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MEASUREMENTS OF THE CHARGE AND MAGNETIC FORM FACTORS OF THE TRITON AT LARGE MOMENTUM TRANSFERS

Jefferson Lab Experimental Proposal - May 2015

Jefferson Lab Triton Collaboration

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Abstract

This is a proposal for a Jefferson Lab experiment on a precision measurement of the charge and magnetic form factors of the triton at large four-momentum transfers, up to 45 fm^{-2}. It is based on a previously submitted Letter of Intent, which received a favorable consideration by the JLab Program Advisory Committee. The two elastic form factors will be determined from measurements of elastic electron-triton scattering. At each four-momentum transfer, the two form factors will be extracted by means of a Rosenbluth separation based on two elastic cross section measurements, one at a very forward electron scattering angle and one at a very backward. The experiment can be performed in the JLab Hall A Facility using the two High Resolution Spectrometers, and the tritium cryotarget system under development for use by four already approved 12 GeV Program experiments. For the forward electron scattering case, scattered electrons will be detected in the Left High Resolution Spectrometer, in coincidence with recoil tritons detected in the Right High Resolution Spectrometer. For the backward electron scattering case, recoil nuclei will be detected at forward angles in the Right High Resolution Spectrometer. Beam energies of 0.63, 0.78, 0.88, 2.2 and 4.4 GeV will be needed for an optimum Rosenbluth separation. The required beam time is just 10 days, including consistency checks, hydrogen target calibrations and empty-target running. The results from this experiment will improve the quality of the existing Saclay triton form factor data, and extend them to the maximum four-momentum transfer possible, limited only by a luminosity constrained by a safe density and operation of the tritium cryotarget system. These form factor data will provide stringent tests of recent state-of-the-art non-relativistic and relativistic calculations, based on immense theoretical efforts on nuclear few-body problems over the past 50 years. They are expected to play a catalytic role in the establishment of a consistent standard hadronic model describing the structure and dynamics of the simplest nuclei in nature. The availability of a tritium target at JLab offers a unique once-in-a-generation opportunity, since the last tritium electronuclear experiment at MIT/Bates, possibly not to be repeated, to bring the experimental state of the tritium form factors up to the same level as that of the deuteron and helium isotopes form factors.

1 Motivation - Triton/Few-Body Form Factors

The availability of a tritium target at Jefferson Lab, which originated by the proposal of the MARATHON [1] JLab Hall A Collaboration to measure the neutron to proton structure function ratio F_2^n/F_2^p and extract the down to up ratio, d/u, of the quark momentum probability distributions of the nucleon, offers a unique opportunity to measure elastic electron scattering from the triton and extract its electromagnetic form factors at large four-momentum transfers. This measurement can significantly improve the quality of the existing Saclay data [2, 3] and provide new precise data in a four-momentum transfer range twice as large as the combined range of all existing Stanford [4], MIT/Bates [5] and Saclay data.

The triton and the other few-body form factors of ^{3}He and ^{4}He, along with the deuteron form factors, are the "observables of choice" [6] for testing the nucleon-meson based standard model [7] of the nuclear interaction and the associated current operator [8]. They have been the subject of extensive experimental and theoretical investigations over the past 50 years following the pioneering, seminal works of R. Hofstadter and Collaborators [4] and L. Schiff [9] (for recent reviews see Refs. [7, 10, 11, 12, 13, 14, 15]).

The cross section for elastic electron scattering from the spin one-half ^{3}H nucleus is given, in the one-photon exchange approximation, by:

$$\frac{d\sigma}{d\Omega}(E,\Theta) = \frac{(Z\alpha)^2 E'}{4E^3 \sin^4\left(\frac{\Theta}{2}\right)} \left[A(Q^2)\cos^2\left(\frac{\Theta}{2}\right) + B(Q^2)\sin^2\left(\frac{\Theta}{2}\right)\right], \tag{1}$$

where Z is the nuclear charge, α is the fine-structure constant, E and E' are the incident and scattered electron energies, Θ is the electron scattering angle, $Q^2 = 4EE'\sin^2(\Theta/2)$ is the squared four-momentum transfer, and $A(Q^2)$ and $B(Q^2)$ are the ^{3}H elastic structure functions, given in terms of the charge and magnetic form factors as:

$$A(Q^2) = \frac{F_C^2(Q^2) + (1+\kappa)^2 \tau F_M^2(Q^2)}{1+\tau}, \tag{2}$$

$$B(Q^2) = 2\tau(1+\kappa)^2 F_M^2(Q^2), \tag{3}$$

where $\tau = Q^2/4M^2$ with M being the mass of the target nucleus, and κ is the anomalous magnetic moment of the nucleus. The two form factors of ^{3}H are determined by measuring the elastic cross section at several angles using variable beam energies for the same fixed Q^2

(Rosenbluth separation). The above formalism describes also electron scattering from the ^{3}He mirror nucleus.

