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*Physics*

# Study of Angular Distributions of Pions in $\pi^-$(p, n, C) Collisions at Momentum of 40 GeV/c

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(Presented by Academy Member Anzor Khelashvili)

**The degree of anisotropy of $\pi^-$ and $\pi^+$ mesons emission can be more directly determined by studying the angular distributions in the CMS of colliding particles. The anisotropy coefficient α of negative and positive pions in $\pi^-$ (p, n, C) meson-nucleon and meson-nucleus (40 GeV/c) collisions was obtained from the analysis of angular cosΘ* distributions (Θ* is the emission angle). The data were obtained from Propane Bubble Chamber (PBC-500) systems utilized at JINR (Joint Institute for Nuclear Research). The experiment was performed at the Serpukhov proton synchrotron. The coefficient of anisotropy α was studied both in different intervals of kinetic energy and in different subgroups of multiplicity, and in all considered interactions the coefficient α for $\pi^-$ mesons is greater than for $\pi^+$ mesons. The anisotropy coefficient α increases almost linearly with increasing kinetic energy for pions of both signs, in these collisions, and after 700 MeV it increases sharply. As the mass of the target increases for pions of both signs, the magnitude of the anisotropy coefficient increases. These distributions are almost the same in $\pi^-$ (p, n, C) collisions, but the dependence is relatively greater for negative pions than for positive ones. At small multiplicities of pions ($n_{\pi\pm} \leq < n_{\pi\pm} >$ ) the degree of anisotropy is greater than at high multiplicities ($n_{\pi\pm} > < n_{\pi\pm} >$). The decrease of the parameter α for more central events ($n_{\pi\pm} > < n_{\pi\pm} >$) indicates that the angular distributions of pions become more isotropic at small impact parameters (b→0). The magnitude of the anisotropy coefficient in $\pi^-$ (p, n, C) meson-nucleon and meson-nucleus (40 GeV/c) collisions is higher than in similar studies conducted for nucleus-nucleus collisions. Thus, the nuclear environment, i.e. the interaction dynamics, is important. Some qualitative agreement of the presented experimental results with the predictions of different theoretical models (Intranuclear Cascade Models (Cugnon, Dubna), QGSM – Quark Gluon String Model and UrQMDM - Ultra-relativistic Quantum Molecular Dynamics Model) was obtained.** *© 2024 Bull. Georg. Natl. Acad. Sci.*

angular distribution, anisotropy coefficient, collision, nucleus, proton, pion

High-energy heavy-ion collisions provide a unique opportunity to study the properties of the hot and dense, strongly-interacting system, so-called quark-gluon plasma (QGP) [1], which is created once the temperature rises above a critical value Tc of about 150 MeV at zero baryo-chemical potential, or density of the system is larger than about 0.5 GeV/fm$^3$. Major motivations for such studies aim to determine the nuclear equation of state (EoS) and to study the basic properties of quantum chromodynamics (QCD). Nowadays, matter under such extreme conditions can be created and studied in the laboratory by colliding heavy-nuclei at ultra-relativistic energies. Heavy ion collisions are suitable conditions for studying the fine properties of nuclear matter. One of the experimental parameters used to describe these collisions (nucleus-nucleus, meson-nucleus, meson-nucleon) is the angular distribution of fission fragments [2].

In particular, the mean free paths of pions [3], the most abundantly created particles, with momenta below 1 GeV/c, are neither large nor small compared to typical nuclear sizes. In this respect, it is very important to investigate the properties of pions, which are the mainly produced particles, as they carry the information about the dynamics of collisions and can be reliably identified. Besides this, pion production is the predominant process at these energies.

An important lesson learned in the last two decades was that definite conclusions on nuclear matter properties based on a single observable had proven to be premature and/or of limited accuracy, aside from not being sufficiently convincing. As an example, original hopes [4], to use deficits in pion production relative to expectations based on compression-free scenarios were not supported by transport theoretical simulations [5]. On the other hand, transport calculations [6] showed that pion azimuthal correlations, or 'flow', qualify as an observable that could significantly constraint on the EoS.

