SHADOWING AND FRAGMENTATION IN HIGH-ENERGY PHOTO-MESON PRODUCTION *

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A model for the description of photonuclear reactions in the multi-GeV range is described that combines the coherent initial state interactions (shadowing) of the incoming photon with an incoherent coupled channel description of final state interactions of outgoing particles. Particle production itself is treated either, at low energies, through nucleon resonance decays or, at higher energies, through string fragmentation. The initial state nucleons can be far-off-shell due to ground state correlations. Results are shown for semi-inclusive meson production.

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1. Introduction

Photo- and electroproduction of mesons in nuclei offers the possibility to study the interaction of photons with nucleons in the nuclear medium. In the energy regime from a few hundred MeV up to a few GeV one passes the (fuzzy) borderline between a purely hadronic and a parton-dominated world. One may thus gain insight into how the transition from meson-production through "classical" t- and s-channel processes to the fragmentation region is achieved; the former processes involve interactions between nucleons and their resonances, mesons and photons, the latter is dominated by primary interactions of the incoming photon with the partons inside the nucleons. How fragmentation is influenced by surrounding nucleons is so far unknown, but the EMC effect has shown that inclusive processes of virtual photons with nucleons change in the nuclear environment [1]. From a study of semi-inclusive processes one may also learn something about the in-medium properties, in particular their masses, of the produced hadrons in the nuclear medium. Such information would be a very valuable supplement to similar studies in

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relativistic heavy-ion collisions. While there significantly higher peak densities are achieved, the reactions proceed through a long history of densities and temperatures and all observables integrate intrinsically over this history. In contrast, in photonuclear reactions the density of the nuclear system is low ($< \rho_0$), but the reactions proceed in a rather stable environment much closer to the groundstate. In addition, the in-medium sensitivity of such reactions is as large as that of ultrarelativistic heavy-ion collions [2].

Photoproduction of particles on nuclei is usually treated within the Glauber model (see the review in [3]). While this model gives an efficient description of coherent initial state interactions (shadowing), it is rather superficial in its treatment of final state interactions of the produced hadrons. The Glauber method — at least in its practical implementations — describes only final state absorption. This may not be sufficient for a reliable description of semi-inclusive reactions where the specific hadron-channel under study can not only be attenuated, but also be fed by interactions with other channels.

In this talk I will present a model that combines the Glauber treatment of initial state interactions with an incoherent coupled-channel description of final states. The latter is based on a coupled channel treatment of hadron interactions in a dense environment, as it was originally developed for the description of relativistic and ultrarelativistic heavy-ion collisions. The model allows to take the important ground state correlations of nucleons into account and thus to use realistic nuclear ground-state spectral functions. Particle production in this model is treated either through a realistic, fixed by experiment description of meson production on nucleons or — at higher invariant energies above roughly 2 GeV — by the LUND string fragmentation model. The description presented here thus has all the essential ingredients for a description of high energy photonuclear processes on nuclei. The details of the model as applied to photomeson production on nuclei can be found in [4]; it can easily be generalized to electroproduction (for the first results in the lower energy (up to a few 100 MeV) region see [5]).

2. Model ingredients

Here I briefly summarize the main ingredients of the present model. Details can be found in [4, 5] and [12].

2.1. Shadowing

The initial state interactions of the incoming photon with the nucleus are dominated at the higher photon energies by a coherent multiple scattering of the photon from the nucleons. The total photon–nucleus cross section is then given by [3]:

$$\sigma_{\gamma A} = A\,\sigma_{\gamma N} + \sum_V \frac{8\pi^2}{kk_V}\,\mathrm{Im}\left\{ i f_{\gamma V} f_{V\gamma} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, n_{12}(\vec{b}, z_1, z_2) \right.$$
$$\left. \times \exp\left[iq_V(z_1 - z_2)\right] \exp\left[-\frac{1}{2}\sigma_V(1 - i\alpha_V) \int_{z_1}^{z_2} dz'\, n(\vec{b}, z') \right] \right\} . \quad (1)$$

Here $\sigma_{\gamma N}$ is the total photon–nucleon cross section, $f_{\gamma V}$ the amplitude for photoproduction of a vector meson V on a nucleon, n the nuclear density, n_{12} the correlated two-body density, q_V the momentum transfer from photon to vector meson, σ_V the total vector meson cross section on a nucleon and α_V the ratio of the real to the imaginary part of the amplitude for forward scattering of a vector meson on a nucleon. While it is known since about 25 years that such a description works well for high energies (> 5 GeV), we have shown that the same expression also describes the recently observed shadowing at low energies, from about 1 GeV photon energy on upwards, if the real part of the VN scattering amplitude is taken into account [6]. In [6] we have furthermore shown that this real part leads to an effective shift of the vector meson mass in the nuclear medium. Thus shadowing is directly tied in to the ongoing research on properties of vector mesons in nuclei (for a recent review see [7]).

