Hadrons in Nuclei

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Abstract. Changes of hadronic properties in dense nuclear matter as predicted by theory have usually been investigated by means of relativistic heavy-ion reactions. In this talk I show that observable consequences of such changes can also be seen in more elementary reactions on nuclei. Particular emphasis is put on a discussion of photonuclear reactions; examples are the dilepton production at ≈ 1 GeV and the hadron production in nuclei at 10–20 GeV photon energies. The observable effects are expected to be as large as in relativistic heavy-ion collisions and can be more directly related to the underlying hadronic changes.

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1. Introduction

That hadrons can change their properties and couplings in the nuclear medium has been well known to nuclear physicists since the days of the Delta-hole model that dealt with the changes of the properties of the pion and Delta-resonance inside nuclei [1]. Due to the predominant p-wave interaction of pions with nucleons one observes here a lowering of the pion branch with increasing pion momentum and nucleon density. A direct observation of this effect is difficult because of the strong final state interactions (in particular absorption) of the pions.

More recently, in-medium changes of vector mesons have found increased interest, mainly because these mesons couple strongly to the photon so that electromagnetic signals could yield information about properties of hadrons deeply embedded into nuclear matter. Indeed, the CERES experiment [2] has found a considerable excess of dileptons in an invariant mass range from ≈ 300 MeV to ≈ 700 MeV as compared to expectations based on the assumption of freely radiating mesons. This result has found an explanation in terms of a shift of the ρ meson spectral function down to lower masses, as expected from theory (see, e.g. [3,4]).

However, the actual reason for the observed dilepton excess is far from clear. Both models that just shift the pole mass of the vector meson as well as those that also modify the spectral shape have successfully explained the data; in addition, even a calculation that just used the free radiation rates with their — often quite large — experimental uncertainties was compatible with the observations [5]. There are also calculations that attribute the observed effect to radiation from a quark–gluon plasma [6].

I have therefore already some years ago proposed to look for the theoretically predicted changes of vector meson properties inside the nuclear medium in reaction on normal nuclei with more microscopic probes [7]. Of course, the nuclear density felt by the vector mesons in such experiments lies much below the equilibrium density of nuclear matter, ρ_0, so that naively any density-dependent effects are expected to be smaller than in heavy-ion reactions.

On the other hand, there is advantage to these experiments: they proceed with the spectator matter being close to its equilibrium state. This is essential because all theoretical predictions of in-medium properties of hadrons are based on an equilibrium model in which the hadron (vector meson) under investigation is embedded in cold nuclear matter in equilibrium and with infinite extension. However, a relativistic heavy-ion reaction proceeds — at least initially — far from equilibrium. Even if equilibrium is reached this state changes by cooling through expansion and particle emission and any observed signal is built up by integrating over the emissions from all these different stages of the reaction.

In this paper I summarize results that we have obtained in studies of observable consequences of in-medium changes of hadronic spectral functions in reactions of elementary probes with nuclei. I demonstrate that the expected in-medium sensitivity in such reactions is as high as that in relativistic heavy-ion collisions and that in particular photonuclear reactions present an independent, cleaner testing ground for assumptions made in analyzing heavy-ion reactions.

2. Dilepton Production

The CERES experiment has received a lot of publicity for its observation of an excess of dileptons with invariant masses below those of the lightest vector mesons [2]. Explanations of this excess have focussed on a change of in-medium properties of these vector mesons in dense nuclear matter. The radiating sources can be nicely seen in Fig. 1 that shows the latest dilepton spectrum obtained in a rather low-energy run at 40 AGeV.

