PROCEEDINGS OF SCIENCE

Nuclear transparency effect in proton and deuteron induced interactions with carbon nuclei

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We used the nuclear transparency effect of π^+-mesons in proton and deuteron induced interactions with carbon nuclei at 4.2 A GeV/c for studying the properties of nuclear matter. The average values of multiplicity, momentum and transverse momentum of the π^+-mesons are analyzed as a function of the number of identified protons in an event. We used the value of pseudorapidity ($\eta_{1/2}$) corresponding to Half angle ($\theta_{1/2}$) to see the effect of nuclear transparency for the π^+-meson in the nuclear medium. The $\eta_{1/2}$ divides the multiplicity of charged particles into two equal parts in nucleon-nucleon interaction at 4.2 A GeV/c. We observed several cases where the behavior could be considered as transparency effect. For quantitative description, the results are compared with cascade model. Some simple calculation using Collective Tube Model (CTM) support the idea of collective interaction with grouped nucleon encountered when propagating through the target nucleus.

XXI International Baldin Seminar on High Energy Physics Problems
September 10-15, 2012
JINR, Dubna, Russia

*Speaker.

PoS(Baldin ISHEPP XXI)052

1. Introduction

Collins and Perry [1] proposed for the first time the existence of a new phase of nuclear matter. The new phase of matter was later called the Quark-Gluon Plasma (QGP) [2] predicted by Quantum Chromodynamics [3] -the theory of strong interaction. From the last about 30 years, study of this new phase of matter get a huge attention of the experimentalist as well as theoreticians. QGP is expected to be produced at extreme conditions. It means that some critical value of temperature [4] and density is required for its production. These conditions can be produced in laboratory with the collisions of relativistic heavy nuclei at high energies. This leads to a continuing quest of leading research centers, including JINR, BNL, JLab and CERN etc, which centers on high-energy physics to create new accelerators of heavy nuclei and enhance the energies of existing accelerators. The transition of the normal nuclear matter to the new dense phase of QGP is a topic of longstanding interest in nuclear physics. A promising observable commonly used to map this transition and to identify the underlying dynamics of hadronic matter is the transparency of the nuclear medium to the propagation of hadrons. The nuclear transparency (NT) effect is connected to the changes take place in the reaction cross-section during nuclear interaction. Increase in nuclear transparency decreases the reaction cross-section. NT is defined as that an impact parameter the projectile will pass through the target nucleus with reduced interaction. It is the ratio of the cross section per nucleon to that of the cross section from a free nucleon. So, the NT provides a measure of the attenuation effects of the nuclear medium on the hadrons produced in a reaction. Energy dependence of the NT effect gives information about the structure [5], states [6], properties [7, 4] and phases [8, 9] of nuclear matter. The idea of nuclear transparency in collisions was apparently first introduced by H. A. Bethe [10] in 1940. An anomalous increase in the behavior of NT is the phenomenon of color transparency (CT) predicted by quantum chromodynamics (QCD). The concept of CT was first introduced by Brodsky and Mueller [11, 12] in 1982. CT is the prediction reduced interactions [13] of hadrons produced in exclusive reactions with high four momentum transfers squared (Q^2) (with $r_\perp \sim (\frac{1}{Q})$. A lot of efforts have been made to search for the CT effect. Results of quasi-elastic A(p, 2p) reaction [14, 15, 16, 17, 18] performed at BNL were found to be inconsistent with CT. Results of the quasi-elastic A(e, $e^{'}$p) reaction [19, 20, 21, 22, 23, 24] at SLAC with the A-dependence as a function of Q^2 also did not produce the effect of CT. In later studies mesons were used with the premise that an earlier onset of CT for mesons production is expected than that for baryons because the at large Q^2 the values of $r_\perp \sim (\frac{1}{Q})$ is significantly smaller than that for nucleons. The results include ρ-meson production [25, 26] [Hermes Collaboration], diffractive dissociation of pions into di-jets [27] and pion photoproduction process [28, 29] at JLab. The intrested reader for a more complete review on the nuclear transparency is referred to a status report by Dutta et al [30].