Our previous results on pion production experiments (cross sections, multiplicities' rapidities, transverse momenta, inter-correlations between various characteristics, etc.) using the streamer chamber spectrometer SKM-200 in inelastic and central nucleus-nucleus interactions are published in [7-10]. It was shown that these particles are produced mainly in independent nucleon-nucleon collisions. The degree of anisotropy in pion emission from the analysis of angular distributions was determined and compared at different energies in [11]. Namely, the dependence of the anisotopy coefficient α on the mass of the projectile ($A_P$ = p, d, He, C) and target ($A_T$ = C, Ta) (4.2, 4.5 and 10 A GeV/c) investigated. Additionally, studies on hadron-nucleus systems p(C, Ta) at varying incident energy (3.7, 10) A GeV) were conducted with data obtained from Propane Bubble Chamber systems (PBC-500) [12, 13] at JINR (Joint Institute for Nuclear Research).

The aim of this work is to present a new detailed analysis of the $\pi^-$ and $\pi^+$ mesons angular distributions in $\pi^-$ (p, n, C) meson-nucleon and meson-nucleus interactions (40 GeV/c) obtained with the **(PBC- 500)** set-up (JINR). The experiment was performed at the Serpukhov proton synchrotron**.**

## Experimental Data

The data were obtained from Propane Bubble Chamber systems (PBC-500). The 2-meter-long Propane Bubble Chamber (PBC-500) was placed in the magnetic field of 1.5 T. The procedures for separating out the $\pi^-$(p, n, C) collisions in propane ($C_3H_8$) and processing of the data, including particle identification and corrections were descrybed in detail in [12, 13]. The identification probability of $\pi^-$C collision events are one, $\pi^-$p - 0.338, of $\pi^-$n - 0.973. The corrections of missing particles are 1.023 for -mesons and 1.046 - $\pi^+$-mesons. The weights of the particles ($\pi^-$ and $\pi^+$) in the distributions are multiplied by two values: the probabilities of the type of interaction ($\pi^-$p, $\pi^-$n and $\pi^-$C) and the corrections of missing particles in these collisions.

The experimental data sample contains 25 422 events, from which 12 765 corresponds to $\pi^-$p, 3 986 - $\pi^-$n, 8 671 - $\pi^-$C collisions, respectively. The average multiplicity of all charged particles ($<n_{\pm}>$) in $\pi^-$(p, n, C) collisions is 6.96±0.03 and $<n_{\pi-}>=$

3.52±0.02, $\langle n_{\pi+}\rangle$ =3.33±0.02. While the average momentum of $\pi^-$-mesons is $\langle p_{\pi-}\rangle$=5.31±0.32 GeV/c, $\langle p_{\pi+}\rangle$ =3.07 ±0.18 GeV/c in $\pi^-$(p, n, C) collisions.

For the study of angular distributions, the events were selected by requiring the minimal numbers of pions ($\pi^-$or $\pi^+$), $N_\pi^+\geq4$, $N_\pi^-\geq4$ in $\pi^-$(p, C) collisions and $N_\pi^+\geq3$, $N_\pi^-\geq3$ in $\pi^-$n collisions, respecttively. For the analysis the pions with momentum of p>0.05 GeV/c and p<40 GeV/c were selected.

## The Analysis of $\pi^-$ Mesons Angular Distributions

In our experiment, a detailed analysis of the mechanism of $\pi^-$ mesons production in a wide range of interacting nuclei with masses $A_P$ (4-24), $A_T$ (6-207) [7, 8], and investigation of the degree of pion emission were performed based on the study of angular distributions [9-11].