2.2. Particle production

The primary production of a meson m on a nucleon N in the nuclear medium is in our method described by

$$\sigma_{\gamma A \to A^* m} = \int d^3x\, n(\vec{x}) s_N(\vec{x}) \sigma_{\gamma N \to N m} \ . \quad (2)$$

Here the *shadowing function* $s_N(\vec{x})$ is implicitly defined by the total photoabsorption cross section on nuclei (1) written in the form

$$\sigma_{\gamma A} = \int d^3x\, n(\vec{x}) s_N(\vec{x}) \sigma_{\gamma N} \quad (3)$$

and $\sigma_{\gamma N \to N m}$ is the free cross section for producing meson m on the nucleon N. Equation (2) essentially corresponds to multiplying the total cross section in (3) with the partial cross section for producing meson m.

For invariant energies in the photon–nucleon system below 2.1 GeV we obtain the needed cross sections for the primary interactions γN as in [8] by an explicit calculation of the cross sections for producing nucleon resonances as well as one-pion, two-pion, eta, vector meson and strangeness. For higher energies, where specific nucleon resonances are no longer visible, we use the string fragmentation model FRITIOF [9] in the way described in [4].

2.3. Final state interactions

The final state interactions are described in a semiclassical coupled channel transport calculation that includes all nucleon resonances up to an invariant mass of 2.1 GeV, all relevant mesons in this range, and the string fragmentation mechanism of the FRITIOF model for higher energies, consistent with the description of the primary production process. The model, described in detail in [10], allows a full coupled channel treatment of final state interactions, including nonforward processes. It has been tested and proven to give a very good description of photonuclear processes in the MAMI energy regime (up to 800 MeV photon energy) [5, 8].

2.3.1. Groundstate correlations

Nuclear groundstate correlations manifest themselves in the presence of high-momentum components, far beyond the Fermi momentum of nuclear matter, in the nuclear wavefunctions. Their presence can have significant consequences for particle production close to or even below the free threshold. While there are very sophisticated many body calculations (see *e.g.* [11]) of these correlations we have recently shown (in [12]) that the spectral function of nucleons in nuclear matter is dominated by phase-space effects and can be calculated from exactly the collision integrals entering the transport calculations just described. An example of these results is shown in Fig. 1.

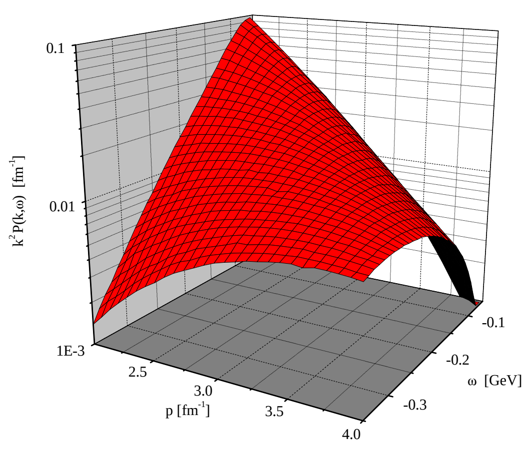

Fig. 1. Energy and momentum dependence of the nucleon spectral function $P(k,\omega)$ for energies below the Fermi energy ω_{F} ([12]).

We have recently implemented this spectral function into our transport calculations. These spectral functions have a strong influence on the primary particle production very close to threshold [13]. In the GeV range treated here, this would be the case, for example, for D-meson or J/ψ photoproduction. In addition, the spectral functions may influence the FSI in the first few reaction steps.

3. Results

In [4] I show results of this approach for pion, eta, kaon and $\pi^+\pi^-$ production. Here I just demonstrate the effects of various model ingredients on kaon photoproduction. In Fig. 2 the total cross sections for photoproduction of K^+ mesons are shown. These results show that shadowing is much more effective in the heavier nucleus Pb than in C, becoming important for

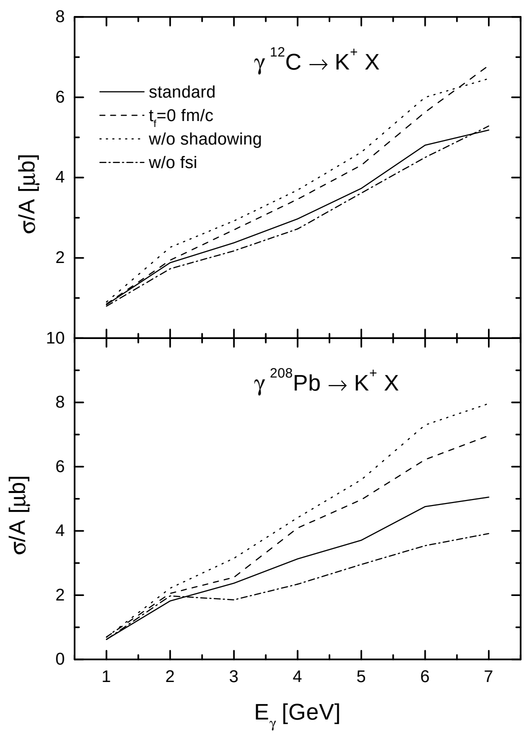

Fig. 2. Total cross section for K^+ production in γ C (top) and γ Pb (bottom). The dotted curve shows the result without shadowing, the dashed curve illustrates the effect of setting the formation time in the string fragmentation model to zero, the solid curve gives the results of the full calculation and the dash-dotted curve those without final state interactions.