2. The Method and Experiment

Using the idea of the half angle method [6] we used the value of pseudorapidity (η) which divides the multiplicity of all charged particles into two equal parts denoted by $\eta_{1/2}$. Using pp collision we determined the values of the $\eta_{1/2}$ to be 1.51. The particles with $\eta > \eta_{1/2}$ are the incone particles and those with $\eta < \eta_{1/2}$ are the outcone particles. We defined the NT as an effect at which the characteristics of π^+-mesons in proton induced interactions with carbon nuclei (pC) and deuteron induced interactions with carbon nuclei (dC) do not depend on N_p. N_p is used to fix the baryon density of nuclear collisions. Besides $\eta_{1/2}$, we used five different values of η including 1.74, 2.03, 2.44 and 3.13 corresponding to θ = 20^o, 15^o, 10^o, and 05^o respectively to check the behavior of the average characteristics at these different values. Finally the results are compared with the data coming from Dubna version of cascade model [31, 32, 34, 35]. The cascade model is a popular model, used to describe the general features of relativistic nucleus-nucleus collisions. It is an approach based on simulation using Monte-Carlo techniques and is applied to situation where multiple scattering is important. The basic assumptions and procedures of the cascade model are given by K. K. Gudima et al. [31] and A. Boudard et. al [32]. We also used some simple calculation using expressions from the Collective Tube Model (CTM) [33]. In the CTM it is assumed that the incoming particle interacts with the tube that lies along its path. It means that the particle/nucleons in the target that lies in the path of the incident particle interact collectively to the latter. In the independent particle approximation for the nucleus, the probabilities $P(i,A)$ for the projectile to encounter a tube with i nucleons is calculated with the assumption that the tube act as a big hadron. We used the experimental data obtained from the 2-m propane (C_3H_8) bubble chamber of the High Energy Laboratory (LHE) of the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The chamber was exposed to beams of protons and deuterons accelerated to a momentum of 4.2 A GeV/c. A magnetic field of 1.5 tesla was used to separate the positively and negatively charged particle, as well as to calculate the momentum of the high energy particles from their trajectories. Threshold values for the momentum charged pions was set to 70 MeV/c, whereas the threshold for protons momentum was set to 150 MeV/c respectively below which the respective hadrons were not identified because of their short range in the chamber. Protons was identified upto 500 MeV/c with certainity beyond which there was a difficulty in the identification of the protons with the π^+-mesons. All positive charged particles above 750 Mev/c were considered as protons. All negative charged particles (expect identified electrons) were considered as π^--mesons. Secondaries having p >3 GeV/c and θ <4^o are stripping fragments while the proton participants are those whose p >300 MeV/c excluding the stripping fragments. An average error in angles was measured to be 0.8^o, whereas the average relative error in momenta of the secondary particles from the curvature of their track in the magnetic field was 11%. The detail discussion on the interaction mechanism is given by H. N. Agakishiyev et al. [36]. In this experiment, we used 12757 pC- and 9016 dC- interactions at a momentum of 4.2 A GeV/c. In the case of cascade code we used 50000 pC- and dC-interactions under the same conditions.

