VALIDATING MONTE CARLO*

Roman Tacik

Department of Physics, University of Regina, Regina, SK, Canada, S4S 0A2

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A simple model of the $^{16}O(\pi, \pi')$ quasifree scattering reaction is presented, and compared to experimental data. The model incorporates the same features as Monte Carlo neutrino generators for the CCQE reaction.

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1. Introduction

A lot of new neutrino–nucleus scattering data is expected to become available in the coming years. Data analysis will rely on comparisons with Monte Carlo simulations, and extracted results will depend on the validity of the underlying physics models used in the Monte Carlo. Uncertainties can be estimated from comparisons of the predictions of various neutrino generators, but agreement does not necessarily mean that models are correct. It would be desirable to test the models against data. In the absence of monoenergetic neutrino beams, one approach might be to consider data obtained with other probes.

One neutrino reaction of particular interest is Charged Current Quasi-elastic (CCQE) scattering, which is used to determine the neutrino beam energy spectrum in oscillation experiments. In any real detector, the reaction occurs not on free neutrons, but on neutrons bound in nuclei. Thus, it is increasingly important that Monte Carlo generators deal adequately with nuclear effects.

It might be of interest to see how the fairly simple model of CCQE in a neutrino generator such at NEUT [1] does when applied to pion–nucleus "quasielastic" scattering. In pion physics, "quasielastic" refers to the process in which a pion interacts with a single nucleon within the nucleus, and knocks it out. The kinematics are similar to free pion–nucleon elastic scattering, but smeared and shifted due to the Fermi motion and binding energy of the struck nucleon.

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2. Modelling the ^{16}O(π,π') reaction

Many pion–nucleus elastic and inelastic scattering experiments have been performed. Most data were compared with the predictions of sophisticated theoretical models which dealt in detail with Delta propagation in the nuclear medium. Simple models were used only for reactions such as pion absorption, for with there is no adequate theoretical description.

One notable experiment with which one can compare the results of a simple model is that of Ingram *et al.* [2], who used a magnetic spectrometer to measure scattered pion energy distributions over a range of angles, at three incident π^+ energies, on a water target.

2.1. The simplest case

One can construct a Monte Carlo model with the following steps:

(1) Choose a random momentum for the struck proton.

(2) Calculate the total available energy available.

(3) Choose a random scattering angle for the outgoing pion, using the free $\pi p\ d\sigma/d\Omega$ distribution at the appropriate energy.

(4) Calculate kinematic quantities of interest and histogram results.

This is the same general procedure employed by NEUT for the CCQE reaction, except that free $d\sigma/dQ^2$ distributions are employed in step (3). These are taken from a theoretical model. In the pion case, one can use the results of global phase shift analysis of all available pion–nucleon scattering data [3].

For neutrino interactions, NEUT employs a Fermi Gas model, and in step (1) chooses a momentum from a uniform distribution with a maximum of k_f=225 MeV/c. In the case of pion scattering, interactions occur close to the nuclear surface, not throughout the entire nuclear volume, and one would not expect the Fermi Gas model to provide a good description of the struck nucleon momentum distribution. A slightly better approach might be to use Harmonic Oscillator wave functions. In momentum space, the s-shell wave function (wf) is $\phi_0(k) \approx \exp(-k^2/2\alpha^2)$, while the p-shell wf is $\phi_1(k) \approx k\exp(-k^2/2\alpha^2)$. A fit to the experimental $(e,e'p)$ data of Ref. [4], which distinguishes between s- and p-shell knockout, using these functional forms gives a value of $\alpha = 83$ MeV/c. It is assumed that pions are more likely to interact with p-shell nucleons.

Figure 1 shows a comparison of the results of the simple model with the data of Ref. [2] for three angles at three energies. It is evident that the agreement is quite poor, especially at the lower incident pion energies and larger scattered pion angles.