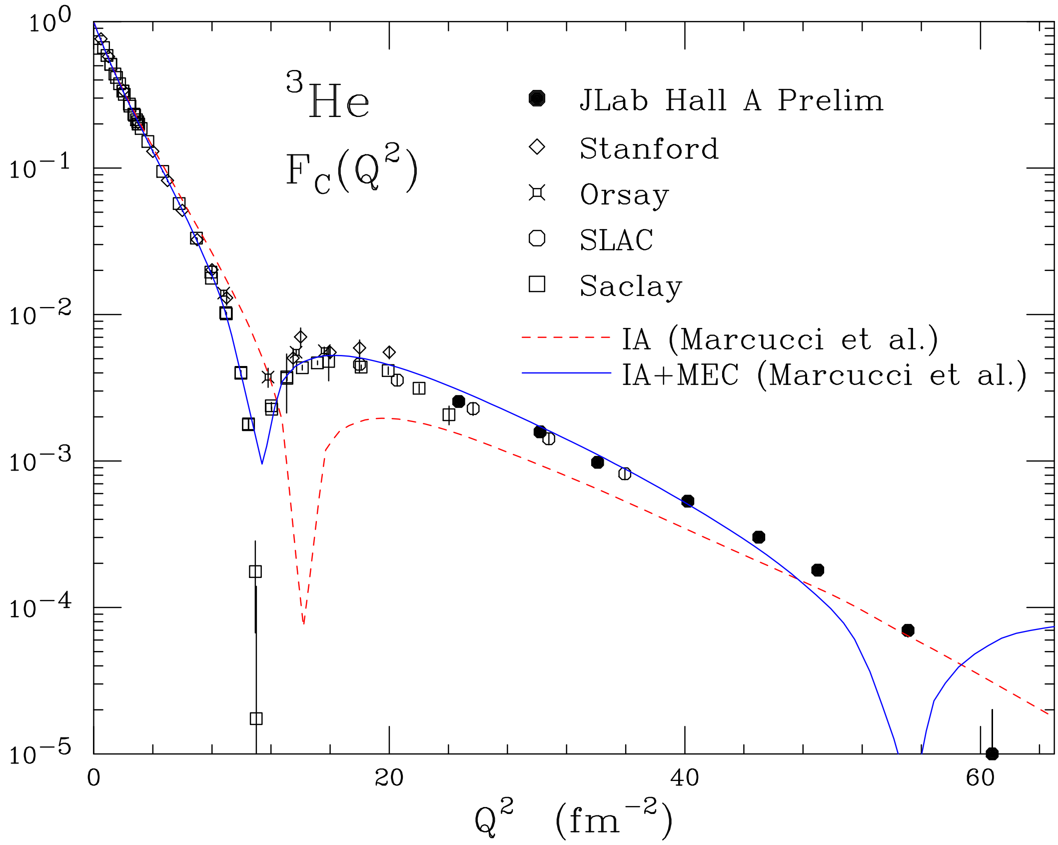

Figure 1: ^{3}He charge form factor data from Stanford [4, 29], Orsay [30], SLAC [35], Saclay [3], Mainz [34] and MIT/Bates [5] experiments, and theoretical IA+MEC calculations by Marcucci *et al.* [6, 8] (see text). The solid squares are the results from the recent E04-018 Hall A experiment on the form factors of the helium isotopes [37, 36].

The electromagnetic form factors of the few-body nuclear systems (^{3}He, ^{3}H and ^{4}He) [16] provide fundamental information on their internal structure and dynamics. They are very sensitive to the choice of the nucleon-nucleon interaction potential, the treatment of meson-exchange currents and relativistic corrections, and to a possible admixture of multi-quark states. At large four-momentum transfers, larger than those accessible now by the JLab energies, they may offer an opportunity to uncover a possible transition in the description of

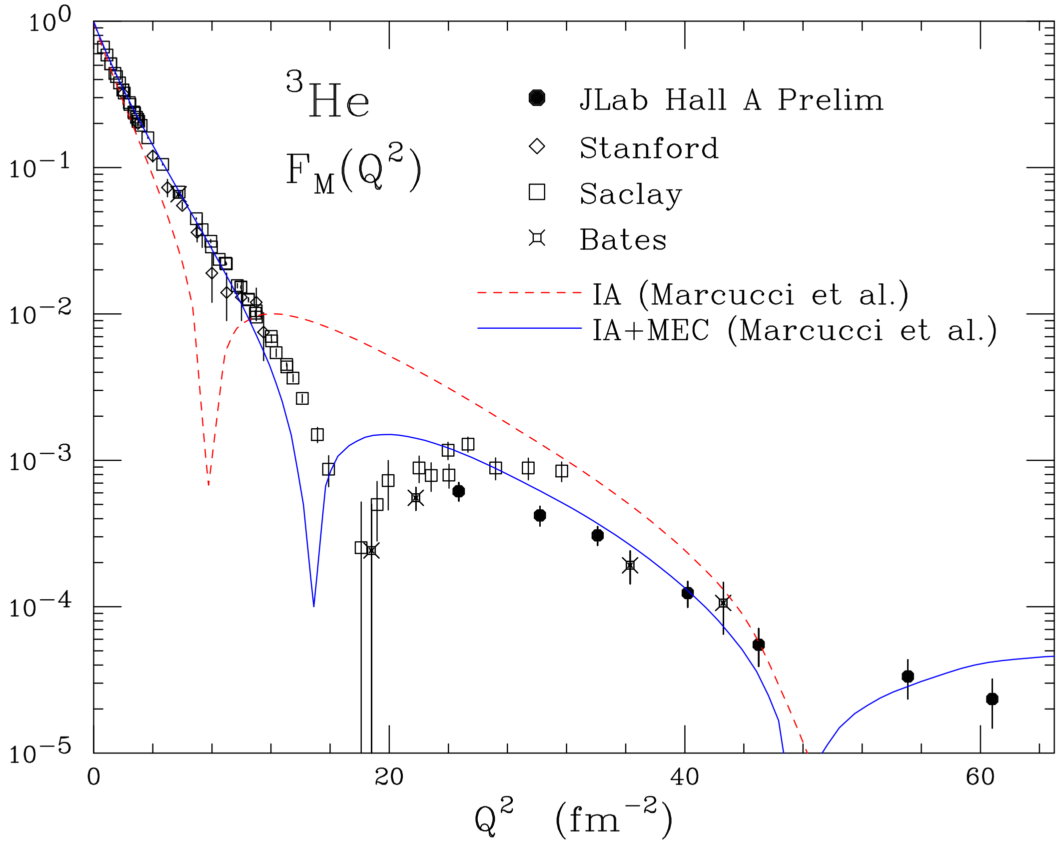

Figure 2: ^{3}He magnetic form factor data from Stanford [4, 29], Saclay [3], MIT/Bates [32], and theoretical IA+MEC calculations by Marcucci *et al.* [6, 8] (see text). The solid squares are the results from the recent E04-018 Hall A experiment on the form factors of the helium isotopes [37, 36].

elastic electron scattering off the few-nucleon systems, from meson-nucleon to quark-gluon degrees of freedom, as predicted by quark dimensional scaling [17].

