NUCLEAR TRANSPARENCIES IN RELATIVISTIC $A(e,e'p)$ MODELS

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The nuclear transparencies extracted form $A(e,e'p)$ reactions are computed within the frameworks of the relativistic distorted-wave impulse appoximation (RDWIA) and relativistic multiple-scattering Glauber approximation (RMSGA). Despite the fact that the RMSGA and RDWIA models adopt distinctive assumptions to quantify the effect of final-state interactions (FSI), they predict comparable nuclear transparencies in an overlapping kinematic regime in which both frameworks are deemed realistic.

The transparency of a medium to the propagation of one of its constituents is a topic of interest in many branches of physics. Hadron physics is no exception to this. The nuclear transparency to protons provides a measure of the probability that a proton of a certain energy escapes from the nucleus without any further interactions. It is a useful quantity for studying nuclear medium effects, and in particular, it is very well suited for investigations of the so-called color transparency (CT) phenomenon. CT predicts a significant enhancement of the transmission of protons through nuclei once QCD mechanisms start playing a role. The CT phenomenon is esteemed as a good lever to determine the limits of the meson-nucleon description and to infer at what distance scales a QCD-based description of the nucleus becomes substantially more straightforward.

Due to the wide range of proton kinetic energies T_p which are probed in the present-day experiments, the prediction of the nuclear transparency in $A(e,e'p)$ processes poses a serious challenge for models. For the ^{12}C target nucleus, for example, the data cover a range $0.15 \leq T_p \leq 4$ GeV [1]. For kinetic energies up to about 1 GeV, $A(e,e'p)$ calculations have traditionally been performed in a DWIA model. Thereby, the many-body mechanisms stemming from the effect of the medium on the emerging nucleon, are computed by means of proton-nucleus optical potentials. Parameterizations for relativistic potentials are not readily available for proton kinetic energies T_p beyond 1 GeV. Beyond

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this energy, the Glauber model, which is a multiple-scattering extension of the eikonal approximation, offers a valid and economical alternative for describing FSI. In a Glauber framework, the effects of FSI on the $A(e,e'p)$ observables are computed directly from the proton-nucleon scattering data. The Glauber method postulates linear trajectories and frozen spectator nucleons, and the lower limit of this treatment to $A(e,e'p)$ has not yet been established.

Here, we report on relativistic and unfactorized calculations for the nuclear transparency extracted from exclusive $A(e,e'p)$ reactions. In Ref. [2] results are presented for four-momentum transfers $0.3 \leq Q^2 \leq 10$ (GeV/c)^2 and the target nuclei C, Si, Fe and Pb. For $Q^2 \geq 0.6$ (GeV/c)^2 (or, $T_p \geq 0.3$ GeV), the transparency results are computed within the framework of the relativistic multiple-scattering Glauber approximation (RMSGA) [3]. The RDWIA calculations adopt the model outlined in Ref. [4] and cover all energies up to $Q^2 \leq 2$ (GeV/c)^2 (or, $T_p \leq 1$ GeV). Interestingly, there is substantial kinematic range for which both relativistic models can provide predictions. This allows one to investigate whether the transition between the typical low-energy and high-energy descriptions of FSI mechanisms is a smooth one. In order to make the comparisons between the RDWIA and RMSGA transparency predictions as meaningful as possible, all the ingredients in the $A(e,e'p)$ calculations not related to FSI, as those concerning the implementation of relativistic dynamics and nuclear recoil effects, are kept identical. In particular, for the results presented here both pictures use the relativistic bound-state wave functions from a Hartree calculation in the "W1" parameterization of the $\sigma\omega$-model. Further, all the results are obtained within the Coulomb gauge with the so-called $CC2$ current operator.

