Shadowing in photo-absorption : role of in-medium hadrons

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We study the effects of in-medium hadronic properties on shadowing in photon-nucleus interactions in Glauber model as well as in the multiple scattering approach. A reasonable agreement with the experimental data is obtained in a scenario of downward spectral shift of the hadrons. Shadowing is found to be insensitive to the broadening of the spectral functions. An impact parameter dependent analysis of shadowing might shed more light on the role of in-medium properties of hadrons.

PACS Nos. : 25.20.Dc, 25.40.Ep, 24.10.Ht, 12.40.Vv

Theoretical studies based on various models of hadronic interaction predict a reduction in the mass of hadrons at or above nuclear matter density \cite{16}. The observation of enhanced dilepton production in the low invariant mass domain in the heavy ion collision experiments \cite{6} does seem to indicate a non-trivial modification of the properties of light vector mesons, particularly the \(\rho\) meson, in hot and dense medium \cite{13}. However, the complicated dynamics both in the initial as well as final states in these experiments inhibits a firm conclusion about nuclear medium effects at present.

On the other hand, the experiments like photo-absorption on nuclei provide much cleaner systems for the study of in-medium properties of mesons \cite{13}. With the availability of better photon beams, there has been a renewed interest in the photo-absorption processes.

The phenomena of shadowing plays an important role in the photo-nuclear reactions. The photo-nuclear data at lower energies, for different nuclei, seem to indicate an early onset of shadowing \cite{6}. In ref. \cite{6} this feature has been interpreted as a signature for a lighter \(\rho\)-meson in the medium, where the shadowing effect was evaluated within a Glauber- Gribov multiple scattering theory \cite{14,15} and generalized vector meson dominance (VMD). In contrast the authors in refs. \cite{12} have claimed that the early onset of shadowing can be understood within simple Glauber theory \cite{14,16} if one takes the negative real part of the \(\rho N\) scattering amplitude into account which corresponds to a higher effective in-medium \(\rho\) meson mass. In a subsequent paper \cite{17}, the authors have concluded that the enhancement of shadowing at low energies occurs due to lighter \(\rho\) mesons as well as intermediate \(\pi^0\) produced in non-forward scattering.

In the backdrop of these different inferences, we have made an attempt to understand the role of in-medium properties of hadrons in the phenomenon of shadowing in photo-nuclear reactions. The shadowing in photon-nucleus reactions can be written as,

\[
\frac{A_{eff}}{A} = \frac{\sigma_{\gamma A}}{A \sigma_{\gamma N}} = 1 + \frac{\delta \sigma_{\gamma A}}{A \sigma_{\gamma N}} \tag{1}
\]

where \(\sigma_{\gamma A} = A \sigma_{\gamma N} + \delta \sigma_{\gamma A}\) consists of the incoherent scattering of the photon from individual nucleons and a correction due to the coherent interaction with several nucleons. The later has been evaluated using both multiple scattering approach \cite{4,7} as well as Glauber’s formula along with VMD \cite{18}. Resonance contribution to \(\gamma - A\) cross-section for photon energy \(\lesssim 1.2\) GeV has been estimated by using the prescription given in \cite{18}.

Let us first consider the in-medium effects on the kinematics of \(\gamma - A\) collisions. For a photon incident on a nucleus with energy \(E_L\), the energy in the rest frame of the nucleon is given by

\[
E_\gamma = \gamma F E_L (1 - \beta F \cos \theta_L), \tag{2}
\]

where \(\beta_F = p_F/E_F\) and \(\theta_L\) is the angle between the incident photon and the Fermi momentum of the nucleon which now depends on the space co-ordinate through the density \(n(r)\). The square of the centre of mass energy \(s\), of the \(\gamma - N\) system can then be written as,

\[
s = (p_\gamma + p_F)^2 = m_N^*^2 + 2 \gamma_F m_N^* E_L (1 - \beta F \cos \theta_L), \tag{3}
\]

where \(m_N^*\) is the effective nucleon mass inside the nucleus. The modification of vector meson masses in nuclear environment has been studied in different models \cite{12,20,21}. Here, we have used two different models namely universal scaling scenario (USS) \cite{21} and Quantum Hadrodynamical model (QHD) \cite{20}. In USS, the effective hadronic masses \((m_H^*)\) vary with nuclear density as

\[
\frac{m_H^*}{m_H} = 1 - 0.2x, \tag{4}
\]

where \(x = n(r)/n_0(r)\), \(n_0(r)\) being the normal nuclear matter density. In QHD the effective masses of nucleons and vector mesons are calculated using standard techniques of thermal field theory \cite{20,21} and is parametrized as :

\[
\frac{m_H^*}{m_H} = 1 + \sum_{j=1} a_j x^j. \tag{5}
\]

