МУИС, Эрдэм Шинжилгээний Бичиг, ФИЗИК №282(14), 2006, хууд. 41-47

Negatively Charged Pion Multiplicity Analysis in Hadron - Hadron and Hadron – Nucleus Collisions at Momenta of 1 - 400 GeV/c

B. Ganhuyag

Institute of Physics and Technology
Mongolian Academy of Sciences
Enhtaivan Ave., 54 B
211651 Ulaanbaatar
Mongolia

Keywords: Monte Carlo, hadrons, nuclei, interactions, Regge scattering, fragmentation

Abstract. Data on the mean multiplicity of negative pion produced in minimum bias proton-proton, proton-neutron and proton-nucleus interactions as well as central nucleus-nucleus interactions at momenta of 1.4÷400 GeV/c per nucleon have been compared within the framework of a modified FRITIOF model [1],[2].The results for neutron-neutron and nucleon-nucleon interactions were then constructed. The dependence of the mean pion multiplicity in proton-nucleus and central nuclear collisions are studied as a function of the collision energy and the nucleus mass number. The model shows good agreement for π^- -mesons, as shown in several comparisons in refs [3-4].

1. Introduction

Relativistic nucleus-nucleus collisions offer the unique possibility to produce hadronic matter at high temperatures and densities in the laboratory. Most of the energy spent on particle creation and a significant fraction of the entropy realized during high energy nuclear interactions is used for pion production. Thus knowledge of the properties of pion production is necessary in order to establish global conditions created in the reaction region and to understand the dynamics of the collision process.

The aim of this paper is to compare data [5] on the mean multiplicities of pions produced in nucleon-nucleon, proton-nucleus and central nuclear collisions within of framework of the modified FRITIOF model.
The analysis of proton-nucleon interactions is expected to yield important information about the space-time properties of the hadronization process. The relativistic nucleus-nucleus collisions give unique opportunity to create in the laboratory "macroscopic " system of strongly interacting matter. At high energy density the transition from matter composed of hadrons and their excitations to Quark Gluon Plasma is expected. The nucleon-nucleon interactions yield the reference data for the analysis of both proton-nucleus and central nucleus-nucleus collisions. The experimental results obtained at incident momenta of 1.4 - 400 GeV/c per nucleon are (compared) analyzed. Most of the results compared in this paper were obtained in experiments in which large acceptance tracking detectors like bubble chambers and streamer chambers were placed inside a magnetic field. This allows for the precise measurement of the total multiplicities of positively and negatively charged hadrons in the studied interactions. More than 90% of the produced negatively charged hadrons h^- are π^--mesons.

In this paper we, analyzed therefore the compiled data on the mean multiplicity of negatively charged hadrons $<h^->$ which in most of the cases can be treated as a satisfactory approximation of the mean multiplicity of π^--mesons.

In sect.2 we define the basic ingredients of the modified FRITIOF model.

In sect.3, the data on $<h^->$ for proton-proton, proton-neutron, neutron-neutron, and proton-nucleus collisions and their corresponding FRITIOF calculations are summarized and their dependence on the incident proton momentum is shown. We also present a construction of the results for neutron-neutron interactions relevant for the comparison with proton nucleus and nucleus-nucleus data. The mean multiplicities of negatively charged hadrons produced in minimum bias proton-nucleus collisions $<h^->_{pA}$ obtained at incident proton momenta of 2.3 - 200 GeV/c the results are grouped according to the incident proton momentum which is given in the first column of the table. In the second column the reaction type is specified. The $<h^->_{pA}$ experimental values are given in the third column and in the last column we present the model calculations respectively are shown in table 3. In this section we also study the dependence of the $<h^->$ multiplicity on the incident proton momentum and on the target nucleus mass number.

Finally, section 4 closed with a few summary of the results and conclusions.

2. Modified FRITIOF model

In this section , the original FRITIOF model is supplemented with a scattering recipe. The masses of the excited objects which are formed in the primary NN collisions are calculated. The Glauber approach is used to determine the primary interacting nucleons and the location of these collisions. The Reggeon approach is used to determine what are the nucleons which rescatter the primary wounded nucleons.

