abscissa at $p_T^0 = 1.67 \pm 0.09$ GeV/c. In order to compare our new data with the results from [17], we plotted the asymmetry versus the π^0-meson energy in the c.m. frame, E. The asymmetry begins to grow in magnitude at $p_0 = 1.75 \pm 0.2$ GeV/c (Fig. 8). The measurements in [17] were carried out at an angle of 90° in the c.m. frame; therefore, the transverse momentum p_T there was

Table 2. Asymmetry in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ at a beam momentum of 40 GeV/c versus x_F

$\langle x_F \rangle$	$\langle p_T \rangle$, GeV/c	A_N, %
−0.133	0.8	0.4 ± 1.4
−0.258	1.1	-3.3 ± 2.4
−0.353	1.3	-1.0 ± 3.9
−0.446	1.5	-12.7 ± 4.8
−0.54	1.65	-14.4 ± 7.2
−0.69	1.8	-18.3 ± 11.9

Table 3. Data from different experiments on the asymmetry A_N measured in the polarized-proton-fragmentation region for $1 < p_T < 2$ GeV/c

Experiment	$\lvert A_N \rvert$, %
E-704, FNAL [3]	12.4 ± 1.4
STAR, BNL [19]	14 ± 4
Present experiment	13.8 ± 3.8

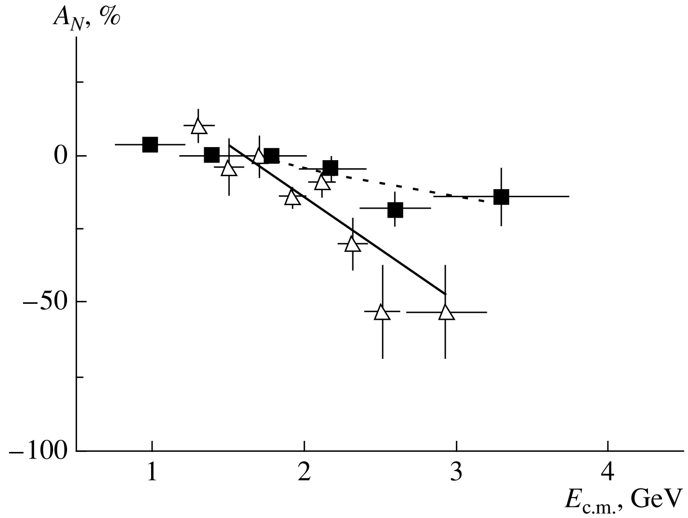

Fig. 8. Asymmetry A_N of π^0-meson production in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ as a function of the π^0-meson energy in the c.m. frame (E) for the target-fragmentation region (■, our experiment) and for the central region (△, data from [17].

virtually coincident with the π^0-meson momentum in the c.m. frame. Thus, we can see that, in the two kinematical regions, the asymmetry begins growing in magnitude at the same π^0-meson energy in the c.m. frame.

3.2. Mechanism of Asymmetry Generation within Various Theoretical Models

The pQCD model predicts zero asymmetry. In order to explain the observed high single-spin asymmetry, Sivers [20, 21] introduced an additional internal transverse momentum $\mathbf{k}_T$ of quarks in the parton distributions within polarized nucleons. Collins [22] assumed that an additional transverse momentum appears in the fragmentation functions $D_{\pi/c}$. Thus, the single-spin asymmetry appears because of the spin dependence of initial-state interaction in the Sivers model and because of the spin dependence of final-state interaction in the Collins model. Figure 7 shows Anselmino's predictions for the single-spin asymmetry A_N in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ within the Collins model [23] (solid curve). His predictions within the Sivers model deviate only slightly from this curve.

Efremov and Teryaev [24, 25] proposed taking into account the contribution of higher twists or the quark–gluon correlation, which reflects quark interaction with a hadron color field [26, 27]. The predictions of Qiu and Sterman [28] within this model also adequately describe the experimental data in the polarized-particle-fragmentation region.

