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ASYMMETRY OF π^- MESON EMISSION IN NUCLEUS-NUCLEUS COLLISIONS AS A MEASURE OF THE TARGET-TO-PROJECTILE RATIO OF THE NUMBERS OF INTERACTING NUCLEONS

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INTRODUCTION

Relativistic nuclear physics is a rather new field of research, so it is only natural that quite a number of methods, approaches, and aspects of investigation came here from hadronic physics and are succesfully applied.

This work may be considered as a direct example of such succession since, on the one hand, asymmetry of charged particle production is the traditional subject of investigation in meson-nucleon collisions at high energies while, on the other hand, the analysis of an analogous phenomenon in interactions of nuclei with unequal masses permits one to obtain important information on multiple production mechanism in nucleus-nucleus collisions. Experimental results on forward-backward asymmetry of π^- meson emission in d, ^{4}He, and ^{12}C interactions with ^{181}Ta nuclei at 4.2 GeV/c per nucleon are given in this paper.

A method we put forward here enabled us to estimate the target-to-projectile ratios of the numbers of interacting nucleons. This method is based on the phenomenon of pion emission asymmetry.

1. EXPERIMENTAL DETAILS

The data were obtained from exposures of the 2m propane bubble chamber to the beams of d, ^{4}He, and ^{12}C nuclei at the incident momentum of 4.2 GeV/c per nucleon from the Dubna synchrophasotron. The target consisting of three tantalum plates 1 mm thick was placed inside the chamber. In more detail the experimental arrangement and data handling procedure are described in refs. [1-3].

When scanning, all negative particles, except identified electrons, were considered as π^--mesons. The contaminations by misidentified electrons and negative strange particles do not exceed 5% and 1%, respectively [4,5].

Corrections were made for the loss of π^- mesons produced at small angles with respect to the target plane or to the optic axes of the objectives [6].

Multiple π^- production was studied in the reactions

$$A_p + Ta \to \pi^- + X , \qquad (1)$$

where $A_p = (d,\ ^4He,\ and\ ^{12}C)$.

Table 1

Numbers of events and π^- meson average multiplicities in (d,He,C)Ta interactions at $p/A = 4.2$ GeV/c

Type of interaction	d Ta	He Ta	C Ta
N_{ev}	1507	868	1227
$\langle n_{\pi^-} \rangle$	0.90 ± 0.06	1.6 ± 0.1	3.4 ± 0.2

Table 1 gives statistics for different types of interactions used for the analysis and the π^- meson average multiplicities[7].

2. FORWARD-BACKWARD ASYMMETRY OF π^- MESON EMISSION IN COLLISIONS OF LIGHT NUCLEI WITH TANTALUM

The coefficient of forward-backward asymmetry of π^--production in reactions (1) was determined by analogy with that in meson-nucleon interactions at high energies as

$$K_{F-B} = (N_F - N_B)/(N_F + N_B), \quad (2)$$

where N_F and N_B are the numbers of π^- mesons produced in the forward and backward hemispheres of the nucleon-nucleon center-of-mass system (NN CMS), respectively.

The obtained values of the coefficients K_{F-B} are presented in Table 2. The K_{F-B} values for π^- mesons with $p_\perp \geq 0.7$ GeV/c are also given here. This sample of data was used to search for a possible dependence of π^- meson asymmetry on the transverse momentum of these particles. It is seen from the data of Table 2 that there is a substantial backward asymmetry ($K_{F-B} < 0$) for negative pion production in d, He and C collisions with tantalum nuclei at 4.2 GeV/c per nucleon. This is true both for all π^- mesons produced in reactions (1) and for π^- mesons with relatively large transverse momenta at our energy* (see Table 2). Presence of such negative asymmetry of π^- meson production in collisions of nuclei with unequal masses is an effect to be expected. But up to now there are no published data analogous to those in Table 2. It should be noted that qualitatively this

*For reactions (1) $\langle p_\perp \rangle_{\pi^-} \simeq 0.24$ GeV/c[6] at 4.2 GeV/c per nucleon.

Table 2

Forward-backward asymmetry coefficients of the π^--distributions versus longitudinal rapidity in the NN CMS.

