ANGULAR DISTRIBUTION OF NEUTRAL KAONS FROM PION-INDUCED REACTIONS ON NUCLEI*

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Angular distributions of K^0 mesons produced in 1.15 GeV/c π^- reactions on carbon and lead targets, measured with the FOPI spectrometer at GSI Darmstadt, are not isotropic. The ratio of these angular distributions shows a strong forward–backward asymmetry, which might be understood as a result of the reabsorption of forward produced kaons in lead nuclei. This effect agrees with the results of IQMD transport model. A simple geometrical model developed in order to estimate the effect of the absorption allows to determine the kaon mean free path equal to about 4 fm.

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1. Introduction

The properties of the hot and dense zone formed in nucleus–nucleus (AA) collisions at relativistic energies and particles created within that zone can be studied with different probes. The most suitable are the electromagnetic probes, which do not suffer from reabsorption in a strongly interacting medium: photons from proton–neutron bremsstrahlung or dileptons from meson decays. Their observation is however difficult. Photon spectra are obscured by electromagnetic decays of hadronic particles (π^0, η *etc.*), which restricts their detection practically to AA collisions below $\sim 200A$ MeV [1]. Dileptons [2] can effectively be studied only at higher energies ($> 1A$ GeV), but the branching ratios of (vector) mesons decay into dilepton channels are very low (at the level of $\sim 10^{-5}$–10^{-4}).

Among the hadronic probes, pions have the advantage of abundant production but suffer from very strong reabsorption (strong coupling to form $\Delta(1232)$ resonances), which limits their usefulness for studies of the initial

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phase of AA collisions. Mesons carrying anti-strange quark (K^+ and K^0), due to the strangeness conservation, propagate relatively free in the strongly interacting medium. Calculated theoretically [3], the mean free path of charged kaons is significantly longer compared to any other hadronic particle at momenta below 1 GeV/c. Therefore, kaons are the favourite probes to study the properties of the hot and dense nuclear medium formed in the relativistic AA collisions. Experimentally, K^+ interactions with light $Z = N$ nuclei have been studied at AGS in BNL [4–7] (earlier measurements were done at the Rutherford Laboratory [8]). The AGS data have been reanalysed in Ref. [9]. The cross section for the K^+ absorption was found to scale approximately as $\sigma_{KA} = \sigma_{Kd} \times \frac{A}{2}$, where σ_{Kd} denotes the cross section of the interaction of kaon with deuterium. Only small deviations (10% level) from that scaling were observed, which indicates weak screening effects and long interaction length.

The predicted strong in-medium effect [10], leading to a significant reduction of the total cross section for the $\pi^- p \to K^0 \Lambda$ process, was the principal motivation to study this process by the FOPI collaboration. The available experimental data for carbon and lead targets allowed to analyse in detail the shape of the angular distribution of K^0 mesons.

2. Experiment

In the experiment performed at SIS18 synchrotron at GSI Darmstadt, the negative pion beam was obtained in interactions of $2A$ GeV $^{14}N^{7+}$ ions on the B_4C production target. The secondary pion beam of 1.15 GeV/c momentum was transported to the target position of the FOPI spectrometer, about 89 m from the production target. The measured pion beam intensity on the target was below 10^4 pions in a 6 seconds long spill. Trajectories of each beam particles close to the target were registered in two thin silicon detectors, which allowed for accurate reconstruction of the interaction point. Several targets were used (in parenthesis: target thickness in g/cm^2): C (2.3), Al (1.6), Cu (4.5), Sn (2.9), Pb (5.7). The neutral kaons ($K^0_{\rm S}$) were identified through their (68.6%) decays into two pions of opposite charges. Charged pions were identified in the FOPI spectrometer, through the energy loss measurements and momentum reconstruction in the Central Drift Chamber (CDC) placed in 0.6 T magnetic field. The invariant mass spectrum of collected pion pairs shows a prominent peak above the combinatorial background, with the width of $\sigma_M = 20$ MeV. The number of registered kaons for a given target allows to make a more detailed analysis of the angular distributions of K^0 mesons in the case of carbon and lead targets (∼20 thousand kaons reconstructed per target).

3. Analysis and preliminary results

The angular distributions of K^0 mesons emitted from carbon and lead targets are not isotropic and show a clear target mass dependence. The ratio of the angular distributions (Fig. 1) shows clearly that the emission of K^0 mesons at forward angles is strongly (factor $\alpha_{\mathrm{C/Pb}}{\sim}3$) favoured in the case of the C target compared to that of the Pb target. As the mean free path of π mesons in nuclear matter is very short, the $\pi^- A \to K^0 X$ reaction occurs predominantly at the surface of the target nucleus. This effect is confirmed by the surface (${\sim}A^{2/3}$) scaling of the target-mass dependence of the K^0 production [11]. The emission of K^0 mesons produced in the backward direction (large scattering angles) should not depend on the target mass, as the distance travelled in the matter is short and approximately the same for all targets. The observed forward–backward asymmetry in the C/Pb ratio indicates that K^0 mesons undergo stronger reabsorption process in lead nuclei compared to carbon nuclei.

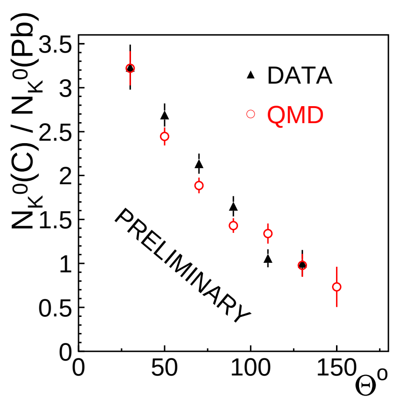

Fig. 1. The ratio of the experimental (full triangles) angular distribution of K^0 mesons on C target to that on Pb target, compared to the IQMD model calculations (open circles) filtered with the FOPI acceptance (preliminary results). The C/Pb ratio is normalised to 1 at 130°.

