HADRONIC IN-MEDIUM EFFECTS WITH ELEMENTARY PROBES

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Abstract

The sensitivity of dilepton production in elementary reactions of photons and pions with nuclei on in-medium changes of hadronic properties is studied. It is shown that this sensitivity is comparable to that encountered in ultrarelativistic heavy-ion collisions. It is also shown how a significant broadening of the vector mesons affects other photonuclear processes.

1 Introduction

Results of the CERES experiment show a significantly higher dilepton yield in the invariant mass region between about 200 and 600 MeV compared to that from a hadronic cocktail based on known reaction channels. After adding in the – expected – secondary $\pi\pi \rightarrow \rho$ yield the observed yield is still underestimated by a hadronic cocktail by a 'sensitivity factor' of about 3. While there is also an attempt to explain these observations in terms of standard 'classical' hadronic sources [1] by exploiting their experimental uncertainties, most theoretical explanations invoke a change of the properties of the vector meson masses and widths. Some of these are based on 'classical' collision broadening whereas others involve $\rho - a_1$ mixing as a precursor to chiral symmetry restoration [2]. However, all these attempts have in common that in a first step they determine the in-medium properties in hot and dense equilibrium and then use these locally either in transport calculations or in more simplified expansion scenarios.

The latter procedure is obviously not a-priori correct for an ultrarelativistic heavy-ion collision which – at least in its early stages – proceeds far away from equilibrium. It is worthwhile to realize that even in ultrarelativistic heavy-ion collisions with their high peak densities about 60 % of all dileptons are produced at densities below $2\rho_0$ (see Fig. 7 in [3]). This is so because the observed

\footnote{http://theorie.physik.uni-giessen.de}
yield inherently contains an integration over the whole reaction history and thus the late stages of the reaction with high pion densities contribute via \( \pi^+ + \pi^- \rightarrow e^+ + e^- \) a significant part to the total observed dilepton yield.

It is, therefore, intriguing to ask if other reactions involving more elementary probes on nuclei that proceed closer to equilibrium can be used to investigate the question of in-medium changes of hadronic properties. While the density in such reactions obviously is always below \( \rho_0 \), this disadvantage may be overcome by the ‘cleaner’ and more stable environment in which dilepton production proceeds in such reactions.

In this talk I show that indeed pion- and photon-induced dilepton production on nuclei is as sensitive to possible in-medium changes as are heavy-ion reactions. I will also – in the last part of this talk – show how in-medium changes of vector mesons are expected to show up not only in dilepton spectra, but also in photo-absorption processes. Such a connection, if it can be firmly established, clearly adds to the consistency of our picture of in-medium changes of hadrons.

Details to all the points I am going to discuss in this talk can be found in a number of recent publications \[4, 5, 6\] and in particular in the PhD thesis of Martin Effenberger \[7\].

2 Model

The calculations shown in this talk are all based on a new development in transport theory that allows one to also transport broad resonances. While former calculations (for a review see \[8\]) had to employ simplifying assumptions the calculations of Effenberger et al. \[5\], for the first time, implemented a transport-theoretical treatment of broad mesons and treated the widths of the vector mesons consistently. The theoretical breakthrough here was to transport not the phase-space density \( f(\vec{x}, \vec{p}, t) \), but a ‘spectral phase space density’ \( F(\vec{x}, \vec{p}, \mu, t) \) that contains also information about the spectral function of the resonance.

In \[5\] (see also \[9\]) we have discussed in detail that a consistent formulation of the scattering term, that takes the spectral function of the particles into account, puts automatically intrinsically broad, collision-broadened resonances (such as, e.g. the \( \rho \) meson) – because of their frequent decay and reformation as they traverse the nucleus – back on their free spectral function when they leave the nucleus. A problem arises, however, when particles with intrinsically sharp spectral functions, such as the nucleon or the \( \omega \) meson, get collision broadened. In such a case the repetitive decay and reformation is not frequent
enough so that these particles would emerge from the collision still collision-

broadened. In order to suppress this unphysical behavior we introduced an
ad-hoc potential that drives all particles back on mass-shell when they leave
the nucleus [5]. It is amusing that this potential, that we intuitively guessed
in ref. [5], can – for sharp resonances, where $\Gamma_{\text{tot}} \approx \Gamma_{\text{coll}}$ – actually be derived
from the Kadanoff-Baym equations [11, 12].

