Vector Mesons in Cold Nuclear Matter

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Abstract. The attenuation of vector mesons in cold nuclear matter is studied through the mechanism of incoherent photoproduction on complex nuclei. The latter is described via the time-dependent multi-collisional Monte Carlo (MCMC) intranuclear cascade model. The results for the transparency ratios of ω mesons reproduce previous measurements of CB-ELSA/TAPS with an inelastic ωN cross section around 40 mb for pω ≈ 1.1 GeV/c. The corresponding in-medium width (nuclear rest frame) is extracted dynamically from the algorithm and depends on the average nuclear density ρN and target nucleus: ~ 49.2 MeV/c² for carbon (ρN ≈ 0.114 fm⁻³) and ~ 77.3 MeV/c² for lead (ρN ≈ 0.137 fm⁻³). The calculations fail to reproduce the huge absorption observed at JLab assuming the same inelastic cross section and the discrepancy between the two experiments remains a challenge.

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1. Introduction
The investigation of in-medium changes of hadrons surrounded by dense and/or hot nuclear matter consists of a promising topic for both theoretical and experimental research. From the theoretical scenario, the expected partial restoration of chiral symmetry with increasing temperature and/or density of the medium can be associated with a broadening of the decay width of hadrons, such as the light vector mesons ρ, ω and ϕ. From the experimental side, Heavy-Ion collisions (HI) provide the most exotic environment since the hadrons are produced at extreme conditions of temperature and density. On the other hand, experiments in cold nuclear matter (CNM) represent cleaner measurements where the hadrons experience “bare” nuclear effects and any additional in-medium effect should manifest already at normal nuclear densities. Complete reviews of the latest developments on the theoretical and experimental aspects related with in-medium properties of vector mesons can be found in Refs [1, 2].

The CNM experiments were carried out using both hadron-[3, 4] and photon-induced [5, 6, 7, 8, 9, 10, 11, 12] nuclear reactions and are characterized by an equilibrated target nucleus. The photoproduction experiments present some advantages since the electromagnetic probe experience the whole nuclear volume and the effects of initial state interactions (ISI) - known as the nuclear shadowing effect - can be evaluated using Monte Carlo techniques under the context of the Vector-Dominance Model (VDM) [13]. Furthermore, the total photoproduction cross section from complex nuclei is dominated by exclusive single vector meson incoherent photoproduction, which is expected to scale with the generally well-understood elementary photoproduction cross section from the nucleon. For hadron-induced nuclear reactions there are evidences that a significant amount of uncertainty in the analysis of complex nuclei data might originate from the interpretation of the baseline measurements from p+p reaction [3].
Recent photoproduction experiments [9, 12] extracted the in-medium $\omega$ width (\(\Gamma^*\)) via the measurement of the nuclear transparency ratios normalized to carbon: $\frac{T_A}{T_C} = \frac{12}{A} \frac{\sigma_{\gamma A}}{2 \pi \rho \sigma_{\gamma C}}$, where $\sigma_{\gamma A}$ and $\sigma_{\gamma C}$ represent the total photoproduction cross sections $\sigma_{\gamma A(\gamma C)} = A_{\text{eff}} \sigma_{\gamma N}$, with $A_{\text{eff}}$ being the effective number of nucleons that contribute to the reaction [13]. Three different approaches were adopted in Refs. [9, 12] to extract the in-medium $\omega$ width: (i) a Glauber calculation [14, 15, 16], (ii) a Boltzmann-Uehling-Uhlenbeck (BUU) transport model [16], and (iii) a calculation by the Valencia group [17]. While the data from CB-ELSA/TAPS Collaboration [9] indicate an in-medium width (nuclear rest frame) in the range of 130 to 150 MeV/$c^2$, the Jefferson Laboratory (JLab) data suggest that the width should be greater than 200 MeV/$c^2$ [Note that the results have a trivial factor two from the adopted nuclear densities ($\rho_N = 0.16 \text{ fm}^{-3}$) and the ratio between the extracted widths is approximately 3].

This discrepancy was not fully interpreted in JLab analysis [12], that pointed out some differences in the experiments related with the average $\omega$ momentum and $\omega$ decay channel, respectively: ($p_\omega$) \~ 1.1 GeV/$c$ with $\omega \rightarrow \pi^0 \gamma$ in [9], and ($p_\omega$) \~ 1.7 GeV/$c$ with $\omega \rightarrow e^+e^-$ in [12]. Additionally, it is also mentioned in [12] that a destructive $\omega - \rho$ interference (manifested in the leptonic decay channels from $\rho$ and $\omega$) could be a plausible cause for the huge $\omega$ absorption.

A recent reanalysis [18] of the transparency ratios of $\omega$ mesons that included the peculiarities (kinematics and decay channels) of both experiments [9, 12] indicate systematically lower in-medium widths (assuming $\rho_N = 0.16 \text{ fm}^{-3}$) compared with the results obtained in [9] (factor \~ 2.3) and [12] (factor \~ 2). Furthermore, the calculations presented in [18] for the first time the interpretation of JLab measurements assuming an inelastic $\omega N$ cross section in the range of 80 mb, even though not solving the puzzling discrepancy between JLab and CB-ELSA/TAPS data that still remains a challenge (see discussion below).

