ϕ meson production in near-threshold proton-nucleus collisions

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The cross section for production of ϕ mesons in proton-nucleus reactions is calculated as a function of the target mass. The decay width of the ϕ meson is affected by the change of the masses of the ϕ, K^+, and K^- mesons in the medium. A strong attractive K^- potential leads to a measurable change of the behavior of the cross section as a function of the target mass. Comparison between the kaon and electron decay modes is made.

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I. INTRODUCTION

Particle production in near-threshold $p+A$ reactions is a sensitive probe of the in-medium modification of the particle properties. A change of the particle spectral function which is mainly characterized by the particle mass may result in a drastic change of the available phase space and hence the production cross section. Decay widths of the produced particles may be influenced in a similar way.

Kaonic atom experiments [1] and the enhanced K^- production observed in heavy-ion collisions by the FOPI [2,3] and the KaoS [4,5] Collaborations point to a strong attractive K^- potential. These results seemed to support the predictions of early theoretical approaches based on effective chiral Lagrangians [6]. However, more sophisticated theoretical calculations [7–11] lead to weaker or strongly momentum dependent K^- potentials, which can even become repulsive for large momenta and densities. On the contrary K^+ and ϕ potentials (repulsive for K^+ and attractive for the ϕ meson) are believed to depend only weakly on the density of nuclear matter.

The study of ϕ meson production in $p+A$ collisions provides an independent test of the in-medium kaon and ϕ potentials. In case of a strong attractive K^- potential and moderate K^+ and ϕ potentials the mean proper lifetime of ϕ mesons decreases from the vacuum value of about 50 fm/c to an order of magnitude smaller value in normal nuclear matter. Therefore, ϕ mesons created in a $p+A$ collision have a large probability to decay into kaon pairs inside the nucleus. These kaons may rescatter before they leave the nucleus, and consequently the kinematic information needed to reconstruct the ϕ meson might be lost. This effect is expected to be bigger for a larger nucleus, therefore studying the mass dependence of the number of ϕ mesons reconstructed from the K^+K^- channel is a suitable probe for studying the in-medium broadening of the ϕ meson.

ϕ meson production in $p+A$ collisions can also be studied via the dilepton-decay channel $\phi \to e^+e^-$. Electrons practically do not interact with the nuclear matter, and the ϕ mesons can be reconstructed using the dilepton invariant mass. The dilepton-decay width of the ϕ meson is expected to be weakly affected by the medium. However, the dramatic increase of the dominant kaonic decay width causes a similar decrease of the dilepton branching ratio, therefore, also the ϕ multiplicity observed via the dilepton channel is affected.

In this paper we present a theoretical study of ϕ meson production in $p+A$ collisions based on calculations carried out using a Boltzmann-Uehling-Uhlenbeck (BUU)-type transport model. We study the effect of in-medium ϕ meson broadening and kaon rescattering. We give predictions for ϕ production cross sections obtained from both the K^+K^- and the e^+e^- channels.

II. THE MODEL

A. Elementary reactions

In addition to ϕ meson production in a primary collision of two nucleons, $NN \to NN\phi$, our model also incorporates the production of ϕ mesons in collisions of secondary particles with nucleons, namely, the channels $\Delta N \to NN\phi$, $\pi N \to N\phi$, and $\rho N \to N\phi$. These channels have already been considered for ϕ meson production in heavy-ion collisions in Ref. [12], and we utilize the respective cross sections from this work.