3. Results

The average multiplicity <n> of the outcone π^+-mesons in pC- interactions at $\eta_{1/2}$ = 1.51 as well as for η = 1.74, 2.03, 2.44 and 3.13 as a function of the N_p are shown in Fig.1(a). Experimental data results are shown by geometrical symbols while the results of the cascade model are shown by lines as given in legend against each value of η. The results from the dC data under the same conditions are given in Fig. 1(b) having the same representation of geometrical symbols and lines for experimental data as well as cascade model respectively. The values of <n> in experimental data of pC- and dC- interactions decreases sharply with N_p = 0 - 2 and then increases slowly, but the results in the case of Cascade model is unable to reproduced the results completely. In the case of pC cascade model can qualitatively describe the results but not in the case of dC data. We did not observe any signal on transparency in the outcone <n> of π^+-mesons. The <n> is suppressed in experimental data as compared to cascade model. The reason being the possibility of mixing of some of the fast π^+-mesons with protons as is explained in [37]. The values for the <p> as a function of the N_p for these pions in pC and dC data are givem in Fig. 1(c) and 1(d) respectively for different values of η. The results of the experimental and the code data are substantially different. The experimental data shows transparency for almost all values of η including $\eta_{1/2}$, whereas the <p> decreases linearly with increasing N_p for all values of η. It means that the observed transparency is not reproduced by the cascade model. Fig. 2(e) and 2(f) demonstrate $<p_T>$ as a function of the N_p for the pC and dC data respectively. One can see a clear differences between experimental and code data. Experimental data shows transparency with some small degree of oscillation. The code data could not explain the results of experimental data and show a decreasing behavior of $<p_T>$ with increasing N_p. So we could say that the experimental data on behavior of the average characteristics of the out cone π^+-mesons demonstrate some transparency which could not be described by the cascade model. This behavior could not be the reason of leading effect due to the fact that the outcone π^+-mesons are secondary produced particles having small energy and η less than 1.51, 1.74, 2.03, 2.44 and 3.13. In the pC- and dC- interactions transparency seems to be more clean on level of about $<p_T> \approx 0.26$ GeV/c. We can roughly calculate the length of the tube (R) radiating pions through the poins $<p_T>$ as R $\sim \frac{1}{<p_T>}$. Using the approximate expression the value of $R \sim 3.8$fm . Diameter of the carbon nucleus is approximately equal to 3.67 which is the same as that of the length of the tube radiating pion in the out cone pions. As we could see the projectile didnt change almost the values of the R because in pC- and dC- interactions the values of $<p_T> \sim 0.26$ GeV/c. So we can say that a reason of the observed transparency is that the size of pion radiation area doesnt change during interaction with increase in the number of protons as well as with the mass of the projectile. The transparency observed for the outcone π^+-mesons is not reproduced by the cascade model. It means that the behavior is connected to some effect which is beyond the scope of the model. Y. Afek et, al., [39] has broadly divided the various models that have been suggested so far for high energy particle-nucleus collisions and for high energy nucleus-nucleus collisions into two categories. The first category of models includes those models which assume that particle nucleus collision is a single step process consisting of successive independent collisions with nucleon in the nucleus while propagating through it. Cascade model is a typical example of the first category of models. The center of mass energy available for the production of new particles in these models is given by $s \lesssim 2mP_{lab}$. The second category included all those models which assume that particle-nucleus collisions in a single step process where a few nucleons in the nucleus respond collectively to the incident particle. Collective Tube Model (CTM) [39, 40] is a typical example of the second category of models. In such models the effective center of mass energy available for the production of particles is approximately given by $s_{eff} \simeq 2m_{eff}P_{lab}$. Where m_{eff} is the mass of the system that interacts collectively to the incident particle. The value of this mass is of the order of a few times the mass of a single nucleon. P_{lab} is a momentum of the incident particles. The model has been successfully applied to various processes at low and high p_T [41, 42, 43, 44, 45]. We think that the observed transparency could be considered as a result of the collective interaction of grouped nucleons with the proton and deuteron in pC- and dC- interactions.