2.1 Determination of the number of knocked-out nucleons.

In [6-8] , were shown that the description of cascading of particles can be achieved in the framework of Regge theory. It is assumed that each interaction of the incident hadron with nucleons of a target nucleus irradiated a cascade of reggeon exchanges. This picture is taken into account in Regge theory. In this theory the interaction of secondary particles with a nucleus is described by cuttings of exchanged diagrams; i.e., diagrams with an interaction between reggeons. It was shown that inelastic rescatterings occur for any secondary particles, both slow and fast ones, and the yield of enhanced diagrams leads to the enrichment of the spectrum by slow particles in the target fragmentation region.
As in [9] we shall assume that the reggeon interaction vertices are small. Therefore of the full set of enhanced diagrams the only important ones will be those containing vertices where one of the reggeons splits into several, which then interact with different nucleons of the nucleus. In studying interactions with nuclei, however, it is convenient, in the spirit of the Glauber approach, to deal not with individual reggeons, but with sets of them interacting with a given nucleons of the nucleus. Unfortunately, the Regge method of calculating the sum of the yields of enhanced diagrams in the case of hA and AA interactions is not developed for practical tasks. Hence a simple model of estimating reggeon cascading in hA and AA interactions was formulated [10] as:

1. Nucleon coordinates of the two colliding nuclei were simulated according to a Gaussian distribution for $A \leq 14$ and a Saxon-Wood distribution for $A>14$, where A is the mass number of either the projectile or target nucleus.
2. The impact parameter is simulated according to [11].
3. At a given impact parameter, the primary interacting or 'wounded' nucleons of the nuclei were identified by Glauber approximation, using DIAGEN code [12]. In [9], the part of the Glauber expressions (e.g., total, inelastic, elastic cross sections) which contains the NN amplitude is rewritten in a form describing the probability of simultaneous occurrence of independent elementary interaction events; whose probabilities depend on whether an interaction between any two nucleons of the colliding nuclei takes played or not. The various terms of the Glauber expressions are then introduced as diagrams representation in DIAGEN code. Each diagram is characterized by the number of interacting nucleons of the projectile and target nuclei and their ordering (see [9] for details).
4. Target and projectile spectator nucleons (i.e., those nucleons which have not been involved in the interaction) are then followed. If the i-th spectator of nucleus A is at $b_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ distance from the j-th wounded nucleons of A, the i-th nucleon is regarded as a participant of the collisions with probability $w = ce^{-b_{ij}^2}, c = 0.25$
5. If the number of newly involved nucleons is not zero, then step (4) is repeated, otherwise step (6) is carried out.
6. The number of spectator nucleons (A_{res}) and the sum of all charged (Z_{res}) are determined. These quantities were identified as the mass number and charge of the nuclear residue.

It should be noted here that, from now on, the wounded nucleons will be defined as those nucleons experiencing primary and secondary collisions.

Basically, this model differs from models incorporate cascading (e.g., [13,14,15] by secondary collisions, which in the latter correspond to the rescattering of the 'wounded' nucleons (i.e., the nucleons which suffer elastic inelastic scatterings in the first impact) in ordinary (three-dimensional) space on a basis of a collision cross section and mean free path picture. From the Regge approach, a cascade of Regge exchanges occurs in two-dimensional space (on the plane of impact parameter) of the target nucleus . Thus we expect that the Regge cascade will be more restricted than it is in the usual cascade models.

In the original FRITIOF model, the primary NN collisions are determined using Glauber approximation. When two hadrons collide, momenta are exchanged and two longitudinally excited objects are created. The excited objects do not rescatter and hadronize independently according to the Lund model of jet fragmentation. The hadronization is assumed to take place outside the nuclei and thus no intranuclear cascading is considered.

In order to include cascading in the FRITIOF model, the primary interacting nucleons are allowed to rescatter through Regge cascading (as outlined above). The combination of FRITIOF primary NN- scattering and Regge cascading will be referred to as the modified FRITIOF model.

2.2 Determination of the masses of the excited strings.

Each primary inelastic NN collision proceed in the FRITIOF model as follows: a - b — a' - b', where a' and b' are the excited states of the two hadrons (*a* and *b*). In the center of mass system the light cone variables are used:

$$P_+ = E + p_z \quad \text{and} \quad P_- = E - p_z$$

for a hadron moving along the + z- and – z- axis, respectively (the z-axis is taken as the collision axis). E and p_z are the energy and the longitudinal momentum component for each hadron. The probability distribution for the total transfer can be written as:

$$dW = \frac{dp_-^{a'}}{p_-^{a'}} \cdot \frac{dp_+^{b'}}{p_+^{b'}}. \qquad (1)$$

In order to take the excitation (increasing mass of the string object) and de-excitation (decreasing mass of the string) processes into account, the variables $P_-^{a'}$ and $P_+^{b'}$ are allowed to vary in the intervals:

$$[E_a - p_{az}, \sqrt{s_{ab}} - m_b] \qquad \text{and}$$

$$[E_b - p_{bz}, \sqrt{s_{ab}} - m_a] \qquad (2)$$

Expressions (2) are calculated at $\sqrt{s_{a'b'}} = \sqrt{s_{ab}} = E_{a'} + E_{b'} = E_a + E_b$, $m_{a'} = m_a$ and $m_{b'} = m_b$.

