Photon and Electron induced Particle Production on Nuclei *

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1. Introduction

Photon and electron induced production reactions on nuclei are of particular interest. First of all, these probes are elementary and non-hadronic and allow therefore in principle to obtain information about the whole nuclear volume. Moreover, looking at different production channels, different fields of physics are covered. To give a few examples, meson photo- and electroproduction at lower energies tells about the in-medium properties of nucleon resonances \[1,2\]. Electron induced nucleon knockout reactions are closely linked to the nucleon spectral function \[3–5\] and also might give experimental evidence of color transparency (see e.g. \[6\]). In this text we want to give an overview over such reactions that can be described in our semiclassical BUU transport model.

2. The Model

2.1. Description of Photon and Electron induced Processes

In the usual one-photon exchange approximation electron induced reactions can be treated theoretically in essentially the same way as photon induced reactions. We assume that the photon (real or virtual) is absorbed by a single nucleon inside the nucleus. This reaction is described by the elementary cross sections, which in both cases actually only differ from each other by an extra flux factor describing the electron vertex. The particle content of the final states of this elementary reaction varies with increasing photon energy from nucleon resonance excitation and single/double pion production at lower photon energies, vector meson and strangeness production at larger energies. The relative importance of these channels is given by the ratios of the corresponding cross sections. At high energies, where more and more multiparticle channels open which have not been measured experimentally, we use the string fragmentation model FRITIOF \[7\].

It is clear that these particles – being produced somewhere inside the nucleus – are subject to final state interactions (FSI) due to the nuclear surrounding and therefore the reliability of calculations of particle production cross sections on nuclei depends crucially on how the FSI are treated. The BUU model includes besides particle scattering and absorption also ’side-feeding’ effects, contrary to other models (e.g. Glauber models).

The cross section for production reactions on nuclei in our model is given by folding

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the cross sections of the elementary reaction on the nucleon and the multiplicity of the particles under consideration reaching the detector and an incoherent summation of the contributions from all nucleons in the nucleus [2].

2.2. The BUU Model

The model is based upon the BUU equation, which for a system of nucleons is given by

\[
\frac{\partial}{\partial t} f(\vec{r}, \vec{p}, t) + \frac{\partial H}{\partial \vec{p}} \vec{\nabla}_r f(\vec{r}, \vec{p}, t) - \frac{\partial H}{\partial \vec{r}} \vec{\nabla}_p f(\vec{r}, \vec{p}, t) = I_{coll}[f].
\]

(1)

Here \( f \) and \( H \) denote the nucleon phase space density and the mean-field Hamilton function of the system, respectively. The left-hand side set to zero yields the Vlasov equation, which gives a sufficient description of the space-time evolution of a system of non-interacting particles. For a proper consideration of interactions amongst the particles on the right-hand side a so-called collision integral is introduced. Besides the nucleon our model contains a lot of other particle species, the most important being nucleon resonances (\( P_{33}(1232) \), \( P_{11}(1440) \), \( D_{13}(1520) \), \( S_{11}(1535) \)) and mesons (\( \pi, \eta, \rho, K \)) (for a review of the model see [2]). For each of these species a BUU equation is introduced, which are coupled to each other via the collisional integrals due to interactions between each other. The usual method to solve the resulting set of coupled integral-differential equations is to make a so-called test particles ansatz for the phase space density \( f \)

\[
f(\vec{r}, \vec{p}) = \frac{1}{N} \sum_i \delta(\vec{p} - \vec{p}_i) \delta(\vec{r} - \vec{r}_i).
\]

(2)

For the propagation of the test particles this ansatz gives the classical equations of motion

\[
\dot{\vec{r}}_i = \vec{\nabla}_p H, \quad \dot{\vec{p}}_i = -\vec{\nabla}_r H.
\]

(3)

3. Results

3.1. Meson Production

Pion and eta production in the nucleon resonance region was calculated and discussed in detail in [3]. The applicability of the model extends also to larger photon energies. However, for \( E_\gamma > 1 \text{ GeV} \) the so-called shadowing effect has to be taken into account. Since this is a coherence effect, it cannot be simulated in a semi-classical transport model. In [3] a procedure was developed to combine the description of these initial state interactions in the Glauber framework with the usual BUU model. Also the calculation of meson photoproduction at GeV energies can be found there.

3.2. Electron induced Nucleon Knockout

The electron induced nucleon knockout from nuclei (for a review see e.g. [9]) is of special interest since it might give experimental evidence for color transparency. The data from SLAC [10] and TJNAF [11] show the so-called transparency ratio which is given by the ratio of the number of protons measured close to the direction of the exchanged virtual photon and the expected number of protons in the absence of FSI. Our model is capable

\(^2\text{BUU=Boltzmann, Uehling, Uhlenbeck}\)
Figure 1. $T$ as a function of $Q^2$. The data are from [10] (solid) and [11] (open).

to provide both numbers consistently without further assumptions concerning the latter number. The transparency ratio was also calculated by other models in the past (see e.g. [6,12] and references therein).

In Fig. 1 we show our results for $T$ as a function of the momentum transfer $Q^2$. For both nuclei Fe and Au we obtain very good agreement with the data. Future work will also cover the region of larger $Q^2$ than available in the experiments of [10,11], where an onset of color transparency is expected and consequently an enhancement of $T$ towards one. Moreover, the influence of the nucleon spectral function on $T$ will be investigated.

3.3. Nucleon Spectral Function and Subthreshold Particle Production

Nucleons in nuclei may be off their mass shell in the nuclear groundstate due to short-range correlations (see e.g. [3–5]). Calculations of the nucleon spectral functions show that these groundstate correlations manifest themselves e.g. in the momentum distribution. The Thomas-Fermi momentum distribution (usually used by transport models to initialize the nucleon phase space density in momentum space) is a step function $\Theta(p_F-p)$.

The effect of the short-range correlations is that some strength ($\sim 10\%$) is moved from momenta below $p_F$ to momenta above $p_F$.

The presence of short-range correlations has an influence on the particle production close to threshold. This can be seen in Fig. 2, where the center-of-mass energy distribution for the $\gamma N$ system involving all nucleons in Calcium is shown for $E_\gamma = 0.8$ GeV. The solid curve shows the distribution caused by usual Fermi motion involving on-shell nucleons. The dashed distribution, involving the full nucleon spectral function, is more smeared out and exhibits contributions for $\sqrt{s}$ larger than the maximal value of $\sqrt{s}$ expected in the Thomas-Fermi model. This is the region responsible for subthreshold particle production effects. In order to perform such calculations, our model has to be modified, because the nucleon phase space density has to be initialized differently than usual and the off-shellness of the nucleons evolves during the reaction. The latter fact is reflected in a modification of the equations of motion for the test particles. A theoretical discussion of
Figure 2. CM energy distribution of $\gamma N$ pairs in $^{40}$Ca for $E_{\gamma} = 0.8$ GeV.

these issues and a derivation of the modified equations of motion can be found in [13]. A numerical implementation of off-shell nucleons in our transport model for the description of heavy ion reactions was developed in [14] and will also used as a basis for future work on the description of subthreshold photoproduction.

4. Summary and Outlook

We have presented several examples for the calculation of inclusive particle production on nuclei within our semi-classical BUU transport model. Future work will cover the extension of our calculations of $(e, e'p)$ to larger $Q^2$ and photon induced reactions involving the nucleon spectral function.

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