E1-2019-21

Ts. Baatar[1], B. Otgongerel[1], M. Sovd[1],
G. Sharkhuu[1], A. I. Malakhov, T. Tulgaa

CUMULATIVE PROTON PRODUCTION IN $\pi^- + \mathrm{C}$ INTERACTIONS AT 40 GeV/c AND THE UNCERTAINTY PRINCIPLE

Submitted to "Eur. Phys. J. A"

[1] Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia

Баатар Ц. и др. E1-2019-21

Образование кумулятивных протонов в $\pi^- C$-взаимодействиях при 40 ГэВ/c и принцип неопределенности

Исследовано кумулятивное образование протонов в $\pi^- C$-взаимодействиях при 40 ГэВ/c. Кумулятивные протоны по сравнению с некумулятивными образуются при больших значениях переменной n_c — более 1,0, и в этой области энергия кумулятивных протонов растет. Экспериментальные значения энергий кумулятивных протонов сравниваются с оценками, полученными по формуле на основе принципа неопределенности. Показано, что энергия кумулятивных протонов, полученных с помощью формулы принципа неопределенности, находится в согласии с экспериментальными результатами с точностью до $\sim 10\,\%$.

Работа выполнена в Лаборатории физики высоких энергий им. В. И. Векслера и А. М. Балдина ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2019

Baatar Ts. et al. E1-2019-21

Cumulative Proton Production in $\pi^- + \mathrm{C}$ Interactions at 40 GeV/c and the Uncertainty Principle

We study the cumulative proton production in $\pi^- + C$ interactions at 40 GeV/c. Cumulative protons, in comparison with the noncumulative ones, are produced at large values of the variable n_c ($n_c > 1.0$) and in this region the energy of cumulative protons also increases. The experimental values of the cumulative proton energies are compared with the estimations obtained by the formula of the uncertainty principle. It has been shown that the energy of cumulative protons obtained by using the formula of the uncertainty principle is in agreement with the experimental results to an accuracy of less than $\sim 10\%$.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2019

1. INTRODUCTION

Investigations of the multiparticle production processes in hadron–nucleon (hN), hadron–nucleus (hA) and nucleus–nucleus (AA) interactions at high energies and large momentum transfers play a very important role in understanding the strong interaction mechanism and the inner quark–gluon structure of nuclear matter.

At present the heavy ion collisions at high energies are regarded as a unique tool to study the nuclear matter features under extreme conditions.

It is well known that in comparison with hN interactions, in hA and AA interactions at high energies the secondary particles are produced in the region kinematically forbidden for hN interactions. These particles are produced as a result of multinucleon interactions. To study characteristics of these particles, it is convenient to use the variable called the cumulative number, n_c. This variable determines the mass value which is required from the target to produce secondary particles.

The investigations carried out on the cumulative particle production have shown that these particles are produced at large values of the transferred momentum not allowed for hN interaction. This means that the study of cumulative particle production in hA and AA interactions at high energies gives us an opportunity to obtain the information about these processes under extreme conditions.

This paper is dedicated to the cumulative proton production in $\pi^- + \mathrm{C}$ interaction at 40 GeV/c.

2. EXPERIMENTAL METHOD

The experimental material was obtained using the Dubna 2-meter propane $(\mathrm{C_3H_8})$ bubble chamber exposed to π^- mesons with a momentum of 40 GeV/c from the Serpukhov accelerator. The advantage of the bubble chamber experiment in this paper is that the distributions are obtained under the condition of 4π geometry of secondary protons.

The average error of the momentum measurements is $\sim 12\%$ and the average error of the angular measurements is $\sim 0.6\%$.

The average boundary momentum from which protons are detected in the propane bubble chamber is ~ 150 MeV/c. In connection with the identification problem between energetic protons and π^+ mesons, protons with a momentum more than ~ 1 GeV/c are included in π^+ mesons. So, protons with a momentum from ~ 150 MeV/c to 1 GeV/c are used in our distributions. 12 441 protons produced in 8791 $\pi^- + \mathrm{C}$ interactions have been used in this analysis.

3. CUMULATIVE NUMBER DISTRIBUTION OF PROTONS

The cumulative number n_c in the fixed target experiment is determined by the following formula [1]:

$$n_c = \frac{P_a\, P_c}{P_a\, P_b} = \frac{E_c - \beta_a P_c^{||}}{m_p} \simeq \frac{E_c - P_c^{||}}{m_p}, \qquad (1)$$

where P_a, P_b and P_c are the four-dimensional momenta of incident, target and secondary particles, E_c and $P_c^{||}$ are the energy and longitudinal momentum of the secondary particle, β_a is the velocity of the incident particle and m_p is the proton mass.

The variable n_c is related with the four-momentum transfer t by the following formula:

$$t = -Q^2 = -(P_a - P_c)^2 = 2E_a\, m_p\, n_c - (m_a^2 + m_c^2) \simeq S_{hN}\, n_c, \qquad (2)$$

where E_a and m_a are the energy and mass of the incident particle, m_c is the mass of the secondary particle.