A high-asymmetry generation can also be associated with the orbital angular momentum of quarks. Troshin and Tyurin [29] formulated a quark model within the U-matrix approach where the main contribution to the asymmetry comes from the orbital angular momentum of current quarks inside a constituent quark. For the reaction being studied, Fig. 7 shows the asymmetry values predicted within the U-matrix quark model [30] (dotted and dashed curves).

Ryskin [31] proposed a model where the asymmetry arises owing to the interaction of the quark chromomagnetic moment with a chromomagnetic field. Using Ryskin's basic idea, Abramov [32] put forward his own model, which also describes the data in question quite well.

The basic models are reviewed in [33–35].

The results on the asymmetry in inclusive π-meson production that were obtained in the PROZA (IHEP) [17] and E-704 (FNAL) [3] experiments gave impetus to the development of these models. The parameters of the models were chosen in such a way as to describe well the results of the E-704 experiment. Since the data presented in this article are similar to those obtained in the E-704 experiment, they are in good agreement with the predictions of the theoretical models.

We also note that the gluon component makes a large contribution to the cross section in the region of small $|x_F|$; therefore, the asymmetry must be small in the region $|x_F| < 0.4$ because the transverse gluon functions depend only slightly on the proton polarization.

4. CONCLUSIONS

The basic results of our study are the following.

(i) The asymmetry in inclusive π^0 production has been measured for the first time in the polarized-target-fragmentation region. The asymmetry measured in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ is $A_N = (-13.8 \pm 3.8)\%$ in the range $-0.8 < x_F < -0.4$ for p_T values ranging between 1 and 2 GeV/c.

(ii) The asymmetry is close to zero in the range $-0.4 < x_F < -0.1$ for p_T values between 0.5 and 1.5 GeV/c.

(iii) Within the uncertainties, the asymmetry measured in our experiment for $|x_F| > 0.4$ is consistent with the results of the measurements performed at FNAL (E-704, 200 GeV) and BNL (20 TeV in the rest-target frame) in the polarized-proton-beam fragmentation region at the same values of $|x_F|$. Therefore, it has been established in a fixed-target experiment that the asymmetry arises in the polarized-proton-fragmentation region and is independent of whether this proton is a beam or a target particle.

(iv) Inclusive π^0-meson production in the polarized-proton-fragmentation region is a new reaction for polarimetry, the experimentally established analyzing power being about 10 to 15%.

(v) From a comparison with the asymmetry measured at an angle of 90° in the c.m. frame, it follows that the absolute value of the asymmetry in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ at 40 GeV begins growing at the same value of the π^0-meson momentum in the c.m. frame for two different kinematical regions, this value being $p_0 \approx 1.7$ GeV/c.

(vi) The existing theoretical models describe well the experimental data in question.