Theoretically, in the non-relativistic impulse approximation approach, the few-body form factors are calculated using numerical solutions of the Faddeev equations, the correlated (or uncorrelated) hyperspherical harmonics (CHH) variational method, or Monte Carlo methods to solve for the nuclear ground states [7]. All three methods provide a solution of the Schrödinger equation for non-relativistic nucleons bound by the nucleon-nucleon interaction. The Faddeev decomposition for the three- or four-body problem rewrites the Schrödinger equation as a sum of three or four equations, in which only one pair of nucleons interacts at a time. The resulting equations are solved in either momentum or coordinate space. The CHH variational method [6] is based on a decomposition quite similar to the Faddeev one. The primary differences are the introduction of hyperspherical coordinates and inclusion of the strong state-dependent correlations, induced by the nucleon-nucleon interaction, directly in the definition of the nuclear wave function. The principal Monte Carlo schemes developed are variational and Green's function Monte Carlo. Variational Monte Carlo (VMC) [18, 19, 20, 21] uses Monte Carlo techniques to perform standard numerical quadratures. Green's function Monte Carlo (GFMC) [20, 22] employs Monte Carlo methods to evaluate the imaginary-time path integrals relevant for a light nucleus. All modern calculations augment their impulse approximation by meson-exchange currents [23]. Satisfactory description of the available ^{3}He, ^{3}H, and ^{4}He form factor data is not possible without inclusion of MEC. Better agreement with the data is obtained by inclusion of contributions from multi-quark clusters within the framework of hybrid quark models, but, as for the deuteron case, these models are still in phenomenological stage [24, 25, 26, 27]. The question whether introduction of possible isobar configurations is necessary for a complete theoretical description of the few-body form factors is still unanswered. Studies [6, 28] have shown that isobar configurations do not produce large contributions.

The state of the existing data on the few-body form factors is given in Figures 1 to 6, along with very recent theoretical calculations based on the impulse approximation with inclusion of meson-exchange currents. Figures 1 and 2 show all the experimental data for the ^{3}He charge and magnetic form factors in the Q^2 range from 0 to 60 fm^{-2} from Stanford [4, 29], Orsay [30], Saclay [31, 3], Bates [32, 33, 5], Mainz [34] and SLAC [35] experiments. Also shown are the new data [36] from the E04-018 recent JLab Hall A experiment [37]. Figures 3 and 4 show all the experimental data for the ^{3}H charge and magnetic form factors in the Q^2 range from 0 to 30 fm^{-2} from Stanford [4], Saclay [2, 3], and Bates [5] experiments. All four form factors demonstrate the presence of diffraction minima, predicted by the nonrelativistic theory. The new JLab Hall A data show the existence of a second diffraction mimimum around $Q^2 = 50$ fm^{-2} for the ^{3}He magnetic form factor. They also indicate the possible presence of a second diffraction minimum in the ^{3}He charge form factor just beyond $Q^2 = 60$ fm^{-2}.

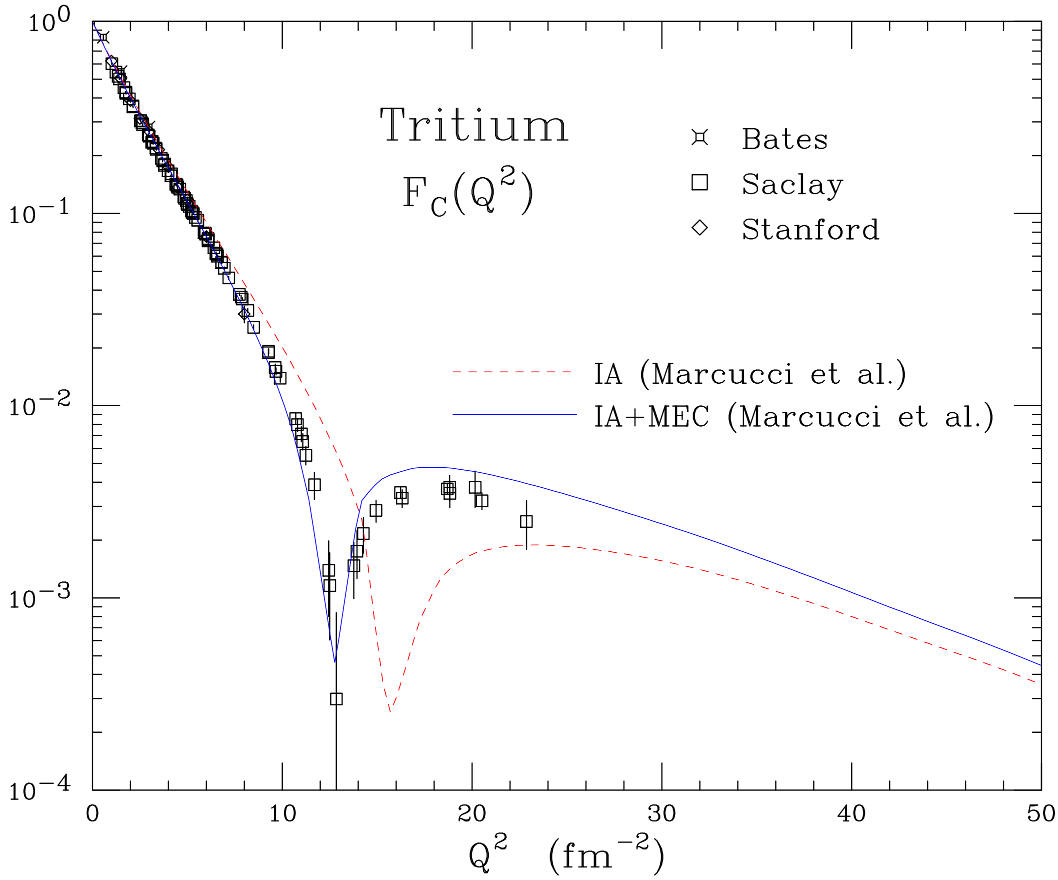

Figure 3: ^{3}H charge form factor data from Stanford [4], Saclay [2, 3], and Bates [5] experiments, and theoretical IA+MEC calculations by Marcucci *et al.* using the correlated hyperspherical harmonics variational method [6, 8] (see text).