Type of interaction	d Ta	He Ta	C Ta
K_{F-B} all $p_\perp$	-0.64 ± 0.02	-0.53 ± 0.02	-0.35 ± 0.02
K_{F-B} $p_\perp \geq 0.7$ GeV/c	-0.6 ± 0.1	-0.7 ± 0.1	-0.41 ± 0.09

effect may be easily explained in most of the existing models for nucleus-nucleus collisions (e.g., see refs.[8,9,10]), and as a matter of fact such asymmetry means that the average number of interacting nucleons from the target, ν_t, is greater than that from the projectile, ν_p.

At any rate the forward-backward asymmetry of negative pion emission, as it is in our case, or, in general, of charged particles is sensitive to the difference in the numbers of participant nucleons from the colliding nuclei and hence it may serve as a measure of such a difference. This question will be dealt with in section 3.

Let us consider now the A dependence of the asymmetry. As is seen from Table 2 and Fig. 1, the absolute values of K_{F-B} fall with the increasing atomic mass of the projectile. This tendency is not so clearly pronounced for the set of the data which consists of π^- mesons with $p_\perp \geq 0.7$ GeV/c, but the errors are too large here. In both cases the data are well described by the power-like function

$$|K_{F-B}| = c \cdot A_p^b, \quad (3)$$

where $c = 0.83\pm0.04$, $b = -0.35\pm0.03$ with χ^2/N.D.F.=0.76 for all π^- mesons produced in reactions (1) and $c = 0.80\pm0.02$, $b = -0.24\pm0.14$ with χ^2/N.D.F.=1.1 for π^- mesons with $p_\perp \geq 0.7$ GeV/c. In the latter case the error of the exponent being rather large, the result should be considered only as an indication of weakening of the dependence of π^- meson emission asymmetry on the projectile atomic mass with the increasing transverse momentum of the particles. To compare high - $p_\perp$ π^- production with inclusive π^- production, we also looked at the dispersion values of respective y* distributions (y* is the longitudinal rapidity in the NN CMS). The results are presented in Table 3. As is seen from Table 3, all the dispersion values of the y*

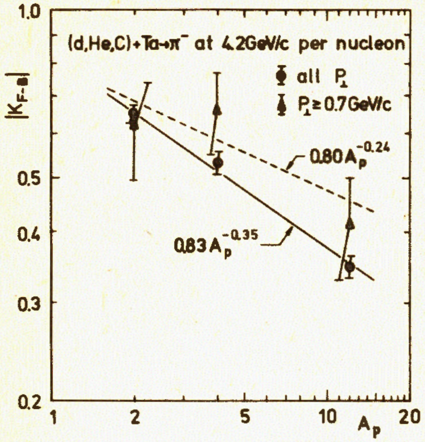

Fig. 1. Absolute values of the coefficient of π^- meson emission asymmetry versus the atomic mass of the projectile for (d, He, C)Ta interactions and the result of the approximation: for all $p_\perp$ (dots and solid line) and for $p_\perp \geq 0.7$ GeV/c (triangles and dashed line).

Table 3

Dispersions of the π^- distributions versus longitudinal rapidity

Type of interaction	d Ta	He Ta	C Ta
$D(y^*)$ all $p_\perp$	0.644±0.025	0.675±0.025	0.614±0.014
$D(y^*)$ $p_\perp \geq 0.7$ GeV/c	0.389±0.084	0.284±0.057	0.279±0.037

distributions for particles with $p_\perp \geq 0.7$ GeV/c are approximately two times less than those for all $p_\perp$. As such selection practically does not affect positions of the maxima of the y^* distributions, one may suppose, that apart from known kinematic reasons, this might mean a more "central" production of pions with relatively high $p_\perp$.

We would like to note that the results obtained are in qualitative agreement with the picture of nucleus-nucleus collisions following from an additive quark model by Białas et al. /10/. In this model particles, populating the central rapidity region, originate from breaking of colored strings. It is quite obvious that characteristics of these particles should be less dependent on the atomic masses of the colliding nuclei than those of the particles from the projectile or target fragmentation regions.

