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Relativistic Description of ^{3}He(e, e'p)^{2}H

Abstract The relativistic distorted-wave impulse approximation is used to describe the ^{3}He$(e, e'p)^2$H process. We describe the ^{3}He nucleus within the adiabatic hyperspherical expansion method with realistic nucleon-nucleon interactions. The overlap between the ^{3}He and the deuteron wave functions can be accurately computed from a three-body calculation. The nucleons are described by solutions of the Dirac equation with scalar and vector (S–V) potentials. The wave function of the outgoing proton is obtained by solving the Dirac equation with a S–V optical potential fitted to elastic proton scattering data on the residual nucleus. Within this theoretical framework, we compute the cross section of the reaction and other observables like the transverse-longitudinal asymmetry, and compare them with the available experimental data measured at JLab.

1 Introduction and Theoretical Framework

Coincidence $(e, e'p)$ measurements at quasielastic kinematics are a powerful tool to study bound nucleon properties. Over the years they have provided us with a wealth of detailed information on bound energies, momentum distributions and spectroscopic factors. This is so because at quasielastic kinematics the $(e, e'p)$ reaction can be treated with confidence in the impulse approximation (IA), *i.e.*, assuming that the exchanged

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photon is absorbed by a single nucleon which is the one detected. Being the electron the probe particle has two important advantages: experimentally it is easy to get a beam of electrons and to choose conditions to select independently both the energy and momentum transferred to the nucleus, and theoretically its interaction with the nucleus is perfectly described within quantum electrodynamics.

^{3}He is a light nucleus belonging to a simple-to-intermediate position in the nuclear systems, which can be described within a Faddeev formalism [1], while the deuteron is the simplest system of bound nucleons. Hence, this reaction provides an almost unique case where a theoretical treatment with the least amount of approximations can be attempted. In this contribution we show the results for cross section and transverse-longitudinal asymmetry (A_{TL}) for ^{3}He$(e, e'p)^2$H within the relativistic distorted waves impulse approximation (RDWIA), compared to the most recent experimental data measured at JLab [2]. These data have unprecedent accuracy and detail and then constitute a very stringent test of the theoretical modelling employed to describe these reactions.

The Relativistic Distorted Wave Impulse Approximation: Under the IA assumptions, the cross section is proportional to the (squared) matrix element given by the sum of the individual current operators of each of the nucleons in the target. The nuclear current is then given by the expression [3–5] $J^\mu(\omega, \boldsymbol{q}) = \int d\boldsymbol{p} \, \bar{\psi}_F(\boldsymbol{p} + \boldsymbol{q}) \, \hat{J}^\mu(\omega, \boldsymbol{q}) \, \tilde{\phi}(\mathbf{p})$ where $|\tilde{\phi}\rangle = \langle \psi_{2H} | \psi_{3He} \rangle$ is the overlap between the initial and final nuclei wavefunctions, also denoted as the quasiparticle wave function within this context. ω and q are the energy and momentum transferred in the reaction. Within the RDWIA [3–5], the outgoing proton wave function ψ_F is a 4-spinor solution of the Dirac equation with Scalar and Vector (S–V) optical potentials fit to describe p-A elastic scattering by the residual system, to take into account the final state interactions (FSI). From the non-relativistic overlap, a relativistic wave function is built for the quasiparticle with only positive energy projections. The upper components of this relativistic quasiparticle wavefunction (properly normalized) coincide with the non-relativistic overlap.

The Hyperspherical Adiabatic Expansion Method: The ^{3}He wave function can be obtained by solving the Faddeev equations with the hyperspherical adiabatic expansion method [1]. We have considered realistic nucleon-nucleon interactions AV18 [6] and a structureless three-body potential. The explicit expression for the wave function can be seen in reference [1].

The Correlated Hyperspherical Harmonic Technique: The standard ^{3}He wave function obtained by a variational wave function derived from a realistic Hamiltonian consisting of the AV18 nucleon-nucleon potential and URIX [7] three-nucleon interactions has been also considered [8,9]. Its high accuracy is well documented and has been used before for similar purposes [10,11]. We will consider it as a reference.

The overlap of the initial and final nuclei wave functions in configuration space can be expanded into spherical harmonics as $\tilde{\phi}(\boldsymbol{y}) = \sum_{lj} a_{lj}(y)\phi_{lj}(\Omega_y)$, separating the radial part from the angular part. Fig. 1 shows the expansion coefficients for four different calculations: one obtained with the variational method from the correlated hyperspherical harmonic technique (labeled as *Pisa* in the figure), and the other three have been calculated within the adiabatic expansion method. If the computations are accurate enough and well converged, both approximations should be equivalent. We have considered different 3-body potentials. In the adiabatic
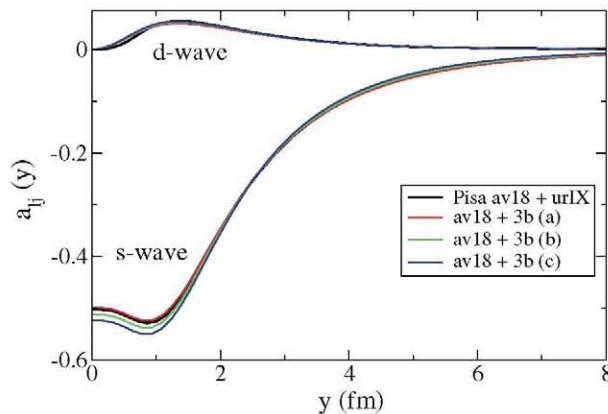