Formula (1) shows that the variable n_c is a relativistic invariant. From formula (2) we see that the four-dimensional transferred momentum t is fully determined by the variable n_c. This means that the variable n_c is sensitive to

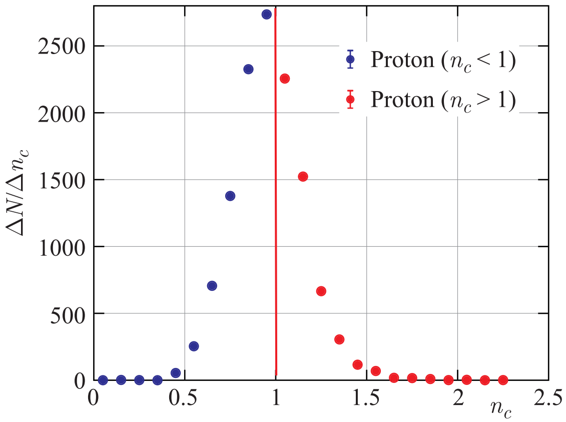

Fig. 1. The cumulative number n_c distribution of protons from $\pi^- + \mathrm{C} \longrightarrow p + X$ interaction at 40 GeV/c

the interaction dynamics as t. Furthermore, this variable gives us an opportunity to know which particles in one event are produced in the cumulative region ($n_c > 1.0$).

The distribution of the variable n_c for the secondary protons from $\pi^- + \mathrm{C}$ interactions at 40 GeV/c is presented in Fig. 1. From this figure we see that the maximum of the distribution is at $n_c \approx 1$ and $\sim 60\%$ of protons are produced in the region of $n_c \leqslant 1$ and $\sim 40\%$ of protons are produced in the $n_c > 1$ region. So $\sim 40\%$ of protons are produced in the cumulative particle production region of $n_c < 1$.

4. AVERAGE VALUES OF PROTON ENERGY $\langle E_p \rangle$ AS A FUNCTION OF VARIABLE n_c

Average values of the proton energy in every n_c interval is calculated by the following formula:

$$E_p = \sqrt{\vec{p}_p^{\,2} + m_p^2},$$

where E_p, $\vec{p_p}$ and m_p are the energy, momentum and mass of proton, correspondingly.

Figure 2 presents the average values of the proton energy in the $\pi^- + \mathrm{C}$ interaction at 40 GeV/c as a function of the variable n_c. With increasing n_c the average values of the energy of protons $\langle E_p \rangle$ are decreasing and reach the minimum at $n_c \simeq 1$ and then in the cumulative particle production region ($n_c > 1$) the proton energy is essentially increasing. In addition to this we note that the average values of the transverse momentum square $\langle p_t^2 \rangle$ (see paper [2]) and the efficient temperature T (see paper [3]) remain practically constant in the region

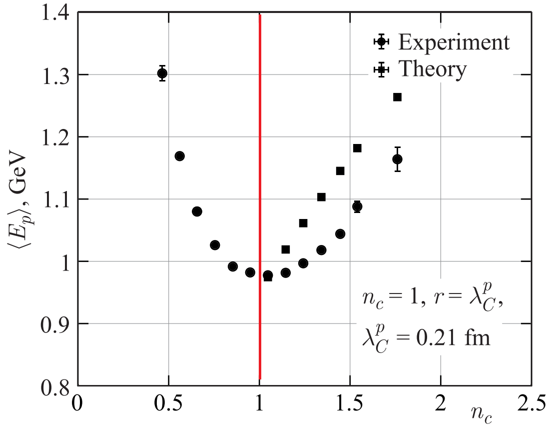

Fig. 2. The average values of protons $\langle E_p \rangle$ as a function of the variable n_c

of $n_c < 1.0$, but in the $n_c > 1.0$ region we see different features; in other words, $\langle E_p \rangle$, $\langle p_t^2 \rangle$ and T are essentially increasing. So, these features of the above-mentioned characteristics in these two different regions ($n_c \leqslant 1.0$ and $n_c > 1.0$), as mentioned in the previous paper [2], indicate a different particle production mechanism in these two different regions.

As mentioned in the methodical part of this paper, we have not taken into account the contribution of protons with a momentum more than ~ 1 GeV/c in our distributions. This fact, of course, gives lower values of $\langle E_p \rangle$ in the n_c intervals.

5. A PARTICLE EMISSION REGION SIZE r IN MULTIPARTICLE PRODUCTION PROCESS AND THE UNCERTAINTY PRINCIPLE

The authors of paper [3] have shown that the particle emission region size r (or a particle formation length) is determined by the following formula:

$$r \simeq \frac{1}{m_p \sqrt{n_c}} = \frac{\lambda_C^p}{\sqrt{n_c}} = \frac{0.21 \text{ fm}}{\sqrt{n_c}}. \tag{3}$$

From formula (3) we see that the parameter r is determined by the Compton wavelength of proton $\lambda_C^p = 1/m_p = 0.21$ fm and the cumulative number n_c. Thus, the determination of the numerical value of the variable n_c gives us an opportunity to obtain the numerical value of the particle emission region size r for every secondary particle produced in collisions of interacting particles and nuclei at high energies. Formula (3) gives us an oppotunity to determine parameter Δt:

$$\Delta t = \frac{r}{c}. \tag{4}$$

We would like to note that a set of parameters r and Δt gives us the picture of the space-time evolution of the multiparticle production process from the interaction point to the particle emission region size r. From formula (4) we see that the parameter r at $n_c = 1$ equals λ_C^p. Figure 2 shows that the Compton wavelength λ_C^p is the cut parameter of the noncumulative and cumulative production of protons. This means that the noncumulative proton production belongs to soft processes and the cumulative proton production belongs to hard processes. It means that for the cumulative proton production mechanism the quantum effects should be taken into account [4].