The total width of the ϕ meson is given by

$$\Gamma_{tot} = \Gamma_{K^+K^-} + \Gamma_{K^0\bar{K}^0} + \Gamma_{e^+e^-} + \Gamma_{\rm rest}, \qquad (1)$$

where $\Gamma_{\rm rest}$ means the sum of the widths of the remaining decay channels. The in-medium values of $\Gamma_{K^+K^-}$ and $\Gamma_{K^0\bar{K}^0}$ depend on the ϕ mass and the kaon three-momentum p_K via

$$\Gamma^{\rm med}_{\phi\to K\bar{K}} = \left(\frac{m_\phi^{\rm vac}}{m_\phi^{\rm med}}\right)^2 \left(\frac{p_K^{\rm med}}{p_K^{\rm vac}}\right)^3 \Gamma^{\rm vac}_{\phi\to K\bar{K}} \qquad (2)$$

for neutral and charged kaon pairs. The superscripts "med" and "vac" refer to the in-medium and vacuum values, respectively. In vacuum the width $\Gamma_{\rm rest}$ amounts to 15% (0.7 MeV) of the total width and originates mainly from three-pion decay or the $\pi\rho$ decay. These channels play a minor role for the change of the total width in nuclear matter. E.g., if one assumes that 50% goes through the $\pi\rho$ channel and the ρ mass is reduced in matter by 200 MeV the corresponding partial width increases to 2 MeV which is still small compared to the expected change of the total width. Thus, the variations of $\Gamma_{\rm rest}$ would not essentially change our results and are therefore neglected in our calculations.

We assume furthermore that $\Gamma_{e^+e^-}$ is not affected by the medium.

We remark that Eq. (2) is a simplification compared to a rigorous treatment of the ϕ meson spectrum in matter. This relation would be justified if the spectral function of kaons could be approximated with a δ function. This is justified for K^+ but hardly for the K^- mesons [7–11,13–16]. However, for an attractive K^- potential of 150 MeV, Eq. (2) provides a width of 45 MeV which is quite similar to the value obtained in Ref. [16].

The rescattering of the kaons proceeds either via elastic ($K^{\pm}N \rightarrow K^{\pm}N$) or inelastic ($K^+N \rightarrow K^+N\pi$, $K^-N \rightarrow \pi\Lambda$, or $K^-N \rightarrow \pi\Sigma$) channels. In our calculations we used a fit to the available experimental data of the cross sections of these processes [17]. We also included the rescattering of the ϕ mesons and their absorption via the reaction $\phi N \rightarrow K\Lambda$.

B. In-medium potentials

The kaonic atom experiments [1] indicated that the K^- mass might decrease by about 200 MeV even at normal nuclear matter density. Theoretical models that are able to reconstruct the antikaon enhancement observed in Ni+Ni reactions favor a density dependent potential that gives a smaller mass drop of about 70–120 MeV at normal nuclear matter density [3,5]. The K^+ potential has been found to be weakly repulsive and we use a linear dependence on the baryonic number density n,

$$U_{K^+}(n) = 25\ \text{MeV}\frac{n}{n_0}, \qquad (3)$$

where n_0 is the normal nuclear matter density. At present there is no experimental information about the ϕ meson potential in the nuclear medium. It is commonly assumed that the mass weakly depends on the nuclear density:

$$m_\phi^{\text{med}} = m_\phi^{\text{vac}}\left(1 - \alpha\frac{n}{n_0}\right). \qquad (4)$$

The parameter α depends crucially on the strangeness content of the nucleons. Hatsuda *et al.* [18] estimated $\alpha=0.025$ while in Refs. [16,19] a shift of the ϕ mass of about 10 MeV and an increase of the width up to 30 MeV was predicted. The authors of Refs. [20,21] showed using the sum rule approach that the mass shift is connected with the value of the four-quark condensate in the QCD vacuum. Reasonable estimates give values up to $\alpha=0.033$. To cover the possible range of the parameter α we compare calculations using $\alpha=0$ and $\alpha=0.033$, respectively.

