Data Analysis of (e, e'p) Argon Electron Scattering Including Final State Interaction

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(Dated: July 31, 2020)

The final state interaction (FSI) describes the interactions a particle produced at the primary interaction vertex while traveling in the nuclear medium. Our study used data collected by experiment E12-14-012 at JLab, which was an electron scattering experiment done on Argon and Titanium nuclei. The purpose of this experiment was to study the spectral function of these nuclei which gives information on the probability of finding nucleons with certain energy and momenta. This is useful for us as it describes the nuclear response in the interaction. In neutrino experiments, since the neutrino cannot be detected directly, we can only reconstruct neutrino energy by using the energy of the final state particles. Through FSI, the nucleus affects the neutrino energy and thus neutrino oscillation. So with this study, we will calculate the cross section of electron-nucleus scattering with relativistic FSI code and compare the Monte-Carlo (MC) with experimental data. The method I used to complete this study was running a Fortran code provided by Prof. C. Giusti to calculate the cross section on both the plane and distorted wave impulse approximation for the different orbitals present in the argon nucleus. Once this was calculated for each orbital, a C program was run to further analyze the data.

I. INTRODUCTION

A. Jefferson Lab Hall A

Between February and March 2017 in Jefferson Lab Hall A, experiment E12-14-012 took place. This experiment fired an electron beam with an incident energy of 2.222 GeV onto a target of either gaseous Argon and solid Titanium foil [1]. The beam was provided by the Continous Electron Beam Accelerator Facility (CEBAF) at Jefferson lab. The beam was directed over a target system in Jefferson Lab Hall A and the resulting outgoing particle focused with the use of quadripole and dipole magnets on a pair of quasi identical spectrometers. One spectrometer is dedicated and optimized for the electron identification, while the other focus on the identification of protons. The beam passed through the target, the final state electron and proton were separated by magnets and their energies and momenta were studied from there. Knowing the energy of the incoming beam and outgoing final state particles, we can use conservation laws to study the final state nucleus. The purpose of this experiment was to better understand the nuclear structure and the interactions on lepton-nucleon reactions. This experiment would provide knowledge on the spectral function of the nucleons. The spectral function describes the state of the nucleon in question. It is the probability of finding a nucleon inside the nucleus with a certain energy and momentum. Current models of the lepton-nucleon interactions are limited by systematic uncertainties and the fact that the internal nuclear structure of complicated nuclei is not well known or modeled. This experiment intended to resolve some of these uncertainties. Argon was used because of future Neutrino experiments investigating neutrino and anti-neutrino scattering such as the Deep Underground Neutrino Experiment (DUNE). The experiment was conducted with 5 different kinematics, i.e. 5 different settings for detecting events with different energies, momenta, and scattering angles. We worked with mostly kinematic 3.

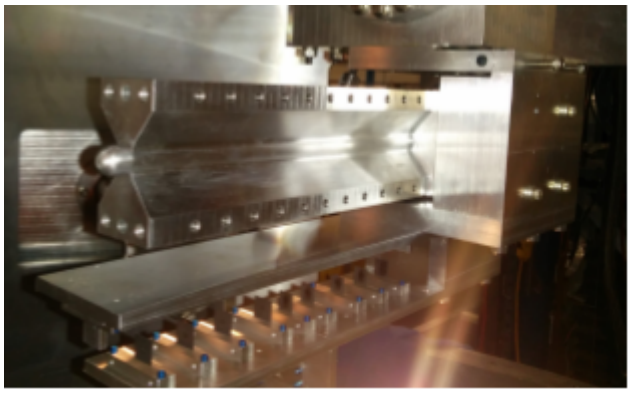

FIG. 1. Experiment E12-14-012

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	p_m
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9
Inc-kin5	2222	-	15.5	-	-		