Another recent measurement of dielectron pairs irradiated from CNM was performed using a proton-induced reaction on Nb with the High Acceptance Dielectron Spectrometer (HADES) at GSI [3]. In this experiment, a Gaussian distribution was used to fit the $e^+e^-$ invariant mass spectra (for the events with $P_{ee} > 0.8 \text{ GeV}/c$, where $P_{ee}$ represents the total momentum of the lepton pair) within the range of the $\omega$ meson, leading to an in-medium width of \~ 13 to 19 MeV/$c^2$ for the case of $p + \text{Nb}$ data. For lower meson momentum ($P_{ee} < 0.8 \text{ GeV}/c$), a significant excess of dielectron pairs within the $\rho$ mass range is observed when comparing the $p + \text{Nb}$ and $p + p$ data, indicating that secondary meson-nucleon interactions could play an important role. In fact, the PYTHIA dilepton cocktail adopted in [3] also does not reproduce the $p + p$ data, suggesting that the source of uncertainty might be linked with the elementary process. A further investigation of the elementary $N + N$ processes that contribute to the $e^+e^-$-invariant mass spectra was recently proposed in the resonance model of Ref. [19]. In this work, the coupling of the $\rho$ meson with nucleon resonances was taken into account and the results reproduce reasonably well both the elementary and complex nuclei data of HADES experiment [3].

In this work, we re-examine the predictions from the Monte Carlo Multi-Collisional intranuclear cascade model (MCMC) for the photoproduction of light vector mesons ($\rho$ and $\omega$) off complex nuclei in the range $2 \lesssim k \lesssim 9 \text{ GeV}$, where $k$ is the incident photon energy in Laboratory frame. For the case of $\omega$ meson, we have extended our analysis also in the photon energy range from threshold up to 2.3 GeV by including the recent JLab data [20]. The calculations do not include any effect from QCD condensates [21] and mass shifts of vector mesons [22] and are based on our previous works dedicated for nuclear incoherent (NI) photoproduction of pseudoscalar [13, 23, 24] and vector [18] mesons. The coupled-channel cascade approach takes into account the nuclear effects of Fermi Motion (FM), Pauli-Blocking (PB), Photon-Shadowing (PS) and meson-nucleus Final State Interactions (FSI). Additionally, the revised code provides an improved method to extract the in-medium widths of vector mesons directly from the time-
dependent algorithm, instead of using the low density approximation [25] adopted in [18].

This article is organized as follows: In section 1 we presented the introduction and the current discrepancies in recent measurements of vector mesons in CNM. Section 2 describes the elementary photoproduction mechanism adopted in the MCMC model. The basic features of the MCMC model to describe the propagation of stable/unstable particles in the nuclear medium are highlighted in Section 3. Some predictions of the code and the comparison between theory and data are presented in Section 4. The conclusions and future prospects are finally addressed in Section 5.

2. The elementary vector meson photoproduction: initializing the MCMC cascade

The relativistic time-dependent MCMC code provides information regarding the total and the differential cross section for incoherent photoproduction off complex nuclei. The normalization and initial sampling of the vector meson polar angles are constrained by the elementary photoproduction mechanism:

\[ \gamma(k) + N(p_1) \rightarrow V(p) + N(p_2), \]  

where \( p_1 \) and \( p_2 \) represent the initial and final momentum of the struck nucleon and \( p \) the momentum of the vector meson \( V \equiv \omega, \rho \). Following our successful program dedicated for incoherent photoproduction, this elementary process can be satisfactorily described above typically 2.3 GeV using a Regge model [18] that includes the Pomeron \( (T^\omega_{P1}) \) and \( \pi \)-meson exchange amplitudes \( (T^\omega_{\pi}) \), such that [26]:

\[ T^\omega_{P1} = iA^\omega_{P1} F_1(t)G(t) \left( \frac{s}{s_0 P_1} \right) \alpha_{P1}(t)^{-1} e^{-i\pi[\alpha_{P1}(t)-1]} \]  

and

\[ T^\omega_{\pi} = iA^\omega_{\pi} m_{\omega,\rho} \sqrt{-t} \tilde{G}(t) \left( \frac{s}{s_0 \pi} \right) \alpha_{\pi}(t)^{-1} e^{-i\pi[\alpha_{\pi}(t)-1]}, \]  

with \( \alpha_{P1}(t) = 1.08 + 0.25t \), \( \alpha_{\pi}(t) = 0.7(t - m_{\pi}^2) \), \( m_{\omega} = 0.782 \text{ GeV}/c^2 \), \( m_{\rho} = 0.769 \text{ GeV}/c^2 \), \( m_{\pi} = 0.134 \text{ GeV}/c^2 \), \( s_{0 P1} = 1.25 \), \( s_{0 \pi} = 0.7 \) and the form factors \( F_1(t), G(t) \) and \( \tilde{G}(t) \) from Ref. [26]. For the case of \( \omega \) photoproduction our analysis also include the data from threshold up to 2.3 GeV. Within this energy range it is observed a sizable contribution for larger polar angles [20] in contrast with the diffractive behavior at lower angles. Consequently, in order to have an accurate determination of the total cross section, we have also included a phenomenological background contribution to fit the data at larger momentum transfer. Within this energy range, the elementary cross section can be described in terms of the center-of-mass meson polar angle \( (\theta^\omega_{\text{c.m.}}) \) using the following parameterization:

\[ \frac{d\sigma^j_N}{d \cos(\theta^\omega_{\text{c.m.}})} = 2 q_{\text{c.m.}}(s^j) \left\{ |T^\omega_{P1} [s^j, t^j(\theta^\omega_{\text{c.m.}})]|^2 + |T^\omega_{\pi} [s^j, t^j(\theta^\omega_{\text{c.m.}})]|^2 + \sum_{i=0}^{3} B_i^j [\cos(\theta^\omega_{\text{c.m.}})]^i \right\}, \]  