3. SYSTEM OF SYMMETRIC PARTICLE EMISSION AND EVALUATION OF THE TARGET-TO-PROJECTILE RATIO OF THE NUMBERS OF INTERACTING NUCLEONS FROM COLLIDING NUCLEI

In order to visualize our further analysis, we took advantage of a qualitative picture of particle production on which the above mentioned additive quark model /10/ is based. Note, however, that our consideration is of a general nature and does not depend on any particular model.

In the model /10/ colored strings span between the wounded constituent quarks of the colliding nuclei. As a result of breaking of colored strings, particles are produced, which populate the central region of rapidities. Most of the pions are created through such a mechanism. Fragmentation of wounded quarks as well as that of spectator quarks which do not exchange colored gluons leads to the formation of target and projectile fragmentation regions populated mainly by nucleons.

Directly from this picture it follows that the velocity of an aggregate of particles, produced via breaking of colored strings, is determined by the number of wounded quarks and hence by the number of interacting nucleons. In other words, the center-of-mass system of the wounded nucleons is essentially the same as that of the particles produced through the break-up of the strings. It is quite reasonable to expect that in this system the spectra of the new produced particles, which mainly hit the central rapidity region, should be in fact symmetric, i.e., this should be the "symmetric emission system". Thus, to obtain some value which characterizes the numbers of interacting nucleons from target and projectile nuclei, one should know the velocity of the center-of-mass system of the particles, mostly pions, produced through the string breaking mechanism, i.e., β_{sc}, the velocity of the "symmetric system" with respect to the NN CMS.

As soon as the value of β_{sc} is known, the target-to-projectile ratio, N_t/N_p, of the interacting nucleons is immediately calculated as follows

$$N_t/N_p = (\beta_0 - \beta_{sc})/(\beta_0 + \beta_{sc}), \quad (4)$$

where β_0 is the absolute value of incident nucleon velocity in the NN CMS. One can easily obtain (4) from the expression for the center-of-mass velocity of the system of N_t target and N_p projectile nucleons in the NN CMS:

$$\beta_{sc} = (N_p p_0^* - N_t p_0^*)/(N_p E_0^* + N_t E_0^*), \quad (5)$$

where p_0^* and E_0^* are the values of momentum and energy of an incident nucleon in this system.

We should like to stress that the above method of determining the N_t/N_p ratio is not justified unless intranuclear cascade processes are negligible. Such an assumption is quite reasonable in the interaction picture being considered as soon as β_{sc} is the velocity of the central cluster consisting mainly of pions while the probability of producing any pions in secondary interactions of the produced particles may be neglected at our incident energy.

Experimental value of β_{sc} can be obtained in several ways giving somewhat different results.

In this paper we have determined the β_{sc} value through the median, y^*_M, of the inclusive rapidity distribution of π^- mesons in the NN CMS, i.e., the actual measured value is the rapidity of the frame where the forward-backward asymmetry vanishes. In this forward-backward symmetric system (F-B SS) the average π^- meson multiplicities coincide in both hemispheres. Then the velocity of the symmetric system is expressed as $\beta_{sc} = \mathrm{th}\, y^*_M$, since $y^*_M = 0.5 \ln[(1+\beta_{sc})/(1-\beta_{sc})]$. Earlier we used a similar method to analyze $\pi^- p$ interactions at 40 GeV/c [11].

Figure 2 illustrates how the difference between the π^--meson yields into the forward and backward hemispheres are altered when transferring from NN CMS to F-B SS for dTa interactions. Some asymmetry of the shape of the y* distribution, well seen in Fig.2b, namely, a more gentle slope in the forward hemisphere of the F-B SS, arises due to a number of factors. If the numbers of participant nucleons were fixed, the spectrum of π^--mesons resulting from the breaking of colored strings would be