Fig. 1 Coefficients of the expansion of the overlap into spherical harmonics. The black line (labeled as "Pisa" corresponds to the correlated hyperspherical harmonic technique. The red, green and blue lines correspond to the adiabatic calculation. *a*, *b* and *c* refer to three different fits of the three-body energy

case the three-body potential has been fitted to three different binding energies: -6.72 MeV (labeled as "a" in the figure), -7.72 MeV (b) and -8.79 MeV (c). The binding energy corresponding to *Pisa* is -7.74 MeV. We can observe that the a curve approaches better the *Pisa* one, even though the b binding energy is the experimental one. This has to be attributed to the different three-body forces employed in this calculation and the one from the Pisa group. The use of three slightly different overlaps allows us to test the sensitivity of the measured data to fine details of the overlap.

2 Results and Conclusions

Figure 2 shows the computed cross section of the reaction ^{3}He$(e, e'p)^2$H together with the data measured at JLab [2]. The experimental data are very well reproduced by our calculations in all the p_m range except for the region around $p_m = 0$. It should be pointed out that the theoretical results are free from any scale factor. The description of the data both for cross section and TL asymmetry is very good, even at this level of IA only contributions and without any adjustable parameter. The agreement with experiment is comparable or better than the one of non-relativistic calculations, which is remarkable considering the difference in the ingredients for the current operator and the final state, while it is true that the overlap integral is essentially the same one used in previous analysis [11]. In the inset of Fig. 2 it is shown that at low missing momentum the curve that better approaches the experimental data is the *Pisa* one, followed by the a one. At higher momenta all of the curves are very similar. This shows that the experimental data are sensitive to small detail of the overlap and that thus these can be used to refine aspects of the description of the target nucleus.
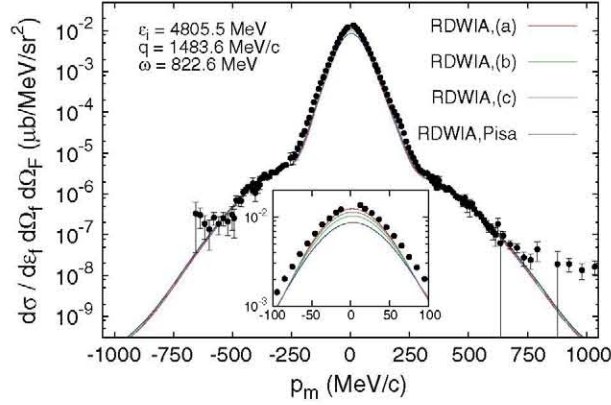

Fig. 2 The ^{3}He$(e, e'p)^2$H differential cross section as a function of the missing momentum

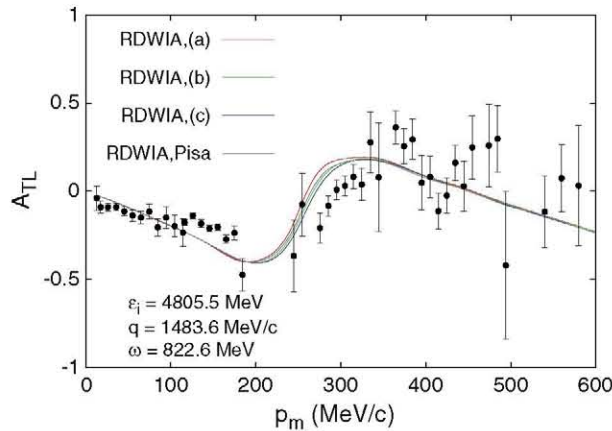**Fig. 3** The A_{TL} for the ^{3}He$(e, e'p)^2$H reaction as a function of the missing momentum

The A_{TL} can be obtained as $A_{TL} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, where $\sigma_\pm$ are the coplanar cross sections measured at positive and negative missing momentum. The agreement between theory and experiment is quite satisfactory, as can only be obtained within a fully unfactorized calculation as shown by previous work [11].

To summarize, in this contribution we have studied the $^3\mathrm{He}(e, e'p)^2\mathrm{H}$ reaction under the RDWIA. The quasiparticle wave function has been obtained from a three-body Faddeev calculation with realistic nucleon-nucleon interactions. It has been compared to the one obtained by the Pisa group. The calculation is completely parameter free and it is in fair agreement with the experiment right out of the box, in a pure Impulse Approximation calculated cross section. We have shown results for the computed cross section and A_{TL} together with the experimental data measured at JLab. The good agreement between experimental and theoretical results found here as well as in previous non-relativistic approaches that employed different framework to describe FSI is a strong indication that this reaction is mostly sensitive to the overlap integral while the other ingredients, once roughly described, introduce small uncertainty. The good agreement for this parameter-free case, also vindicates the assumptions usually taken within RDWIA to analyze $(e, e'p)$ reactions.

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