where \( q_{\text{c.m.}}(s^j) \) represents the meson momentum in the center of mass of the \( \omega N \) system with total energy \( W^j = \sqrt{s^j} \). The index \( j \) range from 1 thru 6 according to the data that were included in the analysis (see figure 1). The four momentum transfer \( t^j \) depends on the total energy \( W^j \) and on the meson polar angle, such that: \( t^j(\theta^\omega_{\text{c.m.}}) = -2 q_{\text{c.m.}}(s^j) [1 - \cos(\theta^\omega_{\text{c.m.}})] \). The coupling constants \( A^\omega_{P1} = 2.73(4) \sqrt{s^j_{\text{GeV}}} \) and \( A^\omega_{\pi} = 7.88(21) \sqrt{s^j_{\text{GeV}}} \), as well as the coefficients \( B_i^j \) were obtained by fitting simultaneously the differential and the total cross sections of \( \omega \) photoproduction presented in figures 1, 2 and 3 (\( \chi^2/\text{DOF} \approx 1.20 \)). For the case of \( \rho \) photoproduction, a similar fitting was achieved \( A^\rho_{P1} = 9.20(12) \sqrt{s^j_{\text{GeV}}} \) and \( A^\rho_{\pi} = 7.87(82) \sqrt{s^j_{\text{GeV}}} \) including the data of figures
4 and 5 ($\chi^2$/DOF $\simeq$ 0.94). In both fittings ($\omega$ and $\rho$), we took into account the uncertainties in the abscissas for the case of the total cross sections (figures 3 and 5).

Figure 1. Differential cross section for $\omega$ photoproduction off protons (data points) versus the prediction from the Regge model with a polynomial background (solid red lines). The data included in our fitting are from JLab [20] (including also a systematic uncertainty of 10%) and cover the photon energy range from slightly above threshold ($W^4 = 1.755$ GeV, $k = 1.173$ GeV) to up to 2.2 GeV ($W^6 = 2.245$ GeV, $k = 2.218$ GeV) in steps of $\Delta k \sim 200$ MeV. The fitted parameters are $B_{10}^1 = -0.889, B_{11}^1 = -2.415, B_{20}^1 = -0.893, B_{21}^1 = 1.636, B_{02}^1 = 0.076, B_{12}^1 = -5.05, B_{22}^1 = -6.347, B_{32}^1 = -3.210, B_{03}^1 = 0.521, B_{13}^1 = -3.914, B_{23}^1 = -5.792, B_{33}^1 = -2.419, B_{14}^1 = 0.875, B_{24}^1 = -2.492, B_{34}^1 = -3.450, B_{44}^1 = -0.919, B_{05}^1 = 0.915, B_{15}^1 = -1.410, B_{25}^1 = -2.368, B_{35}^1 = -1.226, B_{06}^1 = 0.756, B_{16}^1 = -0.457, B_{26}^1 = -1.7458, B_{36}^1 = -1.911$. 

$\gamma + p \rightarrow \omega + p$
Figure 2. Differential cross section for $\omega$ photoproduction off protons (data points) versus the prediction from the Regge model (solid blue lines). The data are from JLab [$k = 2.363$ GeV [20] (squares) and $k = 3.29/3.83$ GeV [27] (up triangles)], SLAC [$k = 2.8, 4.7$ and $9.3$ GeV [28] (circles)] and Cornell [$k = 8.9$ GeV [29] (down triangles)].

Figure 3. Total cross section for $\omega$ photoproduction off protons (data points) versus the fitted Regge model (solid blue line). The red histogram represents the integrals of the differential cross sections (figure 1) that simultaneously fit the data of the total cross section within the corresponding energy bin ($j$ from 1 thru 6). The data are from Refs. [30] (squares), [31] (circles), [28] (losangles), [32] (up-triangles) and [33] (down-triangle). In all cases, the uncertainties in the abscissas were taken into account.
Figure 4. Differential cross section for $\rho$ photoproduction off protons (data points) versus the prediction of the Regge model (solid blue lines). The data are from SAPHIR (squares) [34], ABBHHM (circles) [31], SLAC (triangles) [28, 35] and Eisenberg (losangles) [36]. The Ross-Stodolsky model [37] was adopted for the data of Refs. [34, 31] and the Söding interference model [38] for the SLAC data [28, 35].

Figure 5. Total cross section of $\rho$ photoproduction off protons (data points) versus our Regge model. The data are from SAPHIR (squares) [34], Struczinski et al. (circles) [30], SLAC (up-triangles) [28, 35], DESY (down-triangle) [39] and Eisenberg (losangle) [36]. The Ross-Stodolsky model [37] was adopted for the data of Refs. [34, 39] and the Söding interference model [38] for the data of Refs. [30, 28, 35].

3. Propagation of stable/unstable particles in the nuclear medium: The cascade method
The MCMC cascade consists of a semi-classical approach that evaluates the probability of binary interactions as a function of time. The MCMC routine is implemented as a two-step model. The first step defines the initial conditions for the photoproduced meson, the struck nucleon and the remaining bound nucleons. At this stage, the initial polar angle of the meson
is distributed according to the elementary cross sections (figures 1, 2 and 4) and the final momentum of the struck nucleon is tested for the Pauli principle. If the final momentum lies below the Fermi momentum ($p_F$), the photoproduction mechanism is Pauli-blocked and another nucleon candidate is sorted within the nuclear volume. If the final momentum is higher than $p_F$, the cascade process initiates and the final state of the struck nucleon is updated according to the respective elementary process. During this stage all the remaining nucleons are treated as spectators. As time evolves, the second step (multi-collisional) takes place and the code evaluates the probabilities of binary collisions, particles reaching the nuclear boundary, and unstable particles decaying inside the nucleus. The basic criterion for a binary collision is given by: \[ \pi b_{ij}^2 (\Delta t_{ij}) \leq \sigma_{ij} (s_{ij}), \] where $b_{ij}$ is the impact parameter between particles $i$ and $j$, $\Delta t_{ij}$ the time interval ($t$ from now on represents the cascade time in fm/$c$) for the interaction, and $\sigma_{ij}$ the corresponding total cross section for a given center of mass energy $\sqrt{s_{ij}}$. The microscopic cross section $\sigma_{ij}$ carries the relevant quantum information for the colliding particles and the method becomes more efficient for short-range (strong) interactions with center of mass energies much higher than the typical energies between spectators (Fermi motion).

