Eur. Phys. J. A **31**, 585–587 (2007)
DOI 10.1140/epja/i2006-10227-1

THE EUROPEAN PHYSICAL JOURNAL A

Special Article – QNP 2006

The transparency of nuclei to nucleons and pions in a relativistic Glauber approximation

J. Ryckebusch[a], W. Cosyn, B. Van Overmeire, and C. Martínez[b]

Ghent University, Ghent, Belgium

Received: 8 November 2006
Published online: 8 March 2007 –

Abstract. We present a selection of results obtained within the context of a relativistic eikonal model. First, results of relativistic Glauber calculations for the nuclear transparency extracted from photon-induced pion production are presented. Second, computed differential cross-sections for the ^{12}C$(p, 2p)$ are compared to data.

PACS. 24.10.Jv Relativistic models – 11.80.-m Relativistic scattering theory – 25.40.-h Nucleon-induced reactions – 25.20.Lj Photoproduction reactions

1 Introduction

Electron scattering facilities like Jefferson lab probe nuclei at the femtometer and sub-femtometer scale and provide observables to look for deviations from predictions of models based on traditional nuclear physics. The interpretation of those experiments heavily depends on the availability of traditional nuclear-physics models which can compute the attenuation of fast nucleons and pions when they travel through nuclei. The ultimate goal of many experiments involving nuclei is mapping the transition from the non-perturbative (mesons and hadrons) to the perturbative (quarks and gluons) regime of QCD.

In this short report, a selection of results obtained with a relativistic extension to Glauber multiple-scattering theory is presented. The framework is dubbed the relativistic multiple-scattering Glauber approximation (RMSGA). The RMSGA model allows to compute the probability that a high-energy nucleon or pion will escape from an excited finite nucleus. The RMSGA model provides a unified framework to compute nuclear transparencies as they can for example be extracted from $A(e, e'p)$, $A(p, 2p)$, $A(p, pn)$ and $A(\gamma, \pi N)$ reactions. Here we concentrate on those channels with two hadrons in the final state.

2 Relativistic multiple-scattering Glauber approximation

Glauber theory is an exactly solvable multiple-scattering framework which allows one to compute the attenuation effects on an energetic particle when it moves through a medium. The framework is valid under circumstances whereby, $\lambda < r_s < R$, with λ the wavelength of the particle, R the radius of the medium and r_s the typical interaction range between the energetic particle and the spectator particles in the target nucleus. The RMSGA framework introduced in ref. [1] is a relativistic extension of the Glauber model. It adopts the mean-field approximation with bound-state wave functions from the Serot-Walecka model. The framework involves an involving multiple integral which tracks the effect of all collisions of an energetic nucleon or pion with the remaining nucleons in the target nucleus. Thereby, each of the target nucleons acts as a scattering center and is represented by its own relativistic wave function.

3 Results and discussion

First, results of RMSGA calculations for the ^{4}He$(\gamma, \pi^- p)$ reaction are presented. Second, we turn to $A(p, pN)$ which pose a real challenge to models, as they involve three nucleons subject to attenuation effects.

At Jefferson Lab there are ongoing efforts to measure transparencies in $A(\gamma, \pi^- p)$ and $A(e, e'\pi^+ n)$. The combined presence of a pion and a nucleon in the final state will enhance non-perturbative QCD mechanisms, like color transparency (CT). There is one published result from experiment E91013 [2] for ^{4}He$(\gamma, \pi^- p)$ for $1.6 \leq E_\gamma \leq 4.5$ GeV and $\theta_\pi^{c.m.} = 70, 90°$. The choice for ^{4}He as target is considered to optimize medium effects. Not only is it a dense system, the ratio of the hadron formation length to the nuclear radius is large. In ref. [2] the data

[a] e-mail: jan.ryckebusch@rug.ac.be
[b] *Present address:* Universidad Complutense, Madrid, Spain.

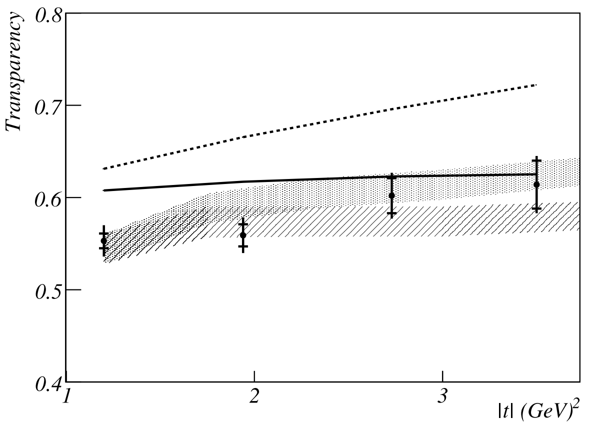

Fig. 1. The nuclear transparency extracted from ^{4}He$(\gamma, p\pi^-)$ *versus* the squared momentum transfer $\mid t \mid$ at $\theta^{\pi}_{c.m.} = 90°$. The solid (dashed) curve is the result of the RMSGA calculations without (with) color transparency. The semi-classical model [3] results are presented by the shaded areas: the hatched (dotted) area is a calculation without (with) CT. Data from [2].