Now we are going to investigate the effects of different in-medium potentials for the K^- meson. We carried out four sets of calculations: (a) without an in-medium K^- potential, (b) with a moderate potential derived in Ref. [10], (c) with the momentum dependent K^- potential of Ref. [8], and (d) with a strong, momentum independent K^- potential. These potentials can be summarized in the form [8]

$$U_{K^-}(n,p_K) = [a + b\ \exp(-cp_K)]\frac{n}{n_0}. \qquad (5)$$

The parameters a, b, and c of Eq. (5) corresponding to these four cases are

$$\text{(a)}\ a=0, \quad b=0, \quad c=0.$$

$$\text{(b)}\ a=-70\ \text{MeV}, \quad b=0, \quad c=0.$$

$$\text{(c)}\ a=-55\ \text{MeV}, \quad b=-130\ \text{MeV}, \quad c=0.0025\ \text{MeV}^{-1}.$$

$$\text{(d)}\ a=-150\ \text{MeV}, \quad b=0, \quad c=0.$$

The potential (d) corresponds to early estimates to fit the energy levels in K^- atoms, but it was shown recently [10] that the moderate potential (b) also satisfies this constraint.

C. The BUU model

The starting point of our calculations is the BUU code used in Ref. [12]. The model has been extended by including the decay of the ϕ meson into a charged kaon pair. We have implemented the propagation of the kaon pair which rescatters in the nuclear medium as described in Sec. II A.

To increase statistics we use the perturbative method for ϕ production, i.e., if in a two-particle collision the threshold is overcome, the ϕ meson is created and weighted with its production probability. In the case of the $\phi \rightarrow K^+K^-$ decay, however, we made a Monte Carlo decision in order to avoid producing too large a number of kaons with very small weights.

We perform calculations for four different systems, p+C, p+Cu, p+Te, and p+Au, in order to study the dependence on the target mass A. The ϕ production cross section was obtained integrating over the impact parameter. We choose a beam energy of 2.5 MeV, which is below the ϕ production threshold in a free nucleon-nucleon collision. Fermi motion of the nucleons and many-step processes in the target nucleus will contribute to gain sufficient energy needed for ϕ production.

In the calculation we keep track of the scattering and absorption processes of the ϕ mesons and the history of the kaon pairs if the ϕ mesons decay. The invariant mass of the K^+K^- pairs can deviate from the vacuum ϕ mass after the kaons have left the nuclear matter. In a static potential the kaons would transform their potential energy into kinetic energy if they could escape the nucleus potential, and their invariant mass would take the value of the original ϕ mass. A K^- meson resulting from the decay of a very slow and light ϕ meson could not leave the attractive potential and will finally get absorbed. However, in reality the excited target nucleus will expand, therefore the potentials depend on time and weakens during the emission process. Therefore, the loss (or gain) of the kinetic energy of a kaon does not generally correspond to the potential at the creation point. Thus, the invariant mass of the emitted kaon pairs are widely spread. Since the strong attractive K^- potential has the dominant influence, the invariant mass will in most cases exceed the vacuum ϕ mass. We apply the criterion

$$|m_{K^+K^-} - m_\phi^{\text{vac}}| < 0.05 \text{ GeV} \tag{6}$$

to select only those kaon pairs from which the ϕ meson can be reconstructed. Thus the ϕ multiplicity which is experimentally observable via the K^+K^- channel is obtained as

$$N_\phi^{\text{obs}} = N_\phi^{\text{surv}} + N_{K^+K^-}^{\text{surv}}/B_{\phi\to K^+K^-}, \tag{7}$$

where N_ϕ^{surv} is the number of the ϕ mesons per event that survived, $N_{K^+K^-}^{\text{surv}}$ is the number of kaon pairs which fulfill the selection criterion (6), and $B_{\phi\to K^+K^-}$ is the vacuum value of the branching ratio of the ϕ decay. The fact that the cross section depends on the selection criterion, Eq. (6), due to the spread of the invariant K^+K^- mass was also discussed in Ref. [22] for photoproduction of ϕ mesons.

We also consider the decay of the ϕ mesons into electron pairs. The invariant masses of the electron pairs are recorded, and Eqs. (6) and (7) are applied accordingly. We mention that the long range Coulomb force leads to an additional spread around the vacuum ϕ mass of less than 10 MeV for a heavily charged target such as Au, a value which is small compared with the expected nuclear effects.