If a binary collision satisfies the cascade criterion, the configuration space is updated ($t \rightarrow t + \Delta t_{ij}$) and the final channel of the scattering is sorted taking into account its respective probability. After the choice of the final state, the angular distributions of the outgoing particles are sorted (in the center of mass frame) according to the MCMC model parameterization and are boosted back to the Laboratory frame. At this step, the final momentum (momenta) of the nucleon(s) is(are) tested for the Pauli-principle using our non-stochastic method [40] and if (either of) the final state(s) is(are) already occupied the collision is Pauli-blocked and another candidate for binary interaction is searched. The rapid cascade stage includes direct and pre-equilibrium nucleon emissions and also the propagation of mesons and resonances in the nuclear medium. After the decaying/exiting of the resonances, the absorption/exiting of the mesons, and the emission of all the nucleons with kinetic energies higher than the nuclear potential the rapid stage is terminated and the compound nucleus evaporation/fission competition starts. The cascade method (including also the statistical decay of the compound nucleus) is described in Ref. [40] and references therein.

For the case of vector mesons, we have taken into account the probability of inelastic and elastic $V N$ scatterings and also the probability that the decay occurs inside the nucleus. The decay time ($t_{\text{decay}}$) is calculated using the survival probability:

\[ N_0(t) \propto e^{-\frac{\Gamma_0}{\hbar} \gamma t} \to t_{\text{decay}} = -\frac{\hbar}{\Gamma_0/\gamma} \ln(1 - x), \]  

where $\Gamma_0$ is the meson decay width in vacuum (particle rest frame), $\gamma$ is the Lorentz factor and $x$ a random number between 0 and 1. For the vacuum widths we have used the PDG recommended values [41] $\Gamma_0 = 8.44$ MeV/$c^2$ for $\omega$ and $\Gamma_0 = 150.2$ MeV/$c^2$ for $\rho$.

For the $V N$ interaction in the medium we took the momentum dependent inelastic $\sigma_{V N}^{inel}$ and elastic $\sigma_{V N}^{el}$ cross sections of Ref. [42], such that:

\[ \sigma_{V N}^* = C_{inel}^2 \sigma_{V N}^{inel} + C_{el}^2 \sigma_{V N}^{el} \text{ with } \] 

\[ \sigma_{V N}^{inel} = (20 + 4/\rho_V^2) \text{ and } \sigma_{V N}^{el} = [5.4 + 10 \exp(-0.6 \rho_V^2)]. \]

The coupling constants $C_{inel}$ and $C_{el}$ are considered free parameters in our analysis with $\sigma_{V N}^*$ representing the in-medium total $V N$ cross section and $p_V$ the meson momentum in GeV/$c$ (laboratory frame). Considering the diffractive behavior of the elastic $V N$ scattering, we have adopted our systematics for the neutral pion [13] also for the $V N \rightarrow V N$ differential cross section: $(\frac{d\sigma}{d\Omega})_{V N \rightarrow V N} = (\frac{d\sigma}{d\Omega})_{\pi^0 N \rightarrow \pi^0 N}$. As pointed out in our recent work [18], the contributions
of secondary vector meson production ($\gamma N \to \pi N; \pi N \to V N$) are neglected in the present analysis. In fact, for the case of $\rho$ photoproduction it is expected that these secondary processes play a role due to the couplings of the $\rho$ meson with nucleon resonances as recently investigated in Ref. [19] for the case of hadron-induced reactions. In this work, the authors pointed out that according to PYTHIA the inclusive $\rho$ production is largely dominated by the $\pi\rho$ channel at the highest HADES energy of $\sqrt{s} \approx 3.2$ GeV. This channel is taken into account in Ref. [19] assuming double-resonance excitations of the type $NN \to \Delta N^* \to NN\pi\rho$ and $NN \to \Delta\Delta^* \to NN\pi\rho$. Obviously that these channels do not contribute (directly) in photon-induced reactions. One could expect a tiny contribution due to secondary $NN$ interactions during the cascade stage for the case where the momentum transfer for the struck nucleon is large (backward angles) and the nucleon has a high kinetic energy ($\approx 3.5$ GeV) to interact with the remaining nucleons. For the case of the JLab data of $\rho$ photoproduction [11] these channels do not contribute.

