Determination of the Ti Spectral Function from JLab \((e,e'p)\) Data

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**Introduction**

The Deep Underground Experiment (DUNE) will study neutrino oscillation to gain insight on the origin of matter, the relationship between the four forces, and black hole formation, among other findings. It will consist of a near detector, a far detector, and a neutrino beamline. In the detectors, the neutrinos and antineutrinos will interact with the protons and neutrons in the argon-40 nuclei, respectively. Since the energy of the incoming neutrinos will not be known precisely, it is essential to understand the nuclear structure of argon to reconstruct the beam energy and find the parameters of the oscillation probability. \((e,e'p)\) scattering in titanium-48 was used to model the spectral function of argon’s neutrinos as \((e,e'n)\) scattering is not efficient.

**Experimental Data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{e'p})</td>
<td>12.50</td>
<td>0.10</td>
</tr>
<tr>
<td>(E_{e'p})</td>
<td>12.30</td>
<td>0.04</td>
</tr>
<tr>
<td>(E_{e'p})</td>
<td>12.25</td>
<td>0.25</td>
</tr>
<tr>
<td>(E_{e'p})</td>
<td>15.86</td>
<td>0.20</td>
</tr>
<tr>
<td>(E_{e'p})</td>
<td>3.57</td>
<td>0.31</td>
</tr>
<tr>
<td>(E_{e'p})</td>
<td>6.86</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Figure 1:** DUNE set-up

**Figure 2:** Proton and neutron shell occupancy of argon and titanium

**Figure 3:** \((e,e'p)\) scattering

**Figure 4:** Experimental set-up

**Figure 5:** Partial momentum distribution for the missing energy range of 0–30 MeV

**Figure 6:** Missing energy distribution for kinematics 2

**Table 1:** Kinematics where \(E_{e'p}\) is the outgoing electron's energy, \(E_e\) the incoming electron energy, \(\Theta\) the four-momentum transfer squared, and \(|p|\) the momentum, \(T_p\) the kinetic energy, \(\theta_p\) the angle of the outgoing proton, and \(p_m\) the missing momentum.

In the experiment E12-14-012 at Thomas Jefferson National Accelerator Facility (JLab) an electron beam with an energy of 2.2 GeV was aimed at gaseous argon and solid titanium, respectively. The resulting particles were detected using a proton and an electron spectrometer. The difference in momentum and energy in the interaction are the missing momentum \(p_m\) and the missing energy \(E_{m}\). For titanium, 4 kinematics with varying incoming angles were used to sample different missing momentum.

**Data Analysis**

We measured the cross section

\[
\frac{d^3\sigma}{d\Omega_{e'p} dE_{e'p} dE_{e}} = \frac{\gamma(p_m, E_m)}{\delta E p_e \times p_{e'} \times E_{e'} \times \text{Crad}}
\]

from the data and found the reduced cross section as a function of \(p_m\) and \(E_{m}\), respectively. By dividing out the elementary cross section \(\sigma_{ep}\), we obtained the reduced cross sections, \(P(p_m)\) and \(P(E_{m})\). The spectral function consists of 80% of the mean field and to 20% of the correlated part. We extracted the spectroscopic factors from the spectral functions and the peak energy positions and their distribution widths from \(P(E_{m})\). The spectroscopic factors were normalized to 80% of 22 for the total strength of the orbitals and to 20% of 22 for the correlated part.

**Fitting Procedure**

We fitted the previously obtained data against a Monte Carlo simulation using a ROOT code for each \(p_m\) and \(E_{m}\). With TMinuit we minimized \(\chi^2\). The \(p_m\) fit had 9 fitting parameters, while the \(E_{m}\) fit had 25. For better comparison of the goodness of fit, we used the reduced \(\chi^2\) value, which is normalized by the number of degree of freedom. This means it is optimal at 1; if the value is larger than 1, the data does not match the fit well; and if it is smaller than 1, the data is either overfitted or the error is overestimated.

**Missing Momentum**

We obtained the spectroscopic factors with and without correlated part of the spectral function. The total spectroscopic strengths, which should be at 22 (as the total number of protons), match within uncertainty, so there is no large bias. The reduced \(\chi^2\) value is slightly better without the correlated part at 0.57 but still either overfitted or the error is overestimated.

**Missing Energy**

We found the spectroscopic factors and peak energy positions and distribution widths with and without the spectroscopic factors from the \(p_m\) fit. Furthermore, we obtained the spectroscopic factors without the correlated spectral function. The total spectroscopic strength with and without the \(p_m\) fit match within uncertainty. There is a difference in the total spectroscopic strength when not using the correlated spectral function but it is small, indicating that there is no large bias. The peak energy positions and their distribution widths all match within uncertainty with and without the \(p_m\) fit. The reduced \(\chi^2\) value is best when using all priors at 0.95.

**Acknowledgements**

I would like to thank my mentor, Camillo Mariani, for his help and guidance. I acknowledge the outstanding support from the National Science Foundation, the Virginia Tech Physics department and the Virginia Tech Center for Neutrino Physics. This work was made possible by the National Science Foundation under grant No. P11V–2149165.