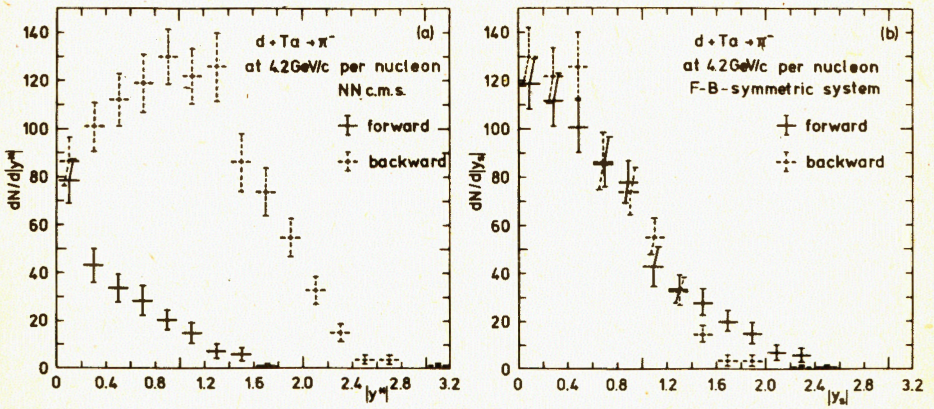

Fig.2. Distributions of π^- mesons versus the absolute value of longitudinal rapidity in the forward hemisphere (solid line) and the backward hemisphere (dashed line) in the NN CMS (a) and F-B SS (b) (see text for definitions) for dTa interactions at $p/A = 4.2$ GeV/c.

symmetric in the F-B SS. But the inclusive π^- spectrum should not be entirely symmetric in this system due to event-by-event fluctuations of the numbers of participant nucleons from the colliding nuclei. Besides, the isotopic asymmetry of tantalum nucleus should be taken into account. Nevertheless, a slight asymmetry of the spectrum of π^- mesons does not play any essential role for a global estimate of the rapidity of the system of produced π^- mesons.

Generally speaking, the center-of-mass velocity of the emitted π^- mesons can be found from the event-by-event distributions over β_{sc} or y_s^{ev}, where y_s^{ev} is the rapidity of the system of π^- mesons in each event. Moreover, one may use directly the N_t/N_p distributions. But we shall study possibilities of the event-by-event analysis in another work.

Experimental values of the N_t/N_p ratios, obtained according to formula (4) for d, He, and C interactions with tantalum nuclei, are presented in Table 4 and Fig.3. The β_{sc} values for each type of interaction were determined, as mentioned above, from the values of median, y^*_M, of the inclusive longitudinal rapidity π^- distributions in the NN CMS.

While calculating the N_t/N_p ratios, the fact of neutron excess in the ^{181}Ta nucleus was taken into account. For this purpose we corrected our ratios knowing that there are 1.064 times more d quarks per one "average" nucleon in ^{181}Ta nucleus as compared to a symmetric nucleus.*

The N_t/N_p experimental values are well described by a power-like dependence (see Fig.3).

$$N_t/N_p = A_t^a / A_p^b, \tag{6}$$

where $a = 0.52 \pm 0.04$, $b = 0.73 \pm 0.09$ at χ^2/N.D.F. = 0.87. Certainly, we do not attach much significance to the A_t dependence here as it is obtained rather mechanically. It would be very important, of course, to know the N_t and N_p values explicitly. Experimentally it is somewhat easier to measure the degree of involvement of the projectile in the interaction.

Previously in our experiment the average values of the numbers of interacting nucleons from the projectiles, ν_p, have been obtained [2,12] by estimating the average charge of stripping particles, $\langle Q_s \rangle_p$ for all inelastic interactions:

$$\langle \nu_p \rangle = 2(Z_p - \langle Q_s \rangle_p), \tag{7}$$

where Z_p is the charge of the projectile.

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* Such a correction could be made more precisely if data on π^--meson production in pp, pn, and nn interactions were available at our energy.

Table 4

Target-to-projectile ratios of the numbers of interacting nucleons

Type of interaction	d Ta	He Ta	C Ta
N_t/N_p	10.5 ± 2.0	5.07 ± 0.66	2.46 ± 0.14

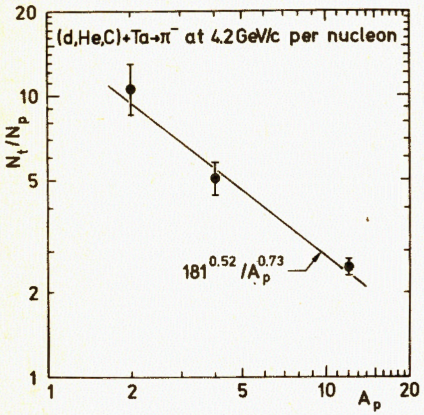

Fig.3. Dependence of the N_t/N_p ratio on the atomic mass of the projectile nucleus in (d, He, C)Ta interactions. The solid line is the result of the fit.