The degree of anisotropy in pion emission can be more directly determined by studying the angular distributions in the CMS of colliding nuclei. Our aim was to study $\cos\Theta^*$ distributions of $\pi^-$ and $\pi^+$ mesons in $\pi^-$(p, n, C) collisions ($\Theta^*$ is the emission angle in the CMS of colliding particles). The experimental distributions were approximated by the ansatz [14]:

$$dN/d\cos\Theta^* = const(1+\alpha\cos^2\Theta^*)\,, \qquad (1)$$

where $\alpha$ is the anisotropy coefficient. The studied $\cos\Theta^*$ distributions of $\pi^-$ and $\pi^+$ -mesons in experimental $\pi^-$ (p, n, C) interactions are presented in Fig. 1. In Table 1 the results of the approximation of $\cos\Theta^*$ distributions using equation (1) – the values of the anizotropy coefficient $\alpha$ for all statistics in these collisions are listed. One can see (Table 1), the anisotropy parameter values in these meson-nucleon and meson-nucleus interactions are much higher than the corresponding values in nucleus-nucleus collisions [9-11].

It is known that for NN → NN$\pi^-$ the parameter $\alpha$ is greater than 3 [14], the nucleus-nucleus collisions are thus providing a more isotropic source of pions at these energies than in the nucleon – nucleon and meson-nucleon interactions. It is also known that, parameter $\alpha$ is similar for symmetric (or approximately symmetric, $A_P \approx A_T$) systems of colliding pairs and increases slowly with mass numbers of projectile ($A_P$) and target ($A_T$) for other systems. That may be the result of asymmetry of the colliding nuclei system ($A_P \ll A_T$) [9-11].

In Fig. 2, the $E_{kin}$ -kinetic energy spectra (in c.m.s.) of $\pi^-$ and $\pi^+$-mesons in $\pi^-$(p, n, C) collisions are presented. The curves are the result of an appoximation using equation (2):

$$dN/dE_k = const\, e^{-(E_k/a)}. \qquad (2)$$

It is shown that the mentioned distributions for $\pi^-$ and $\pi^+$-mesons in $\pi^-$(p, C) collisions have the same form as in nucleus-nucleus collisions. But, in $\pi^-$ n collisions the corresponding distributions for $\pi^-$ and $\pi^+$--mesons are different (their spectra

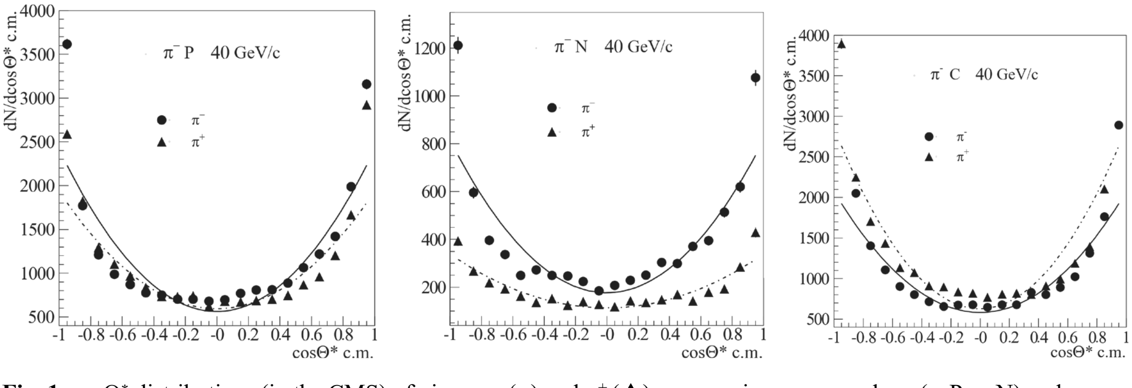


**Fig. 1**. $\cos\Theta^*$ distributions (in the CMS) of pions, $\pi^-$ (●) and $\pi^+$ (▲)-mesons, in meson-nucleon ($\pi^-$P, $\pi^-$N) and meson-nucleus ($\pi^-$C) experimental (40 GeV/c) collisions. The curves are the result of approximation by equation (1).