In order to estimate the contribution of $\rho$ mesons due to secondary scatterings of photoproduced pions ($\gamma N \to \pi N; \pi N \to \rho N$) within the JLab kinematics [11] we rely on our previous calculations done for the neutral pion [13]. In this work, we have described the total $\pi N$ cross section ($\pi \equiv \pi^-, \pi^0, \pi^+$ and $N \equiv p, n$) up to $\sqrt{s} = 6$ GeV (see table I and figures 7 and 8 of Ref. [13]). It is verified that the major sources of $\rho$ can be attributed to the decay of the nucleon resonances $D_{13}(1520)$ (B.R. of 15 to 20% [41]) and $F_{15}(1680)$ (B.R. of 3 to 15% [41]). These two resonances have a dominating contribution ($\sim 24\%$ for $D_{13}(1520)$ and $\sim 29\%$ for $F_{15}(1680)$) in the total $\pi N$ cross section for energies below $\rho$ threshold [$\sqrt{s} \approx 1.5$ GeV ($p_{\pi^0}^{lab} \sim 0.7$ GeV/c) and $\sqrt{s} \approx 1.66$ GeV ($p_{\pi^\mp}^{lab} \sim 1$ GeV/c), respectively. For this reason, these resonances might populate the low energy tail of the $e^+e^-$ invariant mass spectra of JLab [11] via sub-threshold $\rho$'s. An upper limit of the systematic uncertainty in our calculations due to the absence of these mechanisms can be estimated for $k = 2.0$ GeV considering the relative importance of secondary scatterings ($\gamma N \to \pi N; \pi N \to \rho N$) with respect to the exclusive process ($\gamma N \to \rho N$) included in our analysis. For a rough evaluation, we assume that the probability of interaction of the photoproduced pions with the remaining nucleons ($\pi N \to X$) is $100\%$. Considering the neutral pion, the relative contribution of the channels $\{\gamma N \to \pi^0 N \to [D_{13}(1520) \to \rho N]+ [F_{15}(1680) \to \rho N]\}$ with respect to the major contribution ($\gamma N \to \rho N$) at $k = 2.0$ GeV can be estimated taking into account the ratio of the photoproduction cross sections $\frac{\sigma_{\gamma N}}{\sigma_{\gamma \pi^0}} \sim 0.18$ [assuming $\sigma_{\gamma \pi^0} \approx 3.5\mu b$ [43] and $\sigma_{\gamma \rho} \approx 20\mu b$ (see figure 5)] and the joint probability of resonance formation at the peaks of the resonances ($\sim 24\%$ for the $D_{13}(1520)$ and $\sim 29\%$ for $F_{15}(1680)$) and decay [$< 20\%$ for the $D_{13}(1520)$ and $< 15\%$ for $F_{15}(1680)$] into the $\rho$ channel: $0.18 \times (0.24 \times 0.20 + 0.29 \times 0.15) = 0.016$. For the case of $\pi^+$ and $\pi^-$, we can estimate the upper limit of the uncertainty considering that in actual nuclei $\sigma_{\gamma A \to \pi^+ X} + \sigma_{\gamma A \to \pi^- X} \approx \sigma_{\gamma A \to \pi^0 X}$ [since only the neutrons contribute to $\pi^-$ ($\gamma n \to \pi^- p$) and only the protons contribute to $\pi^+$ ($\gamma p \to \pi^+ n$), differently from the cases of $\pi^0$ and $\rho$ where all the bound nucleons are expected to contribute. With this assumption, we can estimate that the relative contribution of the channels $\{\gamma N \to \pi^+/-', N \to [D_{13}(1520) \to \rho N]+ [F_{15}(1680) \to \rho N]\}$ are a factor $\sim 4$ lower than our previous estimates for $\pi^0$ [this factor 4 comes from a factor 2 related with the photoproduction step and another factor 2 related with the secondary scatterings, since the charged pions only interact with half of the nucleons (considering $N = Z$) to produce either the $D_{13}(1520)$ or $F_{15}(1680)$]. So, adding all the pion channels (0.016 for $\pi^0$ and 0.004 for $\pi^+/-'$) we end up with an upper limit of less than $2.4\%$ for the increase in the total cross section from complex nuclei compared with the exclusive channel included in our algorithm. On top of this rough estimate, we also have to consider that the probability of $\pi N$ collisions is much less than unit and that the short-range correlations play an important role in actual nuclei, reducing even more the contributions from secondary scatterings. Additionally, the effect of these secondary processes is supposed to be washed out when evaluating the transparency ratios normalized for Carbon, the aim of the current work. It
is worth mentioning, however, that for the evaluation of the $e^+e^-$ invariant mass spectra of JLab \cite{11} at lower energies (significantly below the $\rho$ pole) one should take into account quantitatively the secondary mechanisms neglected in this work.

The total survival rate of vector mesons [herein denoted $N_{MC}(t)$] can be calculated in the Monte Carlo routine using the formula:

$$N_{MC}(t) = n - n_{\text{decay}}(t) - n_{\text{abs}}(t),$$

(8)

where $n$ represents the total number of photoproduced mesons (equal to the number of cascade events), $n_{\text{decay}}(t)$ the number of vector mesons that decay inside or outside the nucleus and $n_{\text{abs}}(t)$ the number of vector mesons that undergo inelastic collisions. Another interesting possibility is to approximate $N_{MC}(t)$ considering the limiting case where the in-medium decay width $\Gamma^*$ (calculated in the nuclear rest frame from now on) is time-independent, such that:

$$N_{MC}(t) \simeq N(t) \propto e^{-\frac{t}{\langle \Gamma^* \rangle}},$$

(9)

where $\Gamma^*$ represents the maximum value for the in-medium width that is supposed to be achieved deep inside the nucleus (small $t$) and is the sum of the vacuum and the maximum collisional width: $\Gamma^* = \Gamma_0/\gamma + \Gamma_{\text{col}}$.

Therefore, the current approach propitiates the extraction of the in-medium width at early cascade stages directly from the model, instead of using the low density approximation \cite{25} that assumes a homogeneous nuclear matter, such that:

$$\Gamma^* = \Gamma_0/\gamma + \beta\rho_N\sigma_{VN}^{\text{inel}},$$

(10)

where $\beta$ is the meson velocity.

In fact, considering actual nuclei effects, the collisional width should be evaluated dynamically $\Gamma_{\text{col}} \rightarrow \Gamma_{\text{col}}(t)$ as the mesons experience local density fluctuations and approach to the nuclear surface. Moreover, in the MCMC model, the collisional width does not represent the cause for meson absorption, but the consequence due to the probability of inelastic transitions governed by the in-medium cross sections. Differently from other transport calculations that usually adopt a density dependent in-medium width as an input \cite{16}, the MCMC approach takes into account the probabilities for elastic/inelastic meson-nucleon collisions with the in-medium width being a dynamical observable during the reaction mechanism.

