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Low energy onset of nuclear shadowing in photoabsorption

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The early onset of nuclear shadowing in photoabsorption at low photon energies ($\gtrsim 1$ GeV) has recently been interpreted as a possible signature of a decrease of the ρ meson mass in nuclei. We show that one can understand this early onset within simple Glauber theory if one takes the negative real part of the ρN scattering amplitudes into account, corresponding to a higher effective mass of the ρ meson in nuclear medium.

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Recent photoabsorption data [1,2] on C, Al, Cu, Sn, and Pb in the energy range from 1 to 2.6 GeV display an early onset of the shadowing effect. The shadowing of high energy photons can be quantitatively understood in the Glauber approach (see, e.g., [3,4] and references therein) but some of the newer models [5,6] slightly underestimate the effect for low photon energies or even predict antishadowing [7] below 2 GeV when nucleon correlations are taken into account.

The early onset of shadowing has recently [8] been interpreted as a sign for a lighter ρ meson in medium. The shadowing effect was evaluated within a Glauber-Gribov multiple scattering theory [9,10] and generalized vector dominance using realistic spectral functions for the hadronic components of the photon but neglecting the real parts of the hadron-nucleon scattering amplitudes. A decrease of the ρ mass in nuclei was then suggested to fit the data.

The aim of this Rapid Communication is to show how one can understand the data within a simple Glauber model [11–13] which makes use of the eikonal approximation. In addition we assume that the intermediate hadronic states which give rise to the shadowing effect are dominated by the light vector mesons ρ, ω, and ϕ. The model successfully describes the photoabsorption data at high energies and in this work is extrapolated down to photon energies below 3 GeV. We show that one can achieve perfect agreement with the data when taking the real part of the ρN scattering amplitude into account. Experiments [14,15] show that for energies of about 4 and 6 GeV the real part of the ρN forward scattering amplitude is negative and already of the same order of magnitude as its imaginary part. Dispersion theoretical calculations [16,17] indicate that this is also the case for the energies we are considering. A negative real part indeed leads to a positive mass shift of the ρ in medium as pointed out by Eletsky and Ioffe [16]. We also include two-body correlations between the nucleons which avoids unphysical contributions to the shadowing effect in the considered energy region.

Glauber's formalism allows us to express the nuclear amplitudes of high energy particles in terms of more fundamental interactions with nucleons. We are interested in the total photon nucleus cross section which is related to the nuclear forward Compton amplitude via the optical theorem. We will briefly describe the two contributions to the nuclear Compton amplitude in order α_{em}. For a detailed derivation within the Glauber model we refer the reader to [13] and references therein.

Consider a real photon with momentum $k\cdot\vec{e}_z$ that hits a nucleus with mass number A and nucleon number density $n(\vec{r})$. The first contribution to the Compton amplitude in order α_{em} comes from forward scattering of the photon from a single nucleon somewhere inside the nucleus as shown in Fig. 1. This leads to the unshadowed part of the cross section [first term in Eq. (1)]. The second contribution comes from processes as depicted in Fig. 2. Here the photon enters the nucleus at impact parameter $\vec{b}$ and produces an on-shell vector meson V with momentum $k_V\cdot\vec{e}_z$ on a nucleon at position z_1. This meson then scatters at fixed impact parameter (eikonal approximation) through the nucleus and finally at position z_2 back into the outgoing photon.

The resulting expression for the total photon nucleus cross section, neglecting correlations between the single nucleons (independent particle model), is then given by [13]

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

where $\sigma_{\gamma N}$ denotes the total photon nucleon cross section and σ_V the total vector meson nucleon cross section. The momentum transfer $q_V=k-k_V$ is given by

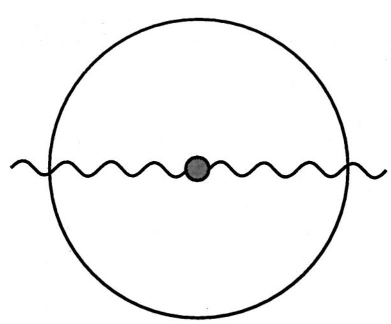

FIG. 1. Contributions to the unshadowed part of the nuclear Compton amplitude in order α_{em}. The photon scatters from a single nucleon.

