In this talk various aspects of in-medium behavior of hadrons are discussed with an emphasis on observable effects. It is stressed that final state interactions can have a major effect on observables and thus have to be considered as part of the theory. This is demonstrated with examples from photo-nucleus and neutrino-nucleus interactions.

Keywords: hadrons in medium; photoproduction; neutrino scattering.

PACS numbers: 25.20.Lj, 25.30.Pt

1. Introduction

Hadrons, embedded inside nuclei, obviously change some of their properties. They acquire complex selfenergies with the real parts reflecting the binding (or non-binding) properties and the imaginary parts reflecting the interactions and possibly their changes inside the medium. Particles that are produced through resonances or – at high energies – through strings become physical, on-shell particles only after some formation time. In this case the nuclear medium may affect the formation process and can thus act as a micro-detector for the early stages of particle production.

Naively, one expects that in lowest order all in-medium effects go linearly with the density of nuclear matter, $\rho$, around the hadron. This has triggered a series of experiments with relativistic and ultrarelativistic heavy-ions, which can reach high densities, that have looked for such effects and have indeed reported in-medium changes of the $\rho$ meson. However, it has been pointed out quite early that also experiments with microscopic probes on nuclei can yield in-medium signals that are as large as those obtained in heavy-ion collisions. Although, of course, the density probed here is always below $\rho_0$ the observed signal is cleaner in the sense that it does not contain an implicit integration over very different phases of the reaction and the nuclear environment. The signal to be expected is also nearly as large as that seen in heavy-ion collisions. This idea has been followed up in recent

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experiments with photons on nuclei, where indeed changes of the $\omega$ meson in medium have been reported.

In Ref. we have discussed the relevant questions and theoretical studies of in-medium properties in some detail. Such calculations necessarily rely on a number of simplifying assumptions, foremost being that of an infinite medium at rest in which the hadron under study is embedded. In actual experiments these hadrons are observed through their decay products and these have to travel through the surrounding nuclear matter to the detectors. Except for the case of electromagnetic signals (photons, dileptons) this is connected with often sizeable final state interactions (FSI) that have to be treated as realistic as possible. For a long period the Glauber approximation which allows only for absorptive processes along a straight-line path has been the method of choice in theories of photonuclear reactions on nuclei. This may be sufficient if one is only interested in total yields. However, it is clearly insufficient when one aims at, for example, reconstructing the spectral function of a hadron inside matter through its decay products. Rescattering and sidefeeding through coupled channel effects can affect the final result so that a realistic description of such effects is absolutely mandatory.

In this talk we will give an overview of this field with an emphasis on observable effects in photonuclear and neutrino-induced reactions. More details can be found in two previous reviews.

2. In-medium effects

The model we are using for the description of photon- and neutrino-induced reactions factorizes into three ingredients. First, there is shadowing in the entrance channel that comes about by a quantum mechanical coherence effect. This is essential for photon energies of about 1 GeV on upwards and for small virtualities $Q^2<1$. Second there is an elementary interaction of the incoming probe with individual nucleons, the assumption being here that the processes under study are all one-body processes. At this stage also 'trivial' many-body effects, such as Fermi motion and Pauli-blocking, can be taken into account.

How these effects influence the inclusive cross section is shown in Fig. for the example of neutrino scattering off a Fe nucleus. The left peak is due to $\Delta$ excitation, the right one to quasielastic scattering. The dashed line shows the elementary cross section for $\Delta$ production. The position of the $\delta$-function of the QE cross section is indicated by the arrow. We subsequently include Fermi motion and Pauli blocking as well as the binding of the nucleons in a mean-field potential. Furthermore, we include the in-medium modification of the width of the $\Delta$ resonance by taking into account that the decay might be Pauli blocked and that there are additional channels for the $\Delta$ in the medium like two and three body collisions which therefore yield to a collisional broadening of resonances in the nuclear medium. Including all these effects leads to a significant change of the cross section compared to the vacuum result.
IN-MEDIUM EFFECTS IN PHOTO- AND NEUTRINO-INDUCED REACTIONS ON NUCLEI

Fig. 1. Inclusive double differential cross section \(\frac{d\sigma}{dQ^2\,dE_\mu}\) for charged current scattering of \(\nu_\mu\) on \(^{56}\text{Fe}\) at \(E_\nu = 1\ \text{GeV}\) and \(Q^2 = 0.15\ \text{GeV}^2\) (from Ref. 10).