are compared with calculations within the context of the semi-classical transport model by Gao, Holt and Pandharipande [3]. An improved description of the data was obtained after including CT effects. We have developed a quantum-mechanical and relativistic framework to extract nuclear transparencies from $\gamma + A \longrightarrow A-1+N+\pi$ reactions. In contrast to the semi-classical models, in the RMSGA model the effect of final-state interactions (FSI) is treated at the amplitude level. Every nucleon in the forward path of the outgoing N and π adds a phase to their respective wave function. Technically, this is achieved by means of the following Glauber phase operator ($\boldsymbol{r}(\boldsymbol{b}, z)$):

$$\mathcal{S}_{\mathrm{FSI}}(\boldsymbol{r}, \boldsymbol{r}_2, \ldots, \boldsymbol{r}_A) = \prod_{j=2}^{A} \left[1 - \Gamma_{N'N}(\boldsymbol{b} - \boldsymbol{b}_j)\theta(z - z_j)\right] \times \left[1 - \Gamma_{\pi N}\left(\boldsymbol{b}'\left(\boldsymbol{b}, z\right) - \boldsymbol{b}'_j\left(\boldsymbol{b}_j, z_j\right)\right)\theta(z' - z'_j)\right].$$

The numerical computation of the effect of the above Glauber phase operator requires knowledge about $\pi N \to \pi N$ and $N'N \to N'N$ cross-sections, as well as a set of relativistic mean-field wave functions for the target nucleus. There are no free parameters to tune. The above-mentioned procedure results in involving multi-dimensional integrals which are performed numerically. The effect of CT is implemented through the model of ref. [4]. In fig. 1 we present results of our transparency calculations together with data and the predictions of the semi-classical model of ref. [3]. The parameters used to compute the CT are such that they maximize (or even, overestimate) the effect. The computed RMSGA nuclear transparencies are systematically about 10% larger than the semi-classical results. The RMSGA predictions overestimate the measured transparancies at small $\mid t \mid$ but do reasonably well for the higher values of $\mid t \mid$. It is clear that $\mid t \mid$ defines the hard scale and that CT mechanisms grow with this parameter.

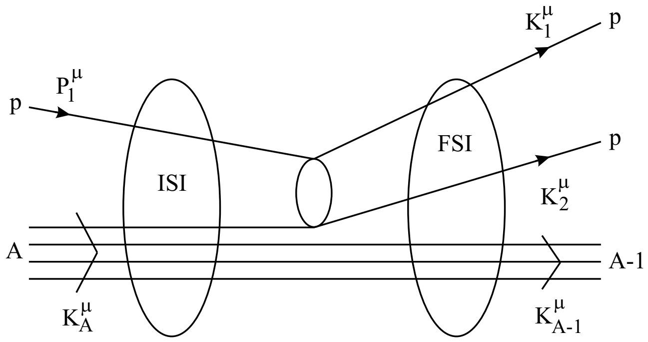

Fig. 2. Schematic representation of the $A(p, 2p)$ reaction. The incoming proton undergoes "soft" initial-state interactions with the target before knocking out a bound proton through the primary high-momentum-transfer pp scattering. Both the scattered and the ejected proton are subject to final-state interactions while leaving the nucleus. The scattered and the ejected proton are detected in coincidence.

As a second type of reaction which can be treated within the context of the relativistic eikonal approximation, we consider $A(p, pp)$ and $A(p, pn)$. A sketch is shown in fig. 2. We consider quasielastic processes: the impinging proton scatters from a single bound nucleon in the target and knocks it out of the target. The "hard" nucleon-nucleon collision is obscured by the "soft" initial- and final-state interactions (IFSI) of the incident and two outgoing nucleons with the nuclear medium. We adopt the cross-section factorized form for the $A(p, pN)$ cross-section

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}E_{k1}\mathrm{d}\Omega_1\mathrm{d}\Omega_2} \approx \frac{sM_{A-1}}{M_p M_A}\frac{k_1 k_2}{p_1} f_{rec}^{-1}\, \rho^D_{\alpha_1}\left(\boldsymbol{p}_m\right)\left(\frac{\mathrm{d}\sigma^{pp}}{\mathrm{d}\Omega}\right)_{\mathrm{c.m.}},$$

where, p_1 is the momentum of the incident proton, (k_1, k_2) those of the two ejectiles and α_1 the quantum number of the bound nucleon on which the hard scattering takes place. In computing $\rho^D_{\alpha_1}$ we consider phase factors from the two ejected nucleons and the impinging proton. Very often, in $A(p, pN)$ reactions one faces situations in which one of the ejectiles is relatively slow and a Glauber multiple-scattering approach is not applicable. To this end, our theoretical framework provides the flexibility to adopt an optical potential and a Glauber approach within the context of the relativistic eikonal approximation. Besides the RMSGA, this gives rise to the so-called relativistic optical model eikonal approximation (ROMEA).