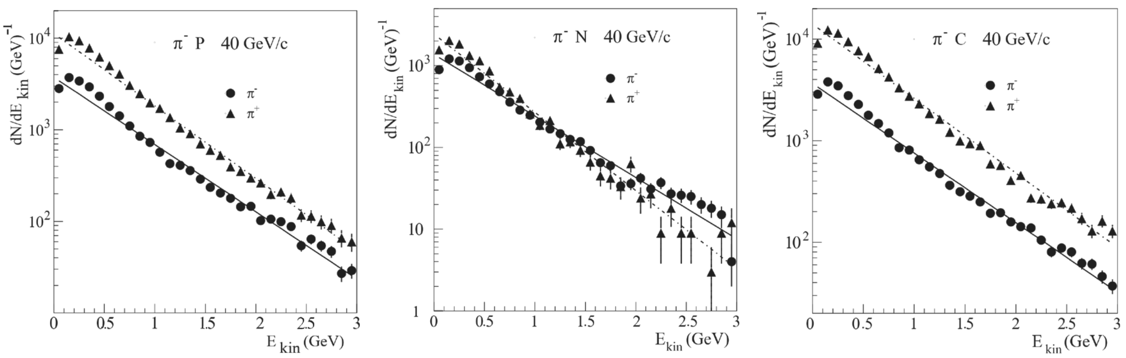


**Fig. 2**. $E_{kin}$ distributions (in the CMS) of pions, $\pi^-$ (●) and $\pi^+$ (▲)-mesons in $\pi^-$P, $\pi^-$N and $\pi^-$C experimental (40 GeV/c) collisions. The curves are the result of an approximation using equation (2).

intersect). The obtained results are explained by the peculiarities of the collision mechanism of this $\pi^-$n – interaction.

It is known that anisotropy coefficient α increases linearly with E-kinetic energy. Up to 100 MeV, the pions are emmited isotropically in nucleus-nucleus collisions [10]. The decrease of the anisotropy parameter may be caused by increase of the number of NN-collisions in nucleus-nucleus collisions. Low-energy pions might be emitted on later stage of collisions that high-energetic ones [15]. The slope is similar for light, symmetric pairs, but for the asymmetric, heavier systems (for the heaviest pairs of nuclei) the slope is larger in nucleus-nucleus and hadron-nucleus collisions [10, 11].

It is shown that the mentioned distributions are of the same type - anisotropy coefficient α increases almost linearly with $E_{kin}$ -kinetic energy for $\pi^-$ and $\pi^+$-mesons in $\pi^-$(p, n, C) collisions. The slope is similar for $\pi^-$(p, n) collisions, but for $\pi^-$ C – the slope is relatively large (Table 2). Table 2 shows the values of the anizotropy coefficient α of pions in various ranges of $E_{kin}$ -kinetic energy in $\pi^-$ (p, n, C) (40 GeV/c). It is to be mentioned that $E_{kin}$ > 700 MeV the values of the anizotropy coefficient α of pions increase sharply. The magnitude of the anisotropy coefficient in $\pi^-$(p, n, C) meson-nucleon and meson-nucleus (40 GeV/c) collisions is higher than in similar studies conducted for nucleus-nucleus collisions. Thus, the nuclear environment, i.e. the interaction dynamics, is important.

We divided the initial events into two subsamples: 1) n ≤ <n>, the events in which pions multiplicity is less than the average multiplicity: $n_{\pi-} \leq \langle n_{\pi-}\rangle$ and $n_{\pi+} \leq \langle n_{\pi+}\rangle$;2) the events, in which $n_{\pi-} > \langle n_{\pi-}\rangle$ and $n_{\pi+} > \langle n_{\pi+}\rangle$. The fraction of the events with n > <n> are ~ 40% for all pairs of particles. We analyzed these two groups of events and obtained the anisotropy parameter for them (Table 1.). The second group of events, which corresponds to more central interactions, the parameter α is smaller than for the first group. The decrease of α for the events with n > <n> indicate, that the angular distributions of pions become more isotropic for more central collisions (small impact parameter).