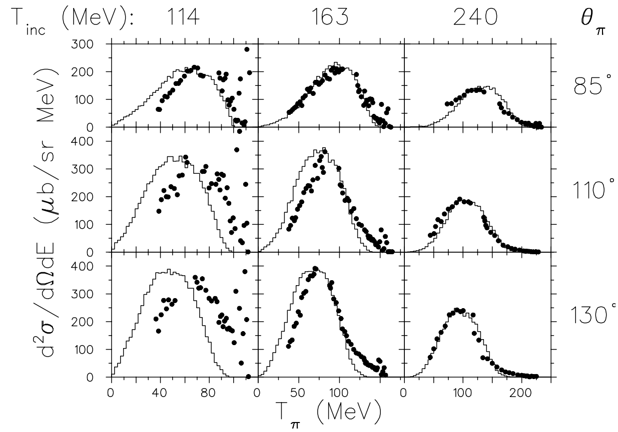

Fig. 1. The data of Ref. [2] compared with the simplest model of (π, π'), as described in the text.

2.2. Accounting for energy dependence

The π^+N elastic scattering reaction is dominated by Δ production, and is consequently strongly energy dependent. This feature was neglected in the simplest model presented above. It can be incorporated by combining steps (1) and (2) and accounting for the energy variation when choosing the struck nucleon Fermi momentum. This is in fact what is done for CCQE in NEUT.

Figure 2 shows a comparison of the results of the improved model with the data of Ref. [2]. The agreement is much better. One possibly disturbing feature is the appearance of peaks in the model distributions at smaller scattering angles at higher scattered pion energies, which are not present in the data.

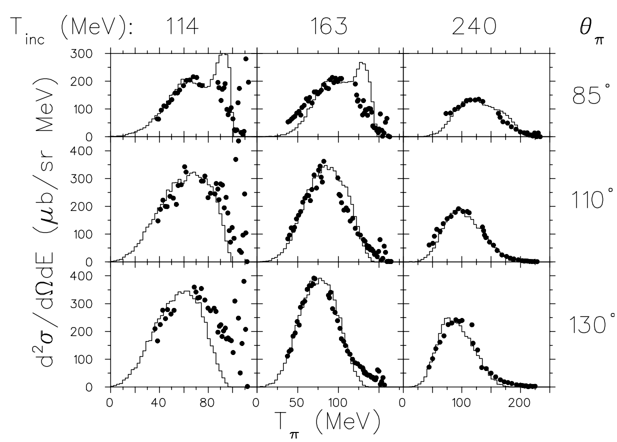

Fig. 2. The data of Ref. [2] compared with the model of (π, π') which accounts for the energy dependence of the π^+N total cross-section.

It should be noted that the agreement seen in Fig. 2 becomes worse if one uses s-shell or uniform Fermi Gas momentum distributions for the struck nucleon. It might also be possible to distinguish between different models of Fermi momentum in the case of neutrino CCQE, by looking at, for example, the width of outgoing proton angular distributions at fixed outgoing lepton angles.

2.3. Accounting for Pauli blocking

The authors of Ref. [2] also present their data as energy integrated single differential cross-sections as a function of scattered pion angle. At backward angles, the data has the same shape as the free πN differential cross-sections. At forward angles, the data fall below the shape of the free cross-sections. They state that this may be understood as a consequence of Pauli blocking.

NEUT imposes Pauli blocking on the CCQE neutrino interaction by rejecting events for which the outgoing proton momentum is less than 225 MeV/c. Figure 3 illustrates the effect such a procedure would have for the pion case. At an incident energy of 240 MeV, rejecting events with outgoing proton momenta less than 225 MeV/c would reduce the number of forward scattered pions without affecting the backward scattered ones. At lower incident energies, the effect would extend to larger angles.