The PNPI $A(p, pN)$ experiments [5] were carried out with an incident proton beam of energy 1 GeV. The scattered proton was detected at $\theta_1 = 13.4°$ with a kinetic energy between 800 and 950 MeV, while the knocked-out nucleon N was observed at $\theta_2 = 67°$ having a kinetic energy below 200 MeV.

Figure 3 displays differential cross-sections for ^{12}C$(p, 2p)$ as a function of the kinetic energy of the most

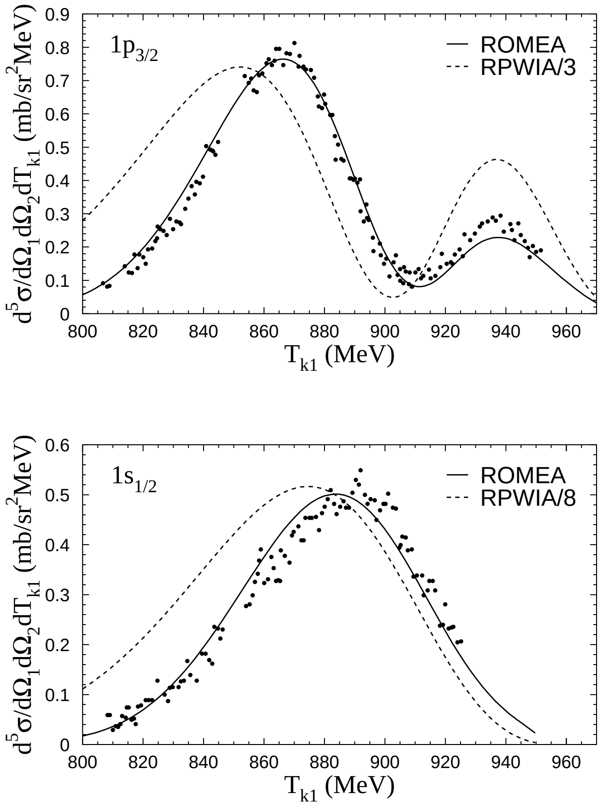

Fig. 3. Differential cross-sections for the ^{12}C$(p,2p)$ reaction. The solid curve represents the ROMEA calculation, whereas the dashed curve is the plane-wave result reduced by the indicated factor. The ROMEA results are normalized to the data. Data points are from ref. [5]. The magnitude of the experimental error bars is estimated to be of the order of 5–10%.

energetic nucleon in the final state. The EDAI optical potential [6] was used for the ROMEA calculations. The RMSGA approach fails to give an adequate description of the data because of the low kinetic energy of the ejected nucleon. Since the experiment of ref. [5] only measured relative cross-sections, the ROMEA results were normalized to the experimental data.

The ROMEA calculations reproduce the shapes of the measured differential cross-sections. Furthermore, comparison of the relativistic plane-wave impulse approximation (RPWIA) and the ROMEA calculations shows that the effect of the IFSI is twofold. First, IFSI result in a reduction of the RPWIA cross-section that is both level and A-dependent. From fig. 3 it is clear that ejection of a nucleon from a deeper-lying level leads to stronger initial- and final-state distortions. This reflects the fact that the incoming and outgoing nucleons encounter more obstacles when a deeper-lying bound nucleon is probed. Besides the attenuation, the IFSI also make the measured missing momentum different from the initial momentum of the struck nucleon.

4 Conclusions

A relativistic eikonal framework to model the propagation of fast nucleons and pions through the nuclear medium has been developed. The framework adopts a mean-field approach to determine the wave functions of the bound nucleons and can be applied to even-even target nuclei with $A \geq 4$. Relativity is accommodated in both the dynamics and the kinematics of the reactions under study. The effect of FSI can be computed with the aid of optical potentials or in the Glauber approach. The model provides a common framework to describe a variety of nuclear reactions with electroweak and hadronic probes. A profound study [7] of nuclear transparencies extracted from $A(e,e'p)$ processes taught that there is a relatively smooth transition between the typical low-energy optical-potential description of FSI and the high-energy Glauber approach. This conclusion was drawn on the basis of comparable transparency predictions in an intermediate-energy regime where both models can be considered realistic.

In this contribution, results for the ^{4}He$(\gamma,\pi^{-}p)$ and the ^{12}C$(p,2p)$ are presented. The computed transparencies for photon-induced pion production ^{4}He$(\gamma,\pi^{-}p)$ are larger than those from semi-classical models. The model has been extended to electroproduction processes for comparison with the forthcoming data from Jefferson lab. The relativistic eikonal method has also been applied to $A(p,pN)$ reactions. With three nucleons subject to attenuation effects, this reaction provides an excellent testing ground for the adopted assumptions. A fair description of the data for quasielastic proton scattering from ^{12}C, ^{16}O, and ^{40}Ca at 1 GeV and ^{4}He$(p,2p)$ at 250 MeV is obtained [8]. The model has also been used to study $A(p,2p)$ transparencies at high energies [9].

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