The dependence of the parameter α on kinetic energy $E_{kin}$ in the CMS in central Ar-KCl collisions at a momentum of 2.6 GeV/c per incident nucleon for $\pi^-$ -mesons has been studied at the Berkeley streamer chamber [16] and the value α=0.52. In this experiment α increases with $E_{kin}$, achieves its maximum and then decreases [16]. Meanwile, the calculations carried out within the framework of the Cugnon intranuclear cascade model [17] for their data, predicts the increase of α with $E_{kin}$. In our paper [8], performed on the experimental setup SKM-200, the angular distributions of the cosΘ* (in the CMS) of pions have been studied and compared with the Dubna Intranuclear Cascade Model (DICM) [18]. The DICM assumes that a nucleus-nucleus interaction consists of a series of subsequent hadron-hadron collisions. Each of the colliding nucleus is treated as a gas of nucleons moving within a potential well, i.e. nucleons are bound within a nucleus. The distribution of the nucleon density, kinematics of Δ isobar formation (but not the dynamics of their subsequent interactions, i.e. it is assumed that isobars decay instantaneously within the nucleus), and absorbtion of pions by pairs of nucleons are taken into account. We can conclude that the present results in meson-nucleon $\pi^{-}$(p, n) and meson-nucleus $\pi^{-}$C interactions qualitatively agree with the prediction of the DICM. Thus, our results, previously obtained and now presented, agree qualitatively with the prediction of the Cugnon model.

In our previous [11] work, we studied the degree of anisotropy of negative pions emission for generated collisions. We used the Quark Gluon String Model (QGSM) [19, 20] and Ultra-relativistic Quantum Molecular Dynamics Model (UrQMDM) [21-23] for comparison with experimental data. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions. The UrQMD model is now widely applied for simulations of particle production and flow effects in various nucleus-nucleus interactions [24, 25], although its original design was directed towards high energies. The QGSM and UrQMDM satisfactorily describe the cosΘ* angular distributions of $\pi^{-}$-mesons for all systems [11].

One can see that the cosΘ* distributions of $\pi^{-}$ and $\pi^{+}$-mesons in $\pi^{-}$(p, n, C) experimental (40 GeV/c) collisions, i.e. the behavior of the anisotropy coefficient α is in qualitative agreement with our previous results [7-11]. The magnitude of the anisotropy coefficient in $\pi^{-}$ (p, n, C) meson-nucleon and meson-nucleus (40 GeV/c) collisions is higher than in similar studies conducted for nucleus-nucleus collisions. Thus, we can conclude that our results qualitatively agree with the predictions of the several theoretical models proposed for nucleus-nucleus collisions at high energy: Intranuclear Cascade Models (Cugnon, Dubna), Quark Gluon String Model (QGSM) and Ultra-relativistic Quantum Molecular Dynamics Model (UrQMDM).

**Table 1. The number of events and pions ($\pi^{-}$and $\pi^{+}$), the anizotropy coefficient α of pions on the whole statistics and in the two groops of average multiplicities (n < <n> and n > <n>) in $\pi^{-}$ (p, n, C) (40 GeV/c) collisions**

| $A_P$ -$A_T$ | $N_{events}$ | pions | $N_{pions}$ | α - anisotropy coefficient | | |
|---|---|---|---|---|---|---|
| | | | | all statistics | n < <n> | n > <n> |
| $\pi^{-}$ N | 3996 | $\pi^{-}$ | 11336 | 3.61 ± 0.19 | 4.16 ± 0.29 | 2.32 ± 0.22 |
| | | $\pi^{+}$ | 7128 | 1.98 ± 0.16 | 2.54 ± 0.27 | 1.57 ± 0.19 |
| $\pi^{-}$ P | 8671 | $\pi^{-}$ | 34698 | 3.29 ± 0.10 | 3.65 ± 0.13 | 2.18 ± 0.13 |
| | | $\pi^{+}$ | 32066 | 2.97 ± 0.09 | 3.34 ± 0.12 | 2.06 ± 0.13 |
| $\pi^{-}$C | 12765 | $\pi^{-}$ | 30350 | 4.04 ± 0.12 | 5.14 ± 0.24 | 2.81 ± 0.12 |
| | | $\pi^{+}$ | 32751 | 3.55 ± 0.10 | 3.91± 0.13 | 2.61 ± 0.14 |