For nucleons \(a_1 = -0.351277\) and \(a_2 = 0.076239\); in case of \(\rho\), \(a_1 = -1.309666\), \(a_2 = 1.78784\), \(a_3 = -1.17524\) and \(a_4 = 0.294456\) and finally for \(\omega\), \(a_1 = -0.470454\), \(a_2 = 0.313825\) and \(a_3 = -0.0731274\). No medium effect
on the $\phi$ meson is considered here as it is expected to be small [23].

At lower energies $\gamma - A$ interaction is known to be dominated by resonance production [13,26]. Beyond this region we have used VMD for a better description. The vector meson produced inside the nucleus will have an effective mass depending on the density of the nuclear medium as seen by the meson. This change in mass would affect the coherence length $\lambda$ which corresponds to the time scale of the fluctuation between the bare photon and the hadronic component of the physical photon. For small $\lambda$, the hadron mediated interaction may become indistinguishable from the bare photon interaction and there will not be any shadowing. In the present case, $\lambda$ becomes a function of the radial distance inside the nucleus. For a vector meson with effective mass $m_{\gamma'}$, one gets,

$$\lambda = \frac{1}{E_{\gamma} - \sqrt{E_{\gamma}^2 - m_{\gamma'}^2}} \sim \frac{2E_{\gamma}}{m_{\gamma'}},$$  (6)

where $E_{\gamma}$ itself depends on the position of the struck nucleon through eq. [3]. Multiple scattering with the nucleons in the nucleus results in a modified mass of this meson. The correction to the nuclear photo-absorption cross section due to multiple scattering can be written in terms of $n$-fold multiple scattering amplitude $A^{(n)}$ as [17],

$$\delta \sigma_{\gamma A} = \frac{1}{2m_N k} \sum_{n=2}^{A} A^{(n)},$$  (7)

$k$ is the wave vector of the photon and the $n = 1$ term corresponds to the incoherent part. In the present work we show results up to double scattering only (see ref. [10] for details).

In the high energy limit, under the eikonal approximation, the summation of the multiple scattering series goes over to the Glauber’s formula if one neglects the width of the vector mesons. The photon entering the nucleus at an impact parameter $b$ produces a vector meson at position $z_1$. Inside the nucleus, the coherence length $\lambda$, in general, would be different at $z_1 (\lambda_1)$ and $z_2 (\lambda_2)$ as the different densities will yield different masses. The expression for the shadowing part of the cross section is then given by [14],

$$\delta \sigma_{\gamma A} = \frac{q^2}{4\pi\alpha} \delta \sigma_{\gamma A} = \frac{1}{2kk_{V}} \int d^2b \int dz_1 \int dz_2 \exp \left[ -\frac{1}{2} \int \sigma_{V N}(z')n(b, z')dz' \right] \times k_{V}(z_1)k_{V}(z_2)\sigma_{V N}(z_2)n^{(2)}(b, z_1, z_2) \times \left( (\alpha_{V}(z_1)\alpha_{V}(z_2) - 1) \cos \left( \frac{z_1}{\lambda_1} - \frac{z_2}{\lambda_2} \right) + \frac{1}{2} \int_{z_1}^{z_2} \alpha_{V}(z')\sigma_{V N}(z')n(b, z')dz' - (\alpha_{V}(z_1) + \alpha_{V}(z_2)) \right) \times \sin \left( \frac{z_1}{\lambda_1} - \frac{z_2}{\lambda_2} + \frac{1}{2} \int_{z_1}^{z_2} \alpha_{V}(z')\sigma_{V N}(z')n(b, z')dz' \right),$$  (8)

where $\alpha_{V} = \text{Ref}_{V}/\text{Im}_{f_{V}}$ is the ratio of the real and imaginary part of the $VN$ forward scattering amplitude. $\sigma_{V N}$ is the $V - N$ scattering cross section [13] and $k_{V}$ is the wave vector of the vector meson. The attenuation of the vector meson amplitude is described by the exponential factor. We have included 2-body correlation in the two-particle density as [2], $n^{(2)}(b, z_1, z_2) = n(b, z_1)n(b, z_2)[1 - J_0(q_c|z_1 - z_2|)]$ where $q_c = 780$ MeV and $J_0$ is the spherical Bessel function.