Also shown in the Figures are very recent theoretical calculations by Marcucci and Collaborators [6, 8], based on the impulse approximation with and without inclusion of meson-exchange currents. They used the CHH variational method to construct high-precision wave functions obtained with the Argonne v_{18} two-nucleon [39] and Urbana-IX three-nucleon interactions model [40]. In this calculation, the two-body MEC operators have been constructed by the same method of the earlier calculation by Schiavilla *et al.* [18, 19] and significant new advances have been made in the construction of the irreducible three-nucleon exchange current operator and in the systematic treatment of Δ-isobar configurations in the nuclear bound states. It can be seen that the impulse approximation alone totally fails to describe all

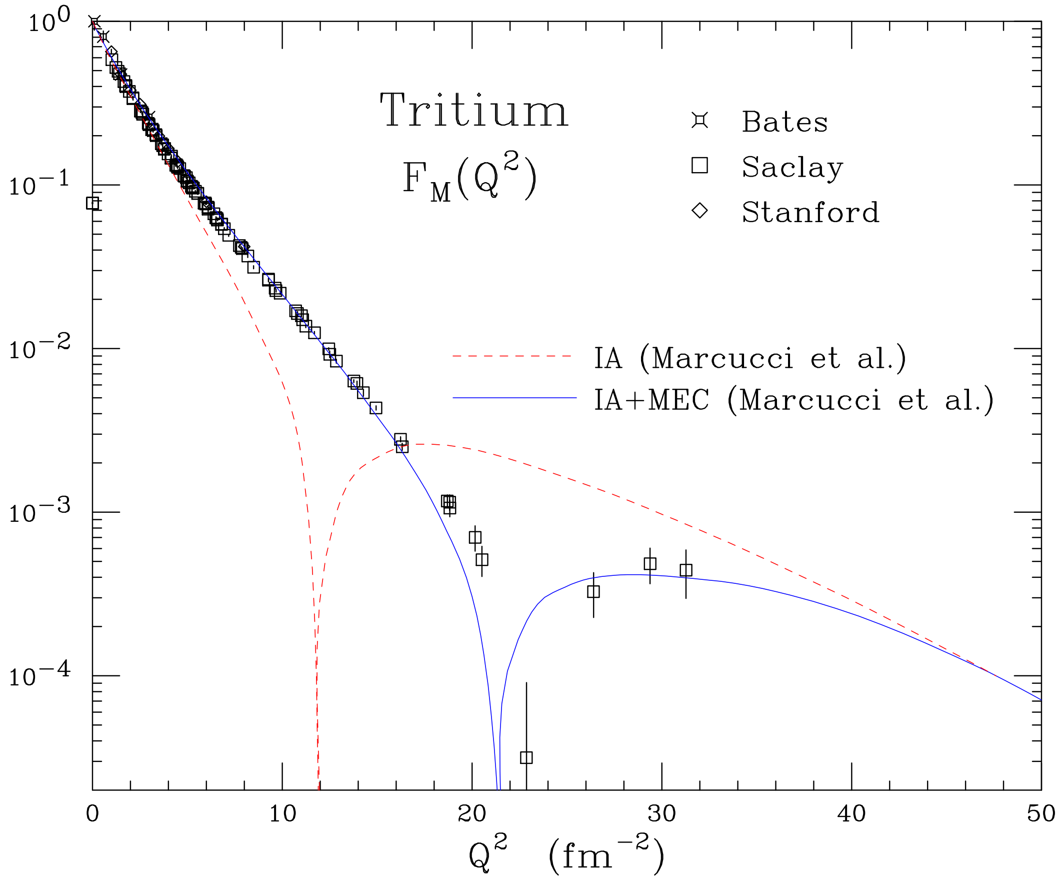

Figure 4: ^{3}H magnetic form factor data from Stanford [4], Saclay [2, 3], and Bates [5] experiments, and theoretical IA+MEC calculations by Marcucci *et al.* using the correlated hyperspherical harmonics variational method [6, 8] (see text).

data, necessitating the need for inclusion of meson-exchange currents. The full calculation describes very well the ^{3}He charge form factor data up to large momentum transfers, quite well the ^{3}H magnetic form factor data, fairly well the ^{3}H charge form factor data, but significantly fails to reproduce all the ^{3}He magnetic form factor data around its first diffraction minimum.

The above well known ^{3}He magnetic form factor discrepancy between theory and experiment has been attributed to the need for fully relativistic calculations [41, 42, 43] for the three-body form factors. Gross, Stadler and Collaborators have initiated a serious effort to calculate the three-body form factors in a consistent relativistic framework. Their initial work [43] eventually led to a seminal paper [44] where a complete Feynman diagram expansion for the elastic form factor of the three-body bound state was derived using the covariant spectator theory [45]. Their first results from this significant advancement of few-body theoretical physics on the three-body form factors were published recently [46], but they cannot yet be compared with the data without inclusion of interaction currents, which have not been calculated yet. Also, the Rome Few-Body Physics Group has begun a serious effort to calculate the trinucleon form factors using a Poincaré-covariant approach by adopting a light-front form of relativistic Hamiltonian dynamics [47], extending their previous similar significant work on the deuteron form factors.

Of particular note is that the new Hall A data for the ^{3}He magnetic form factor seem to agree very well with the MIT/Bates data, forming a trend that is in apparent strong disagreement with the trend of the Saclay data. It should be noted that the JLab datum at $Q^2 = 25$ fm^{-2} was extracted from i) forward electron scattering angle Hall A measured cross sections and ii) a backward 160° cross section from an interpolation of the MIT/Bates measured cross sections. If the above apparent disagreement is ultimately attributed to abnormalities in the Saclay backward (155°) cross sections (which appear to be "high" as compared to the MIT/Bates ones), there is a possibility that the corresponding tritium backward Saclay cross sections, measured under similar conditions, may be abnormal too. The availability of the tritium target at JLab offers the unique opportunity not only to extend the Saclay tritium measurements but also thoroughly check their accuracy.

There is good agreement on the ^{3}He charge form factor data from different Laboratories, as can be seen in Figure 1 (with the exception of some "old" Stanford data). In particular, it should be also noted that the new Hall A data on the charge form factor of ^{3}He are in very good agreement with the previous SLAC and Saclay data, as can be seen in the same Figure. Figure 5 shows the world data on the ^{3}He elastic structure function $A(Q^2)$, which is a function of both charge and magnetic form factors (see Equation 2). It is evident that the new high-statistics JLab data from the E04-018 Hall A experiment are in excellent agreement with the SLAC data.