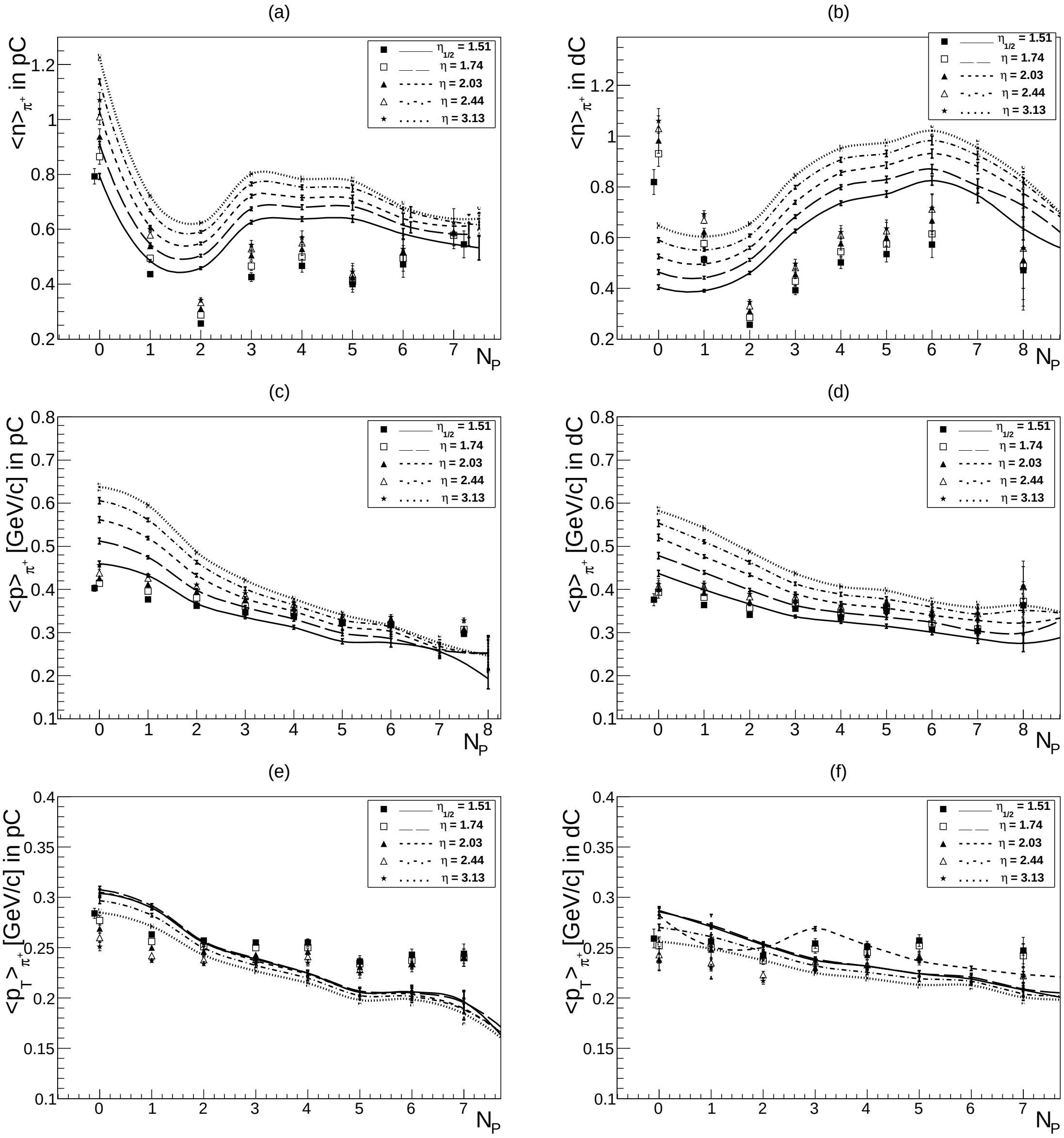

Figure 1: Behavior of the average characteristics of outcone π^+-mesons as a function of number of identified protons (N_p). Fig 1(a) is the behavior of average multiplicity ($< n >$) of outcone π^+-mesons as a function of N_p in pC- interactions, 1(b) is the $< n >$ of outcone π^+-mesons as a function of N_p in dC- interactions, 1(c) is the $< p >$ versus N_p in pC- and 1(d) is $< p >$ in dC- interactions, 1(e) is the $<p_T>$ versus N_p in pC- and 1(f) is the $<p_T>$ in dC- interactions.

Using the following expression from CTM [39] for the average multiplicity of secondary charged particles (<n(s)>) as a function of the number of fast protons N_p, we can calculate roughly the number of nucleons in tube (i_p).

$$< n(s) >_{ip} \simeq < n(s) >_{pp} \text{ x } (< i_p >)^{\alpha}$$

here $< n(s) >_{ip}$ is the multiplicity of the secondary charged particles produced in tube with ip nucleons whereas $< n(s) >_{pp}$ is multiplicity of the secondary charged particles in pp-interaction at same energy in center of mass. A and Z are the mass number and charge number of target nucleus respectively (for carbon nucleus A = 12, Z = 6). For estimation we take $\alpha \sim \frac{1}{4}$ [46] so we get $i_p \sim 3.1 \pm 0.3$ (the average values) which is almost independent of the η The diameter of the carbon nucleus is about 3.6 fm which can accommodate 2.5 nucleons in its diameter. Our calculated value for the number of nucleons in the tube is close to the number of nucleon in the diameter of the carbon nucleus. This result give us opportunity to say that the collective interaction of grouped nucleons in the nucleus / nuclear medium is a reason for observed transparency for out cone π^+-mesons produced in pC- and dC-interactions.

4. Summary and Conclusion

For looking the properties of nuclear matter, we used the nuclear transparency effect of the π^+-mesons. To get a signal on the NT, we studied the average characteristics of π^+-mesons using pC- and dC- interactions at 4.2 A GeV/c. Using the idea of half angle technique we used the value of η which divides the charged particles multiplicty into two parts. We observed some signal of the nuclear transparency effect in the behavior of outcone ($\eta_{1/2} \leq 1.51$ as well as for $\eta \leq$ 1.74, 2.03, 2.44 and 3.13) π^+-mesons. We consider the effect of nuclear transparency as some signal which could be connected to some particular properties of the medium. The results of the experimental data are compared with the cascade model and Coherent Tube Model. Cascade model could not explain the results which were used as a typical example of the first category of models. The transparency appears due to the collective interaction of the grouped nucleon which interact collectively with the incident particle. The number of nucleon which responds collectively to the interaction of incident particle is calculated using CTM which comes out to be about 3. We have also calculated the length of the tube radiating pions which come out to be the same as that of the diameter of the carbon nucleus. So we could conclude that the source of these particles could be the collective interaction of target nucleons with the projectile.

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