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HADRON PROPERTIES IN THE NUCLEAR MEDIUM – THE PANDA PROGRAM WITH $\overline{\mathrm{p}}$A REACTIONS

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Abstract

The PANDA experiment at FAIR comprises the possibility to study antiproton annihilations on nuclear targets. Such reactions are ideally suited to investigate the in-medium-potential of hadrons – charmed mesons, charmonium, antikaons, antibaryons – making use of the PANDA detector system to detect the final state particles. The paper discusses connected experimental results, predictions i.a. for the so far unexplored region of the charm quark mass, and the intended experimental procedure.

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1 Introduction

In the framework of Quantum Chromo Dynamics (QCD), a (partial) restoration of chiral symmetry should appear when going to high temperatures and/or high densities. As a consequence, the expectation value of the light quark condensate $\langle \mathrm{q}\bar{\mathrm{q}} \rangle$, simplified expressed the measure of the medium effects dependent on temperature and density, is predicted to be reduced by about 35% (at $T = \rho = 0$ it has the value 1) already at normal nuclear matter density. This should therefore lead to in-medium modifications of hadrons embedded in the nuclear matter. These modifications could express themselves in changing the width and/or the mass of hadrons. Beside this, vector meson contributions to the hadron-nucleon interaction will result in a different potential for charge conjugated partners.
Indeed there are several experimental hints for modified hadron properties in the nuclear medium. Three examples are mentioned here. First, in Ref. [1], the Sn(d,^{3}He) recoilfree pion transfer reaction has been used to populate bound 1s π^- states in neutron-rich nuclei. The binding energies and widths have been determined, and via the modified pion decay constant a reduction of $\langle \mathrm{q}\bar{\mathrm{q}} \rangle$ to 64% has been deduced. Second, in the studies of strangeness production in heavy ion collisions [2], it has been found that in such reactions the yield at comparative subthreshold energies of kaons and antikaons is the same, i.e. in the case of the K^- much higher than expected from nucleon-nucleon collisions. This result could be explained by a reduced K^- production threshold in medium. However, this is not the only possible explication since in heavy ion collisions other channels contribute to the production of K^- mesons. Finally, in Ref. [3] the in-medium mass shift of the ω meson has been reported; here, the photon-induced ω production on a LH$_2$ and a Nb target has been compared, and a significant change of the invariant ω mass has been found in the Nb case, assigning an in-medium mass of the ω meson reduced by about 60 MeV/c^2.
With the PANDA [4] experiment at FAIR [5], the study of antiproton annihilations on nuclear targets will be possible. The $\bar{\mathrm{p}}$ kinetic energy avaible ranges from 0.8 to 14 GeV, which is ideally suited to extend the just reported physics studies from the light quark to the charm quark mass sector. The left panel of fig. 1 illustrates the situation schematically going from vacuum to normal nuclear matter density and from light and strange to charmed mesons. In the case of the charmed mesons ($\mathrm{D}^{\pm}$), where so far no data exist, the lines indicate a prediction from Ref. [6]. This region can for the first time be explored by the PANDA experiment.

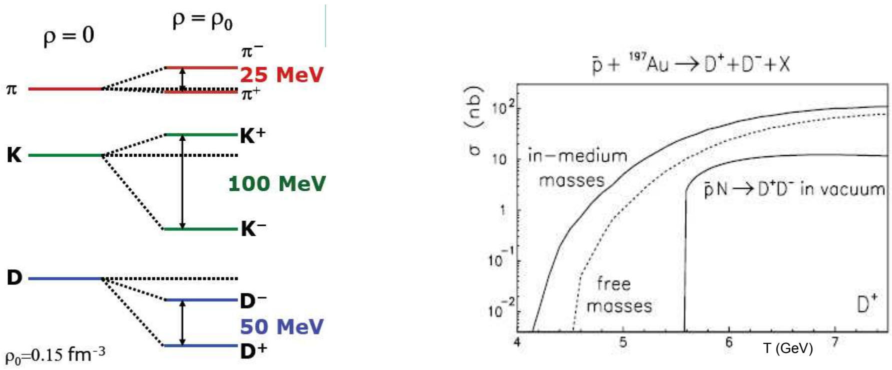

Figure 1: Left panel: Schematic representation of the mass shifts for pions, kaons and D-mesons from the vacuum value ($\rho = 0$, left) to normal nuclear matter density ($\rho = \rho_0$, right). Right panel: Calculated D^+ production cross section for different scenarios (see text).

2 Charmed mesons and charmonium in matter

Apart from Ref. [6], which is showing an attractive mass shift for the D^- and an even stronger one for the D^+, various theory papers are dealing with this argument. For example Ref. [7] predicts a threshold reduction at normal nuclear matter density of 164 MeV, and Ref. [8] obtains a more complicated spectral function with a strongly attractive and a weakly repulsive mode for the D^+, furthermore a repulsive mass shift for the D^- of about 18 MeV.