The nuclear transparency is extracted from the measured $A(e,e'p)$ differential cross sections $d^5\sigma^{exp}(e,e'p)$ starting from

$$T_{exp}(Q^2) = \frac{\int_{\Delta^3 p_m} d\vec{p}_m \int_{\Delta E_m} dE_m \; S_{exp}(\vec{p}_m, E_m, \vec{p}_F)}{c_A \int_{\Delta^3 p_m} d\vec{p}_m \int_{\Delta E_m} dE_m \; S_{PWIA}(\vec{p}_m, E_m)} \; . \tag{1}$$

Here, S_{exp} is the experimentally determined reduced cross section

$$S_{exp}(\vec{p}_m, E_m, \vec{p}_F) = \frac{\frac{d^5\sigma^{exp}}{d\Omega_p d\epsilon' d\Omega_{\epsilon'}}(e,e'p)}{K\sigma_{ep}}, \tag{2}$$

where K is a kinematical factor and σ_{ep} is the off-shell electron-proton cross section. The quantities $\Delta^3 p_m$ and ΔE_m specify the phase-space volume in the missing momentum and energy and are commonly defined by the cuts $|p_m| \leq 300$ MeV/c and $E_m \leq 80$ MeV. These kinematic cuts, in combination with the requirement that the Bjorken variable $x = \frac{Q^2}{2M_p\omega} \approx 1$, guarantee that the electro-induced proton-emission process is predominantly quasi-elastic. For example, the effects of two-body meson-exchange and isobar currents, which are neglected within the impulse approximation, have been shown to be at the percent level for quasi-elastic kinematics.

In the above equation, S_{PWIA} denotes the reduced cross section within the plane-wave impulse approximation (PWIA). The factor c_A in the denominator of Eq. (1) has been introduced to correct for short-range mechanisms and is assumed to be moderately target-mass dependent. It accounts for the fact that short-range correlations move a fraction of the single-particle strength beyond the ranges covered in the integrations $\int d\vec{p}_m \int dE_m$

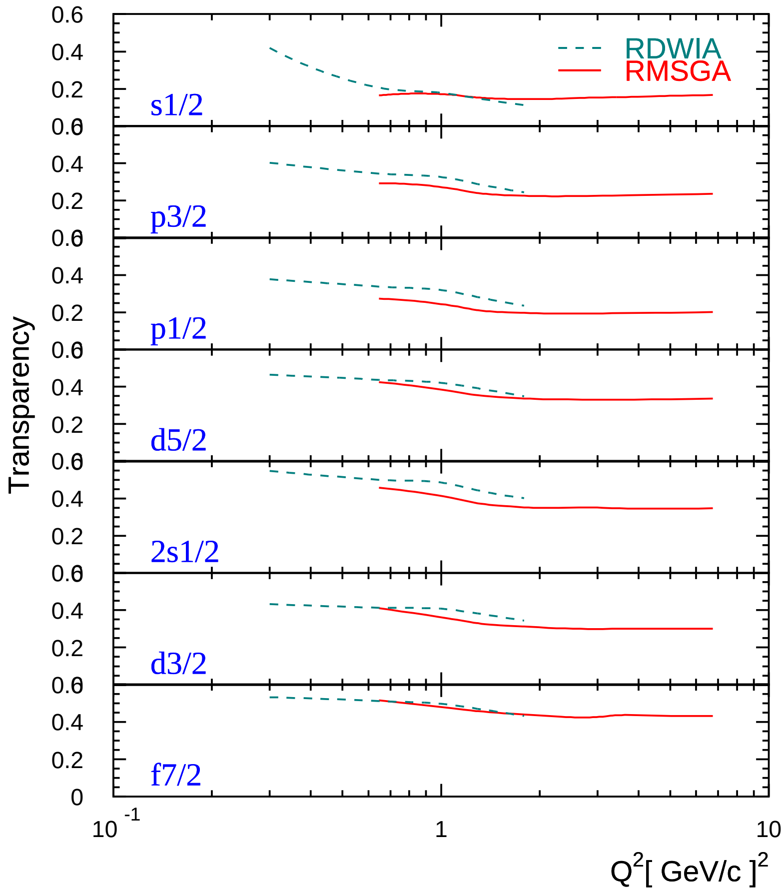

Figure 1. The Q^2 dependence of the computed nuclear transparency for the proton levels in ^{56}Fe as obtained in the RDWIA (dashed line) and RMSGA (solid line) approach.

of Eq. (1). The values for c_A which are adopted to extract the transparency from the $A(e,e'p)$ measurements are 0.9 (^{12}C), 0.88 (^{28}Si), 0.82 (^{56}Fe) and 0.77 (^{208}Pb).