FIG. 2. The various kinematics from experiment E12-14-012

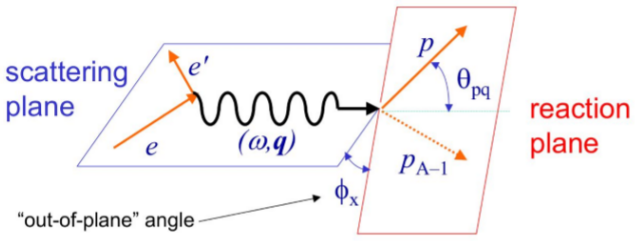

FIG. 3. Kinematics of (e,e'p) reaction

B. (e,e'p) reaction

The (e,e'p) reaction is helpful way to study the structure of the nucleus as the incoming energy can be easily controlled compared to a neutrino beam and there are well known ways of finding out the energy of the final state particles. The data analyzed was of the interaction where an electron ejects a proton from the nucleus as shown in Fig. (3). The (e,e'p) reaction is of particular interest because, like neutrinos, electrons are leptons and can interact with the weak force. As the incoming neutrino energy in a neutrino-nucleon cannot be known, to do a similar analysis of the neutrino energy, the final state of the nucleus in such an experiment cannot be an unknown, as is the purpose of this experiment. As we know, neutrinos oscillate between 3 different flavor states [2]. This oscillation is affected by the energy of the neutrino itself. By studying neutrino scattering, we are able to study its energy and thus its oscillation. However to be able to do this, we must first understand the final state of the nucleus in such a interaction first.

C. Final State Interaction

Previous studies of the (e,e'p) reaction did not include the FSI, but excluding FSI gives results that do not closely match actual data so more depth of thought must be given into the (e,e'p) reaction. Fig. (4) gives an example of a possibility for FSI. Clearly in the neutrino-nucleon reaction the FSI must be considered. Studying the FSI in the (e,e'p) will give further insight into the structure of the nucleus and thus be used in future neutrino experiments.

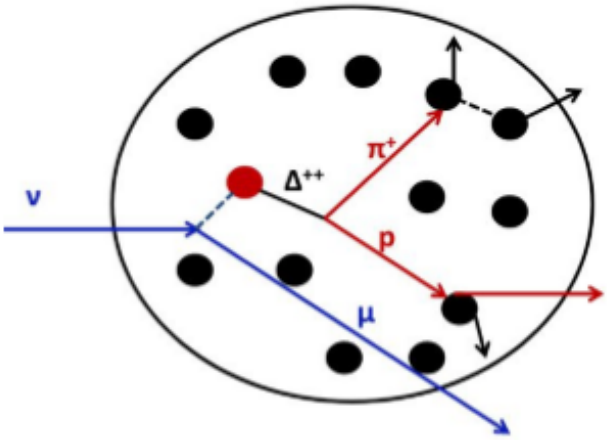

FIG. 4. An incoming neutrino can interact with nucleons before exiting

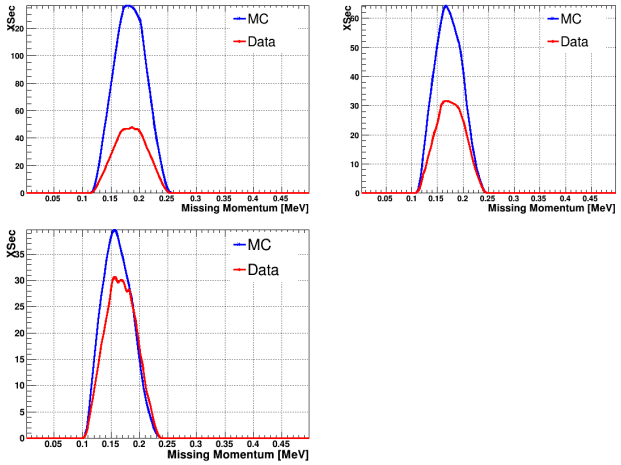

FIG. 5. MC compared to actual data

II. METHODS

A. Calculating Cross Section With DWIA and PWIA

To calculate the cross section and reduced cross section over various energy ranges and orbitals, a fortran script was run with various inputs. This code came from the Carlotta group [3]. Inputs included which orbital to calculate the cross section for and a choice of cross section type. One important input for the code was between Distorted - Wave Impulse Approximation (DWIA) and Plane Wave Impulse Approximation (PWIA). The difference between these options is that DWIA includes FSI and PWIA does not. There are two effects of FSI to the cross sections. First is that there is a shift given by the optical potential, second is that there is a calculated cross section reduction. This is useful for us as both can be calculated to then find the shift and ratio which can be used to reweigh the MC to account for the FSI. By comparing cross sections calculated by DWIA and PWIA, we can study the effect of FSI.