III. RESULTS

The main results of our calculations are shown in Fig. 1. There we display the ϕ meson production cross sections reconstructed from the K^+K^- and the e^+e^- decay channels for the four sets of in-medium potentials. The cross sections are rescaled by $A^{2/3}$ to remove the effect of the geometrical cross section of the nucleus.

The comparison of the left and the right hand part of Fig. 1 shows the effect of the change of the mass of the ϕ meson. The main effect is that the cross section increases if the mass is diminished in nuclear matter. That is seen especially for larger nuclei while the size of a nucleus such as carbon is not large enough to allow sufficient secondary collision inside dense matter.

Without a K^- potential the ϕ production cross section increases with A faster than the geometrical cross section. For target masses below the copper mass the cross section is roughly proportional to the mass number. This is because the ϕ mesons are predominantly created in two-step processes by secondary π and ρ mesons. For larger nuclei the increase is moderate because ϕ mesons get absorbed in large nuclei. This is obvious if the decay is hindered inside the nucleus because of a reduction of the mass (see right-hand side of Fig. 1). We observe an enhancement of the dilepton channel relative to the K^+K^- channel. This enhancement is largest if the K^- potential vanishes and is explained by the fact that the dilepton branching ratio increases with dropping ϕ meson mass and increasing K^+ mass.

A strong attractive K^- potential causes a rapid decay of the ϕ mesons inside the nucleus. This effect increases with the size of the target nucleus and is seen in both the numbers of observed K^+K^- and the e^+e^- pairs. In the case of the K^+K^- channel the reduction of the ϕ cross section is caused by the rescattering of the kaons while in the case of the e^+e^- channel a similar reduction occurs because of the decrease of the dilepton branching ratio in nuclear matter.

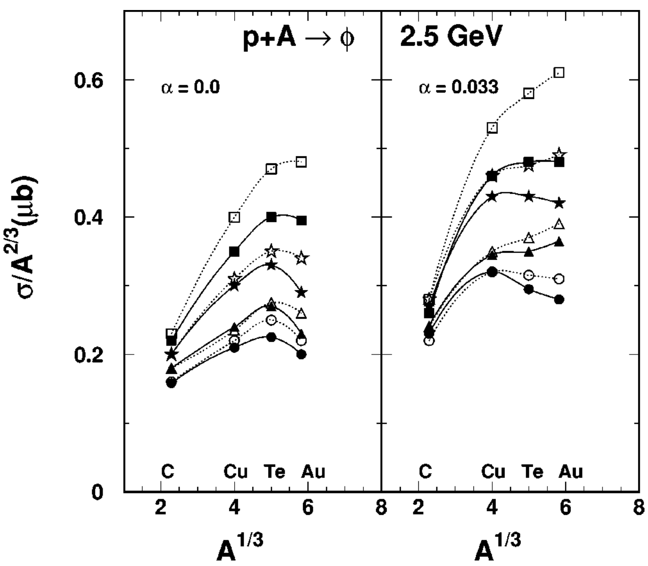

FIG. 1. Rescaled cross sections for ϕ meson production as a function of the target mass for different kaon potentials. The left-hand side picture shows the result without changing the ϕ mass while on the right-hand side the mass diminishes according to Eq. (4) with $\alpha=0.033$. The cross sections are reconstructed from electron pairs (open symbols) and from kaon pairs (full symbols), respectively. Squares—without K^- potential [parameters (a) of Eq. (5)], stars—with a moderate K^- potential [parameters (b) of Eq. (5)], triangles—with momentum dependent potential [parameters (c) of Eq. (5)], and circles—strong momentum independent potential [parameters (d) of Eq. (5)]. The lines are included to guide the eyes.

IV. CONCLUSIONS

The results show that the target mass dependence of the observed ϕ production cross section is strongly altered if strong changes of the kaon masses in nuclear matter occur. If such effects exist they should be measurable by detecting kaon or electron pairs in subthreshold proton-nucleus reactions with energies available at the COSY or SIS accelerators at FZ Jülich and at GSI Darmstadt, respectively.

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