The authors of ref. [12] have indicated that the scattering of the vector meson with the nucleons in the nucleus leads to a change in its mass ($\Delta m \sim -2\pi n(r) \text{Re}f/m$) [27] and concluded that using an external mass would mean an overcounting of the medium effects. This observation may not be valid entirely. Let us consider the QHD model to discuss this point. It is well known that the small increase in the vector meson mass due to its interaction with the Fermi sea is overwhelmed by the large decrease due to Dirac sea interaction. This statement, though model dependent, does point out that the vacuum fluctuation (VF) which in free space renormalizes the particle to its physical mass, may have a different role in the medium. Presently, this phenomena can not be described from first principles. The increase in $\rho$ mass due to negative real part of the $\rho - N$ scattering amplitude ($\sim 10 - 100$ MeV [28,29] depending on the parameterization) may not be effective enough due to the larger drop from VF corrections and the net decrease might show up in the experimental data. So, while considering the vector meson in the medium, one should consider both the effects. Furthermore, in QHD, a drop in nucleon mass causes a larger drop in $\rho$ mass. Hence, for the present study it is also necessary to consider the effective nucleon mass inside the nucleus which was ignored in the previous studies. We should mention here that any increase in mass will lead to a reduction in the shadowing because of the decrease in $\lambda$. Moreover, the experimental data from other sources, e.g. heavy ion collisions [3] and proton-nucleus collisions [20] seem to indicate a softening of the vector meson spectral function.

Before presenting the theoretical results we discuss the available experimental data. To get the experimental numbers for $A_{\gamma eff}$, we have used $\sigma_{\gamma A}$ from ref. [6] and $\gamma$-proton cross section from refs. [28,51]. The $\gamma$-neutron cross section is obtained as $\sigma_{\gamma n} = \sigma_{\gamma d} - \sigma_{\gamma p} + \sigma_{\gamma G}$, where $\sigma_{\gamma d}$ is taken from ref. [31] and $\sigma_{\gamma G}$ is the Glauber correction which is known to be small at lower energies [13]. The data for $\gamma - p$ and $\gamma - n$ are interpolated for the relevant energies corresponding to given $\sigma_{\gamma A}$. The average photon-nucleon cross section for a nucleus with mass number $A$ is given as

$$\sigma_{\gamma N} = \frac{Z\sigma_{\gamma p} + (A - Z)\sigma_{\gamma n}}{A}$$  (9)
from which the experimental numbers are obtained as,

\[ \frac{A_{\text{eff}}}{A} = \frac{\sigma_{\gamma A}}{A\sigma_{\gamma N}}. \]  \hspace{1cm} (10)

We discuss the results now. Depending on the size of the nucleus we have used two different density distributions; for \( A < 16 \) the shell model density profile of Ref. [32] and for heavier nuclei \( (A > 16) \) the density profile from Ref. [33] has been used. According to eq. (2), \( E_{\gamma} \) is a function of angle, \( \theta_L \) for non-zero \( p_F \). The results which are presented below have been averaged over all the angles. We find that the effect of Fermi momentum in the kinematics (through eq. (2)) is negligibly small.

The variation of \( \lambda \) with \( E_{\gamma} \) for \( \rho \) mesons is plotted in Fig. 1 for Pb and Al nuclei. In order to take both the in-medium mass and width into account we have folded the coherence length with the spectral function (as in eq. (12) below). We observe that \( \lambda \) is larger at lower values of \( E_{\gamma} \) in the QHD scenario than in the universal scaling approach. Again the heavier nuclei seem to be affected earlier. These observations are crucial in the understanding of shadowing effects.

