Using data mined from Jefferson Lab Hall A experiment E08-014, a new measurement of the $^3$He elastic cross section at $Q^2 \approx 34.2$ fm$^{-2}$ was extracted. This new data point falls approximately halfway between the first and second diffractive minima of the $^3$He charge form factor. This point’s location, along with other recent $^3$He elastic cross section measurements, fill out a previously understudied kinematic region. The new data make an improved fit of the $^3$He elastic cross section world data possible. This report will discuss the new cross section measurement and global fits in comparison to previous fit results.

$^3$He Cross Section Extraction

Experiment ‘E08-014: X > 2 SRC’, which ran in Hall A in Spring 2011 studied quasi-elastic scattering from $^3$He, but there were approximately 1000 events in the acceptance which can be attributed to elastic scattering [1]. These events are located at $Q^2 = 34.2$ fm$^{-2}$. Previous data, shown in Figure 1, is relatively scarce in this region lying approximately halfway to a possible second diffractive minima. This makes the new point an important validation check for previous data [2]. This new data further constrains the various models predicting the form factors which differ in this high $Q^2$ region.

Before form factors or charge radii can be calculated the cross section for this interaction must be extracted from the experimental data. Calculating an experimental cross section includes determining the electron yield of the experiment, finding the efficiencies of various detectors and cuts, modelling the spectrometer’s acceptance to get a solid angle, applying radiative corrections to the data, and finally applying bin centering corrections based on a cross section model. More explicitly, the unpolarized cross section is given by Equation 1.

$$
\sigma^\text{raw}_0 = \frac{d^2\sigma^\text{raw}}{d\Omega dE'} = \frac{p_s N_e}{N_{in} \rho LT \epsilon_{det} \Delta \Omega \Delta E' \Delta Z} \cdot (1)
$$

Here $p_s$ is the prescale value for the detector trigger, $N_e$ is the number of ‘good’ electrons that survive the particle ID and acceptance cuts, $N_{in}$ is the number of electrons incident on the target, $\rho$ is the target density, $LT$ is the live time correction for the DAQ, $\epsilon_{det}$ is the product of the hardware and software efficiencies, $\Delta \Omega$ is the spectrometer’s solid angle acceptance, $\Delta E'$ is the spectrometer’s momentum acceptance, and $\Delta Z$ is the target length seen by the spectrometer [3].

To find the number of elastically scattered electrons we need to be able to count how many electrons are in the elastic peak. To accomplish this we need a method to fit the data such that the area of the elastic peak can be measured. A plot of $X_{Bj}$ for experiment E08-014’s production runs showing the elastic peak is shown in Figure 2. This plot can be broken down in to two areas, the quasielastic region and the elastic peak. We want to use one function to describe each region and then combine these two functions and fit the relevant region of $X_{Bj}$ with this combined fit. This is done using an exponential for the quasielastic region and a Gaussian for the elastic peak as in Equation 2. The result is the blue line in Figure 2, and we find 565 electrons in the elastic peak region.
Now we need to determine how this electron yield from the production data corresponds to a cross section value. To do this the Monte Carlo simulation program SIMC was used. SIMC has a built in model of the \(^3\)He cross section that has the correct shape of the form factors and cross section derived from older fits of the \(^3\)He world data [4]. We use SIMC to simulate electrons elastically scattering off of \(^3\)He and then being transported through the spectrometers with the same energy, angle, charge, and acceptance cuts as our experiment.

The goal at this point is to use the same combined fit we used for the production data to fit the SIMC data for a direct comparison. Clearly, having only the elastic events from SIMC is not sufficient to match our experimental data since the SIMC data has no quasielastic events which make up the bulk of our dataset. To make the SIMC data comparable to the production data we need to add in the equivalent quasielastic events. This was done by taking an exponential and fitting it to the quasielastic region below the elastic peak of the production data. This exponential fit was done in the region where SIMC predicts there to be fewer than ten elastic electrons so as to only fit quasielastic data.

A histogram was then binned to this fit of the quasielastic data and was then summed with the SIMC elastics only histogram in the same region before and up to the \(^3\)He elastic peak. This new combined SIMC and quasielastic histogram then has the same shape as the production data in the region of interest allowing it to be fit with the combined exponential and Gaussian fit in Equation 2. The areas under the Gaussian portions of the combined fits are then directly proportional to the cross section values for SIMC and the production data.

While the shape of the form factors and cross section built into SIMC are correct the magnitude at \(Q^2 \approx 34.2 \text{ fm}^{-2}\) is likely off. This is why the SIMC elastic electron yield doesn’t perfectly match the experimental data electron yield. To find the cross section value of the production data we scale the SIMC elastic data by a constant magnitude up or down until the area of the Gaussian of the combined SIMC fit, the elastic electron yield, matches the area of the Gaussian portion of the combined fit of the production data. When the two Gaussian areas of the combined fit match the electron yields of SIMC and the experimental data then match meaning the cross sections are equivalent. This matching of the SIMC yield to the production yield leaves us with the scale factor, \(C_{SIMC}\), that must be applied to the SIMC data to match the real data.

Since the Gaussian areas of the combined fits and the cross sections are directly proportional, and we have matched the Gaussian areas of SIMC and experimental data, we can multiply the cross section value in SIMC by \(C_{SIMC}\) to find the cross section value of the production data. Figure 3 shows the \(X_{BJ}\) plot for the production data and it’s combined exponential and Gaussian fit in blue as well as the SIMC elastics summed with the fitted quasielastic background histogram with its combined fit in red.

