Calculations of $K^\pm$ and $\phi$ Production in Near-Threshold Proton-Nucleus Collisions

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$K^\pm$ and $\phi$ meson production in proton-nucleus (pA) collisions has been calculated within a BUU transport model. It is shown that the nucleon-hyperon strangeness transfer channel is essential. The role of three-body reactions has been investigated within the medium. The target mass dependence of $\phi$ production is predicted to give important information on the in-medium properties of all three mesons.

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1 Introduction

Heavy-ion reactions and hadron-nucleus reactions are an important tool to investigate in-medium properties of produced particles. Heavy-ion collisions probe the properties at high densities while hadron beams interact with matter of normal nuclear density $n_0$. At threshold the production rates depend sensitively on the potentials which reflect the interaction with the ambient medium. If the reaction mechanism would be sufficiently known the potential can be fixed by comparison with data. Therefore, we will concentrate in this contribution on the different elementary reactions that lead to particle production near the respective thresholds in free nucleon-nucleon collisions.

An increasing number of sophisticated studies of $K^+$ production has lead to sufficient experience for their theoretical description. Cross sections as estimated in refs. \cite{1, 2} have successfully been applied and a weak repulsive potential being roughly proportional to the nuclear density $n$ of about 25 $n/n_0$ MeV has been extracted \cite{3}. This knowledge is very important for understanding the production of $K^-$ which in threshold region are mainly produced in secondary collisions of nucleons and pions with hyperons (Y) that has been created together with $K^+$ mesons. Nevertheless, the mechanism for production of the rarer mesons $K^-$ and $\phi$ is not well understood.

Our contribution is organized as follows. In section \textsuperscript{2} we investigate the role of the $NY \rightarrow NNK^-$ channel the contribution of which has been largely underestimated in the past. The role of three-body collisions we discuss in subsection \textsuperscript{3.1} in connection with $\phi$ production. In subsection \textsuperscript{3.2} we investigate how the in-medium properties of the $\phi$ meson influence the production rates as a function of the target mass.
2 The Role of the NY Channel in pA Collisions

Strangeness transfer reactions have a comparably large cross section for $K^-$ production since no strange quark pairs have to be created. In heavy-ion collisions (AA) the reactions $\pi Y$ and $NY$ are relevant. In the former reaction two secondary particles have to be created as initial state. This can easily be achieved in AA collisions. However, in pA collisions the probability that the incoming proton alone can create both particles is small and the latter reaction should become more important despite its higher threshold. In ref. \cite{4} we have investigated its contribution in pA collisions. First estimates of the experimentally unknown cross section were done in ref. \cite{5} and later in ref. \cite{6}. We have extended these calculations using the experimentally known $K^-N$ cross sections. Our results fairly agree with the foregoing estimates as can be seen in Fig. \ref{fig:1}.

Now we study the role of the $NY \to NNK^-$ reaction in pA collisions. The NY channels are incorporated into a transport model calculation which is based on the Boltzmann-Ühling-Uhlenbeck (BUU) equation \cite{7}. In Fig. \ref{fig:2} we present the differential cross sections at a laboratory angle of $40^\circ$ for collisions of protons at 2.5
GeV beam energy with $^{12}$C and $^{197}$Au. The dotted lines are calculated without using potentials for the kaons and antikaons. These calculations underestimate clearly the measured data \cite{8}. The attractive antikaon potential of $-120n/n_0$ MeV in addition with the NY channels leads to an increase of the cross section as shown by the full lines. The dashed curves depict results where the NY $\rightarrow K^-$ channels has been excluded. Disregarding these channels the cross section diminishes by about 40% in pAu collisions. This shows the importance of the NY $\rightarrow K^-$ channels when one intends to determine the K$^-$ potential. For the light C target the influence is much smaller as the hyperons have a smaller chance to collide with further nucleons before leaving the reaction zone.

Finally, we compare in Fig. 3 our calculations for $K^+$ and $K^-$ production with data obtained by the KaoS collaboration \cite{8} for proton-nucleus collisions at bombarding energies of 2.5 GeV and 3.5 GeV on C and Au targets and $K^\pm$ meson emission angles of 40° and 56°. The kinetic beam energy $T_{kin} = 2.5$ GeV is close to the production threshold in nucleon-nucleon collisions. In the calculations we use the parameters of
ref. [1 2] and obtain $K^+$ cross sections which fairly well agree with the data for both targets and angles.

![Figure 3: Invariant differential $K^\pm$ cross section as a function of the transverse kaon mass at 2.5 and 3.5 GeV proton beam energy. The solid lines refer to our calculations including the NY channels for the antikaon production. Data are taken from ref. [8].](image)

### 3 $\phi$ Production

#### 3.1 The Role of Three-Body Collisions

Now we study whether three-body collisions could remarkably contribute to the production of $\phi$ mesons. At threshold such a mechanism could be dominant because less bombarding energy is required if the projectile nucleon interacts with two target nucleons instead with a single one. For two nucleons the threshold reduces from 2.6 GeV to 1.8 GeV.
We describe three-body processes by Feynman diagrams with propagators representing the propagation of intermediate particles \[9\]. There are subspaces in the phase space, where the intermediate particles move on shell. Such processes are described within the current transport models by sequential two-step processes which also allow to accumulate the energy of several nucleons. It is our aim to separate the on-shell and off-shell propagation and relate them to the standard treatment as sequential two-step processes.

