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Transport analysis of in-medium hadron effects in pA and AA collisions

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Abstract. The production and decay of vector mesons (ρ, ω) in pA and AA reactions is studied with particular emphasis on their in-medium spectral functions. It is explored within transport calculations if hadronic in-medium decays like $\pi^+\pi^-$ or $\pi^0\gamma$ might provide complementary information to their dilepton (e^+e^-) decays. Whereas the $\pi^+\pi^-$ signal from the ρ-meson is found to be strongly distorted by pion rescattering, the ω-meson Dalitz decay to $\pi^0\gamma$ appears promising even for more heavy nuclei in γA and pA reactions. Furthermore, the influence of nucleon and kaon/antikaon potentials on the $K^\pm$ yields and spectra in pA collisions is calculated and compared to the recent data from the ANKE Collaboration.

PACS. 13.60.Le Meson production – 13.75.Jz Kaon-baryon interactions – 14.40.Aq π, K, and η mesons – 25.40.-h Nucleon-induced reactions

1 Introduction

The modification of the meson properties [1,2] in nuclear matter has become a challenging subject in hadron physics from γA, pA and AA collisions. Here the dilepton (e^+e^-) radiation from ρ's and ω's propagating in finite-density nuclear matter is directly proportional to their spectral function which becomes distorted in the medium due to the interactions with nucleons. Apart from the vacuum width Γ_V^0 $(V = \rho, \omega)$ these modifications are described by the real and imaginary part of the retarded self-energies Σ_V, where the real part $\Re\Sigma_V$ yields a shift of the meson mass pole and the additional imaginary part $\Im\Sigma_V$ (half) the collisional broadening of the vector meson in the medium. We recall that the meson self-energy in the t-ρ approximation is proportional to the complex forward VN scattering amplitude $f_{VN}(P,0)$ and the nuclear density $\rho(X)$, *i.e.* $\Sigma_V(P,X) = -4\pi\rho(X) f_{VN}(P,0)$. The scattering amplitude itself, furthermore, obeys dispersion relations between the real and imaginary parts [3], while the imaginary part can be determined from the total VN cross-section according to the optical theorem. Thus the vector meson spectral function,

$$A_V(X,P) \sim \frac{\Im\Sigma_V(X,P)}{\left(P^2 - M_V^2 - \Re\Sigma_V(X,P)\right)^2 + \Im\Sigma_V(X,P)^2}, \quad (1)$$

can be constructed once the VN elastic and inelastic cross-sections are known. Note that in (1) all quantities depend on space-time X and 4-momentum P.

2 Production and decay of vector mesons

Though strong modifications of the ρ-meson properties in relativistic $A + A$ reactions have been reported by the CERES Collaboration [4], the interpretation of the data is not unique since the latter may be explained by a dropping of the pole mass as well as by ordinary nuclear many-body effects [1,2]. In general, the medium effects on the ρ-meson are expected to increase when decreasing the bombarding energy from 160 A · GeV down to about 2 A · GeV for central Au + Au collisions [5]. At the lower range of bombarding energies we expect new data coming up from the HADES Collaboration in the near future [6]. Nevertheless, it is inevitable to study also γA and pA reactions where the time evolution of the baryon density is much better under control and the vector-meson spectral function is essentially tested at density ρ_0 in heavy nuclei [7,8].

The in-medium vector meson spectral functions can be measured directly by the leptonic decay $V \to e^+e^-$ (cf. refs. [7,8]), the strong decay $\rho^0 \to \pi^+\pi^-$ or the Dalitz decay $\omega \to \pi^0\gamma$, respectively. Thus it remains to be seen which of the decay modes is most effective for experimental studies.