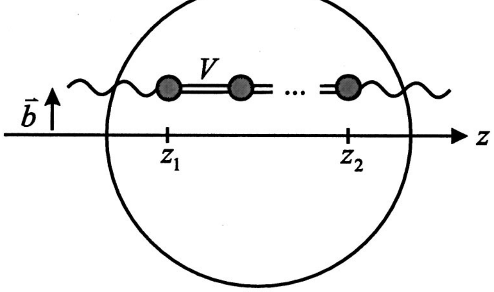

FIG. 2. Shadowing contribution to the nuclear Compton amplitude in order α_{em}. The photon produces a vector meson V that scatters through the nucleus and finally back into the outgoing photon.

$$q_V = k - \sqrt{k^2 - m_V^2}, \tag{2}$$

where m_V is the vacuum mass of the vector meson V. We use the vector dominance model (VDM) to relate the photoproduction amplitude $f_{\gamma V}$ for the vector meson V in the forward direction to the VN forward scattering amplitude f_{VV} in the following way:

$$f_{\gamma V} = f_{V\gamma} = \frac{e}{g_V} f_{VV}. \tag{3}$$

The optical theorem allows us to express the amplitude f_{VV} as

$$f_{VV} = \frac{i k_V}{4\pi} \sigma_V (1 - i\alpha_V), \tag{4}$$

where $\alpha_V = \mathrm{Re}\, f_{VV} / \mathrm{Im}\, f_{VV}$ is the ratio of the real to imaginary part of the VN forward scattering amplitude. From Eq. (3) one sees that within VDM the photoproduction amplitude also depends on α_V.

The effect of two-body correlations between the nucleons has been investigated, e.g., in Refs. [4,13]. We are interested in how these correlations influence the shadowing in the low energy region where q_V is large. From Eq. (1) we see that for very large q_V the second term on the right-hand side contributes most if $z_1 \approx z_2$, that is when the first and the last nucleon in the scattering process are approximately at the same position. Replacing the product of one-particle densities by the two-particle density

$$n_2(\vec{b}, z_1, z_2) = n(\vec{b}, z_1) n(\vec{b}, z_2) + \Delta(\vec{b}, |z_1 - z_2|) \tag{5}$$

as proposed in Ref. [7], avoids such unphysical contributions. Since for $z_1 \approx z_2$ the last exponential in Eq. (1) is approximately 1, consideration of correlations between the first and the last nucleon should be sufficient. For the two-body correlation function Δ we use the same Bessel function parametrization as in Ref. [7]:

$$\Delta(\vec{b}, |z_1 - z_2|) = -j_o(q_c |z_1 - z_2|) n(\vec{b}, z_1) n(\vec{b}, z_2) \tag{6}$$

with $q_c = 780$ MeV.