The experimental results were compared to the IQMD [12] transport-model calculations for the π^- reactions on C and Au nuclei. In order to validate the comparison, the results of the model were treated on similar footing as the data, *i.e.* tracked through the FOPI acceptance filter described within the GEANT simulation package and the FOPI reconstruction algorithm. The ratio of angular distributions of K^0 mesons for the IQMD simulations on C and Au nuclei reproduce very well the tendency observed in the experiment (Fig. 1). This result indicates the proper treatment of K^0 production and transport in the IQMD code.

Assuming the direct K^0 meson production and reabsorption, a simple method can be worked out in order to determine the mean free path of K^0 in the nuclear matter (or the value of K^0 interaction cross section in the nuclear matter). The number of K^0 mesons backscattered ($\vartheta = \pi$) with respect to the direction of the incident pion beam can be written as (neglecting the finite pion size):

$$N(R, \vartheta = \pi) \sim \int_0^R b db \int_0^{2\sqrt{R^2-b^2}} dx \exp\left(-\frac{x}{\lambda_\pi}\right) \exp\left(-\frac{x}{\lambda_K}\right), \tag{1}$$

where the first integral describes averaging over the impact parameter, b, for target nucleus of a radius R, and λ_π (λ_K) denotes pion (kaon) interaction length. With the same parameters, the number of K^0 mesons emitted forward are described as:

$$N(R, \vartheta = 0) \sim \int_0^R b db \int_0^{2\sqrt{R^2-b^2}} dx \exp\left(-\frac{x}{\lambda_\pi}\right) \exp\left(-\frac{2\sqrt{R^2-b^2}-x}{\lambda_K}\right). \tag{2}$$

The double ratio of the number of kaons emitted at forward angles to those emitted backward for C and Pb nuclei, written as:

$$\alpha_{\mathrm{C/Pb}} = \frac{N(R_{\mathrm{C}}, \vartheta = 0)/N(R_{\mathrm{Pb}}, \vartheta = 0)}{N(R_{\mathrm{C}}, \vartheta = \pi)/N(R_{\mathrm{Pb}}, \vartheta = \pi)}, \tag{3}$$

can be compared to the experimental results shown in Fig. 1. If one assumes that the pion interaction length is about 1 fm, the K^0 interaction length turns out to be $\sim$ 4 fm. This procedure, applicable to quite a well controlled situation of pion induced reaction, allows for an independent verification of one of the parameters used in complex transport-model calculations carried out for modelling AA collisions.

4. Strangeness from proton–nucleus interactions

In the past decade several measurements that concentrated on strangeness production in proton–nucleus reactions were performed. The summary of experimental conditions, in terms of the proton beam energy and the angular range of measured kaons (mainly K^+), presented in Fig. 2 clearly show that the acceptance of the used detectors was restricted to the forward angles only. Unfortunately, there are no experimental data that can be directly compared to the angular distributions obtained in the FOPI measurement presented in this contribution. Such a measurement could be quite important, as usually it is assumed that the kaon angular distributions are isotropic, and the differential cross sections measured at limited polar angles are extrapolated to the full solid angle.

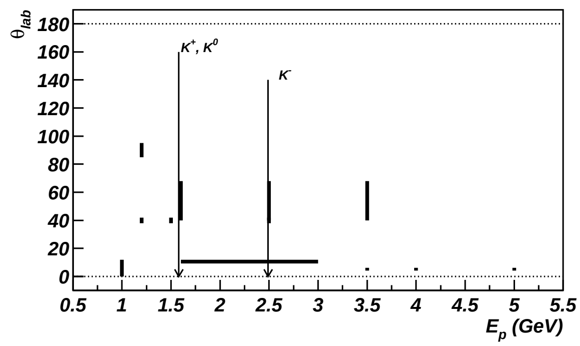

Fig. 2. Experimental conditions of charged kaon (mainly K^+) production in proton–nucleus reactions in terms of the proton beam energy and the angular coverage of the experimental set-up. The graph summarises the experimental effort of the past decade (1996–2006) which includes the SPES3 [13], KEK-PS [14], CELSIUS [15], ITEP [16], ANKE [17] and KAOS [18] experiments. The arrows indicate thresholds for production of K mesons carrying $\bar{s}$ or s quark.

5. Conclusions

The angular distributions of K^0 mesons produced in 1.15 GeV/c π^- reactions on carbon and lead targets are not isotropic. The ratio of these angular distributions shows a strong forward–backward asymmetry, which can be understood as a result of stronger reabsorption of kaons produced in the forward direction on lead nuclei as compared to those produced on carbon nuclei. This effect agrees with the results of IQMD transport model. A simple calculation of the observed forward–backward anisotropy, based on geometrical considerations, allows to determine K^0 absorption length in the nucleus to be about 4 fm.

Better understanding of the observed effect might require, apart from theoretical investigations, experimental efforts aiming at:

1. measurement of K^0 production by 1.15 GeV/c pion beam on an intermediate mass target,

2. measurement of the K^0 angular distribution in a wide angular range in proton–nucleus reactions, and

3. search for K^+ mesons in pion and proton-induced collisions, which, as those partially resulting from in-medium $K^0p{\to}K^+n$ interactions, will provide additional information about the nature of the K^0 reabsorption process.

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