Finally, Figure 6 shows the existing world data on the charge form factor of ^{4}He from Stanford [48, 29], SLAC [35], Orsay [49] and Mainz [34], along with a very recent calculation

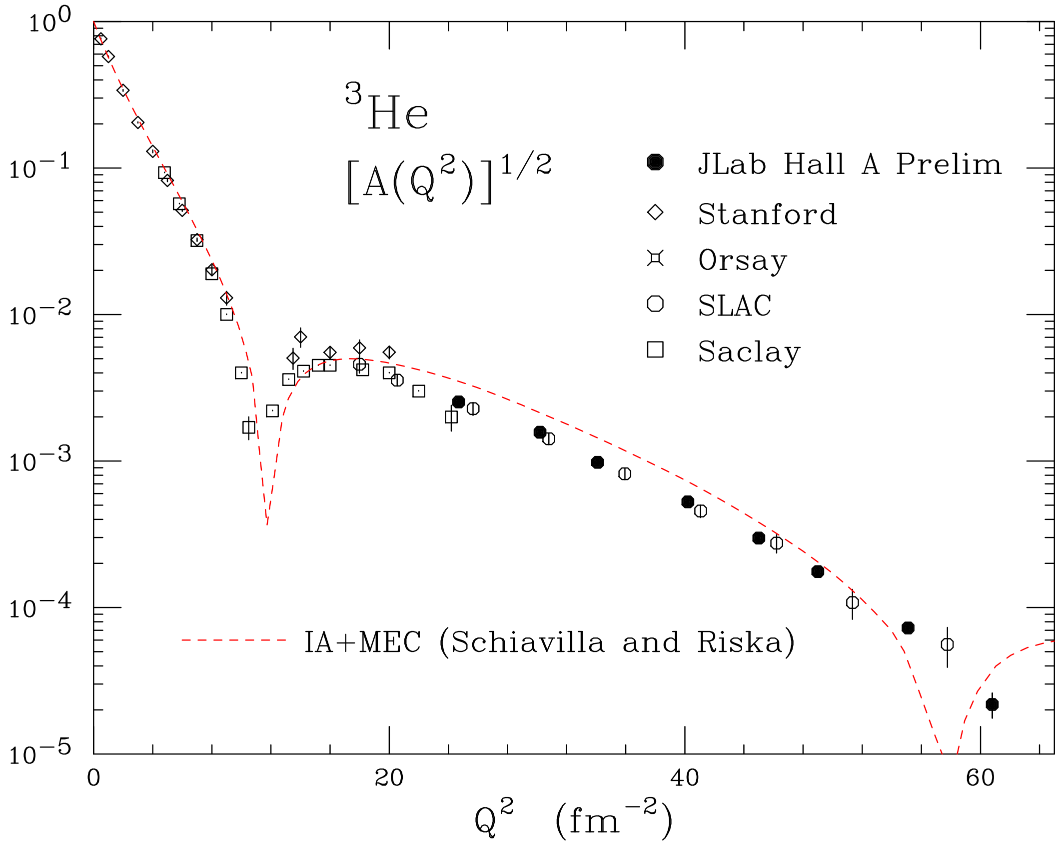

Figure 5: Sample of the world data on the ^{3}He elastic structure function $A(Q^2)$ from Stanford [4, 29], Orsay [30], SLAC [35] and Saclay [3], and a theoretical IA+MEC calculation by Schiavilla and Riska [18, 19]. The solid squares are the new results from the recent E04-018 Hall A experiment [37, 36].

by Marcucci and Collaborators [38]. The calculation uses the correlated hyperspherical harmonic coordinates variational method and makes use of the latest versions of the Argonne nucleon-nucleon potential and the Urbana three-body force model. Also shown are the new results [38] from the recent E04-018 JLab Hall A experiment [37]. This experiment has uncovered a second diffraction minimum of the ^{4}He charge form factor, predicted by the theory. It is evident from the Figure that the theory cannot describe yet well all the large Q^2 data. This could be, again, pointing to the need for a fully relativistic calculation, or to a missing (new) physics part in the theory.