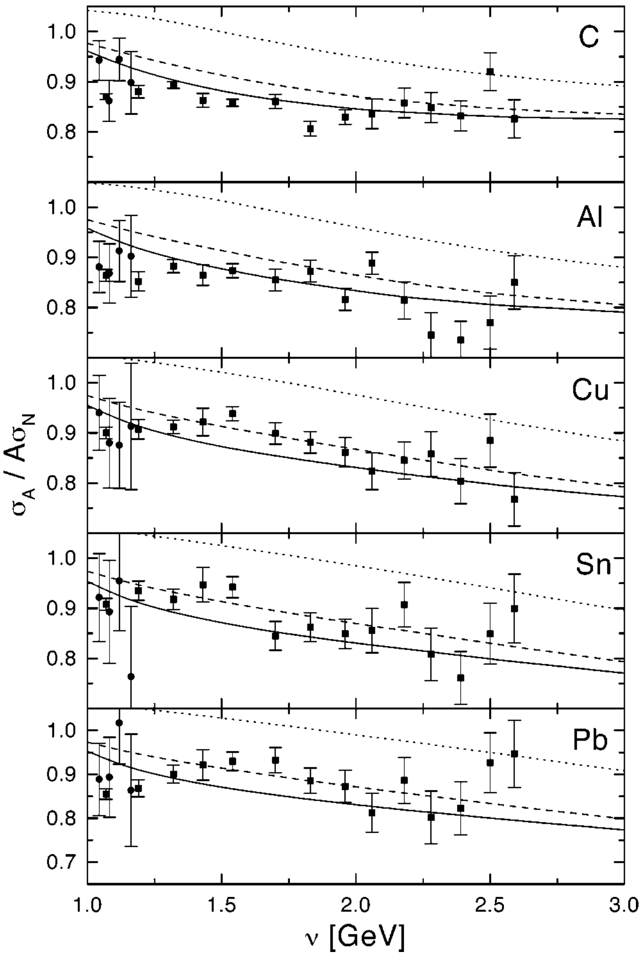

FIG. 3. Ratio of nuclear and nucleon photoabsorption cross section plotted against the photon energy (dotted line: real part of the scattering amplitudes set to 0; dashed line: real part as in Ref. [3]; solid line: ρN scattering amplitude as in Ref. [17]). The data are taken from Refs. [1] (circles) and [2] (squares).

Since the largest contributions to shadowing stem from the lighter vector mesons we only allow for $V = \rho, \omega, \phi$, neglecting higher mass intermediate states with large q_V. Since the ρ is the lightest vector meson and its photoproduction amplitude $f_{\gamma\rho}$ is about 3 times larger than that of the ω and ϕ, it will make the main contribution to the sum in Eq. (1) for low energies. Hence, the shadowing effect at low photon energies is very sensitive to the properties of the ρ and in particular to the choice of α_ρ. We neglect the widths of the vector mesons and the contribution from nonresonant 2π pairs with the quantum numbers of the photon since, as can be seen from [8], the realistic spectral functions of the hadronic intermediate states alone cannot explain the early onset of the shadowing effect.

In Fig. 3 we compare the ratio $\sigma_{\gamma A} / A \sigma_{\gamma N}$ plotted against photon energy with the data from Refs. [1,2] for different nuclei. We assume a Woods-Saxon distribution [18] for $n(\vec{r})$ and approximate the photon nucleon cross section $\sigma_{\gamma N}$ for each nucleus with mass number A and proton number Z by

$$\sigma_{\gamma N} = \frac{Z \sigma_{\gamma p} + (A - Z) \sigma_{\gamma n}}{A}, \tag{7}$$

fitting the data on $\sigma_{\gamma p}$ and $\sigma_{\gamma n}$ for photon energies between 1 and 5 GeV. Note that we do not use VDM to describe the total photon nucleon cross section. Only the intermediate hadronic states that are coherently produced in the forward direction as shown in Fig. 2 are limited to the light vector mesons.

The dotted line in Fig. 3 represents the result one gets using the quark model parametrization for σ_V and the coupling constants g_V of model I of Ref. [3] with α_V set to zero. One clearly underestimates the shadowing effect at the considered energies and even gets antishadowing at photon energies below 1.5 GeV (^{12}C) and 2 GeV (^{208}Pb) as stated in Refs. [2,7].

The effect of the real part of $f_{\rho\rho}$ is shown by the dashed line in Fig. 3. The parametrization of α_V is also taken from model I of Ref. [3].[1] Taking the negative real parts of the amplitudes into account leads to two competing effects. The negative value of α_V in the exponential of Eq. (1) diminishes the shadowing effect. However α_V also enters the prefactor $f_{\gamma V} f_{V\gamma}$ via Eqs. (3) and (4) and thereby increases shadowing. In total this leads to an enhancement of the shadowing effect and improves the agreement with experiment significantly. This result is also obtained in [19] which investigates the influence of shadowing on the photoproduction of mesons for photon energies between 1 and 10 GeV.