After the collision, the masses of the two excited hadrons are calculated by

$$P_+P_- = m_\perp^2 = m^2 + p_x^2 + p_y^2. \qquad (3)$$

The two longitudinally excited objects are given an average square of transverse momentum equal to 0.3 (GeV/c)^2.

2.3 Momentum characteristics of the spectator and wounded nucleons.

The Fermi motion of the nucleons in the nucleus are taken into account using the algorithm in [23] and energy-momentum conservation is enforced in primary collisions. In the case of two nuclei A and B, the i-th constituent nucleon of nucleus A is fully characterized by the variables:

$$x_i^+ = \frac{E_i - p_{zi}}{W_A^+} \text{ and } p_{i\perp}. \qquad (4)$$

and the j-th constituent nucleon of nucleus B by

$$y_j^- = \frac{E_j - q_{zj}}{W_B^-} \text{ and } q_{j\perp}. \qquad (5)$$

where $W_A^+ = \sum_{i=1}^{A}(E_i + p_{zi})$ and $W_B^- = \sum_{j=1}^{B}(E_j + q_{zj})$. Here E_i (E_j) and p_i (q_j) are the energy and the 3-momentum of the i^{th} (j^{th}) constituent from A(B).

The value of x_i^+ (y_j^-) is chosen according to the distribution:

$$dP \sim \prod_{i=1}^{A} e^{-(x_i^+ - \frac{1}{A})^2 / d^2} \delta\left(1 - \sum_{i=1}^{A} x_i^+\right) dx_i^+, \quad (6)$$

where d=0.05. This distribution is defined by fitting the average emission angle of evaporated singly and multiply charged nuclear fragments (black particles) [16-17]. The value of $p_{i\perp}(q_{i\perp})$ is simulated according to

$$dP \sim \prod_{i=1}^{A} e^{-(p_{i\perp}^2/\prec p_\perp^2 \succ)} \delta\left(\sum_{i=1}^{A} p_{i\perp}\right) dp_{i\perp}, \quad (7)$$

where $\prec p_\perp^2 \succ = 0.05\ (GeV/c)^2$.

The sum of transverse momenta gives the Fermi motion to the nucleons of the nucleus A (B).
As for the wounded nucleons (which are determined either from the Glauber approach or Regge cascading) the values of $[x_i^+, p_{i\perp}]$ and $[y_i^-, q_{i\perp}]$ are simulated using the distributions (6) and (7) at $\prec p_\perp^2 \succ = 0.3\ (GeV/c)$ and *d=0.21.*

3. Comparision with the Modified Fritiof Model

3.1 Proton-proton and neutron-neutron collisions

Here we summarized the results regarding the mean multiplicity of negatively charged hadrons produced in minimum bias pp-interactions $<h^->_{pp}$ from the threshold momentum for π^- meson production (~ 1.2 GeV/c) up to 400 GeV/c in Table 1 (The experiment - the second column, Calculations – the third column respectively). The quality of the data on neutron-neutron interactions is very poor due to problems with neutron beams. Therefore, there were attempted to deduce the values of the mean multiplicity of negatively charged hadrons produced in neutron-neutron interactions $<h^->_{nn}$ from data on hadron production in proton-proton collisions. The data on $<h^->_{nn}$ are given in the 4th (experiment) and the 5th column of the table (calculations respectively).

Table 1. The mean multiplicities of negatively charged hadrons $<h^->_{pp}$ produced in minimum bias proton-proton collisions and in minimum bias neutron-neutron collisions, $<h^->_{nn}$ at different incident momenta p_{lab} and their corresponding modified FRITIOF calculations.