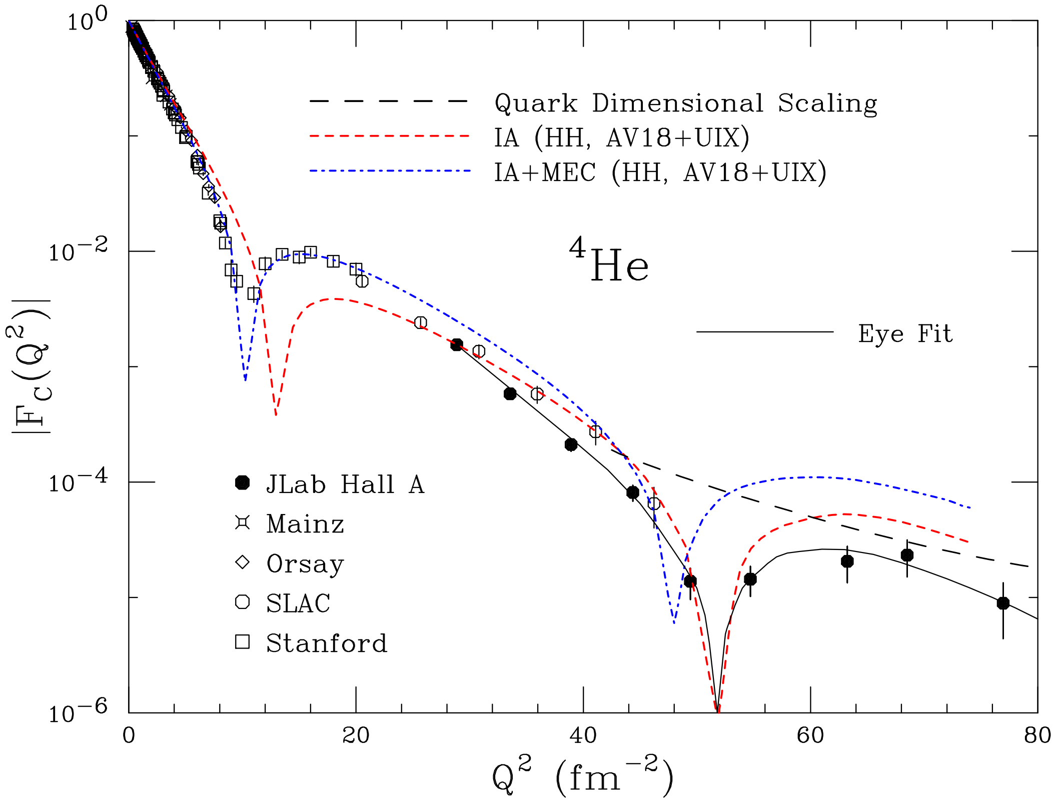

Figure 6: World data on the ^{4}He F_C charge form factor [29, 34, 35, 48, 49] compared to a recent variational method calculation by Marcucci and Collaborators based on the IA approximation with and without inclusion of MEC [38]. Shown is also the asymptotic prediction of the quark dimensional scaling model (DSQM) [17], arbitrarily normalized at $Q^2 = 40$ fm^{-2}. The solid circles are the new results [38] from the recent E04-018 JLab Hall A experiment [37]. The solid line is just a line to guide the eye.

Shown also in Figure 6 is the long-standing, more than 35 years old, prediction by Brodsky and Chertok [17], from the dimensional scaling quark model (DSQM). The new JLab data do not exhibit the asymptotic behavior of DSQM and definitely rule out the applicability of this model in the momentum transfers accessible today for elastic electron scattering off few-body nuclei. These ^{4}He form factor data dictate that the relevant degrees of freedom in the description of elastic electron scattering from the few-body nuclear systems are hadronic, nucleons and mesons, not quarks and gluons, at least for today's accessible momentum transfers. Finally, it should be pointed out that Figure 6 shows some sizable disagreement between the SLAC and JLab data, dictating the need to have high quality measurements on fundamental nuclear physics observables from new Laboratories like Jefferson Lab and with the highest quality modern instruments like the state-of-the-art High Resolution Spectrometer systems of JLab, able to provide crystal-clear electron-nucleus coincidence spectra.

A measurement of the tritium form factors at JLab will complete its many-years-long program on basic, classic measurements of elastic scattering from light nuclei, which started with the deuteron form factor and tensor polarization measurements in Halls A and C. A comprehensive theoretical study and the formulation of a standard model describing the structure and dynamics of the few-body systems requires input from the triton and as precise as possible measurements for all light nuclei. Also, triton form factor data will be of unique value for the separation of isoscalar and isovector contributions to the elusive meson-exhange current mechanism in electron scattering off few body nuclear systems. An experiment at JLab is now possible, given the availability of a tritium target, which can provide outstanding quality data on the ^{3}H form factors in a very timely fashion that will significantly advance the fundamental few-body nuclear physics.

2 The ^{3}H Proposed Measurements

The proposed experiment will employ the two High Resolution Spectrometer (HRS) systems of the Hall A Facility of JLab, to detect scattered electrons and recoiling tritons. The Left HRS will be used as the electron detection spectrometer, in its current configuration for electron scattering from the proton. For the Right HRS, to be used as the recoil nucleus detection spectrometer, it is proposed to add a thin, single plastic scintillator counter right after the end of the vacuum aperture pipe of the spectrometer, which is just below the vertical drift chamber (VDC) tracking system. This addition will allow for the formation of a triple coincidence logic trigger signal for the recoil nuclei in order to reduce accidental background.

The proposed measurements will use the tritium cryotarget system which is under development. Details on this target system, which provides for a 25 cm long cell filled with high pressure tritium gas of density 0.00325 g/cm^3, are provided in Reference [50]. The target ladder structure includes a high pressure hydrogen gas cell of identical shape for calibrations and overall normalization checking of the measured cross sections.

The experiment requires electron beams from the CEBAF machine with energies between 0.63 and 4.4 GeV and with beam current of 20 μA, the maximum allowed for a safe operation of the tritium target cell of the cryotarget system. To allow for time-of-flight (TOF) measurements in the Right (recoil) High Resolution Spectrometer, it is proposed that the beam is tuned in the 31 MHz gun-operation rate instead of the standard 499 MHz rate.

For each momentum transfer setting, elastic electron-triton scattering will be measured at one forward electron scattering angle and one backward electron scattering angle. In the forward electron scattering case, electrons will be detected with the Left HRS, in coincidence with recoil tritons, which will be detected with the Right HRS, using the TOF method between the electron/Left HRS and the triton/Right HRS trigger signals. The coincidence solid angle for the calculation of the cross section values will be determined by means of a Monte Carlo simulation [51], as in previous coincidence elastic electron-nucleus experiments with the Hall A HRS systems.

In the backward electron scattering case, recoiling tritons will be detected at forward angles with the Right HRS system, which correspond to backward electron angles. Any contribution of tritons originating from the target cell endcaps will be measured in special empty-replica (dummy) target runs. Although the cross sections will be determined from the recoil tritons, the Left HRS will also be used to detect electrons in coincidence, for consistency checks, and for the determination of cross sections in coincidence. These latter electrons, because of the solid angle Jacobian relationship, will be a subset of the scattered electrons which correspond to all detected recoil tritons. In the unlikely event that the online analysis shows that the rate of tritons from the endcaps is intolerable, the run plan will be converted to full coincidence mode, but with elimination of settings for $Q^2 > 40$ fm^{-2}.