To determine the on-shell contribution we define the genuine three-body cross section as the difference of the total cross section and all possible two-step cross sections. In ref. \[9\] it has been shown that the difference always has a finite value even when using the undressed propagators. In a heavy-ion collisions the intermediate particles interact with the medium which can be approximately described by adding the collisional width $\Gamma$ to the mass $m_c$ of the intermediate particle. In this case the three-body term is calculated by the difference

$$
\sigma_{\text{three}} = C \int dL_{\text{inv}} \left( |T|^2 - \sum_c |\hat{T}_c|^2 \delta(p_c^2 - m_c^2) \frac{\pi}{\Gamma m_c} \right).
$$

(1)

Under the phase-space integral the sum runs over all open channels $c$ for two-step collisions, where resonances are included as intermediate particles as long as their decay channels are open. The full $T$ matrix of the process is denoted by $T$ while $T_c$ is the product of the two $T$ matrices describing the subprocesses of the two steps of the production \[9\].

In Fig. 4 we show the result for the $\phi$ production for a proton colliding with a two protons at density $n_0$. The three-body cross section is calculated without in-medium effects and is presented in Fig. 4 by the thin upper line. However the total cross section (thick full line) is much smaller if the rescattering effects of the intermediate particles are taken into account. (We have used an in-medium cross section of 25 mb for both pions and $\rho$ mesons.) The sum of the two corresponding two-step processes (dashed and dot-dashed lines) with an intermediate $\rho$ meson and pion, respectively, has nearly the same value as the total cross section. In the case considered here the two-step processes slightly overestimate the cross section (see thick dashed line). Thus it turns out that genuine three-body processes are not important as most of the reaction rate can be evaluated via consecutive two-body reactions. However, it is necessary that all intermediate particles which can be transferred to the mass shell are treated properly within the transport code.

### 3.2 Target Mass Dependence of $\phi$ Production

The study of $\phi$ meson production in pA collisions provides an independent test of the in-medium kaon and $\phi$ potentials. In case of a strong attractive $K^-$ potential and moderate $K^+$ and $\phi$ potentials the mean proper lifetime of $\phi$ mesons decreases from the vacuum value of about 50 fm/c to an order of magnitude smaller value in normal nuclear matter. This effect is mainly caused by the attractive $K^-$ potential. Therefore, $\phi$ mesons created in a pA collision have a large probability to decay into kaon pairs inside the nucleus. These kaons may rescatter before they leave the nucleus, therefore
Figure 4: Cross sections for $\phi$ production by a proton colliding with two protons at rest. For details see text.

the kinematic information needed to reconstruct the $\phi$ meson might be lost. This effect is expected to be bigger for a larger nucleus. Therefore, studying the mass dependence of the number of $\phi$ mesons reconstructed from the $K^+K^-$ channel is a suitable probe for studying the in-medium broadening of the $\phi$ meson.

In the following we present results [10] obtained for different $K^-$ potentials of the form

$$V_{K^-} = -(v + w \exp(-sp_{K^-}/\text{MeV})) \text{ MeV}$$

with $p_{K^-}$ being the kaon momentum. We use four different parameter sets $(v, w, s)$ of increasing strength: (i) $(0, 0, 0)$, (ii) $(70, 0, 0)$, (iii) $(55, 130, 0.0025)$ and (iv) $(150, 0, 0)$.

The comparison of the left and the right hand part of Fig. 4 shows the effect of the change of the mass of the $\phi$ meson. We have assumed that the relative mass change is proportional to $\alpha n/n_0$. Without a $K^-$ potential the $\phi$ production cross section increases faster than the geometrical cross section as a function of the target mass number $A$. For masses below the copper mass the cross section is roughly proportional to the mass number. This is because the $\phi$ mesons are predominantly created in two-step processes by secondary $\pi$ and $\rho$ mesons. For larger nuclei the increase is moderate because $\phi$ mesons get absorbed due to $\phi N \rightarrow \pi N$ reactions. This effect is especially seen on the right hand side of Fig. 4 where the $\phi$ mass is reduced and the decay inside the nucleus is hindered. $\phi$ meson production in pA collisions can also be studied via the dilepton-decay channel $\phi \rightarrow e^+e^-$. Since electrons are marginally influenced by the nucleus the $\phi$ cross sections extracted from their invariant mass are somewhat larger.
Figure 5: Rescaled cross sections for $\phi$ meson production as a function of the target mass for different $K^-$ potentials. The left panel shows the result using the vacuum $\phi$ mass while on the right hand side the mass is diminished using $\alpha = 0.033$. The cross sections are reconstructed from electron pairs (open symbols) and from kaon pairs (full symbols), respectively. Symbols denote $K^-$ potentials i(see text) used: squares (i), stars (ii), triangles (iii) and circles (iv).

4 Conclusions

In summary we have reviewed our transport model studies of $K^\pm$ and $\phi$ meson production in proton-nucleus collisions near threshold. Inclusive $K^\pm$ production requires strong strangeness transfer channels $NY \rightarrow NNK^-$ and a mildly repulsive $K^+$ and a strongly attractive $K^-$ potential. The correlated $K^+K^-$ yields are sensitive to in-medium effects of all three mesons which may be accessible in a precision measurement of the $K^+K^-$ pairs with an invariant mass corresponding to the $\phi$ meson. The tight coupling of $K^-$ and $\phi$ production rates has been emphasized in ref. [11] for heavy-ion collisions. The systematic study of meson production of open and hidden strangeness in proton-nucleus and heavy-ion collisions yields complementary information on the importance of the various elementary reaction channels.

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