

RECENT ADVANCES IN QUASIELASTIC CHANNEL IN NuWro MONTE CARLO EVENT GENERATOR*

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In this proceedings contribution, I summarize recent developments of the spectral function approach implemented in the NuWro Monte Carlo event generator. The modified framework provides a consistent treatment of multinucleon final states in quasielastic scattering. The model is first validated using inclusive electron–carbon scattering data and then applied to the exclusive MicroBooNE measurements. I demonstrate that the implemented improvements play a crucial role in reproducing both the shapes and normalizations of the experimental data.

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1. Introduction

The current and upcoming generations of accelerator-based neutrino oscillation experiments [1, 2] aim to accurately determine the oscillation parameters. In these setups, uncertainties associated with neutrino–nucleus interaction modeling constitute a leading source of systematic error. Since neutrinos interact with bound nucleons, nuclear effects such as Fermi motion, nucleon correlations, and final-state interactions (FSI) distort the observable final states used for energy reconstruction.

Monte Carlo (MC) event generators provide the essential link between theoretical models and experimental observables. Among them, NuWro is used worldwide in various experiments.

In this proceedings contribution, I summarize recent developments of the spectral-function (SF) approach in NuWro, focusing on a consistent treatment of multinucleon final states in quasielastic (QE) scattering [3]. We

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give special attention to the argon nucleus, motivated by the short baseline programs at Fermilab such as SBND [4], MicroBooNE [5], ICARUS [6], and upcoming experiments such as DUNE [2].

2. NuWro

NuWro [7] is an MC event generator designed to simulate lepton–nucleus interactions. It covers an energy range from a few hundred MeV to a few hundred GeV. It has been developed since 2004 by the Neutrino Theory Group at the University of Wrocław. The current NuWro version, tagged as version 25.11, is available on [GitHub](#).

In the QE channel, NuWro has several nuclear models to choose from, such as different Fermi gas models or an SF description of the nuclear ground state.

Recent developments in NuWro have focused on improving the SF framework beyond the plane-wave impulse approximation (PWIA) toward a more physical description of the nuclear final state [3]. In particular, updates relevant for this contribution include the inclusion of a state-of-the-art spectral function for argon, and the incorporation of nuclear effects such as Coulomb corrections and FSI.

2.1. JLab spectral functions

The recent NuWro version includes the argon SF which has become available from electron scattering experiments performed in Hall A at Jefferson Laboratory, Newport News, Virginia. Using a 2.222 GeV electron beam, ($e, e'p$) data were collected for argon [8, 9] and titanium [10] targets, allowing for the extraction of proton spectral functions over a wide range of removal energy and missing momentum.

The nucleon spectral function $P(p, E)$ is defined as the joint probability distribution of removing a nucleon with momentum p from the nucleus, and leaving the residual system with excitation energy E . The mean-field component of the SF is associated with nuclear shell structure, and the correlated component arising from short-range correlations (SRC) generates high-momentum and high-removal energy tails.

In NuWro, the experimentally extracted proton SF for argon is implemented, see Ref. [11]. Since neutron spectral functions cannot be measured directly in experiments, the neutron SF for argon is constructed using the proton SF of titanium. The process utilizes mirror symmetry between the proton states in titanium and the neutron states in argon, with the necessary corrections [12].

2.2. Short-range correlations

Short-range nucleon–nucleon correlations give rise to high-momentum and high-removal energy components of the SF that are absent in mean-field descriptions. The total distribution is decomposed into mean field (MF) and correlated components

$$P(p, E) = P_{\text{MF}}(p, E) + P_{\text{corr}}(p, E). \quad (1)$$

For argon, the correlated SF is modeled assuming that the dynamics of the correlated nucleon pair is largely decoupled from the residual ($A - 2$) system [13]. Following this approach, it can be written as a convolution of the relative and center-of-mass momentum distributions of a pn pair [14]

$$P_{\text{corr}}(p, E) = \int d^3h \delta(E - E_{\text{thr}} - T_{A-1}) \times n_{\text{cm}}(|\mathbf{p} + \mathbf{h}|) n_{\text{rel}}\left(\left|\frac{\mathbf{p} - \mathbf{h}}{2}\right|\right), \quad (2)$$

where \mathbf{p} and \mathbf{h} denote the momenta of the struck nucleon and its correlated partner, respectively. Here, E_{thr} is the two-nucleon emission threshold and T_{A-1} is the recoil kinetic energy of the residual system.

When a QE interaction occurs on a nucleon belonging to the correlated part of the SF, a second nucleon is associated with the primary vertex. A distinctive feature of our implementation is that the correlated SF is used not only to weight the cross section, but also to sample the kinematics of the second nucleon. The resulting momentum distributions show that the correlated nucleon pairs are not strictly back-to-back. Instead, the combined effects of the relative and center-of-mass motion of the pair lead to complex dynamics [3].

2.3. Coulomb corrections

The Coulomb field of the nucleus modifies the kinematics of charged particles. In NuWro, this effect is implemented using the modified effective momentum approximation (EMA') [15]. The charged lepton experiences an average electrostatic potential V_C within the nucleus [16], which modifies its energy and momentum at the interaction vertex. The charged-lepton energy is replaced by

$$E_\ell \rightarrow E_\ell^{\text{eff}} = E_\ell + s V_C, \quad (3)$$

where $s = +1(-1)$ for neutrino(antineutrino)-induced reactions [17].