The results presented here are based on this method (for more details see
[5, 7, 9]). The equation of motion for the spectral phase space distribution
reads

$$
\left( \frac{\partial}{\partial t} + \nabla_p H \nabla_x - \nabla_x H \nabla_p \right) F_i = G_i A_i - L_i F_i 
$$

(1)

with the spectral phase-space-density

$$
F_i((x, p, \mu, t) = A_i (x, p, \mu, t) f(x, p, \mu, t),
$$

(2)

the spectral function

$$
A_i(\mu) = \frac{2}{\pi} \frac{\mu^2 \Gamma_{\text{tot}}(\mu)}{(\mu^2 - M_i^2)^2 + \mu^2 \Gamma_{\text{tot}}^2(\mu)},
$$

(3)

and the usual phase-space density $f(x, p, \mu, t)$. As stressed in particular by
Knoll [10] it is essential to maintain the consistency condition that the total
width appearing in the spectral function is related to the loss-term $L$ in the
transport equation

$$
\Gamma_{\text{tot}} = \gamma L.
$$

(4)

Since this condition presents a major consistency problem it has been ful-
filled in the calculations reported here only for the vector mesons. In [14] it
was shown that the two-body collisional width does not broaden the nucleon
resonances significantly. For all further details I refer the reader to [5, 9, 7].

### 3 Pion-Induced Dileptons

With the availability of a $\pi^-$ beam at GSI and the detectorsystem HADES [13]
it will be possible to explore dilepton production in pion-induced reactions on
nuclei. We have, therefore, performed extensive studies of such reactions [4].
Input to these calculations are cross sections predicted by the Manley coupled
channel analysis of $\pi N$ data [17] on which our analysis is based.

The transport calculations allow one to follow the collision history of all
vector mesons produced. With realistic $VN$ cross sections we obtain a collision
width $\Gamma_{\text{coll}} = \rho\sigma_{VN}v_{VN}$ of up to 500 MeV for the $\rho$ meson and 70 MeV for the $\omega$, both at normal nuclear matter density [3].

The overall sensitivity to these effects is about a factor 2, which is close to the expected systematic uncertainty of these transport calculations. However, this sensitivity can be enhanced by performing appropriate cuts on the dilepton cm momenta. Fig. 1 shows that with a cut that selects only slow vector mesons the sensitivity to various in-medium scenarios, in particular for the $\omega$ meson, is clearly strong enough to be seen experimentally.

![Figure 1: Effects of medium modifications on dilepton invariant mass spectra in $\pi^{-}C$ and $\pi^{-}Pb$. Here only dileptons with total momentum < 300 MeV have been considered](image)

4 Photon-Induced Dileptons

Pions have one possible disadvantage for such in-medium studies: they experience a strong initial-state interaction and thus a pion-beam illuminates only a part of the nucleus. This is visible in Fig. 2 which shows in the two lower figures the location of the first collision of the pion with the nucleons of the
target (left) and all meson-baryon collisions (right). The upper two figures

give the same information for a photon beam. The left part shows clearly
how the photon illuminates the whole nuclear volume and not just the surface.
Subsequent collisions remember this initial state as shown in the right part
of this figure. Thus, we expect that photon-induced experiments will be even
more sensitive to in-medium changes of hadronic properties than experiments
with pions.

That the theory, with the proper, consistent treatment of in-medium broad-
ening describes the 'normal' photonuclear processes very well is shown in a
comparison with data for photo-pion, photo-2pion and photon-eta production
data at energies up to 800 MeV [6]. We are thus quite confident that we
have these photonuclear processes well under control and can thus use these
methods to predict and investigate the sensitivity of photonuclear dilepton
production data to in-medium changes of vector meson properties.

Photon-induced dilepton data have the problem that they necessarily con-
tain a big contribution from the so-called Bethe-Heitler process in which the
incoming photon radiates already a dilepton pair before any coupling to the
hadrons takes place. As is well known, however, this contribution can be suppressed by proper kinematical cuts \[5, 15\], both for the incoherent and the coherent part \[7\].

Fig. 3 then shows the sensitivity of the dilepton spectra to various in-medium changes of the vector mesons. It is immediately apparent, that this

![Figure 3: Effects of various in-medium modifications of the vector meson properties on dilepton invariant mass spectra in $\gamma + C$ (top) and $\gamma + Pb$ (bottom). Only dileptons with a total momentum of < 300 MeV have been considered.](image)

sensitivity is just as large as for the ultrarelativistic heavy-ion collisions. In particular, again the $\omega$ properties are reflected quite clearly in the (still to be measured) dilepton spectra. As in the case of pions one can enrich the in-medium sensitivity by making a cut on the dilepton cm momentum.