The actual transport calculations have been performed for pA and γA collisions by introducing a real and

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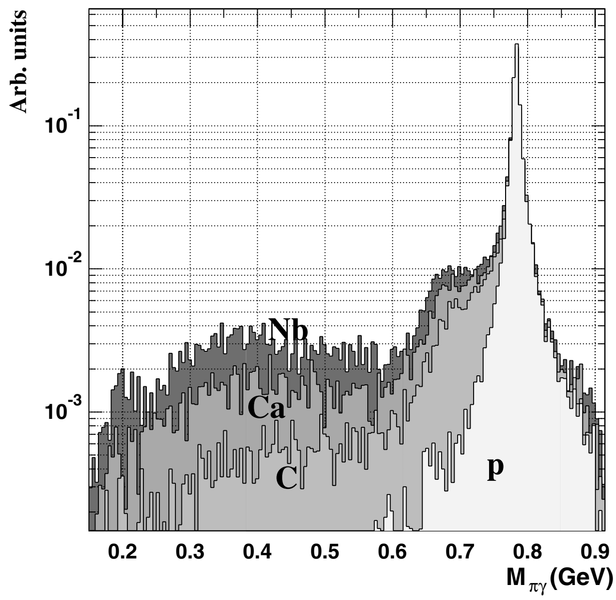

Fig. 1. The $\pi^0\gamma$ invariant-mass distribution from ω-meson decays in γA reactions including an attractive mass shift and collisional broadening at $E_\gamma = 1.2\,\text{GeV}$ for a proton, ^{12}C, ^{40}Ca and Nb target according to ref. [12]. The spectra have been normalized to the vacuum decay peak at 0.783 GeV.

imaginary part of the vector meson self-energy and width as

$$U_V = \frac{\Re\Sigma_V}{2M_0} \simeq M_0\beta\frac{\rho(X)}{\rho_0}\,, \tag{2}$$

$$\Gamma^* = \frac{\Im\Sigma_V}{2M_0} \simeq \Gamma_V^0 + \Gamma_{\rm coll}\frac{\rho(X)}{\rho_0}\,, \tag{3}$$

in the t-ρ approximation. Here M_0 and Γ_V^0 denote the bare mass and width of the vector meson in vacuum, while $\rho(X)$ is the local baryon density ($\rho_0 = 0.16\,\text{fm}^{-3}$). The parameter $\beta \simeq -0.16$ was adopted from the models discussed in refs. [1,2]. The predictions for the ω-meson collisional width $\Gamma_{\rm coll}$ at density ρ_0 range from 20 to 50 MeV [9] —depending on the number of ωN final channels taken into account— while the collisional width of the ρ-meson should be about 100–120 MeV at ρ_0 due to the strong coupling to baryon resonances (cf. fig. 6 of ref. [3]).

As a first remark we quote the result from ref. [10], where it has been found that the $\pi^+\pi^-$ decay mode of the ρ^0 in nuclei is not well suited to reconstruct the in-medium ρ^0 spectral function except for very light nuclei due to the strong $\pi^\pm$ final-state interactions. The situation changes for the in-medium ω-meson Dalitz decay since here only a single pion might rescatter whereas the photon escapes practically without reinteraction. In this case it is found [11,12] that though most of the ω-mesons — produced in photon induced reactions on nuclear targets— decay in the vacuum, there is a sizeable contribution of ω's decaying in the medium leading to $\pi^0\gamma$ pairs of invariant mass 0.6–0.9 GeV, however, also π^0 rescattering gives a substantial background essentially below 0.65 GeV.

As an example we show in fig. 1 the $\pi^0\gamma$ invariant-mass distribution from ω-meson decays including an attractive mass shift and collisional broadening at $E_\gamma = 1.2\,\text{GeV}$ for a proton, ^{12}C, ^{40}Ca and Nb target according to ref. [12]. The background —in the invariant-mass range $0.6 \le M \le 0.9\,\text{GeV}$ of interest— can be suppressed effectively by kinematical cuts on higher π^0 energies [12] or angular correlations between the photon and the pion [13] which provides good perspectives for the $\pi^0\gamma$ decay mode of the ω-meson.