For the backward electron scattering case, when detecting only tritons, the identification of tritons will be primarily accomplished by TOF between the recoil/Right HRS scintillator trigger signal and the accelerator provided beam-bunch signal. Additional separation of tritons from proton and deuteron target-originated background will be provided by comparison

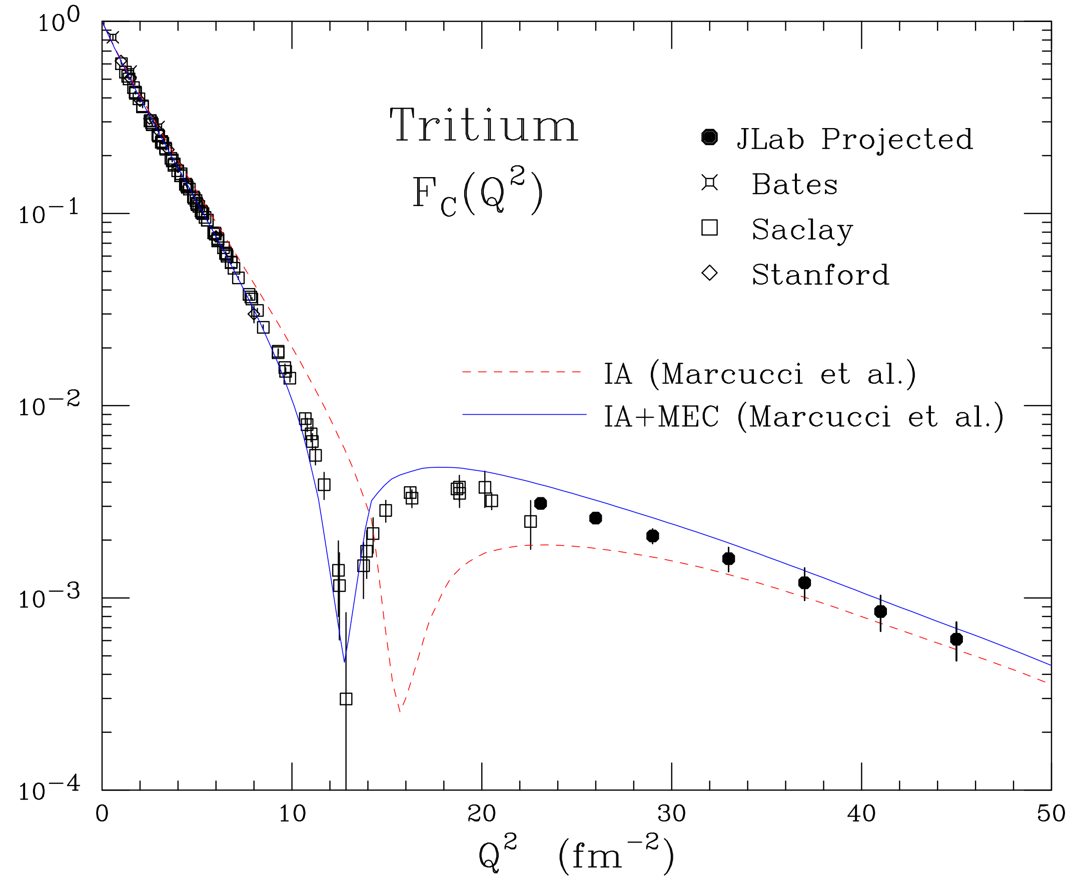

Figure 7: Projected data for the triton charge form factor $F_C(Q^2)$ from the proposed JLab Hall A experiment. The required beam time is 10 days, including calibrations etc (see text). Also shown are data from Stanford [4], Saclay [2, 3], and Bates [5] experiments, and theoretical IA+MEC calculations by Marcucci *et al.* using the correlated hyperspherical harmonics variational method [6, 8] (see text).

of their TOF between the front and rear scintillator planes of the HRS system, spaced apart by a sufficient 2.9 m distance. The information from the ADC pulse heights of the scintillator analog signals will provide additional information for the identification of tritons and their separation from background particles [52]. The Cherenkov detector of the recoil HRS system would have to be pushed to the side of the detector hut, as was done in previous experiments, in order to avoid triton absorption in its mirrors and windows.

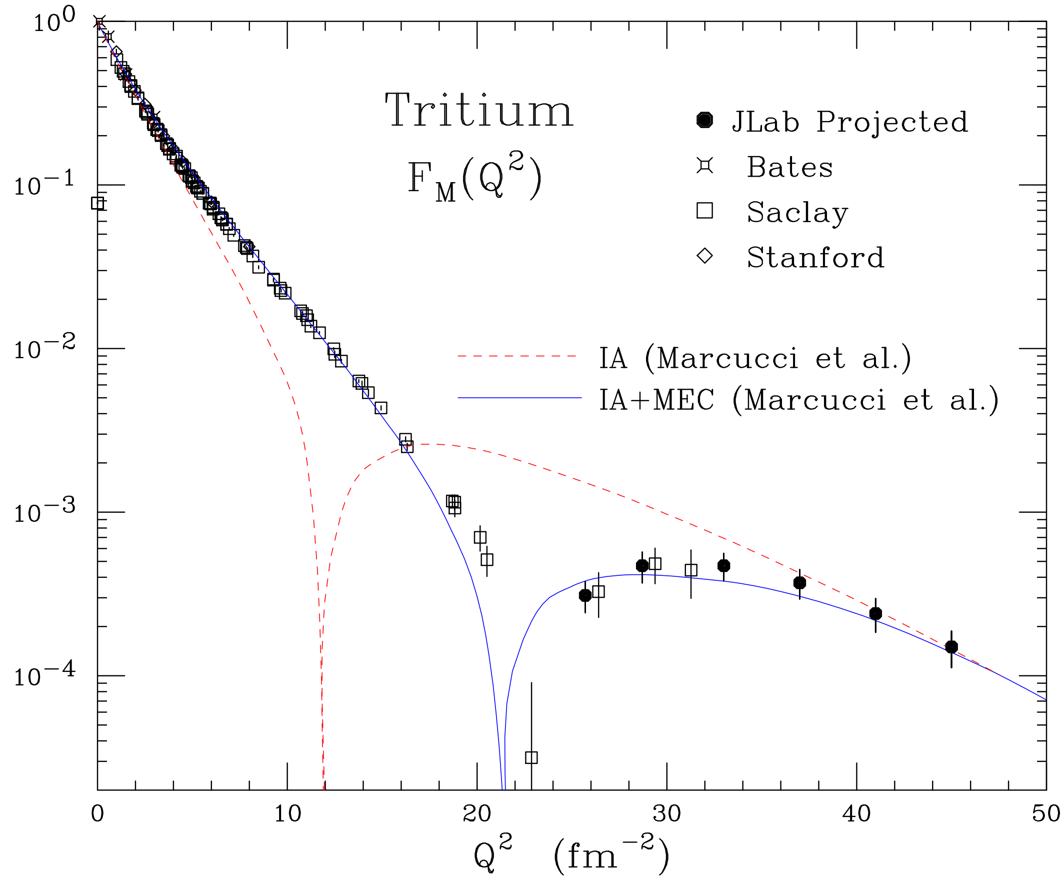

Figure 8: Projected data for the triton magnetic form factor $F_M(Q^2)$ from the proposed JLab Hall A experiment. The required beam time is 10 days, including calibrations etc(see text). Also shown are data from Stanford [4], Saclay [2, 3], and Bates [5] experiments, and theoretical IA+MEC calculations by Marcucci *et al.* using the correlated hyperspherical harmonics variational method [6, 8] (see text).