4. Results

4.1. In-medium decay width of vector mesons

The in-medium decay widths of vector mesons can be extracted via the analysis of the survival rates (from the MCMC model) that include the kinematics and detection constraints from the CB-ELSA/TAPS \cite{9} and JLab \cite{12} experiments. In order to properly include the CB-ELSA/TAPS \cite{9} kinematics in our analysis we have sorted the incident photon energy in the interval $1.2 \leq k \leq 2.2$ GeV taking into account the normalized joint probability of $\omega$ photoproduction (proportional to the total cross section depicted by the histogram of figure 3) times the bremsstrahlung energy spectra ($\sim 1/k$) of the experiment. With this constraint, we obtained an average photon energy of $\langle k \rangle \simeq 1.645$ GeV and an average meson momentum (after running the cascade model) of $\langle p_\omega \rangle \sim 1.1$ GeV/c for all targets. For the case of JLab data, we have considered a single photon energy of 2.0 GeV that leads to an average meson momentum of 1.7 GeV/c. Figure 6 shows the survival rates (normalized to unit for $t < 0.1$ fm/c) from the MCMC model (histograms) for $\omega$ mesons on carbon (left) and lead (right) assuming the CB-ELSA/TAPS \cite{9} kinematics. The dashed (solid) histograms were obtained with $C_{el} = C_{inel} = 1.0$ ($C_{el} = C_{inel} = 1.3$) and collecting all the events of $\omega$ decay or inelastic collisions. The dashed
(solid) red lines represent the fits of the corresponding histograms (assuming a time-independent collisional width) at early cascade stages \( t < 1 \text{ fm}/c \). The average nuclear densities probed by the mesons at \( t < 1 \text{ fm}/c \) are extracted directly from the cascade model and range from \( \sim 0.114 \) \text{ fm}^{-3} \) for carbon to \( \sim 0.137 \) \text{ fm}^{-3} \) for lead. The dashed (solid) blue lines are the fits of the corresponding histograms within the asymptotic region where \( \Gamma_{\text{col}} \to 0 \) (outside the nucleus). In all cases, we have fitted the cascade results to the precision of 1\% using the exponential distributions \( N(t) \) and \( N_0(t) \) defined in the previous section.

It is verified that the meson survival rates can be well approximated by exponential distributions \( N(t) \) during the early cascade stages and match the vacuum distributions \( N_0(t) \) when the \( \omega \) mesons exit the nucleus. The vacuum distributions depend on the ratios \( \Gamma_0/\gamma \), which are calculated taking the average meson momentum \( \langle p_\omega \rangle \) from the cascade model. The results for carbon \( (\Gamma_0/\gamma \simeq 5.10 \text{ MeV}/c^2) \) and lead \( (\Gamma_0/\gamma \simeq 5.12 \text{ MeV}/c^2) \) are slightly different since \( \langle p_\omega \rangle \) also depend on the momentum distributions of the bound nucleons. The latter are taken from realistic proton knock-out reactions [23] for carbon and from a Fermi distribution for intermediate and heavy nuclei. There are smooth transitions between \( N(t) \) and \( N_0(t) \) as the mesons experience lower densities and approach to the nuclear surface. For this reason, the values obtained for \( \Gamma_{\text{col}} \) represent the maximum collisional widths for each system as a function of \( C_{\text{el}} \) and \( C_{\text{inel}} \). As expected, the absorption for lead is much higher due to the higher probability of secondary scatterings. Furthermore, the elastic \( \omega N \) scattering also plays a crucial role for the case of heavy nuclei since the mesons have a much higher probability of a secondary inelastic collision after experiencing one elastic scattering. For the case of light nuclei the probability of secondary scatterings is quite small and it is likely that the mesons exit the nucleus after a primary elastic scattering. This complex scenario influence the in-medium width which should be different for each nuclei.

Figure 7 presents the \( \omega \) meson survival rates for carbon (left) and lead (right) at \( k = 2.0 \) \text{ GeV} considering the leptonic decay \( (\omega \to e^+e^-) \) and the JLab kinematics [12]. The meaning of the histograms and the fitted functions are the same adopted in figure 6. The arguments of the vacuum distributions \( N_0(t) \) are \( \Gamma_0/\gamma \simeq 3.56 \text{ MeV}/c^2 \) for carbon and \( \Gamma_0/\gamma \simeq 3.58 \text{ MeV}/c^2 \) for lead.

Considering the CB-ELSA/TAPS constraints [9], the \( \omega \) collisional widths range from 27.4 to 44.1 \text{ MeV}/c^2 for carbon and from 43.2 to 72.1 \text{ MeV}/c^2 for lead if the couplings are increased from \( C_{\text{el}} = C_{\text{inel}} = 1.0 \) to \( C_{\text{el}} = C_{\text{inel}} = 1.3 \). Similar results are also obtained with the JLab kinematics [12] with the collisional widths being typically 5 to 7\% higher due to the average ratio \( \frac{\langle \sigma_{\text{inel}}^{\text{JLab}} \rangle}{\langle \sigma_{\text{inel}}^{\text{TAPS}} \rangle} \sim 1.06 \).

Figure 8 presents the survival rates of \( \rho \) mesons from carbon (left) and lead (right) at \( k = 2.0 \) \text{ GeV} taking into account the leptonic decay and JLab kinematics [12]. The meaning of the histograms and the fitted distributions \( N(t) \) and \( N_0(t) \) are the same adopted for the \( \omega \) meson with \( \Gamma_0/\gamma \simeq 62.95 \text{ MeV}/c^2 \) for carbon and \( \Gamma_0/\gamma \simeq 63.19 \text{ MeV}/c^2 \) for lead. The collisional widths are consistent with the previous results for \( \omega \), since we have used the same elastic and inelastic \( VN \) cross sections. Despite that the \( \rho \) decays almost instantaneously and mostly inside the nucleus, this result shows that the multi-collisional approach is very relevant also for the analysis of the \( \rho \) absorption in nuclei. The total in-medium widths of \( \rho \) range from 91.3 to 109.3
MeV/c² (C) and from 110.1 to 139.6 MeV/c² (Pb) if the couplings are increased from 1.0 to 1.3.