3 K$^\pm$ production

The in-medium properties of kaons (and antikaons) show up in their suppressed (enhanced) yields in pA or AA collisions [14,15] as well as in their low-momentum spectra [1], which are most sensitive to the meson nuclear potentials. The experiments of the FOPI [16] and KaoS Collaboration [17] on nucleus-nucleus collisions at SIS energies have demonstrated that the abundancy and collective flow of kaons and antikaons indicate slightly repulsive potentials for K^+ and more strongly attractive potentials for K^-. However, as pointed out in ref. [15], the K^- yield is dominated by the strange flavor exchange reaction $\pi + Y \leftrightarrow \bar{K}N$ which by strangeness conservation strongly links the K^+ and K^- yields. The problem is that the cross-section for the latter reaction at high baryon density is not sufficiently known and that data from AA reactions do not allow for a unique conclusion. Thus $K^\pm$ production in pA reactions is a necessary and complementary study since in this type of reactions the $\pi + Y \to \bar{K}N$ channel plays a minor role and the $K^\pm$ potentials can be extracted with less ambiguities.

In pA reactions the $K^\pm$-mesons are dominantly produced with a finite momentum relative to the nucleus at rest and —once they do not rescatter elastically or inelastically— are accelerated or decelerated by the nuclear and Coulomb potential. For orientation the effective nuclear and Coulomb potentials are displayed in fig. 2 for a ^{12}C and ^{197}Au target as a function of the coordinate z. Here the $K^\pm$ nuclear potentials have been approximated by

$$V_{\rm N}^\pm(\mathbf{r}) = V_0^\pm\frac{\rho(\mathbf{r})}{\rho_0}\,, \tag{4}$$

with $V_0^+ = 20\,\text{MeV}$ [18] and $V_0^- = -60\,\text{MeV}$ [19]. As seen from fig. 2 the Coulomb potential $V_{\rm C}$ plays only a minor role for ^{12}C, however, is even larger than the K^+ potential in case of a ^{197}Au target. Thus the minimum kinetic energy of a K^+-meson —produced in the center of a Au target— (without rescattering) is about 45 MeV in the continuum and about 23 MeV in case of ^{12}C. Kaons produced at the nuclear surface will have a minimum kinetic energy that is determined by $V_{\rm C}$ at the point of production. Thus K^+ ratios from heavy-to-light targets have to show a strong suppression for low K^+ momenta. In fact, it has been demonstrated in ref. [20] that ratios of cross-sections for light and heavy targets in pA reactions provide a sensitive tool to measure the K^+ potentials in an almost model-independent way.

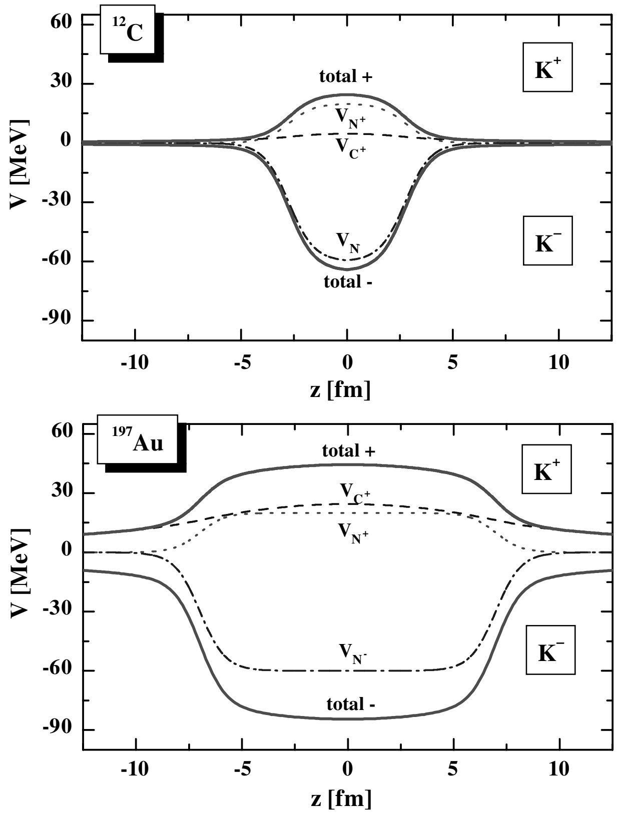

Fig. 2. The effective nuclear (4) (dotted lines) and Coulomb (dashed lines) potentials for K^+- and K^--mesons in case of a ^{12}C and ^{197}Au target (see text).