P_{lab}(GeV/c)	$<h^->_{pp}$		$<h^->_{nn}$	
	Experiment	*FRITIOF*	*Experiment*	*FRITIOF*
1.99	0.027± 0.02	0.02	0.76 ± 0.03	0.55
2.23	0.048± 0.01	0.03	0.84 ± 0.03	0.68
2.81	0.111± 0.03	0.11	0.87± 0.03	0.76
4.00	0.27± 0.01	0.25	0.97± 0.10	0.92
5.50	035± 0.02	0.38	1.05± 0.10	1.06
6.60	0.42± 0.03	0.44	1.13 ± 0.10	1.15
12.0	0.71± 0.01	0.75	1.41 ± 0.10	1.46
19.0	1.00 ±0.01	1.05	1.71 ± 0.10	1.76
24.0	1.12± 0.01	1.19	1.82 ± 0.10	1.85
35.7	1.39± 0.02	1.44	2.09 ± 0.10	2.14
50	1.68± 0.05	1.70	2.38 ± 0.11	2.41
60	1.80± 0.05	1.83	2.50 ± 0.11	2.55
69	1.92± 0.04	1.93	2.62 ± 0.11	2.64
100	2.24 ±0.06	2.22	2.94 ± 0.11	2.90
147	2.51± 0.04	2.51	3.21 ± 0.11	3.23
175	2.76± 0.12	2.74	3.46 ± 0.15	3.37
200	2.86± 0.05	2.79	3.56 ± 0.11	3.49
205	2.84± 0.04	2.76	3.54 ± 0.11	3.48
250	2.94± 0.04	2.94	3.64 ± 0.11	3.63
303	3.25± 0.06	3.20	3.95 ± 0.11	3.88
360	3.53± 0.05	3.38	4.23 ± 0.11	3.96
400	3.57± 0.03	3.49	4.27 ± 0.10	4.16

3.2 Proton-neutron collisions

In this section we have compared the data on the mean multiplicity of negatively charged hadrons produced in minimum bias proton-neutron collisions $\langle h^- \rangle_{pn}$ obtained at incident proton momenta of 1 – 400 GeV/c and are presented in Table 2 (The experiment - the second column, Calculations – the third column respectively). The data on particle production in p+n interactions are usually obtained by studying p+d and d+p collisions and extracting events with a spectator proton from the deuteron nucleus. All results on the mean multiplicity of negatively charged hadrons produced in proton-neutron collisions $\langle h^- \rangle_{pn}$ from threshold momentum (~ 0.8 GeV/c) up to 400 GeV/c are presented in Table 2.

Table 2. The mean multiplicities of negatively charged hadrons $\langle h^- \rangle_{pn}$ produced in minimum bias proton-neutron collisions at different momenta of incident protons p_{lab} and modified FRITIOF calculations

P_{lab} (GeV/c)	$\langle h^- \rangle_{pn}$	
	Experiment	*FRITIOF*
1.25	0.13 ± 0.03	0.117
1.73	0.25 ± 0.03	0.197
2.23	0.34 ± 0.02	0.320
2.37	0.36 ± 0.01	0.346
2.58	0.39 ± 0.01	0.388
3.83	0.57± 0.02	0.547
4.20	0.57± 0.01	0.597
4.50	0.60 ± 0.00	0.642
5.10	0.71 ± 0.02	0.690
6.10	0.72 ± 0.02	0.750
9.90	0.94 ± 0.01	1.016
11.60	0.90 ± 0.03	1.100
14.60	1.13 ± 0.01	1.254
19.0	1.27 ± 0.04	1.298
28.0	1.69 ± 0.05	1.666
100	2.65 ± 0.06	2.578
200	3.13 ± 0.05	3.119
300	3.42 ± 0.09	3.468
400	3.91 ± 0.06	3.848

3.3 Proton-nucleus interactions

Here we have compared the data on the mean multiplicity of negatively charged hadrons produced in minimum bias proton-nucleus collisions $<h^->_{pA}$ obtained at incident proton momenta of 2 – 200 GeV/c and are presented in Table 3 (Type of reactions - the second column, Experiment - the third and Calculations – the fourth column respectively). One can see that Modified Fritiof model describes the experiment good.

4. Summary

Data on the mean multiplicity of negatively charged hadrons produced in minimum bias proton-proton, proton-neutron and proton nucleus interactions at momenta of 1.25 – 400 GeV/c compared within the modified FRITIOF model and analyzed.
The dependence of the $<h^->_{pp}$ and the $<h^->_{pn}$ on the incident proton momentum has been shown and the construction of the results for neutron-neutron and nucleon-nucleon collisions has been described. The modified Fritiof Model shows good agreement with the above data.