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REFERENCES

1. R. D. Klem *et al.*, Phys. Rev. Lett. **36**, 929 (1976).
2. W. H. Dragoset *et al.*, Phys. Rev. D **18**, 3939 (1978).
3. D. L. Adams *et al.*, Z. Phys. C **56**, 181 (1992).
4. C. E. Allgower *et al.*, Phys. Rev. D **65**, 092008 (2002).
5. N. I. Belikov *et al.*, Preprint No. 97-17, IHEP (Protvino, 1997).
6. V. D. Apokin *et al.*, Instrum. Exp. Tech. **41**, 464 (1998).
7. N. S. Borisov *et al.*, Preprint No. 1-80-98, JINR (Dubna, 1980).
8. M. M. Bukharin *et al.*, Prib. Tekh. Éksp., No. 1, 30 (1981); O. A. Grachev *et al.*, Prib. Tekh. Éksp., No. 3, 189 (1993).
9. G. A. Akopdjanov *et al.*, Nucl. Instrum. Methods **140**, 441 (1977).
10. D. L. Adams *et al.*, Preprint No. 91-99, IHEP (Protvino, 1991).
11. A. N. Vasiliev *et al.*, Preprint No. 97-60, IHEP (Protvino, 1997).
12. Yu. V. Bushnin *et al.*, Preprint No. 72-49, IHEP (Serpukhov, 1972); O. I. Alferova *et al.*, Prib. Tekh. Éksp., No. 4, 56 (1975).
13. S. A. Zimin *et al.*, Preprint No. 93-50, IHEP (Protvino, 1993).
14. *GEANT—Detector Description and Simulation Tool* (CERN, 1994).
15. F. Binon *et al.*, Nucl. Instrum. Methods **188**, 507 (1981).
16. E704 Collab., private communication.
17. N. S. Amaglobeli, V. D. Apokin, Yu. N. Arestov, *et al.*, Yad. Fiz. **50**, 695 (1989) [Sov. J. Nucl. Phys. **50**, 432 (1989)]; V. D. Apokin *et al.*, Phys. Lett. B **243**, 461 (1990).
18. R. M. Sulyaev, Preprint No. 88-100, IHEP (Protvino, 1988); R. M. Sulyaev, in *Relativistic Nuclear Physics and Quantum Chromodynamics, Dubna, 1988*, Vol. 1, p. 237.
19. L. C. Bland, in *Proceedings of the 15th International Spin Physics Symposium (SPIN 2002), Long Island, New York, 2002*; hep-ex/0212013.
20. D. Sivers, Phys. Rev. D **41**, 83 (1990).
21. D. Sivers, Phys. Rev. D **43**, 261 (1991).
22. J. C. Collins, Nucl. Phys. B **396**, 161 (1993).
23. M. Anselmino, private communication; M. Anselmino, M. Boglione, and F. Murgia, Phys. Rev. D **60**, 054027 (1999); Phys. Lett. B **362**, 164 (1995); M. Anselmino and F. Murgia, Phys. Lett. B **442**, 470 (1998); hep-ph/9808426.
24. A. V. Efremov and O. V. Teryaev, Yad. Fiz. **36**, 242 (1982) [Sov. J. Nucl. Phys. **36**, 140 (1982)]; **36**, 950 (1982) [**36**, 557 (1982)]; **39**, 1517 (1984) [**39**, 962 (1984)]; Phys. Lett. B **150B**, 383 (1985).
25. A. V. Efremov, V. M. Korotkiyan, and O. V. Teryaev, Phys. Lett. B **348**, 577 (1995).
26. J. Qiu and G. Sterman, Phys. Rev. Lett. **67**, 2264 (1991); Nucl. Phys. B **378**, 52 (1992).

27. A. Schäfer, L. Mankiewicz, P. Gornicki, and S. Güllenstern, Phys. Rev. D **47**, R1 (1993); B. Ehrnsperger, A. Schäfer, W. Greiner, and L. Mankiewicz, Phys. Lett. B **321**, 121 (1994).
28. J. Qiu and G. Sterman, Phys. Rev. D **59**, 014004 (1999).
29. S. M. Troshin and N. E. Tyurin, Phys. Rev. D **52**, 3862 (1995); **54**, 838 (1996).
30. S. M. Troshin, private communication.
31. M. G. Ryskin, Yad. Fiz. **48**, 1114 (1988) [Sov. J. Nucl. Phys. **48**, 708 (1988)].
32. V. V. Abamov, Preprint No. 98-84, IHEP (Protvino, 1998); V. V. Abramov, Eur. Phys. J. C **14**, 427 (2000); hep-ph/0110152; Preprint No. 2001-13, IHEP (Protvino, 2001); hep-ph/0111128.
33. Zuo-tang Liang and C. Boros, Int. J. Mod. Phys. A **15**, 927 (2000); hep-ph/0001330.
34. M. Anselmino, *Lectures at Advanced Study Institute on Symmetries and Spin (PRAHA SPIN 2001), Prague, 2001*; hep-ph/0201150.
35. M. Anselmino *et al.*, *Talk at 3rd Circum-Pan-Pacific Symposium on High-Energy Spin Physics (SPIN 2001), Beijing, China, 2001*; hep-ph/0201076.

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