The third step is the propagation of the produced particles from their production through the nuclear medium out to the detector. During this propagation the particle originally produced can loose parts of its energy and change its direction or even charge through rescattering. It can also be absorbed, thus transferring its energy and momentum to nucleons. These nucleons can then either be knocked out of the nucleus or produce other, secondary hadrons in collisions with other nucleons. The hadron ultimately seen leaving the nucleus may thus not be that that was originally, in the first interaction of the probe with a nucleon, produced.

The latter step is handled by a semiclassical coupled channel transport theory with the help of the GiBUU code \(^{11}\) that takes Fermi motion and Pauli blocking into account and allows for a propagation of all hadrons in their mean field potentials. Originally it has been developed for the description of heavy-ion collisions and has since then been applied to - and tested against - various more elementary reactions on nuclei with protons, pions, electrons, photons and neutrinos in the entrance channel. In this method the spectral phase space distributions of all particles involved are propagated in time, from the initial first contact of the probe with the nucleus all the way to the final hadrons leaving the nuclear volume on their way to the detector. The spectral phase space distributions \(F_h(\vec{r}, \vec{p}, \mu, t)\) give at each moment of time and for each particle class \(h\) the probability to find a particle of that class with a (possibly off-shell) mass \(\mu\) and momentum \(\vec{p}\) at position \(\vec{r}\). Its time-development is determined by the BUU equation

\[
\left(\frac{\partial}{\partial t} + \frac{\partial H_h}{\partial \vec{p}} \frac{\partial}{\partial \vec{p}} + \frac{\partial H_h}{\partial \vec{r}} \frac{\partial}{\partial \vec{r}}\right) F_h = G_h a_h - L_h F_h.
\]

Here \(H_h\) gives the energy of the hadron \(h\) that is being transported; it contains the mass, the self-energy (mean field) of the particle and a term that drives an off-shell particle back to its mass shell. The terms on the lhs of \(^{11}\) are the so-called drift terms since they describe the independent transport of each hadron class \(h\). The terms on the rhs of \(^{11}\) are the collision terms; they describe both elastic and
inelastic collisions between the hadrons. Here the term *inelastic collisions* includes those collisions that either lead to particle production or particle absorption. The former is described by the *gain term* $G_h a_h$ on the rhs in (1), the latter process (absorption) by the *loss term* $L_h F_h$. Note that the gain term is proportional to the spectral function $a$ of the particle being produced, thus allowing for production of off-shell particles. On the contrary, the loss term is proportional to the spectral phase space distribution itself: the more particles there are the more can be absorbed. The terms $G_h$ and $L_h$ on the rhs give the actual strength of the gain and loss terms, respectively. They have the form of Born-approximation collision integrals and take the Pauli-principle into account. The free collision rates themselves are taken from experiment or are calculated.\textsuperscript{12}

The collision term on the rhs of (1) is responsible for the collision broadening that all particles experience when they are embedded in a dense medium. Collisions either change energy and momentum of the particles are absorb them altogether. Both processes contribute to collisional broadening. The detailed structure of the gain and loss terms can be obtained from quantum transport theory.\textsuperscript{13,14}

A very dramatic example, which demonstrates the importance of coupled channel effects, is provided by the charged current neutrino-induced neutron knockout of nuclei. Since charged current interactions by themselves always change the charge of the hit nucleon by one unit there cannot be any charged current knock-out neutrons in a quasielastic process. This is indeed born out in the results of calculations (see Fig. 2, left)\textsuperscript{10}. The few events visible in that picture at $Q^2 \approx 0.05$ GeV$^2$ and $E_\mu \approx 0.6$ GeV stem from events where first a $\Delta^+$ is produced that then decays into $\pi^+ n$.

When final state interactions are turned on, this picture changes dramatically (see Fig. 2, right). Now a significant neutron knockout signal appears at $E_\mu \approx 0.9$ GeV with a long ridge in $Q^2$. In addition the $\Delta$-like events now show also considerably more strength. The former effect is caused by charge-transfer reactions where in a first interaction a proton is knocked on that then travels through the nucleus and transmits its energy and momentum to a hit neutron that is being knocked out of the nucleus. The same applies to the $\Delta$-like events: due to charge-exchange FSI now also the initial decay channels $\Delta^+ \rightarrow \pi^0 p$ and $\Delta^{++} \rightarrow \pi^+ p$ can contribute to final neutrons being knocked out.

We shall now present two more applications, namely photon and neutrino induced neutral current pion production on nuclei.