In the right panel of fig. 1, a cross section calculation from Ref. [7] for the D^+ production with antiprotons on a gold target is shown. The figure shows the predicted separate nuclear effects induced by Fermi motion and medium mass shifts on the D^+ yield as compared to the free D^+D^- production. Experimentally, PANDA will study the subthreshold (here: the $\bar{p}N$ threshold in vacuum) production of $D\bar{D}$. The final states to be analyzed are D^+D^-X or $D^-\Lambda_c^+X$, and following e.g. Ref. [7], the experiment should see a cross section enhancement and due to D^+ absorption a reduced D^+D^- yield ratio. However this measurement will not provide information about a possible mass splitting (like indicated in fig. 1, left).

A modified mass of the D meson in matter should also lead to consequences for states which potentially decay in a $D\bar{D}$ pair since the threshold for this decay channel would change, too. Assuming a zero mass shift of the charmonium states themselves, a dropping $D\bar{D}$ threshold (vacuum value 3.75 GeV/c^2) could allow for instance the ψ(3686) to decay into $D\bar{D}$, hence leading to an increased width. Also the ψ(3770) and the higher $c\bar{c}$ states should increase their widths. The effect has been calculated e.g. in Ref. [9], experimentally one should observe a broadening in the dilepton invariant mass spectra. However, the situation becomes more complicated if one takes into account a possible mass shift of the charmonium states themselves in matter. While for the η_c and J/ψ only small effects are predicted [10], for the higher mass c$\bar{\mathrm{c}}$ states like χ_{cn} and ψ(2S,1D) Ref. [11] finds an attractive mass shift of up to 140 MeV. This should be observed looking into the appropriate decay channels like J/$\psi\gamma$ or dileptons.

The study of the J/ψ in matter is of particular interest since the knowledge about J/ψ absorption in nuclei is important regarding ultrarelativistic heavy ion collisions and their interpretation of the J/ψ yield. In fact, J/ψ suppression is being discussed as an indicator for the quark gluon plasma formation. Here, PANDA could perform a measurement of the cross section (e.g. in $\mu^+\mu^-$) as function of target nucleus and antiproton energy, thus deducing the J/ψN dissociation cross section for a defined J/ψ momentum.

3 Antikaons and antibaryons in nuclear matter

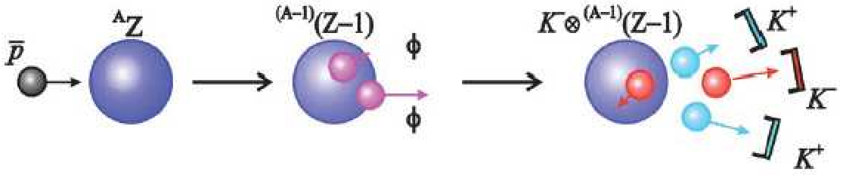

Figure 2: Schematic representation of the course of the preparation of an antikaon in a nucleus using the production of two ϕ mesons in antiproton annihilations on a nucleus.

Recently the determination of the K$^-$ nuclear potential has become of particular interest [12] in view of the possible creation of deeply bound antikaonic clusters in nuclei. A possibility to prepare K$^-$ mesons inside nuclei is $\bar{\mathrm{p}}$ annihilation on a proton in a nucleus by the reaction $\bar{\mathrm{p}}$A $\rightarrow \phi\phi \rightarrow$ K$^+$K$^-$K$^+$K$^-$. Here, one kaon pair is going forward taking nearly all the momentum, and the K$^-$ of the other kaon pair is very slow and eventually going slightly backward to be bound in the nucleus. Fig. 2 shows schematically how the reaction proceeds [13]. The K$^-$ nuclear potential will be determined from the K$^+\phi$ missing mass.

Accordingly, the potential of antibaryons in nuclei can be studied at PANDA. For example, a recent prediction [14] sees deep antibaryon potentials in nuclei, leading to strong local compression and bound antibaryon-nuclear systems. To study the antiproton nuclear potential, PANDA could exploit the reaction $\bar{\mathrm{p}}\mathrm{A} \rightarrow \mathrm{p}_{\mathrm{forward}}(\mathrm{A}-1)^{*}_{\bar{\mathrm{p}}}$, where the (A$-$1) spectral function is determined from $\bar{\mathrm{p}}$A$\rightarrow$p$\bar{\mathrm{p}}$X.

With a similar technique, the $\bar{\mathrm{p}}$A $\rightarrow \Lambda\bar{\Lambda}$X reaction can be used to study the $\bar{\Lambda}$ nuclear potential. Furthermore, the study of elementary D-nucleon reactions is possibile via antiproton deuteron reactions (with a produced D hitting the the spectator neutron, e.g.).

In summary, an overview of planned physics studies possibile with antiproton annihilations on nuclei at FAIR/PANDA was given. This experiment will offer an unique opportunity to study the in-medium properties of hadrons in cold nuclear matter.

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