The figure exhibits clearly the rather strong contributions of the vector mesons — both direct and through their Dalitz decay — at invariant masses above about 500 MeV. If this strength is shifted downward, caused by an in-medium change of the vector-meson spectral functions, then the observed excess can be explained as has been shown by various authors (see, e.g. [8]).
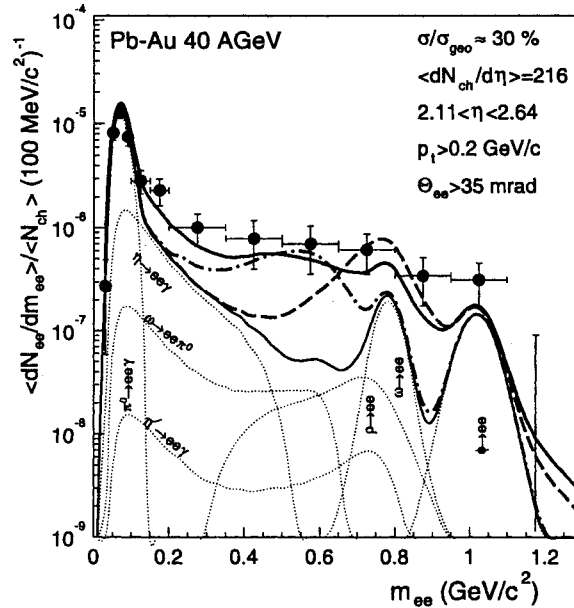
Fig. 1. Invariant dilepton mass spectrum obtained with the CERES experiment in Pb + Au collisions at 40 AGeV (from [2]). The thin curves give the contributions of individual hadronic sources to the total dilepton yield, the fat solid (modified spectral function) and the dash-dotted (dropping mass only) curves give the results of calculations employing an in-medium modified spectral function of the vector mesons

As mentioned above such explanations always suffer from an inherent inconsistency: while the observed signal integrates over many different stages of the collision — non-equilibrium and equilibrium, the latter at various densities and temperatures — the theoretical input is always calculated under the assumption of a vector meson in nuclear matter in equilibrium. We have therefore looked for possible effects in reactions that proceed much closer to equilibrium and have thus studied the dilepton production in photon-induced reactions on the nucleus. It is not *a priori* hopeless to look for in-medium effects in ordinary nuclei: Even in relativistic heavy-ion reactions that reach baryonic densities of the order of 3–10 ρ_0 many observed dileptons actually stem from densities that are much lower than these high peak densities. Transport simulations have shown [8] that even at the CERES energies about 1/2 of all dileptons come from densities lower than 2ρ_0. This is so because in such reactions the pion density gets quite large in particular in the late stages of the collision, where the baryonic matter expands and its density becomes low again. Correspondingly many vector mesons are formed late in the collision (through $\pi + \pi \rightarrow \rho$) and their decay to dileptons thus happens at low baryon densities.

The calculations are done in a combination of coherent initial state interactions that lead to shadowing at photon energies above about 1 GeV and incoherent final state interactions. The shadowed incoming photon produces, for example, a vector meson which then cascades through the nucleus. The latter process we describe by means of a coupled-channel transport theory. The details are discussed in Ref. [9]. A new feature of these calculations is that vector mesons with their correct spectral functions can actually be produced and transported consistently. This is quite an advantage over earlier treatments in which the mesons were always produced and transported with their pole mass and their spectral function was later on folded in only for their decay.

A typical result of such a calculation for the dilepton yield — after removing the Bethe–Heitler component — is given in Fig. 2. Comparing this figure with
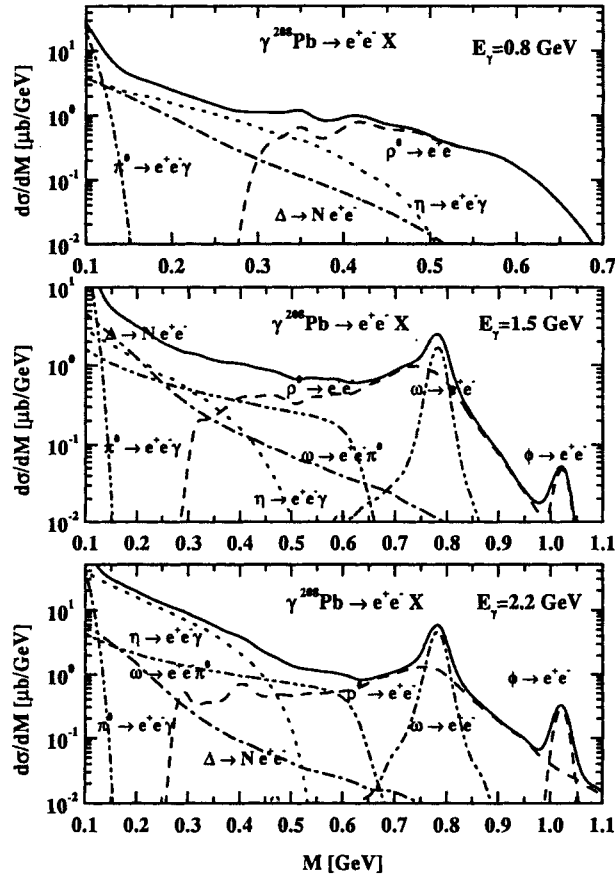