### 3. Photoproduction of pions on nuclei

An example for the method and the quality of its results is shown in Fig. 3. Here we show the momentum-differential distributions for neutral pions produced by real photons on the nuclei Ca and Pb. The overall behavior of the spectra is described quite well by the BUU calculations. The clear deficiencies that show up at the lowest photon energy of 250 MeV, where the calculated cross section is only about $2/3$ of
the experimental one, is due to the fact that the data here contain a significant contribution from coherent pion production\cite{15} which cannot be described by the transport calculations. At the higher photon energies a distinct shape emerges – in agreement with experiment – that reflects the \(\pi N\Delta\) dynamics in nuclei. The spectra always start out at zero momentum with zero cross section reflecting the \(p\)-state coupling of pions to the \(\Delta\). The following peak drops off steeply at momenta of around 200 MeV reflecting the strong pion absorption through the \(\Delta\) resonance. After the fall-off the spectrum flattens and smoothly decreases to zero, as mandated by phase-space limitations. The structure just described shows up in the data and the calculations as well only for photon energies above about 450 MeV where the \(\Delta\) resonance is well excited.

4. Neutrino induced neutral current pion production

Exactly the same behavior as for photoproduction of pions on nuclei also shows up in the neutrino-induced pion production from nuclear targets\cite{10,16}. We illustrate this in Fig. 4 with the momentum-differential spectrum of pions produced by neutral current scattering of neutrinos on \(^{56}\)Fe for 3 neutrino energies. While the overall shape of the result without FSI (dashed line) is again dictated by the predominant \(p\)-wave production mechanism through the \(\Delta\) resonance, the shape of the solid lines which denote the full calculation is influenced by the energy dependence of the pion absorption and rescattering. The main absorption mechanism for pions above \(p_\pi \approx 0.2\) GeV is \(\pi N \to \Delta\) followed by \(\Delta N \to NN\) which leads to a considerable reduction of the cross section. Elastic scattering \(\pi N \to \pi N\) redistributes the kinetic energies and thus also shifts the spectrum to lower energies.

While this is equivalent to the photoproduction case, we want to point out an interesting feature specific to neutrino reactions. As a direct consequence of the
Fig. 3. Photoproduction of $\pi^0$ on Ca (left) and Pb (right) as a function of pion momentum. Shown is the BUU calculation in comparison with data. The photon energies are given in the individual frames (from Ref. 15).

isospin structure of the resonance decay, the cross section for $\pi^0$ production is significantly higher than those of the $\pi^+$ and $\pi^-$ channels. When FSI are included, we find an enhancement of the peaks in the middle and bottom panels of Fig. 4 over the value obtained without FSI. This is due to the fact that the $\pi^0$ undergo charge exchange and contribute to the charged channels (side-feeding). The effect in the opposite direction is less important due to the smaller elementary $\pi^+$ and $\pi^-$ production cross section.

Pions can also emerge from the initial QE neutrino-nucleon reaction when the produced nucleon rescatters producing a $\Delta$ or directly a pion (see dash-dotted line). This contributes mostly to the low energy region of the pion spectra due to
the redistribution of the energy in the collisions. However, this process is not very sizable because it is relevant only at high $Q^2$.

Finally, we show in Fig. 5 our result for the neutral current $\pi^0$ production on $^{12}$C. Plotted is the momentum differential cross section versus the pion momentum averaged over the incoming neutrino energy distribution of the MiniBooNE experiment\cite{18} as given in Ref.\cite{18}. In principle, our model allows for the inclusion of detector acceptances, however, it is not considered in this calculation. The dashed line shows the spectrum including Fermi motion and Pauli blocking, but no FSI, the solid curve gives the spectrum with the FSI turned on. Again, we find, that the shape of the spectrum changes significantly.

5. Summary

In this talk various aspects of in-medium effects have been demonstrated. Any in-medium signal that involves hadrons in the final states is subject to final state interactions, thus, for a reliable predictions of observables one has to take these final state interactions with all their complications in a coupled channel calculation into account; simple Glauber-type descriptions are not sufficient. It was outlined
that transport theory is at present the only reliable method to calculate the observable consequences of in-medium properties of hadrons and their interactions; usable quantum-mechanical approaches for the description of semi-inclusive events do not exist. Special emphasis was put on the demonstration of the overwhelming influence of final state interactions using examples from photon-nucleus and neutrino-nucleus interactions.

6. Acknowledgements

This work has been supported by DFG and BMBF.

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