The solid line in Fig. 3 shows the result one gets if one uses the ρN scattering amplitude from the dispersion theoretical analysis by Kondratyuk *et al.* [17] and assuming that $f_{\omega\omega}=f_{\rho\rho}$. For the ϕ we still use the parametrization from Ref. [3]. In Ref. [17] the dependence of $f_{\rho\rho}$ on the momentum of the ρ meson yields a positive mass shift for ρ momenta larger than 100 MeV. This is compatible with the result of Eletsky and Ioffe [16] for energies above 2 GeV who obtained an increase of the ρ mass in medium with growing ρ momentum. Again one sees that considering the (negative) real part of the ρN scattering amplitude leads to a very good agreement with the data. The difference between the dashed and the solid lines in Fig. 3 reflects the uncertainty in the elementary ρN amplitude; it is, however, obvious that both parametrizations used lead to the same conclusion that using a negative real part for the ρN scattering amplitude explains the early onset of shadowing.

This result can be interpreted in terms of an in-medium change of the ρ meson properties. For large energies $k \approx k_\rho \gg m_\rho, q_\rho \approx m_\rho^2/2k_\rho$ the last two exponentials in Eq. (1) simplify to

[1] Due to a misprint, the sign of α_V in Table XXXV of Ref. [3] is wrong.

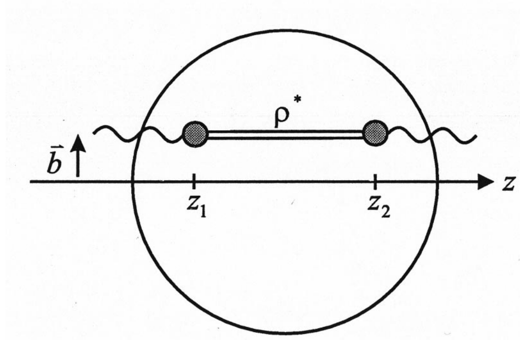

FIG. 4. The effective propagator of the ρ^* replaces the multiple scattering of the ρ meson in Fig. 2.

$$\exp\left[\frac{i}{2k_\rho}(m_\rho^2 - 4\pi f_{\rho\rho} n_0)(z_1 - z_2)\right],$$

where we have assumed a uniform density n_0. We would have gotten the same result if we had taken for the ρ contribution to the Compton amplitude the process pictured in Fig. 4. Here the photon produces an effective ρ^* with mass m^* and width Γ^* at the first nucleon at position z_1 which propagates formally without further scattering to the nucleon at position z_2 and scatters back into the photon. The effective propagator contains the multiple scattering of the ρ and can be calculated from the effective optical potential

$$U = -4\pi f_{\rho\rho} n_0. \tag{8}$$

In the calculation reported here the negative real part of the amplitude $f_{\rho\rho}$ results in a *larger* effective mass of the ρ meson in medium

$$m^* = \sqrt{m_\rho^2 - 4\pi\,\mathrm{Re}(f_{\rho\rho}) n_0}. \tag{9}$$

Thus, the multiple scattering contained in Eq. (1) generates the mass shift of the ρ meson. On the other hand, using an external mass shift for the ρ meson in a multiple scattering approximation such as Eq. (1) double counts the in-medium effects. This explains why the authors of [8] were led to the conclusion that the early onset of shadowing reflects a *lowering* of the ρ meson mass in medium.

We have demonstrated that the early onset of shadowing can be understood if one allows for a negative real part of the vector meson scattering and photoproduction amplitudes. This corresponds to an increase of the ρ meson mass in the nuclear medium at large momenta, in agreement with dispersion theoretical analyses.

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