But in our ratios we deal with N_p numbers, which, unlike ν_p, represent only the nucleons that took part in π^- production. Of course, we cannot measure these N_p numbers, but we can find ν_p for events with $n_{\pi^-} \geq 1$. Then, assuming that N_p is roughly proportional to ν_p as well as $N_t \sim \nu_t$, we may admit that $\nu_t/\nu_p \simeq N_t/N_p$, and hence, multiplying our ratios by ν_p, we get immediately the values of ν_t, which are much more difficult to extract, at least in bubble-chamber experiments.

Presented in Table 5 are the values of $\langle\nu_p\rangle$ obtained according to (7) from the reprocessed data of refs. /2,12/ for events with $n_{\pi^-} \geq 1$ along with the results of the fit to a powerlike function

$$\langle\nu_p\rangle = c \cdot A_p^b, \tag{8}$$

with $c = 0.94\pm0.02$, $b = 0.83\pm0.01$ at χ^2/N.D.F.=0.88. The values of ν_p for all inelastic events from ref. /2/ are also given in Table 5 for comparison. Table 5 also contains the values of $\langle\nu_t\rangle$ obtained by simple multiplication of the N_t/N_p values (see Table 4) by the experimental values of $\langle\nu_p\rangle$ for events with $n_{\pi^-} \geq 1$. The values of $\langle\nu_t\rangle$ are considered as average numbers of participant nucleons in target nuclei for the same subset of collisions with $n_{\pi^-} \geq 1$. As the $\langle\nu_t\rangle$ values are calculated using two independently measured quantities: N_t/N_p (formulae (4) and (5)) and $\langle\nu_p\rangle$ (formula (7)) and thus they contain uncertainties of two methods, we also give in Table 5 "smoothed" values of ν_t, which are the product of (6) and (8) approximating N_t/N_p and $\langle\nu_p\rangle$ separately.

Table 5

Average numbers of participant nucleons from target and projectile and results of the approximation of the data

Type of interaction		d Ta	He Ta	C Ta
	$\langle\nu_p\rangle$ /2/	1.60 ± 0.04	2.86 ± 0.10	6.60 ± 0.30
$n_{\pi^-} \geq 1$	$\langle\nu_p\rangle$	1.66 ± 0.03	3.02 ± 0.06	7.36 ± 0.14
	$\nu_p=0.94\,A_p^{0.83}$	1.67	2.97	7.39
	$\langle\nu_t\rangle$	17.4 ± 3.2	15.1 ± 2.0	18.1 ± 1.2
	$\nu_t=14.0\,A_p^{0.1}$	15.0	16.1	18.0

In order to test consistency of our estimate of the number of participating nucleons with an independent measurement of a similar kind, we turn now to the result obtained in ref. /13/, namely, the total number of participating protons, N_{part}, in CTa interactions in the same experiment at 4.2 GeV/c per nucleon according to the formula /14/,

$$\langle N_{part}\rangle = n_{ch} - n_{\pi^+} - n_{\pi^-} - (n_p^f + n_t^f), \tag{9}$$

where n_{ch}, n_{π^+}, n_{π^-}, n_p^f, n_t^f are the average multiplicities of all charged particles, π^+ mesons, π^- mesons and charged fragments of projectile and target, respectively. It has been found that $\langle N_{part}\rangle = 14.1\pm0.4$ /13/. Calculating the number of participant protons from our data (keeping in mind the isotopic asymmetry of the ^{181}Ta nucleus); we obtain $\langle N_{part}\rangle \simeq 0.5\langle\nu_p\rangle + 0.4\langle\nu_t\rangle = 11.0\pm0.5$. This value should be considered to be in reasonable agreement with the above estimate of $\langle N_{part}\rangle$ from ref. /13/ since, on the one hand, our experimental value is based on the set of data with $n_{\pi^-} \geq 1$, in contrast to the set of all inelastic events of ref. /13/, while, on the other hand, the n_p^f and n_t^f values in (9) contain certain ambiguities. In fact, these values turn out to be dependent on the particular choice of momentum and angular cuts.