5 Photoabsorption

All the in-medium effects on vector meson spectral functions are connected with a significant broadening and corresponding shift of strength to lower masses. This has an interesting consequence for the decay of the $N(1520)$
resonance that I have already pointed out in [16] in 1997. According to the
particle data group listing, which is based on Manley’s analysis [17] in this
respect, this $D_{13}$ resonance decays on resonance with a probability of 15 -
25 % into $N \rho$ and this, even though this decay is energetically closed if one
works with the pole mass of the (broad) $\rho$. Thus the decay can proceed only
through the low-mass tails of the $\rho$-meson spectral function; the rather large
partial decay width in turn indicates a large coupling constant for the vertex
$N(1520)N\rho$. If the $\rho$ meson’s spectral function in nuclear matter indeed gains
strength at low masses then the partial $\rho$ decay width of the $N(1520)$ resonance
would increase dramatically.

This effect may already have been experimentally seen. The data for pho-
toabsorption on nuclei exhibit a universal behavior that – beginning with rather
small mass numbers $A$ – scales with $A$. This universal cross section exhibits
the $\Delta$ resonance – though somewhat broadened –, but the second and third
resonance regions around 1500 and 1650 MeV, respectively, that are well seen
in photoabsorption on the nucleon, have disappeared in nuclei [18].

Fermi-motion alone is the more effective in smearing out resonance strength
the higher the energy of the resonance is. This alone explains the absence of
the third resonance region [19]. The second resonance region, around 1500 MeV,
however, survives the effects of Fermi-smearing. We have shown in [16, 18, 20]
that this finds a natural explanation in the opening of the $\rho$-decay channel of
the $N(1520)$ resonance. With $\rho$ strength moving in medium down to lower
masses the formerly nearly closed decay opens up dramatically thus leading
to a very large (several hundred MeV) total width of this resonance. Crucial
for this argument is the high partial decay width of the $D_{13}$ resonance into
the $N\rho$ channel. This has so far, not been directly verified by experiment;
the cited large partial decay width is based only on a theoretical coupled
channel analysis [17]. Although it is gratifying to see that a similar result also
emerges now from the CC calculations of Friman, Lutz and Wolf [20], a direct
experimental verification of this decay branch would necessitate a detailed
partial-wave analysis of $(\gamma, 2\pi)$ reactions on the nucleon which so far does not
exist. It is, however, encouraging, that the DAPHNE collaboration [21] and
the TAPS collaboration [22], both at MAMI, have found experimental evidence
for pion invariant mass spectra in such reactions that show clear deviations
from phase-space.
6 Summary

In this talk I have shown that pion- and photon-induced reactions show a sensitivity to in-medium changes of hadrons that is as large as that observed in ultrarelativistic heavy ion collisions. This result was originally unexpected because of the much lower baryon densities probed in such elementary reactions on nuclei (< 1), compared with those obtained in ultrarelativistic heavy-ion collisions (> 5). It finds its explanation in the fact that all experimentally observed dilepton spectra contain an integration over the whole reaction history, which, in the case of heavy-ions, runs from $1\rho_0$ to more than $5\rho_0$ and then back down again to nearly $0\rho_0$ while the pion- or photon-induced reaction on nuclei always proceeds close to $\rho_0$, i.e. much closer to equilibrium.

In my opinion, an unequivocal identification of the origins of changes of hadronic spectral functions observed in ultrarelativistic heavy-ion collisions will not be possible as long as the more elementary reactions on nuclei have not been studied as well. It is obvious that hadronic in-medium effects, if they are observed in such reactions at or below $\rho_0$, have nothing to do with any transition to the QGP and even a possible connection with chiral symmetry restoration, a very popular keyword in this field, will be hard to establish (of course, duality arguments can always be used to keep this connection alive!). What we can learn, however, are interaction rates of hadrons with baryons, also for unstable hadrons, and this alone will be an exciting prospect. Experiments with HADES using the pion beam at GSI and experiments with photon beams, starting now with TAPS at MAMI, will help us to clarify the issue of in-medium changes of hadrons. For example, a close comparison of dilepton spectra obtained in pion-induced reactions with those obtained with photons should allow one to sample quite different density regions and thus in-medium effects, in particular for the $\omega$ meson. This is illustrated without further words in Fig. [4].

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