energies > 2 GeV. At the highest energy shown here (7 GeV) it reduces the cross section to about 60% of its unshadowed value. The formation time of the string fragmentation model has a somewhat larger effect in the heavier nucleus because there reabsorption has more time to act in the case of zero formation time (the standard value used is 0.8 fm/c). The most interesting effect is the *enhancement* of the K^+ production cross section *due to the final state interactions*. This is a clear coupled channel effect: since the $\bar{s}$ quark in the K^+ meson cannot be absorbed in collisions with nucleons, there is only very little reabsorption of low-energy K^+ mesons. The final state interactions then act only to populate this channel through secondary interactions, such as, *e.g.* $\pi^+ N \to K^+ \Sigma$. We expect a similar behavior for the charmed $\bar{D}^0$ and D^- mesons with a free threshold of about 3.7 GeV.

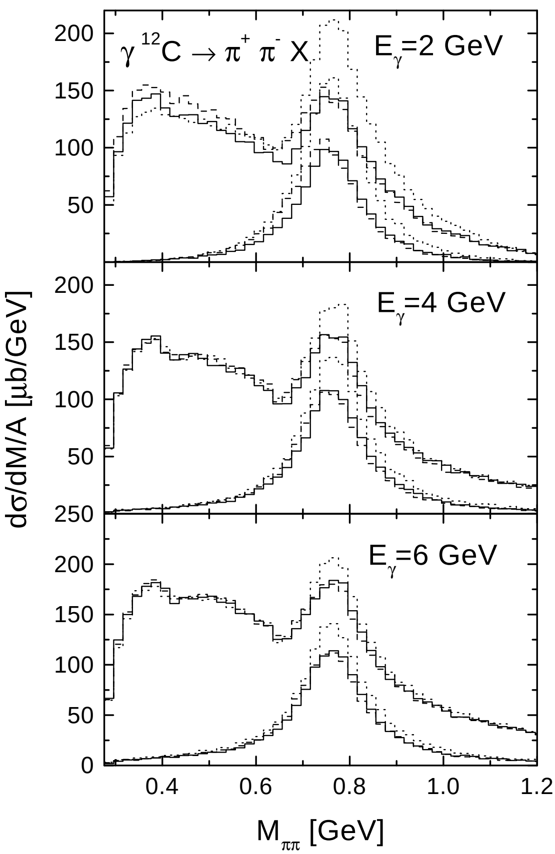

Fig. 3. Invariant mass spectrum of inclusive $\pi^+\pi^-$ production in γ C reactions. The dashed lines give the results of a dropping mass scenario for the ρ meson. The dotted lines are obtained without any final state interactions. The total mass-differential cross sections as well as the contributions of the ρ are shown.

Thus, the full coupled channel treatment of final state interactions is important for all those particles whose mean free path in matter is long. Here the sidefeeding has to be taken into account.

As a second example of the results obtained with this method I show in Fig. 3 the invariant mass distribution of $\pi^+\pi^-$ pairs for bombarding energies of 2–6 GeV on a C target. This reaction is of interest in connection with the ρ-electroproduction in high-energy reactions [14].

In the calculations presented here we know which pions originated from a ρ; we can thus distinguish between true and random coincidences. The final state interactions (FSI) play a dominant role at the lowest energies whereas their effect becomes smaller at the highest one. This is due to the energy dependence of the πN cross section. It is also seen that the ρ meson can be identified in the mass-spectrum at all energies; this becomes more difficult in heavier nuclei. The strong background rising down to the threshold at $2m_\pi$ is due to pions from resonance decays. The figure also shows that a mass shift of the ρ meson according to the prediction of [15]

$$m_\rho^* = \left(1 - 0.18\frac{\rho}{\rho_0}\right) m_\rho \tag{4}$$

is hardly visible in the pion invariant mass spectrum. This is simply due to the strong reabsorption and rescattering of pions in the nuclear medium; the ρ peak finally seen is then that of a ρ meson already decaying in the nuclear surface.

4. Summary

In this talk I have described a new theoretical approach to photo- and electroproduction at high energies. This approach combines shadowing in the incoming state with a coupled-channel treatment of final state interactions. The FSI are treated in a transporttheoretical method, originally developed for the description of heavy-ion reactions, and later also extended to hadron–nucleus [16] and photo- and electroproduction experiments at smaller energies [5, 8, 17] where it yielded very good results in comparison to MAMI data. I have illustrated some results of this method for photoproduction in the GeV energy regime; more can be found in a recent publication [4].

The method, when extended to higher energies and electroproduction, shows some promise for investigations of phenomena such as color transparency and the EMC effect. Since the model also allows to include realistic nuclear spectral functions in a simple way [12] we expect it also to be useful for a quantitative, realistic description of semi-inclusive reactions on nuclei. It should also help in a reliable analysis of experiments aiming for a determination of nuclear structure functions and their transition to partonic degrees of freedom, since the model contains the transition from nucleon-resonance dominated particle production at lower energies to a string fragmentation production at the higher energies.

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