**Table 2. The anizotropy coefficient α of pions in verious range of E -kinetic energy in $\pi^{-}$ (p, n, C) (40 GeV/c) collisions (the result of the approximation of cosΘ* distributions using equation (1), see text)**

| $A_P$ -$A_T$ | pions | 0.00 ÷ 0.20 | 0.20 ÷ 0.35 | 0.35 ÷ 0.70 | 0.70 ÷ 2.00 | 2.00 ÷ 3.00 |
|---|---|---|---|---|---|---|
| $\pi^{-}$ N | $\pi^{-}$ | 0.49 ± 0.10 | 1.54 ± 0.19 | 4.23 ± 0.42 | 11.75± 1.97 | 21.33 ± 3.01 |
| | $\pi^{+}$ | 0.06 ± 0.01 | 0.81 ± 0.19 | 3.08 ± 0.44 | 8.97 ± 1.57 | 17.87 ± 2.11 |
| $\pi^{-}$ P | $\pi^{-}$ | 0.30 ± 0.05 | 1.42 ± 0.10 | 4.19 ± 0.23 | 11.15± 1.29 | 20.33 ± 2.77 |
| | $\pi^{+}$ | 0.17 ± 0.05 | 0.98 ± 0.09 | 3.87 ± 0.22 | 9.58 ± 1.41 | 18.42 ± 2.11 |
| $\pi^{-}$C | $\pi^{-}$ | 0.59 ± 0.09 | 1.84 ± 0.16 | 5.52 ± 0.33 | 13.15± 1.97 | 25.85 ± 3.56 |
| | $\pi^{+}$ | 0.49 ± 0.06 | 1.46 ± 0.12 | 4.19 ± 0.22 | 10.18 ± 1.41 | 21.020 ± 2.98 |

It is known that the study of angular distrubutions in $\pi^-$(p, n, C) collisions (40 GeV/c, PBC-500, Dubna), started several decades ago [26]. Currently, relevant databases are not available and unfortunalely we have no information about further research in this direction.

## Conclusion

The analysis of $\cos\Theta^*$ angular distributions of $\pi^-$ and $\pi^+$ -mesons in $\pi^-$(p, n, C) experimental collisions (40 GeV/c) has been carried out. The colliding systems are meson-nucleon and meson-nucleus types and the lightest studied one, in which the analysis of $\cos\Theta^*$ angular distributions of pions have been investigated for these particles. Finally, the dependence of α on kinetic energy in CMS, multiplicity of pions and the mass numbers of projectile ($A_P$ ) and target ($A_T$) for all interactions was studied and the following results were obtained:

1. The anisotropy coefficient α increases almost linearly with increasing $E_{kin}$ -kinetic energy for $\pi^-$ and $\pi^+$ -mesons in $\pi^-$ (p, n, C) meson-nucleon and meson-nucleus (40 GeV/c) collisions and after 700 MeV, it increases sharply. The magnitudes of α in these collisions are higher than in similar studies conducted for nucleus-nucleus collisions.

2. As the mass of the target increases in $\pi^-$ (p, n, C) collisions, the magnitude of the anisotropy coefficient increases for both signs pions, is almost the same in $\pi^-$ (p, n) collisions but greater in $\pi^-$C collisions.

3. At small multiplicities of $\pi^-$and $\pi^+$ -mesons ($n_{\pi-} \leq \langle n_{\pi-}\rangle$, $n_{\pi+} \leq \langle n_{\pi+}\rangle$), the degree of anisotropy is greater than at high multiplicities ($n_{\pi-} > \langle n_{\pi-}\rangle$, $n_{\pi+} > \langle n_{\pi+}\rangle$), i.e. the angular distributions of pions become more isotropic for more central events.

4. The value of the anisotropy coefficient α of $\pi^+$ -mesons are relatively smaller than that of $\pi^-$ -mesons in the $\pi^-$ (p, n, C) experimental (40 GeV/c) collisions.