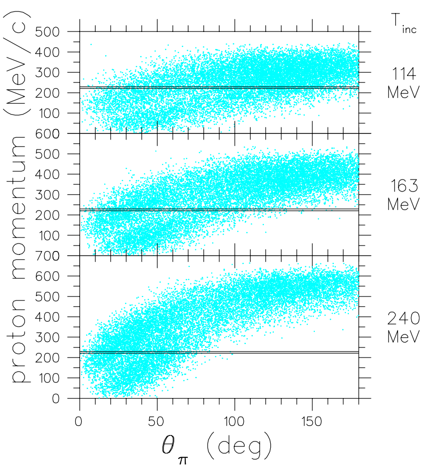

Fig. 3. The dots show the correlation between pion angle and proton momentum for the (π,π') model. Horizontal lines are drawn at proton momenta of 225 MeV/c to illustrate the effect of a simple Pauli blocking cut.

Figure 4 compares the energy integrated data of Ref. [2] with the predictions of the (π,π') model without Pauli blocking, and with Pauli blocking applied as a straight cut at three different values of outgoing proton momentum. It is clear that Pauli blocking is an important effect, but it does not appear that a straight cut at a single value can be used to simultaneously describe the angular distributions at all three incident pion energies.

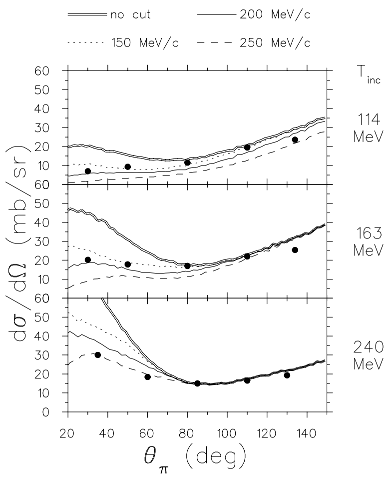

Fig. 4. The energy integrated data of Ref. [2] compared with the (π, π') model with Pauli blocking imposed by rejecting events with outgoing nucleon momenta below particular values, as indicated in the figure.

Figure 5 shows the same comparison as Fig. 2, but with Pauli blocking imposed on the (π, π') model by rejecting events with outgoing nucleon momenta below 225 MeV/c. This has the effect of eliminating the extraneous peaks which appeared in Fig. 2, but clearly also cuts away too many events at higher scattered pion energies.

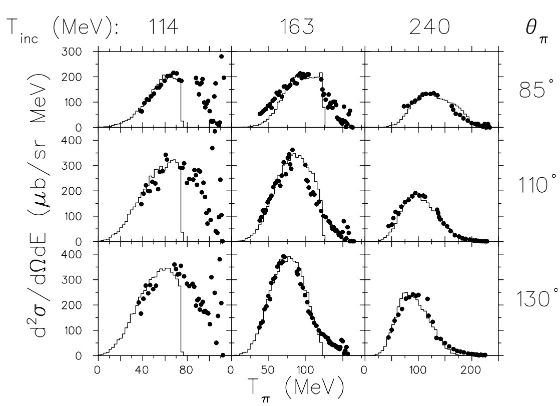

Fig. 5. The data of Ref. [2] compared with the model of (π, π') which accounts for the energy dependence of the πN total cross-section, and imposes a Pauli blocking cut at p_p=225 MeV/c.

In summary, one could conclude that this study has shown that a simple model can describe many of the general features of pion–nucleus quasielastic scattering, but fails to reproduce the details.

3. Beyond quasielastic scattering

In neutrino experiments, the main experimental background to CCQE comes from CC1π, where the final state pion is not observed. It is therefore of some importance that the CC1π reaction be adequately modelled. One way of testing whether this is the case is to run the neutrino generators with incident pion beams, and compare the results with experimental data. Preliminary investigations at the Winter School showed that the NEUT and Genie generators predicted similar pion–nucleus total reaction cross-sections, but differed in the relative importance of pion absorption and pion production at incident pion kinetic energies above around 500 MeV. Further studies are underway.

At this point, is not clear how crucial it is for the neutrino generators to reproduce all of the details of pion induced reactions. But it might be worth drawing the attention of people in the neutrino community to the work done by the LADS collaboration at PSI, and their study of pion–nucleus absorption. This is reported in several publications. In particular, Ref. [5] provides tables of energetic particle (p, n, and d) multiplicities following π^+ absorption on N and Ar.

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