For this analysis the scale factor needed to match the yields, \(C_{SIMC}\), was found to be 1.01984. This means that the model cross section in SIMC needed to be increased by 1.984\% to match the experimental data. When this adjustment is made the model built into SIMC will then yield the correct cross section value for elastic scattering off of \(^3\)He at our kinematics. This cross section is found to be \(1.335 \times 10^{-6} \pm 0.0857 \times 10^{-6} \mu b/sr\) at \(Q^2 = 34.2 \text{ fm}^{-2}\). Most of the uncertainty comes from the small number of elastic electrons as well as the \(^3\)He target’s density.

**New Global Fits**

The world data for \(^3\)He elastic cross sections was gathered including several new datasets not previously included. To extract form factors from this cross section data a sum of Gaussians (SOG) technique was applied. The SOG parametrization for \(F_{ch}(q)\) and \(F_{m}(q)\) is given by Equation 3.
The blue histogram shows the production data for E08-014 with physics cuts, and its elastic peak is fit by the blue line. The red histogram is the sum of the SIMC elastics histogram and the histogram binned to the fit of the quasielastic background, and its elastic peak is fit by the red line.

$$F(q) = \exp\left(-\frac{1}{4}q^2\gamma^2\sum_{i=1}^{n} \frac{Q_i}{1 + 2R_i^2/\gamma^2}\right) \left(\cos(qR_i) + \frac{2R_i^2}{\gamma^2} \sin(qR_i) \right).$$  \hspace{1cm} (3)

Here $\gamma = \sqrt{\frac{3}{2}} = 0.8 \text{ fm}$ or roughly the r.m.s. radius of the proton, $Q_i$ are free parameters, and $R_i$ are the radii at which the Gaussian are positioned [4]. The experimental cross sections are then fit using this parametrization and Equation 4.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{q^2}{q^2} F_{2\text{ch}}^2(q) + \frac{\mu^2q^2}{2M^2} \left(\frac{1}{2} \frac{q^2}{q^2} + \tan\left(\frac{\theta}{2}\right)^2\right) F_{2\text{m}}^2(q).$$  \hspace{1cm} (4)

With $\eta = 1 + q^2/4M^2$, $q^2$ is the three-momentum, $\mu$ is the magnetic moment of the target, and $M$ is the mass of the target [4].

These SOG fits are performed many different times on the world data with different $R_i$ covering the range of possible ‘models’ of Gaussian distributions. The resultant fits with low $\chi^2$ and physically correct features were kept. Figure 4 and Figure 5 show the result of 375 ‘good’ SOG fits for the charge and magnetic form factors respectively. These results are broadly in agreement with previous fits as seen by the blue line in Figures 4 and 5.

The charge form factor’s second minima may approach slightly earlier than [4]’s fits, but this is in agreement with the impulse approximation and meson exchange current theories represented in Figure 1. Due to the lack of high $Q^2$ data the magnetic form factor is much less constrained than the charge form factor. This leads to a wider range in which the diffractive minima may exist, but these results are still consistent with those of [4].

Finally the charge form factors can be inverse Fourier transformed to yield the charge distributions [5]. Figure 7 shows the charge distributions for the 375 SOG fits. Each of the charge form factor fits can also be used to calculate a charge radii of $^3\text{He}$ using Equation 5 and these radii are shown in Figure ??.

The average charge radii of these fits is found to be...
1.90 ± 0.009 fm. This value is slightly smaller than measurements from Saclay giving about 1.96 ± 0.03 fm, and slightly larger than measurements from Bates of 1.87 ± 0.03 fm. It is also smaller than predictions of Green’s function Monte Carlo methods of 1.97 ± 0.01 fm and χ effective field theory giving 1.962 ± 0.004 fm.

Figure 6: $^3$He Charge Densities Result of 375 SOG fits of the $^3$He world data.

\[ \langle r^2 \rangle = -6\hbar^2 \frac{dF_{ch}(Q^2)}{dQ^2} \bigg|_{Q^2=0} \]  

(5)

Figure 7: $^3$He Charge Radii Result of 375 SOG fits of the $^3$He world data.

Conclusion

This work has extracted a new $^3$He elastic cross section of 1.335 ± 0.0857 * 10^{-6} µb/sr at $Q^2 = 34.2$ fm^{-2}. This value lies between previous measurements and slightly below theory predictions, but is still in relatively good agreement with the literature. Using this new point along with the modern world data of $^3$He new cross section fits using the SOG parametrization yielded the most up-to-date form factor results for $^3$He. These results use new high $Q^2$ data to extend our knowledge of the form factors to higher $Q^2$, which is especially important to understanding the magnetic form factor. A charge radii of 1.90 fm ± 0.009 fm was found for $^3$He using these new fits. Work is currently ongoing to fit the world data of $^3$H.

Acknowledgements

I would like to extend my sincerest thanks to the JSA for supporting me with a graduate fellowship as well as the DOE for funding this research. I would also like to thank all those at JLab who made this work possible, particularly Douglas Higinbotham for sharing his knowledge of fitting best practices and cross section extractions, my advisor Todd Averett for his constant support and advice, and Dien Nguyen for pioneering this dataset and offering her insights.

Talks


Publications

1. Efforts are underway to prepare this work for publication in a journal of physics, however it is in the earliest stages currently and no journal has yet been targeted.
2. This work will be published in the thesis of Scott Barcus titled “Extraction and Parametrization of Isobaric Trinucleon Elastic Cross Sections and Charge Form Factors” through the College of William and Mary in early 2019.

Fellowship Travel Support

JSA Graduate Fellowship funds were used to present this work at:

1. The Gordon research conference held in Holderness, New Hampshire in August 2018.
2. The American Physical Society Division of Nuclear Physics Meeting held in Waikoloa Village, Hawaii on October 27 2018.

References