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*ფიზიკა*

# პიონების კუთხური განაწილებების შესწავლა $\pi^-$ (p, n, C) დაჯახებებში 40 გევ/c იმპულსის დროს

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ნაშრომში შესწავლილია $\pi^-$ და $\pi^+$ -მეზონების გამოსხივების ანიზოტროპიულობა უშუალოდ მათი კუთხური განაწილებებიდან ურთიერთმოქმედი წყვილების მასათა ცენტრის სისტემაში (მცს). ამდენად, დადებითი და უარყოფითი პიონების $\cos\Theta^*$ კუთხური განაწილებებიდან ($\Theta^*$ არის გამოსხივების კუთხე) $\pi^-$ (p, n, C) მეზონ-ნუკლონურ და მეზონ-ბირთვულ (40 გევ/c) დაჯახებებში დადგინდა α ანიზოტროპიის კოეფიციენტი. ექსპერიმენტული მასალა მიღებულ იქნა ბირთვული კვლევების გაერთიანებული ინსტიტუტის (JINR) მაღალი ენერგიების ლაბორატორიაში ფილმური დეტექტორის პროპანის ორმეტრიანი ბუშტოვანი კამერის (PBC-500) მეშვეობით. ექსპერიმენტი განხორციელდა სერპუხოვოს სინქროფაზოტრონზე. ანიზოტროპიის α კოეფიციენტი შესწავლილ იქნა როგორც კინეტიკური ენერგიის სხვადასხვა ინტერვალში, ასევე პიონების მრავლობითობის სხვადასხვა ქვეჯგუფში და ყველა განხილულ ურთიერთქმედებაში α კოეფიციენტი $\pi^-$ -მეზონებისთვის მეტია ვიდრე $\pi^+$ -მეზონებისთვის. კინეტიკური ენერგიის ზრდისას α ანიზოტროპიის კოეფიციენტი იზრდება თითქმის წრფივად ორივე ნიშნის პიონებისათვის ყველა ურთიერთქმედებაში, ხოლო 700 მევ-ის შემდეგ მკვეთრად იზრდება. ორივე ნიშნის პიონისთვის სამიზნის მასის გაზრდისას ანიზოტროპიის კოეფიციენტის სიდიდე იზრდება, თითქმის ერთნაირია $\pi^-$(p, n) დაჯახებებში და უფრო მეტია $\pi^-$C დაჯახებებში. მცირე მრავლობითობის მქონე პიონებისათვის ($n_{\pi\pm} \leq < n_{\pi\pm} >$) ანიზოტროპიის კოეფიციენტი α მეტია, ვიდრე შედარებით დიდი მრავლობითობის მქონე პიონებისათვის ($n_{\pi\pm} > < n_{\pi\pm} >$). α პარამეტრის შემცირება შედარებით ცენტრალურ არეში ($n_{\pi\pm} > < n_{\pi\pm} >$) მიუთითებს $\pi^\pm$ -მეზონების კუთხური განაწილებების იზოტროპიულობაზე დაჯახების პარამეტრის შემცირებისას (b→0). $\pi^-$ (p, n, C) მეზონ-ნუკლონურ და მეზონ-ბირთვულ ურთიერთქმედებებში ანიზოტროპიის კოეფიციენტის სიდიდე მეტია ვიდრე ბირთვ-ბირთვული დაჯახებებისთვის ჩატარებულ ანალოგიურ კვლევებში. ამდენად, მნიშვნელოვანია ბირთვული გარემო, ანუ ურთიერთქმედების დინამიკა. მიღებულ იქნა წარმოდგენილი ექსპერიმენტული შედეგების გარკვეული თვისობრივი თანხვედრა სხვადასხვა თეორიული მოდელის (შიდა ბირთვული კასკადური მოდელი, QGSM -კვარკ გლუონური სიმური მოდელი და UrQMD -ულტრა რელატივისტური კვანტურ-მოლეკულურ დინამიკური მოდელი) წინასწარმეტყველებასთან.

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