Theoretically, the nuclear transparencies are extracted from the computed relativistic $A(e,e'p)$ angular cross sections for the individual single-particle states, according to

$$T_{theo}(Q^2) = \frac{\sum_\alpha \int_{\Delta^3 p_m} d\vec{p}_m S^\alpha(\vec{p}_m, E_m, \vec{p}_F)}{c_A \sum_\alpha \int_{\Delta^3 p_m} d\vec{p}_m S^\alpha_{PWIA}(\vec{p}_m, E_m)} \,. \tag{3}$$

This expression reflects the one used to determine T_{exp}. Indeed, we obtain the "theoretical" transparencies by adopting identical expressions and cuts as in the experiments. Essentially, we replace the measured $A(e,e'p)$ angular cross sections by the computed ones. In addition, the integration over the missing energy $\int_{\Delta E_m} dE_m$ has been substituted by a sum over all occupied shells ($\sum_\alpha$) in the ground state of the target nucleus. Indeed, the relativistic Hartree approximation does predict bound-state eigenfunctions with a fixed energy-eigenvalue and zero width. When determining the denominator in Eq. (3), in our calculations the PWIA limit is accomplished by nullifying all sources of FSI mechanisms and neglecting those contributions introduced by the presence of negative-energy components in the relativistic bound nucleon wave function.

The target-mass and Q^2 dependence of the RMSGA predictions are compared with relativistic distorted-wave impulse approximation (RDWIA) calculations in Ref. [2]. Despite the very different model assumptions underlying the treatment of the final-state interactions in the RMSGA and RDWIA frameworks, they predict comparable nuclear transparencies for kinematic regimes where both models are applicable. Investigating the attenuation for each individual shell in the target nucleus allows one to study the radial dependence of the FSI mechanisms. The attenuation for the individual states represents also a more stringent test of the (non-)similarity of the optical-potential and Glauber-based models for describing proton propagation through nuclei. In Fig. 1, the RMSGA and RDWIA predictions for the attenuation for the individual shells in ^{56}Fe are compared. These numbers are computed according to the definition of Eq. (3) without performing the sum over the states α. As expected, both models predict a stronger attenuation for proton emission from a level which has a larger fraction of its density in the nuclear interior. The results illustrate that the proton-nucleus (RDWIA) and the proton-nucleon (RMSGA) picture are not dramatically different in their predictions. These findings provide us additional confidence that when computing the effect of FSI mechanisms in a relativistic framework, the "low-energy" and "high-energy" regime can be bridged in a relatively smooth manner.

In conclusion, fully relativistic calculations for the nuclear transparency for the process $e + A \rightarrow e' + (A-1) + p$ are presented. An optical-potential approach has been used up to the highest kinetic energy ($T_p \approx 1$ GeV) for which potentials are readily available. Beyond that region we gathered our results within the context of a relativized and unfactorized Glauber framework. In a medium-Q^2 range, both models have been applied and their predictions compared. Both frameworks accomodate relativistic effects in the bound-state and scattering wave functions, as well as in the electromagnetic current operator. Despite the very different assumptions underlying the description of FSI effects in an optical-potential and Glauber based approach to $A(e, e'p)$, their predictions for the nuclear transparency and, in general, the effect of attenuation for different single-particle levels, are comparable.

REFERENCES

1. K. Garrow et al., Phys. Rev. C 66 (2002) 044613.
2. P. Lava, M.C. Martínez, J. Ryckebusch, J.A. Caballero, J.M. Udías, Phys. Lett. B 595 (2004) 177.
3. J. Ryckebusch, D. Debruyne, P. Lava, S. Janssen, B. Van Overmeire, and T. Van Cauteren, Nucl. Phys. A 728 (2003) 226.
4. J.M. Udias, J.A. Caballero , E. Moya de Guerra, J.R. Vignote, A. Escuderos, Phys. Rev. C 64 (2001) 024614.