The situation is quite different for antikaons since K^- produced with low kinetic energy in the medium cannot escape to the continuum without elastic rescattering. Most of them are absorbed in the flavor exchange reaction $K^-N \to Y+\pi$ or, if their energy $E_K < 0$, they might form antikaonic atoms when escaping the nuclear medium.

We now turn to the kinematical conditions of the ANKE experiments at COSY-Jülich, that have taken K^+ spectra in forward direction for $\theta_{\text{lab}} \leq 12°$. The calculated differential K^+ spectra for $p + {}^{12}$C at 1.0 GeV for $\theta_{\text{lab}} \leq 12°$ are displayed in fig. 3 in comparison to the data from ref. [21]. The dotted line is obtained from transport calculations without baryon and kaon potentials, the dashed line shows the result with baryon potentials included while the solid line corresponds to a calculation with both, nucleon and kaon potentials. At this low bombarding energy the net attractive baryon potential in the final state enhances the K^+ yield by about a factor of 2 whereas the additional repulsive K^+ potential leads to a decrease by a factor ~ 3. The data from ref. [21] are rather well described by the calculations that include the baryon and K^+ potentials (solid line), whereas the other limits clearly fail. This might be considered as a first indication for the observation of a repulsive K^+ potential in pA reactions, however, a full systematics in target mass A and laboratory energy T_{lab} will be needed to pin down this effect unambiguously.

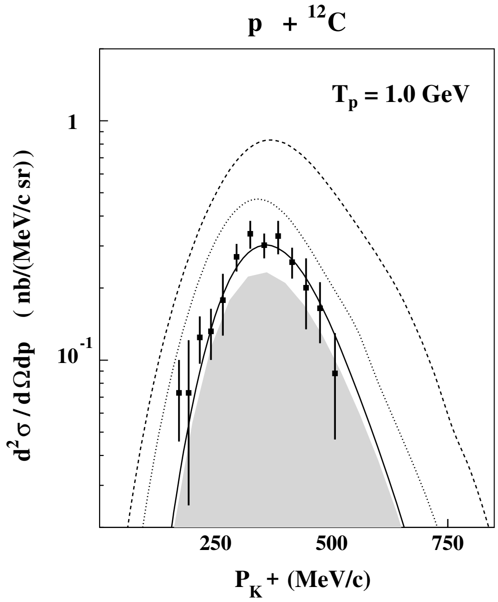

Fig. 3. The calculated differential K^+ spectra for p + C at 1.0 GeV for $\theta_{\text{lab}} \leq 12°$ within the acceptance of the ANKE spectrometer (from ref. [14]) in comparison to the data from [21]. The dotted (middle) line is obtained from transport calculations without baryon and kaon potentials, the dashed (top) line shows the results with baryon potentials included, while the solid line corresponds to calculations including both, nucleon and kaon potentials.

The shaded area in fig. 3 indicates the contributions from the two-step mechanisms $\Delta N \to K^+YN$ and $\pi N \to K^+Y$, respectively, for the case of nucleon and kaon potentials included (solid line). Thus secondary (Δ and π induced) reaction channels give the dominant fraction of the K^+ yield at 1 GeV even for the light target ^{12}C.

4 Summary

The production and decay of vector mesons (ρ, ω) especially in γA and pA reactions has been studied with particular emphasis on signals from their in-medium spectral functions. Whereas the $\pi^+\pi^-$ decay mode from the ρ-meson is found to be strongly distorted by pion rescattering with the surrounding nucleons, the ω-meson Dalitz decay to $\pi^0\gamma$ appears promising even for more heavy nuclei. Furthermore, the influence of nucleon and kaon/antikaon potentials on the $K^\pm$ yields and spectra has been evaluated within the transport approach. A comparison to the recent data from the ANKE Collaboration [21] yields a repulsive K^+ potential of ≈ 20 MeV at normal nuclear matter density [14,20] which is in line with the data from AA reactions at SIS energies [16,17].

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