Fig. 2 shows the variation of \( A_{\text{eff}}/A \) with \( E_{\gamma} \) for different nuclei. The region below 1.2 GeV can be well described by the contribution of the baryonic resonances alone. For the region \( 1.2 < E_{\gamma} < 3 \) GeV we have used VMD with (Glauber) and without (multiple scattering) eikonal approximation. We find that the USS gives a better description of the data both in the multiple scattering approach and Glauber model. The dotted, long-dashed and solid lines indicate calculations using Glauber model for vacuum, QHD and USS respectively. The circles, dot-dashed (shown for C and Pb) and short-dashed lines correspond to the same in the multiple scattering approach.

As mentioned before the shift in the hadronic spectral function in the nuclear medium is an unsettled issue. The experimental data on dilepton production from heavy ion collisions at CERN super-proton synchrotron energies can be explained either by shifting the pole mass \( (m_V) \) to a lower value or by increasing the width \( (\Gamma_V(M)) \) of the spectral function. We would like to demonstrate here how these kind of medium effects (pole mass shift or broadening) affect the shadowing. For this we have considered the quantity,

\[ \langle A_{\text{eff}} \rangle = \frac{\int \rho(M) A_{\text{eff}}(M) dM}{\int \rho(M) dM} \]  \hspace{1cm} (11)

where

\[ A_{\text{eff}} = \frac{\sigma_{\gamma A}}{A\sigma_{\gamma N}}. \]  \hspace{1cm} (10)

\[ \lambda (\text{fm}) \]

\[ E_{\gamma} (\text{GeV}) \]

\[ \rho(M) \]

\[ \int \rho(M) dM \]

\[ \int \rho(M) A_{\text{eff}}(M) dM \]
\[
\rho(M) = \frac{1}{\pi} \frac{M \Gamma_V(M)}{(M^2 - m^2_V)^2 + M^2 \Gamma^2_V(M)}.
\]

$A_{\text{eff}}(M)$ gets maximum weight at the peak of the spectral function, i.e. from the point $M^2 = m^2_V$ and the contribution from either side of this point is approximately averaged out. Therefore, the results become sensitive to the pole mass and is largely insensitive to the broadening of the spectral function. In fig. 3 we show the quantity \(\langle A_{\text{eff}} \rangle/A\) as a function of photon energy for $\rho$-meson only. As explained above the results for vacuum mass 770 MeV and widths 150 MeV (solid line) and 230 MeV $^{22}$ (dotted line) are indistinguishable. However, a pole mass shift in USS shows a larger shadowing as $\lambda$ increases substantially in this case. Moreover, an increase ($\sim 40$ MeV $^{22}$) in $\rho$ mass results in the decrease in shadowing (dot-dashed line).

In all the results shown above, the shadowing is evaluated by integrating over all the values of impact parameter. On the other hand, an incident photon passing through the nucleus peripherally would see less shadowing due to lower densities. To visualize it we have plotted $d(A_{\text{eff}}/A)/db$ with impact parameter in fig. 4. While going from C to Pb, we observe that at the lower impact parameter shadowing is larger for lighter nuclei. This phenomena is a reflection of the nuclear density profile, which for lighter nuclei is larger in the core region compared to the heavier nuclei. It will be interesting to know whether one can define a centrality parameter for $\gamma - A$ collisions as is usually done for heavy ion collisions (percentage minimum bias etc.).

To conclude, we have studied the effects of in-medium properties of hadrons on shadowing in photo-absorption processes both in the framework of Glauber model and multiple scattering approach. The general pattern of experimental data seem to prefer a dropping vector meson mass scenario. The universal scaling appears to be closer to the data. The shadowing effect is insensitive to the spectral broadening of the vector meson in the nuclear medium. In contrast to the previous works the spatial dependence of the masses of both vector mesons and nucleon are considered here. The effect of Fermi motion is found to be small in the kinematics of the process. However, the effect of two-body correlation is important as its absence overestimates the data. We would also like to comment on QHD. The simple Walecka model, which we have used here has its own limitations (e.g., large incompressibility etc.). In this model, the reduction in the nucleon and vector meson masses is substantially larger than other models, which leads to large amount of shadowing.

![FIG. 3. $\langle A_{\text{eff}} \rangle/A$ as a function of photon energy for lead nucleus.](image)

![FIG. 4. Impact parameter dependence of the shadowing factor. Solid, dashed and dotted lines are the results for vacuum, USS and QHD respectively for $E_{\gamma} = 1$ GeV. Filled circle, diamond and square are the corresponding results for $E_{\gamma} = 2$ GeV.](image)
certainties.

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