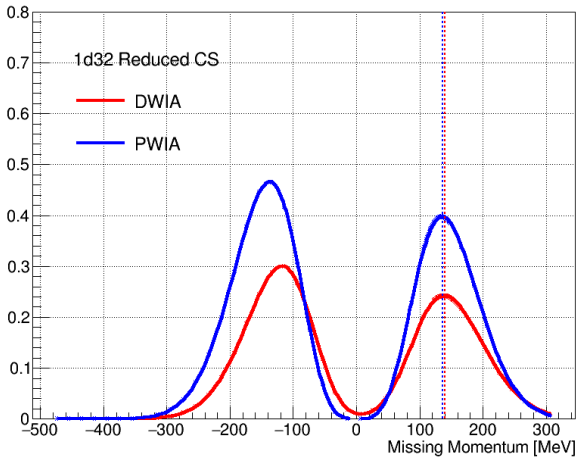

FIG. 6. The DWIA reduced cross section is in red while the PWIA is in blue. The two vertical lines corresponds to the highest points of the two distributions

B. Shift/Ratios

Once the cross sections were calculated using PWIA and DWIA, the relation between them must be calculated to reweigh the MC. To do this, we used a C file compiled with ROOT to read the outfile of the fortran code to perform these calculations. ROOT is an object oriented data analysis framework designed by CERN for particle physics. From Fig. (6), both the PWIA and DWIA plots make a distinct curve for each orbital. From these curves the C code calculated the ratio of the integral between each curve and the shift of the peaks in the positive region between the curves (the dotted line in Fig. (6)) This was calculated for each orbital and these values were used for C program to reweigh the MC which is then compared to actual data. This was done with ROOT as well. This method of using shifts and ratios to reweigh the MC is used to include FSI because this way is simpler than than including FSI directly into the MC. Since DWIA and PWIA are related by this constant shift and ratios, it is easier to reweigh afterwards than to implement FSI directly.

III. RESULTS

The results of the ratios and shift values are displayed in table I. One of the main processes we worked on was seeing if the values for shift and ratio were different between different form factors as input for the fortran code and it was shown that these value are constant over these changes.

Shown in table II are the results of the total integrated cross section for the MC. CC2 or CC1 are parameterization for the e-p elementary cross section. Different parametrization affects differently our final results. Taking CC2 IFIT = 12 to be the default, where IFIT = 12 refers to taking a democratic fit of optical potential. We take this result and subtract each of the other results and divide by the default. Each of the different results gives the systematics of the FSI coming from the choice of the cross section.

Fig. (7) shows the result of the reweighing of the MC compared to the original MC. To re-weight the MC we compute event by event the missing energy and missing momentum, then using the missing energy we try to determine the orbital from which the electron was emitted. Once we know the orbital we can determine with ratio and shiift to use for that single event. We repeat for all events in the MC. The result of reweighing much more closely resembles the actual data than the original data and thus the FSI was more successfully modeled by our methods.

IV. ACKNOWLEDGEMENTS

We would first like to thank the work of Carlotta Guiti's group for the (e,e'p) fortran code they created. Without this a lot of this wouldn't be possible. I would also like to thank the Virginia Tech REU staff and Office of Undergraduate research, for teaching a lot of important and interesting things and providing this opportunity to students like me. I would also like to personally thank Dr. Camillo Mariani and Dr. Libo Jiang for all the help guiding me through this process through out the summer. I learned a lot and feel I gained a lot of scientific skills I can carry throughout my career.

[1] H. Dai, M. Murphy, V. Pandey, D. Abrams, D. Nguyen, B. Aljawrneh, S. Alsalmi, A. M. Ankowski, J. Bane, S. Barcus, and et al., First measurement of the ar(e,e)x cross section at jefferson laboratory, Physical Review C **99**, 10.1103/physrevc.99.054608 (2019).

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[3] S. Boffi, C. Giusti, and F. Pacati, Nuclear response in electromagnetic interactions with complex nuclei.