Acknowledgement. I would like to thank Dr. V.V. Uzhinskii for his idea and introducing me to the field of high energy nuclear collisions and programming.

Table 3. The mean multiplicities $<h^->_{pA}$ and the corresponding modified FRITIOF calculations.

P_{lab} (GeV/c)	*Type of Reactions*	$< h^- >_{pA}$	
		Experiment	*FRITIOF*
2.3	*p+C*	0.15 ± 0.01	0.15
2.3	*p+Ta*	0.14 ± 0.01	0.18
4.2	*p+C*	0.33 ± 0.02	0.37
4.2	*p+Ta*	0.45± 0.02	0.43
5.4	*p+C*	0.52 ± 0.03	0.54
5.4	*p+Ta*	0.65± 0.04	0.62
9.9	*p+C*	0.93 ± 0.05	0.96
9.9	*p+Ta*	1.17 ± 0.06	1.09
14.6	*p+Au*	2.15 ± 0.33	2.09
100	*p+Au*	5.14 ± 0.18	4.92
200	*p+Au*	7.00 ± 0.40	6.87
360	*p+Au*	8.90 ± 0.40	8.79
28.0	*p+Ne*	2.10 ± 0.10	2.09
300	*p+Ne*	4.91 ± 0.05	4.72
100	*p+Mg*	3.80 ± 0.30	3.69
200	*p+Mg*	4.90 ± 0.40	4.72

References

[1] V.V. Uzhinskii // JINR preprint, 1996. **E2-96-192**, Dubna

[2] B. Ganhuyag // Description on π^- mesons and protons in *np*-interactions at p_n = 1.25 -5.1 GeV/c within the Modified Fritiof Model, 1998, **P2-97-397**, Dubna

[3] B. Ganhuyag and V.V. Uzhinskii // Modified Fritiof Code. Czechoslovak Journal of Physics, **47 (1997), 913**.

[4] B. Ganhuyag and V.V. Uzhinskii // Description on π^- mesons in *np*-interactions at p_n = 1.25 -5.1 GeV/c within the Modified Fritiof Model, **1997**, **P1-97-315**, Dubna

[5] M. Gazdzicki and D. Roerich // Z.Phys. **C 65, 215-223 (1995)**

[6] Abdel-Waged Kh. and V.V. Uzhinskii // Phys. At. Nuclei, **60 (1997), 828**.

[7] Abdel-Waged Kh. and V.V. Uzhinskii // Jour. Phys. G: Nucl. Part. Phys., **24 (1998), 1723**.

[8] El-Nadi M, Abdel-Salam A, Hussein A, Shaat EA, Ali-Mousa N, Abou-Mousa Z, Kamel S, Abdel-Waged Kh and El-Falaky E. **(1997)** Int. Jour. Mod. Phys. E **.6 191**

[9] Boreskov K. G, Kaidalov A. B, Kiselev S. T, and Smorodinskaya N. Ya. **(1991)** Fiz. Yad **53, 569** (Engl. transl. **(1991)** Sov. J. Nucl. Phys. **53**).

[10] Abdel-Waged Kh. and V.V. Uzhinskii // Phys. At. Nuclei, **60 (1997), 828**.

[11] Yu. S. Shmakov, V.V. Uzhinskii and A.M. Zadorozhny // **(1989)** Comput. Phys. Commun. **54, 125**.

[12] Boreskov K. G, Kaidalov A. B, Kiselev S. T. and Smorodinskaya N. Ya. // **(1991)** Fiz. Yad **53, 569** (Engl. transl. **(1991)** Sov. J. Nucl. Phys. **53**).

[13] Ferrari A, Ranft J. Roesler S. and Sala P. R. // **(1996)** Z. Phys. **C 71, 75**

[14] Uzhinskii V.V. and Pak A. S. // **(1996)** Phys. At. Nuclei **59, 1064**

[15] Werner K. // **(1993)** Phys. Rep. **232, 87**

[16] Armutlisky D. // **(1987)** et. al., Z. Phys. **A 328, 455**

[17] Baldin A. A. // **(1993)** Fiz. Yad **56, 174** (Engl. transl. **(1993)**), **56**

[18] Abdel-Waged Kh and. Uzhinskii V.V. // **(1998)** Jour. Phys. G: Nucl. Part. Phys.**24, 1723**.

[19] Schuettauf et. al., // **(1996)** Nucl. Phys. A **607, 457**