From the other hand, the Heisenberg uncertainty principle is determined by the following formula:

$$\begin{aligned} \Delta p \, \Delta x &\geqslant \hbar, \\ \Delta E \, \Delta t &\geqslant \hbar. \end{aligned} \tag{5}$$

Formula (5) gives the following expression:

$$\Delta x \geqslant \frac{\hbar}{m_p c} = \lambda_C^p. \tag{6}$$

Using formulae (3) and (6), we obtain the following relation between r and Δx:

$$\Delta x = r\sqrt{n_c}. \tag{7}$$

From this relation we obtain the following formula:

$$r = \frac{\lambda_C^p}{\sqrt{n_c}} = \frac{\Delta x}{\sqrt{n_c}}. \tag{8}$$

Formula (8) shows that the parameter r can be used instead of the parameter Δx.

Using formulae (3) and (4), we have obtained the formula which determines the energy ΔE:

$$\Delta E \geqslant \frac{\hbar}{\Delta t} = \frac{\hbar\, c}{r} = \frac{\hbar\, c}{0.21\ \mathrm{fm}}\sqrt{n_c} = m_p\sqrt{n_c}. \tag{9}$$

We note that the combination of constants of the Compton wavelength λ_C^i $\left(\frac{\hbar\, c}{\lambda_C^i} = \frac{0.197\ \mathrm{GeV}\cdot\mathrm{fm}}{0.21\ \mathrm{fm}} = 0.938\ \mathrm{GeV} = m_p\right)$ gives the proton mass and formula (9) gives the upper limit of the cumulative protons in the given n_c interval.

Formula (9) shows that the energy of the protons produced at the given value of the variable n_c is determined by $\sqrt{n_c}$. This means that cumulative protons are produced at large transferred momenta (kinematically not allowed for hN interaction, see formula (2)) or at large values of the target mass, more than one nucleon mass, localized at small distances of the parameter $r < \lambda_C^p \simeq 0.21$ fm. The average values of the energy of cumulative protons in the given n_c interval estimated by formula (9) are presented in Fig. 2 by squares. From the theoretical formula (9) we see that with increasing variable n_c the energy of cumulative protons is also increasing as in the case of the experimental result. Figure 2 shows that the values of the experimental and theoretical estimations agree with an accuracy of less than $\sim 10\%$.

Figure 3 shows the baryonic matter density as a function of the parameter r. We see that the baryon density is essentially increasing with decreasing parameter r. This means that the cumulative proton production is related with the production of high density state of the nuclear matter.

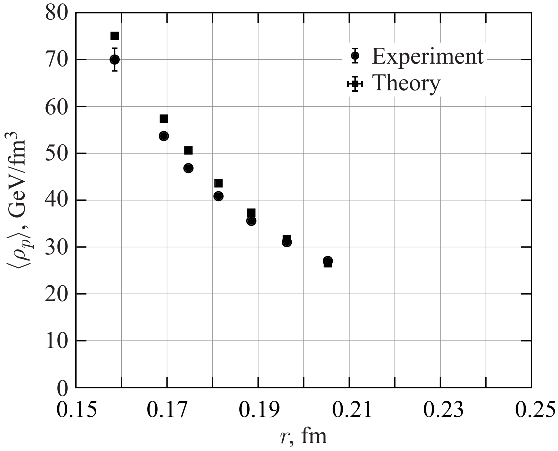

Fig. 3. The baryonic matter density as a function of parameter r

6. CONCLUSIONS

On the basis of the experimental analysis used to describe the cumulative processes and the analysis by means of the uncertainty principle formula, we conclude that the energies of the cumulative protons obtained by using the formula of the uncertainty principle are in agreement with the experimental results to an accuracy of less than $\sim 10\%$.

REFERENCES

1. *Baldin A. M.* // Part. Nucl. 1977. V. 8, Part 3. P. 429.
2. *Baatar Ts. et al.* JINR Preprint E1-2012-13. Dubna, 2012.
3. *Baatar Ts. et al.* // Proc. of XXII Intern. Baldin Seminar on High Energy Physics, JINR, Dubna, Russia, September 15–20, 2014.
4. Physical Encyclopedia. Moscow, 1990. V. 2. P. 433.

Received on April 11, 2019.

Редактор *Е. И. Кравченко*

Подписано в печать 14.06.2019.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,68. Уч.-изд. л. 0,88. Тираж 255 экз. Заказ № 59713.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/