Fig. 2. Hadronic contributions to dilepton invariant mass spectra for $\gamma+^{208}$Pb at the three photon energies given (from [9]). Compare with Fig. 1

Fig. 1 shows that exactly the same sources, and none less, contribute to the dilepton yield in a photon-induced reaction at 1–2 GeV photon energy as in relativistic heavy-ion collisions at 40 AGeV! The question now remains if we can expect any observable effect of possible in-medium changes of the vector meson spectral functions in medium in such an experiment on the nucleus where — due to surface effects — the average nucleon density is below ρ_0. This question is answered by the results of Fig. 3. This figure shows the dilepton spectra to be expected if a suitable
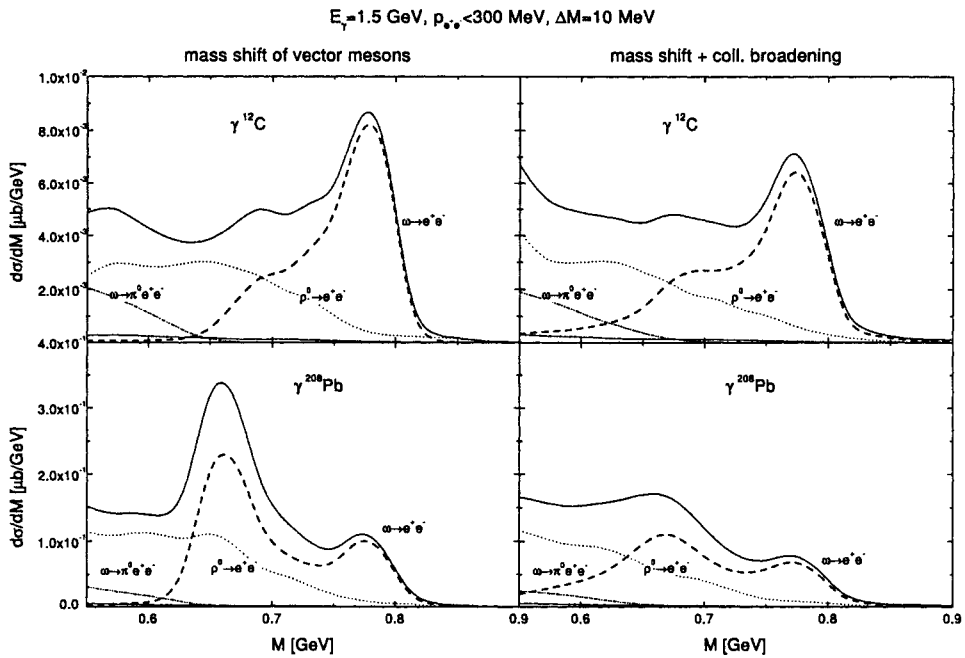
Fig. 3. Dilepton mass yield with a dilepton-momentum cut of 300 MeV. Shown on the left are results of a calculation that uses only a shift of the pole mass of the vector mesons. On the right, results are given for a calculation using both mass shift and collisional broadening (from [9])

cut on the dilepton momenta is imposed. In the realistic case shown on the right, which contains both a collision broadening and a mass shift, it is obvious that a major signal is to be expected: in the heavy nucleus Pb the ω-peak has completely disappeared from the spectrum. The sensitivity of such reactions is thus as large as that observed in ultrarelativistic heavy-ion reactions.

An experimental verification of this prediction would be a major step forward in our understanding of in-medium changes.[b] It would obviously present a purely hadronic base-line to all data on top of which all 'fancier' explanations of the CERES effect in terms of radiation from a QGP and the such would have to live.

3. Hadron Formation

A major experimental effort at RHIC experiments has gone into the observation of jets in ultrarelativistic heavy-ion collisions and the determination of their interaction with the surrounding quark or hadronic matter [11]. Such experiments are obviously very sensitive to hadron formation times. In addition they can yield information on interactions while the final hadron is still being formed.

