Measurements of the Helium Form Factors at Jlab

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Abstract. An experiment to measure elastic electron scattering off $^3\text{He}$ and $^4\text{He}$ at large momentum transfers is presented. The experiment was carried out in the Hall A Facility of Jefferson Lab. Elastic electron scattering off $^3\text{He}$ was measured at forward and backward electron scattering angles to extract the isotope’s charge and magnetic form factors. The charge form factor of $^4\text{He}$ will be extracted from forward-angle electron scattering angle measurements. The data are expected to significantly extend and improve the existing measurements of the three- and four-body form factors. The results will be crucial for the establishment of a canonical standard model for the few-body nuclear systems and for testing predictions of quark dimensional scaling and hybrid nucleon-quark models.

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INTRODUCTION

Elastic scattering off the few-body systems and the deuteron has been a major part of the experimental programs of nuclear physics laboratories for the past 40 years. It is the simplest experimentally measurable and theoretically calculable reaction of the electromagnetic probe with the lightest nuclei in nature. The few-body electromagnetic form factors, extracted from elastic scattering, provide fundamental information for understanding the structure and internal dynamics of these nuclei. Theoretical calculations of the $^3\text{He}$ and $^4\text{He}$ form factors are sensitive to the choice of methods to solve for the nuclear ground states, of current operators and relativistic or other corrections. The cross section for elastic electron scattering in the one-photon exchange approximation is given in terms of form factors. For $^3\text{He}$ is given by:

$$d\sigma = \frac{Z^2\alpha^2E'}{4E^2\sin^4(\frac{\theta}{2})}[A(Q^2)\cos^2(\frac{\theta}{2}) + B(Q^2)\sin^2(\frac{\theta}{2})]$$  \quad (1)$$

where $E$ and $E'$ are the incident and scattered electron energies, $\theta$ is the electron scattering angle, $\alpha$ is the fine-structure constant, $Z = 2$ is the nuclear charge, $Q^2 = 4E\cdot E'\sin^2(\theta/2)$ is the squared four-momentum transfer. $A(Q^2)$ and $B(Q^2)$ are structure functions given in terms of the charge, $F_C$ and magnetic, $F_M$ form factors as:

$$A(Q^2) = \frac{F_C^2(Q^2) + \mu^2\tau F_M^2(Q^2)}{1 + \tau}$$  \quad (2)$$
\[ B(Q^2) = 2\tau\mu^2F_M^2(Q^2) \]

where \( \tau = Q^2/4M^2 \), and \( M \) and \( \mu \) are the mass and magnetic moment of the target nucleus. Cross section measurements at different scattering angles for the same \( Q^2 \) allow us to separate the two \( ^3\text{He} \) form factors (Rosenbluth separation).

For the spinless \( ^4\text{He} \) nucleus, the elastic cross section is free of a magnetic contribution:

\[
\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2E'\cos^2\left(\frac{\theta}{2}\right)}{4E^3\sin^4\left(\frac{\theta}{2}\right)}F_C^2(Q^2)
\]

and a single forward-angle measurement directly determines the \( ^4\text{He} \) charge form factor.

**THEORY AND DATA REVIEW**

The simplest attempt to model the interaction of light nuclei with the electromagnetic probe is by describing the electromagnetic current operators in terms of those associated with the individual protons and neutrons [Impulse Approximation (IA)] [1]. The problem of solving for the nuclear ground states relies on using the Faddeev-Yakubovsky equations, correlated hyperspherical harmonic functions or Green’s function and variational Monte Carlo methods. The IA results cannot adequately describe the experimental form factor data. Inclusion of Meson-Exchange Currents (MEC) brings the theory in better agreement with the data. There are two kinds of MEC: model-independent and model-dependent. Model-independent MEC (pion-like exchanges) are those currents directly determined from the nucleon-nucleon interaction without free parameters. Model-dependent MEC are with free parameters and can be associated with either meson transitions or with intermediate nucleon resonances. Even better agreement with the data can be achieved by incorporating in the nuclear wave function multi-quark clusters (hybrid nucleon-quark models) [2], but this approach is still in a phenomenological phase. Finally, it should be noted that, at large \( Q^2 \), quark dimensional scaling [3] predicts an asymptotic fall off with \( Q^2 \) for the few-body form factors. The helium form factors have been measured in the past in the \( Q^2 \) range from 0 to about 45 fm\(^{-2}\), and all three of them exhibit the presence of a (first) diffraction minimum, consistent with calculations based on the IA with inclusion of MEC. Of particular interest is the experimental exploration of the few-body form factors at larger momentum transfers, where the theoretical predictions for the second diffraction minima of the form factors significantly diverge. It is possible, as for the case of the deuteron form factors, that large momentum transfer measurements will dictate the need for fully-relativistic calculations for the helium form factors [4].

**RECENT JLAB MEASUREMENTS**

Jefferson Lab (JLab) offered the possibility to extend the existing measurements of \( ^3\text{He} \) and \( ^4\text{He} \) form factors to larger \( Q^2 \). The experiment, E04-018 [5], was carried out in the fall 2006 and spring and summer 2007 in the Lab’s Hall A Facility. Elastic electron scattering off \( ^3\text{He} \) was measured at forward and backward electron scattering angles to
extract its charge and magnetic form factors using the Rosenbluth separation method. For $^4$He, only forward elastic electron scattering was measured to extract directly its charge form factor. The experiment used high intensity electron beams with energy in the range between 0.7 and 4.4 GeV, and a high density cryogenic helium and hydrogen (for calibration) target systems. Scattered electrons and recoil nuclei were detected in coincidence in the Electron and Hadron High Resolution Spectrometers, respectively. Electrons were identified using a Cherenkov counter and an electromagnetic calorimeter. Both spectrometers used two planes of scintillation counters, for triggering and timing purposes, and two set of drift chambers for the reconstruction of the kinematical parameters of the detected particles. The identification of electron-nucleus coincidences was accomplished by double-arm time-of-flight measurements between the electron and recoil detector electronic trigger signals. Electron-proton elastic scattering was also measured for normalization and calibration purposes. A Monte Carlo simulation model was also developed to calculate the double-arm solid angle with radiative corrections, needed for the determination of the cross sections. Data have been obtained in the $Q^2$ range from 25 to 65 fm$^{-2}$ for $^3$He, and from 10 to 75 fm$^{-2}$ for $^4$He. Figures 1 and 2 show two online plots indicating clear identification of elastic events via the time-of-flight method and kinematical correlation of the momenta of the scattered electrons and recoil helium nuclei. The data analysis is in progress and preliminary results are expected within a year.

**SUMMARY**

The Hall A Collaboration of Jefferson Lab has just completed an experiment to measure the elastic form factors of the stable helium isotopes. The experimental data will be crucial for advancing our understanding of the internal structure and dynamics of the
FIGURE 2. Raw “elastic stripe” with radiation tail (and some background) for elastic e-$^3$He scattering at $Q^2=34$ fm$^{-2}$. The quantity plotted in the left(bottom) axis is proportional to the momentum of the recoil(electron) spectrometer detected particle. The stripe corresponds to elastic events. The events to the left of the stripe are mainly elastic events where the incident or scattered electrons have suffered radiation and/or ionization losses in the target.

few-body nuclear systems. They are expected to initiate new theoretical calculations that will result in the formulation of a canonical theory for the few-body systems.

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