Coulomb effects also induce a focusing of the charged-lepton wave function which modifies the Mott cross section. This is applied by multiplying the cross section by a focusing factor

$$\left(\frac{|\mathbf{k}_\ell^{\text{max}}|}{|\mathbf{k}_\ell^{\text{eff}}|}\right)^2, \quad (4)$$

where

$$|\mathbf{k}_\ell^{\max}| = \sqrt{(E_\ell + s V_C^{\max})^2 - m_\ell^2} \quad (5)$$

corresponds to the lepton momentum evaluated at the Coulomb potential V_C^{\max} of the nuclear center with m_ℓ denoting the charged lepton mass.

2.4. Final-state interactions

After the primary QE interaction, the struck nucleon propagates through the nuclear medium and may undergo further reinteractions with the spectator system. Within the SF framework, FSI effects are implemented in NuWro using the convolution scheme [18]. The cross section including FSI is obtained by folding the PWIA result with a function describing interactions between the struck nucleon and the residual nucleus,

$$\frac{d\sigma_{\text{FSI}}}{d\omega d\Omega} = \int d\omega' f_q(\omega - \omega') \frac{d\sigma_{\text{PWIA}}}{d\omega' d\Omega}, \quad (6)$$

where

$$f_q(\omega) = \sqrt{T_A} \delta(\omega) + (1 - \sqrt{T_A}) F_q(\omega), \quad (7)$$

T_A is the nuclear transparency [19, 20] and $F_q(\omega)$ is a finite-width distribution that induces the broadening of the QE peak [17, 21].

In addition to the broadening effect, FSI induce a shift in the energy spectrum of the struck nucleon described by including the real part of the optical potential, U_V , [17, 22] in the argument of the folding function

$$f_q(\omega - \omega') \rightarrow f_q(\omega - \omega' - U_V). \quad (8)$$

In the exclusive picture, hadronic reinteractions are modeled using the NuWro intranuclear cascade [23]. Events are classified as transparent or non-transparent at the primary vertex, ensuring consistency between the inclusive and exclusive parts. An event tagged as non-transparent necessarily has at least one intranuclear collision, whereas in a transparent event, the struck nucleon does not interact with the nuclear matter [3].

3. Results and discussion

A validation of the NuWro predictions with inclusive electron scattering cross sections is first done. A theoretical model that does not reproduce electron scattering results is unlikely to provide reliable predictions for neutrino interactions. Here, I choose two different beam energies with a fixed scattering angle to demonstrate the effect of FSI in electron-carbon scattering. As Fig. 1 clearly shows, our results, including the effects of FSI reproduce the data very well compared to the results without FSI.

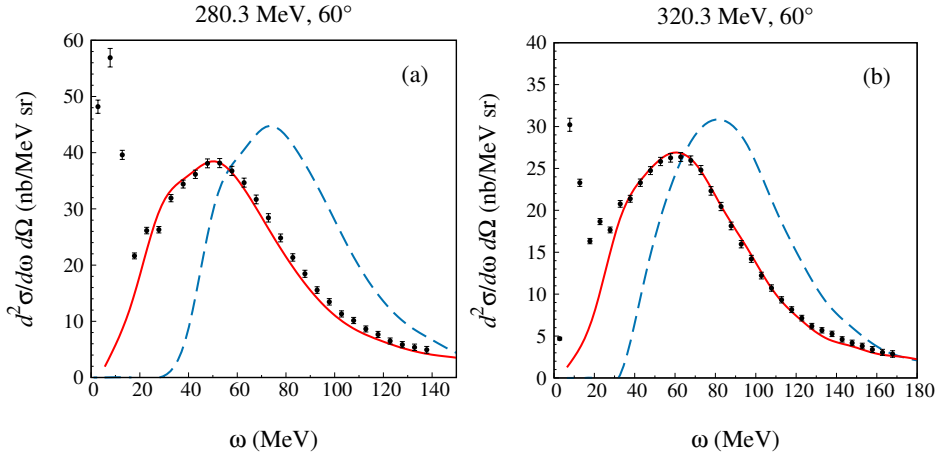


Fig. 1. Inclusive electron-carbon double-differential cross sections calculated within the SF approach in NuWro. Results obtained with FSI (solid red lines) are compared to calculations without FSI (dashed blue line) and to experimental data. The experimental data is reported by Barreau *et al.* [24]. The panels are labeled according to beam energy and scattering angle.

In Ref. [25], the MicroBooNE Collaboration reports on various observables for the CC1p0 π event topology. In this contribution, I present a transverse kinematic imbalance variable δp_T for which the applied selection criteria strongly enhance the QE component, allowing for a more direct assessment of our modifications. For a meaningful comparison with the data,

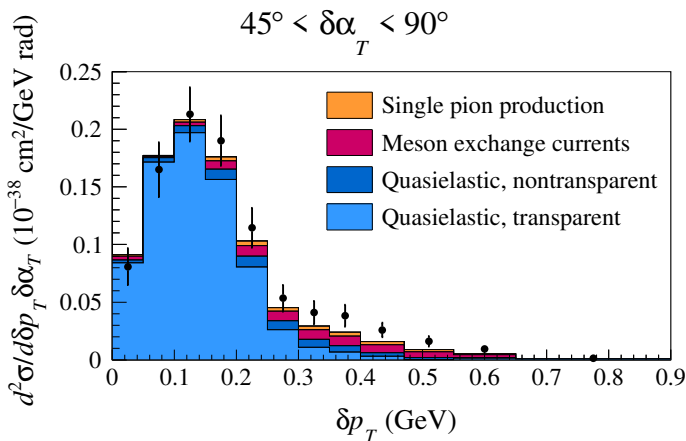


Fig. 2. MicroBooNE CC1p0 π double-differential cross sections [25] are compared with smeared NuWro predictions.

the NuWro predictions are smeared with the additional smearing matrix reported by the collaboration. In the chosen QE-dominated phase spaces, our model performs very well in matching both the shape and the normalization of the experimental data, as seen in Fig. 2.

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