A complementary process is given by the latest HERMES results at HERA for photon-induced hadron production at high energies [12]. Here the photon energies are of the order of 10–20 GeV, with rather moderate $Q^2 \approx 2$ GeV. Again, the
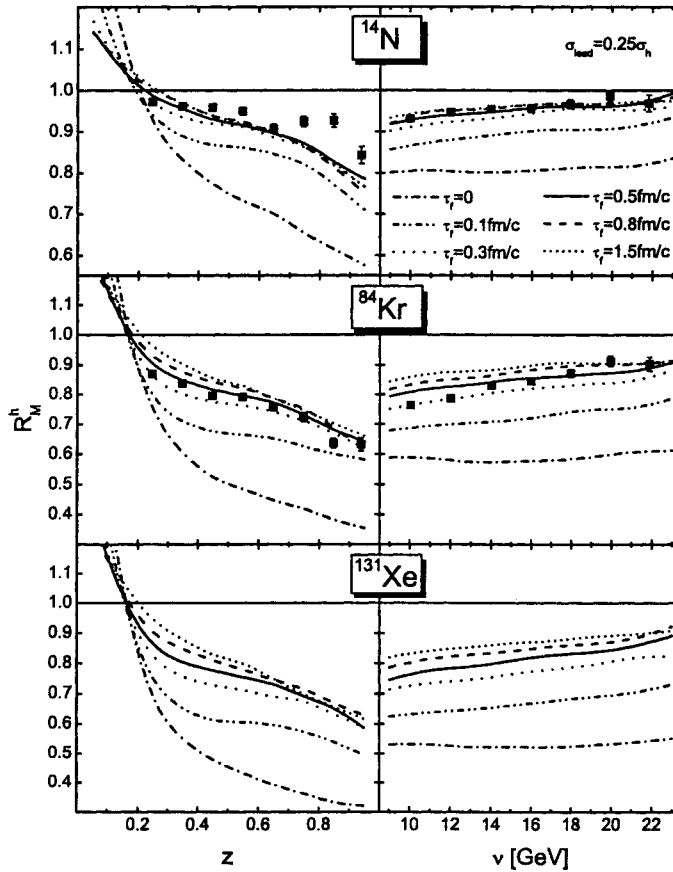
Fig. 4. Multiplicity of produced hadrons normalized to the proton as a function of photon energy ν (right) and of the energy of the produced hadrons relative to the photon energy, $z = E_h/\nu$. The curves are calculated for different formation times given in the figure (from [14])

advantage of such experiments is that the nuclear matter with which the interactions happen is at rest and in equilibrium.

In the high-energy regime the shadowing of the incoming photon, which is due to interference between interactions of the incoming bare photon and its hadronic components with the nucleons, becomes important. This coherence in the incoming state has to be combined with the incoherent treatment of the final state interactions in transport theory. For this purpose Falter has derived a novel expression for incoherent particle production on the nucleus [13] that allows for a clean-cut separation of the coherent initial state and the incoherent final state interactions which we again treat with our coupled-channel transport theory.

An example of the results obtained is given in Fig. 4. The figure clearly shows that the observed hadron multiplicities can be described only with formation times $\gtrsim 0.3$ fm. The curves obtained with larger formation times all lie very close together. This is a consequence of the finite size of the target nucleus: if the formation time is larger than the time needed for the preformed hadron to transverse the nucleus then the sensitivity to the formation time is lost. In [14] we have also shown that the z dependence on the left side exhibits some sensitivity to the interactions of the leading hadrons during the formation; the curves show in Fig. 4 are obtained with a leading hadron cross section of $0.25\sigma_h$, where σ_h is the 'normal' hadronic interaction cross section.

4. Conclusions

In this talk I have illustrated with the help of two examples that photonuclear reactions can yield information that is important and relevant for an understanding of high-density–high-temperature phenomena in ultrarelativistic heavy-ion collisions. I have shown that the expected sensitivity of dilepton spectra in photonuclear reactions in the 1–2 GeV range is as large as that in ultrarelativistic heavy-ion collisions. I have also illustrated that the analysis of hadron production spectra in high-energy electroproduction experiments at HERMES gives information about the interaction of forming hadrons with the surrounding hadronic matter. This is important for any analysis that tries to obtain signals for a QGP by analysing high-energy jet formation in ultrarelativistic heavy-ion reactions.

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Notes

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b. An experiment at JLAB is under way [10].

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