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TABLE I. Results of shift and ratio values for various orbitals

Orbital	CC1		CC2	
	Shift (MeV)	Ratio	Shift (MeV)	Ratio
1d32	3.5	0.65	1.5	0.58
1d52	0.5	0.65	-2	0.58
1p12	17.5	0.46	12.5	0.43
1p32	11	0.56	9	0.46
1s12	14.1	0.51	13	0.42
2s12	8.9	0.81	8	0.78

	Kin1	Kin3
CC1	1696.33	2091.64
CC3 IFIT=12	1367.17	1708.68
CC2 IFIT=12	1502.48	1869.05
CC2 IFIT=8	1474.07	1834.12
CC2 IFIT=10	1408.25	1760.59
CC2 IFIT=12 DHB[a]	1506.28	1863.56

[a] DHB refers to the type of wave function used to calculate cross section

TABLE II. Total integrated cross section of reweighted MC

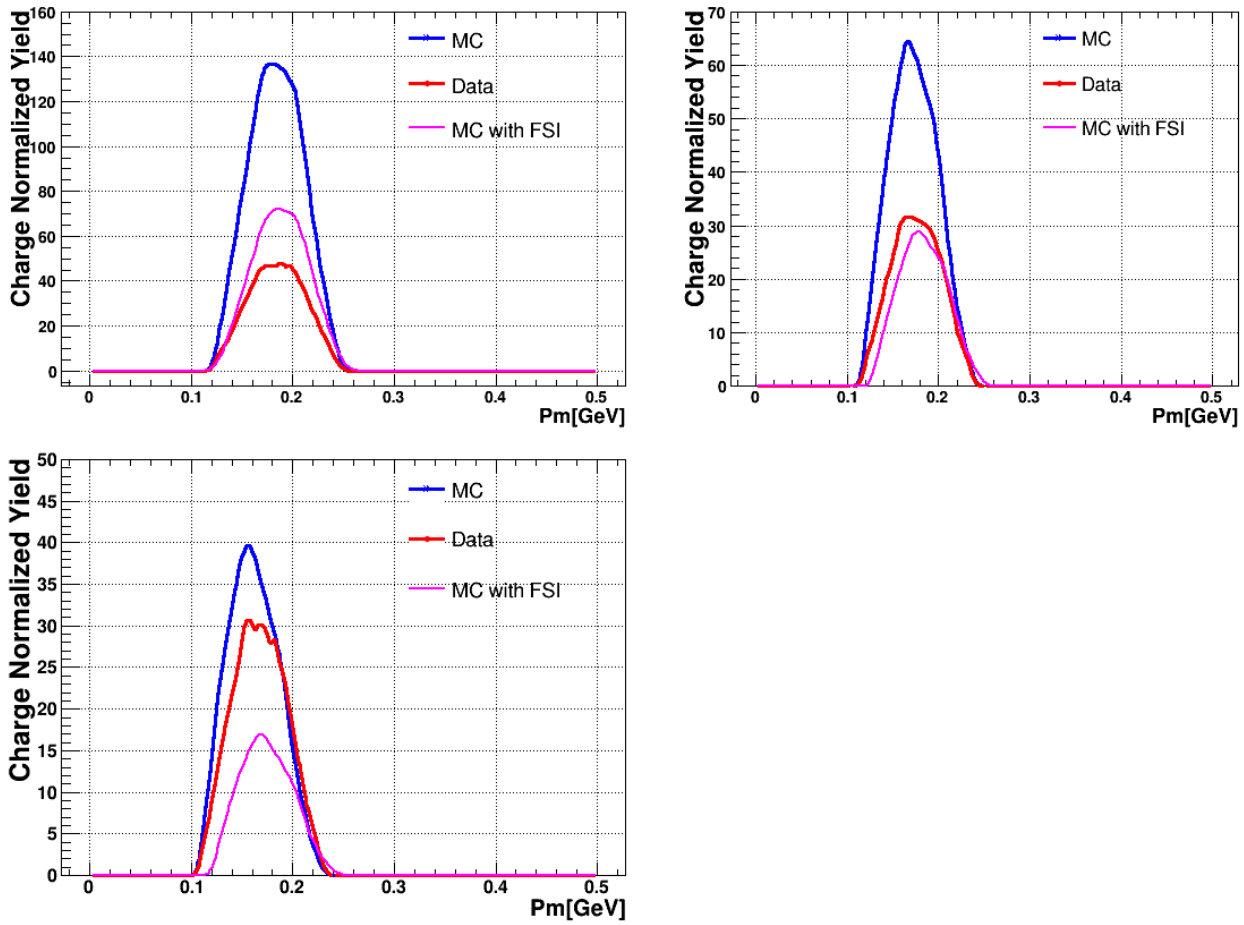

FIG. 7. Plot of reweighted MC vs. old MC compared to data