Figure 6. Survival rates of ω mesons (normalized to unit for t < 0.1 fm/c) from carbon (left) and lead (right) taking into account the CB-ELSA/TAPS kinematics [9] and the hadronic decay ω → π⁰γ. The dashed (solid) black histograms were obtained assuming C_{el} = C_{inel} = 1.0 (C_{el} = C_{inel} = 1.3). Details in the text.

Figure 7. Survival rates of ω mesons from carbon (left) and lead (right) at k = 2.0 GeV taking into account the JLab kinematics [12] and the leptonic decay ω → e⁺e⁻. The meaning of the histograms and the fitted functions are the same as in figure 6.

4.2. Nuclear transparency ratios of vector mesons in CNM

The nuclear transparencies are calculated using the relationship T_A = (A_{eff}/A)σ_{γN}, with the number of effective nucleons A_{eff} being extracted directly from the MCMC code [13, 18, 23]. The disadvantage of the above expression is that T_A depends on the elementary cross section σ_{γN}, which is generally constrained using the available data from different laboratories (figures 1-5). Furthermore, σ_{γN} also depends on the (poorly known) photoproduction cross section from the neutron. In order to overcome these uncertainties, it is usually convenient to normalize the transparencies with the results obtained for a spherical nuclei, such as carbon, and to calculate
the ratios: \( \frac{T_A}{T_C} = \frac{12 \sigma_{\gamma A}}{\sigma_{\gamma C}} = \frac{12 A_{eff}(A)}{A_{eff}(C)} \). These ratios do not depend on the photoproduction mechanism and should reflect the absorption of vector mesons inside the nucleus.

**Figure 8.** Survival rates of \( \rho \) mesons from carbon (left) and lead (right) at \( k = 2.0 \) GeV taking into account the JLab kinematics [12] and the leptonic decay \( \gamma \rightarrow e^+e^- \). The meaning of the histograms and the fitted functions are the same as in figure 6.

The transparency ratios (TR) for \( \omega \) and \( \rho \) were calculated including the kinematics, VM decay modes and detection constraints of the experiments of Refs. [9, 12]. For the case of CB-ELSA/TAPS measurement [9], we took into account the realistic \( \omega \) photoproduction cross sections (figure 1) in the range of photon energies adopted in the experiment: \( 1.2 \leq k \leq 2.2 \) GeV. The initial photon energy was sorted considering that the photoproduction probability is proportional to the bremsstrahlung spectra \((\sim 1/k)\) times the total cross section given by the red histogram of figure 3. An average value of \( \langle k \rangle \approx 1.645 \) GeV was achieved using this procedure. After the choice of the photon energy, we divided the whole energy range \((1.2 \leq k \leq 2.2 \) GeV\) into 6 energy bins of 200 MeV and evaluate the corresponding \( j \)-index associated with our choice of \( k \). In the last step, we sample the vector meson polar angles according to the angular distribution associated with \( W^j \) (see figure 1). After the photoproduction step, the vector mesons are propagated thru the nuclear matter evaluating the probabilities for \( \omega N \) binary scatterings (elastic/inelastic) and for meson decay \((\omega \rightarrow \pi^0 \gamma)\) inside the nucleus. In the latter, we also include the possibility of a subsequent \( \pi^0 \) rescattering. With this prescription we end-up with an average \( \omega \) momentum close to 1.1 GeV/c for all targets.

For the case of JLab measurement [12] we have adopted a simpler approach that considers a monochromatic photon beam of 2.0 GeV that reproduces the average meson momentum of \( \sim 1.7 \) GeV for all targets.

The MCMC model reproduces with good accuracy the CB-ELSA/TAPS data [9] with \( C_{el} = C_{inel} = 1.3 \). This result suggests that the in-medium \( \omega N \) inelastic cross section should be in the range of \( \sim 40 \) mb (for \( p_N \approx 1.1 \) GeV/c) with a total in-medium width of \( \Gamma^* \approx 49.2 \) MeV/c\(^2\) for carbon (\( p_N \approx 0.114 \) fm\(^{-3}\)) and \( \Gamma^* \approx 77.3 \) MeV/c\(^2\) for lead (\( p_N \approx 0.137 \) fm\(^{-3}\)). In all cases, the average meson momentum obtained directly from the code was very close to 1.1 GeV/c (\( \langle p_\omega \rangle = 1.096 \) GeV/c (C), \( p_N \approx 1.092 \) GeV/c (Ca), \( p_N = 1.107 \) GeV/c (Nb) and \( p_N = 1.114 \) GeV/c (Pb)). The inelastic cross section so obtained is a factor two higher than our previous result [18] and this difference is related with three improvements in the current version:
i) the inclusion of the diffuseness nuclear parameter for intermediate and heavy nuclei [13], ii) the evaluation of the vector meson decay time uniquely in terms of the vacuum width, and iii) the inclusion of the joint ω photoproduction probability described before. In order to compare our current results for ω with our previous estimates [18], as well as with other approaches [9] it is necessary to match the nuclear density. Considering for instance a normal nuclear density of ρN ≃ 0.16 fm–3, we have Γ∗ ≃ 70 MeV/c2 for carbon and Γ∗ ≃ 90 MeV/c2 for lead. These results are ≃ 20 (carbon) to 50 % (lead) higher than our previous calculations [18] and a factor ≃ 1.8 lower than the result found in [9] (Γ∗ ≃ 140 MeV/c2).