Ending this section, we would like to call one's attention to the fact that the number of participant nucleons from the target rises only slowly with the number of participant nucleons from the projectile ($\langle\nu_t\rangle \approx \nu_p^{0.1}$) as it follows from our data (see Table 5). However, the origin of such a weak dependence is difficult to understand so far, especially in view of the fact that we do not know any published experimental data on the subject.

CONCLUSIONS

The experimental data on forward-backward asymmetry of π^--meson emission in nucleus-nucleus collisions at the incident momentum of 4.2 GeV/c per nucleon are obtained. The dependence of this asymmetry on the atomic mass of the projectile and on the transverse momentum of π^--mesons is investigated. With the increasing mass of the projectile the absolute value of the asymmetry coefficient for the inclusive π^- production in the NN CMS decreases: $|K_{F-B}| \sim A_p^{-0.35}$ .There is an indication that for π^--mesons with $p_{\perp} \geq 0.7$ GeV/c this dependence becomes weaker ($\sim A_p^{-0.24}$).

On the basis of the fact that particle emission asymmetry reflects the difference in the rate of involvement of the colliding nuclei in particle production, the method of measuring the target-to-projectile ratio of the numbers of interacting nucleons is proposed. To determine this ratio, one should measure the velocity of the center-of-mass of produced particles. In our case the ratio of the nucleons taking part in π^- production was estimated via measuring the velocity of the system in which π^- multiplicities in the forward and backward hemispheres are equal. This ratio decreases with the increasing projectile mass: $N_t / N_p \sim A_p^{-0.73}$.

Experimental values of the numbers of interacting nucleons in the projectile obtained by measuring the average charge of its stripping fragments for events with $n_{\pi^-} \geq 1$ were used to estimate the numbers of participant nucleons in the target, which were found to be weakly rising with A_p.

Finally we would like to stress that it would be of indubitable interest to investigate the energy dependence of the asymmetry of pion emission and of the numbers of participant nucleons in various nucleus-nucleus collisions.

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Асимметрия испускания π^--мезонов в ядро-ядерных столкновениях как мера отношения чисел участвующих во взаимодействии нуклонов мишени и снаряда

Представлены экспериментальные данные по асимметрии "вперед-назад" рождения π^--мезонов в $(d, {}^4He, {}^{12}C)$ ${}^{181}Ta$ -взаимодействиях при $p/A = 4{,}2$ ГэВ/с. Коэффициент асимметрии инклюзивных распределений π^--мезонов по быстроте в нуклон-нуклонной с.ц.м. падает с увеличением массы ядра-снаряда как $A_p^{-0,35}$. Предложен метод определения отношения чисел нуклонов мишени и снаряда, участвующих во взаимодействии, N_t/N_p, через скорость системы симметричного разлета π^--мезонов. Найдено, что $N_t/N_p \sim A_p^{-0,73}$.

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Asymmetry of π^- Meson Emission in Nucleus-Nucleus Collisions as a Measure of the Target-to-Projectile Ratio of the Numbers of Interacting Nucleons

Experimental data on forward-backward asymmetry of π^- emission in $(d, {}^4He, {}^{12}C)$ ${}^{181}Ta$ interactions at $p/A = 4.2$ GeV/c are presented. The absolute value of the asymmetry coefficient of the inclusive π^- production in the nucleon-nucleon CMS decreases as $A_p^{-0.35}$ with the increasing atomic mass of projectile nucleus. A method of obtaining the target-to-projectile ratio of the numbers of participant nucleons, N_t/N_p, through measuring the velocity of the symmetric pion emission system, is proposed. It has been found that $N_t/N_p \sim A_p^{-0.73}$.

The investigation has been performed at the Laboratory of High Energies, JINR.

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