![Figure 9](image_url)

**Figure 9.** Transparency ratios of ω mesons from CB-ELSA/TAPS (squares) [9] and JLab (circles) [12] experiments in comparison with the MCMC predictions for C_{el} = C_{inel} = 1.0 (dashed-dotted lines) and C_{el} = C_{inel} = 1.3 (solid lines). The error bars in CB-ELSA/TAPS data are the sum in quadrature of the statistical and the systematic uncertainties (3.5%) [9] of the experiment.

For the case of the JLab data [12], a much stronger ω absorption is observed and the cascade model cannot describe both datasets with the same parameters. In fact, one should expect that the JLab transparency ratios would be slightly higher than the CB-ELSA/TAPS measurements, since for the latter one has to take into account the π0 rescattering. In our previous analysis [18], we have proposed one possible explanation for the JLab data assuming a much higher ωN inelastic cross section (≃ 80 mb). However, the CB-ELSA/TAPS data are not compatible with this huge cross section and the discrepancy between the experimental results seems to be related with the analysis of the background in Ref. [12]. We argue that in order to solve this puzzle unambiguously the current nuclear models should try to describe the e⁺e⁻ invariant mass (IM) spectra of JLab for all targets simultaneously. The contributions of the ρ meson decay in the IM spectra of Ref. [12] were obtained by scaling separately for each target the acceptance-corrected BUU mass shapes [11]. A further investigation of all the competing processes [vector meson decays V → e⁺e⁻ (V ≡ ω, ρ and φ) and Dalitz decays (ω → π⁰e⁺e⁻, φ → π⁰e⁺e⁻ and φ → ηe⁺e⁻)] that contribute to the e⁺e⁻ IM spectra of JLab is currently underway and we expect new results shortly.

For the sake of completeness, figure 10 presents the TR for ρ meson assuming the Jlab kinematics/detection constraints [12]. As one would anticipate, the TR for ρ is much higher than for ω, since most of the mesons decay promptly inside the nucleus. It is worth-mentioning, however, that even for ρ the TR also depends on the inelastic ρN cross section and presents a
reduction of approximately 9% for $T_{\text{Pb}}/T_{\text{C}}$ when the couplings are increased from 1.0 to 1.3.

![Figure 10](image_url)

**Figure 10.** Transparency ratios of $\rho$ mesons from the MCMC model for $C_{\text{el}} = C_{\text{inel}} = 1.0$ (dashed line) and $C_{\text{el}} = C_{\text{inel}} = 1.3$ (solid line). The calculations assume the leptonic decay and JLab kinematics/detection constraints [12].

5. Conclusions and final remarks

The process of incoherent photoproduction of vector mesons off complex nuclei has been revisited with the MCMC model. The Monte Carlo algorithm provides a sophisticated framework to address possible in-medium changes of vector mesons produced at few GeV deep inside the nucleus. Differently from similar transport models that generally assume a Fermi momentum distribution for the bound nucleons, the time-dependent MCMC cascade allows the inclusion of realistic distributions from proton knock-out reactions [13]. This constrain is very important for light systems, since the mechanism of Pauli-blocking during photoproduction is strongly dependent on the initial momentum of the struck nucleon. Additionally, the cascade method propitiates the extraction of the in-medium decay width via the corresponding vector meson survival rate. This width represents the sum of the vacuum and the effective collisional width resulting from the interactions of the mesons with the bound nucleons. With this approach, the in-medium widths are not fixed and the effects of broadening depend on the peculiarities of the target nucleus.

The meson survival rates have two basic regimes that can be fitted by exponential functions. At early cascade stages, the argument of the exponential depends on $\Gamma^*$, while for longer interaction times it is governed by $\Gamma_0$. There are transition regions between the two regimes (figures 6, 7 and 8) where the mesons are supposed to probe lower densities and have a high probability of escaping from the nucleus.

The MCMC results reproduce the TR measurements of Ref. [9] assuming $C_{\text{el}} = C_{\text{inel}} = 1.3$ (left panel of figure 9). This result suggests an inelastic $\omega N$ cross section of $\sim 40$ mb with a corresponding in-medium width (nuclear rest frame) of $\sim 49.2$ MeV/$c^2$ for carbon ($\rho_N \approx 0.114$ fm$^{-3}$) and $\sim 77.3$ MeV/$c^2$ for lead ($\rho_N \approx 0.137$ fm$^{-3}$) for $\langle p_\omega \rangle \sim 1.1$ GeV/$c$. By matching the nuclear densities, these results are approximately 20 to 50% lower than our previous estimate [18] and a factor $\sim 1.8$ lower than the result found in [9].

On the other hand, the cascade model does not reproduce the severe $\omega$ absorption obtained at JLab [12] assuming the same inelastic cross section. This huge attenuation and the discrepancy between the TR from CB-ELSA/TAPS [9] and JLab [12] remains a challenge. One could tentatively attribute this absorption to a destructive $\omega - \rho$ interference in the leptonic decay $V \to e^+e^-$, but it would be necessary a further investigation of the leptonic background in the $e^+e^-$ IM spectra from Jlab data before any definite conclusion. This background is dominated by $\rho$ decay and the MCMC model represents a sophisticated candidate to solve this puzzle in the near future.
Considering $C_{\text{el}} = C_{\text{inel}} = 1.3$ and the JLab kinematics [12], we found a total $\omega$ in-medium width of $\approx 49.3$ MeV/$c^2$ for carbon and $\approx 79.8$ MeV/$c^2$ for lead. With these same parameters we found a total in-medium width of $\approx 109.2$ MeV/$c^2$ (carbon) to $\approx 139.6$ MeV/$c^2$ (lead).

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