It should be noted that the central momentum setting of the Right HRS system, when operated for forward recoil triton detection, will always be above the beam momentum. This means that there can be no background in the detectors through the spectrometer from light mass particles like positrons, muons, pions and kaons. The only kinematically allowed background will be protons and deuterons, which will be easily separated with the planned TOF measurements.

The kinematics of the proposed forward and backward running are given in Tables 1 and 2. The forward electron running will require electron beams with energy of 2.2 and 4.4 GeV. The backward electron running will offer an optimum Rosenbluth form factor separation if three single-pass beam energies of 0.63, 0.78 and 0.88 GeV are used. The electron scattering angle for the forward running will vary between 14.2° and 27.6°. The triton recoil angle for the backward running will vary between 15.5° and 31.2° (corresponding to electron scattering angles from 140° to 105°). The scattered electron energy will be in the range from 0.47 to 4.20 GeV, and the recoil nucleus momentum from 0.96 to 1.36 GeV/c. It should be noted that for forward electron running, the Left HRS central momentum will be set with a -2.0% offset, staying close to the maximum operational value of about 4.1 GeV, as was done in the E04-018 elastic electron-helium experiment [37].

Tables 3 and 4 contain estimated values of the cross sections to be measured, using reasonable interpolations or extrapolations of the existing form factor data. The assumed form factor values are also given in Tables 3 and 4, along with the required beam time for each kinematics, the desired event statistics, and the projected uncertainties on the form factors from the Rosenbluth separation. The estimated expected counting rates assume a nominal solid angle of 5.0 msr for both HRS systems, a maximum beam current of 20 μA for the safe operation of the target cell, and an approximate radiative correction factor of 0.8. The estimated beam time to achieve the listed uncertainties in the extraction of the two form factors is 195 hours. Assuming 55 hours mainly for empty-target running, and for hydrogen calibrations and consistency checks, the total time to perform this experiment will be just 250 hours (10 days).

The projected data from this experiment are shown in Figures 7 and 8. It can be seen that this very short Jlab experiment will provide high quality, very precise data, far better, in the range of overlap, than the previous Saclay experiment. The new data will be sufficient to accurately map the form factors of the triton up to $Q^2 \simeq 45$ fm^{-2}. This possible JLab experiment will double the Q^2 range of the existing measurements. The new data will be highly complementary to the precise JLab data on the deuteron, ^{3}He and ^{4}He form factors. The results will be of utmost importance for testing our knowledge of the nucleon-nucleon interaction, possible three-body force effects and the nature of isoscalar and isovector contributions of meson-exchange currents, and for constraining the parameters of the theoretical few-body standard model. Obtaining this ^{3}H data set is simply a once-in-a-generation opportunity (the last tritium electronuclear experiment was at MIT/Bates 30 years ago!) or even forever, as there may not be another chance again for development of such a tritium target worldwide.

3 Summary

We propose a Jefferson Lab experiment on elastic electron-triton scattering, in order to extract the ^{3}H electromagnetic form factors over a wide range of four-momentum transfers and up to $Q^2 = 45$ fm^{-2}. The availability of a tritium target presents a unique opportunity to JLab and to the nuclear science community to complete the Laboratory's program of high Q^2 measurements of the elastic form factors of the light nuclei of nature. The required beam time is 10 days, including hydrogen calibrations and empty-target running. The results from this experiment will be crucial for the establishment of a canonical hadronic standard model describing the electromagnetic structure and dynamics of the lightest nuclei in nature, and for advancing the field of few-body physics.

4 Tables

ELECTRON-TRITON FORWARD ELASTIC KINEMATICS

Q^2 (fm^{-2})	E (GeV)	E' (GeV)	Θ (deg.)	P_r (GeV/c)	Θ_r (deg)	β_r	$d\Omega_e/d\Omega_r$
23.0	2.2	2.041	25.81	0.960	67.78	0.323	0.585
26.0	2.2	2.020	27.62	1.022	66.34	0.342	0.638
29.0	4.4	4.199	14.20	1.082	72.27	0.359	0.218
33.0	4.4	4.171	15.21	1.156	71.09	0.381	0.237
37.0	4.4	4.143	16.16	1.227	69.98	0.400	0.256
41.0	4.4	4.116	17.08	1.295	68.93	0.419	0.275
45.0	4.4	4.088	17.96	1.360	67.93	0.436	0.295

Table 1: Forward elastic electron-triton kinematics in the Q^2 range from 23 to 45 fm^{-2}, where E is the incident electron energy, E' and Θ are the scattered electron energy and angle, and Θ_r, P_r and β_r are the angle, momentum and speed of the recoil triton. The last column is the Jacobian transformation ratio of the scattered electron and recoil triton solid angles.

ELECTRON-TRITON BACKWARD ELASTIC KINEMATICS

Q^2 (fm^{-2})	E (GeV)	E' (GeV)	Θ (deg.)	P_r (GeV/c)	Θ_r (deg)	β_r	$d\Omega_e/d\Omega_r$
23.0	0.633	0.474	119.6	0.960	25.41	0.323	4.54
26.0	0.633	0.453	140.0	1.022	16.54	0.342	5.32
29.0	0.780	0.579	104.5	1.082	31.21	0.359	4.08
33.0	0.780	0.551	119.7	1.156	24.45	0.381	4.84
37.0	0.780	0.523	140.0	1.267	15.90	0.400	5.72
41.0	0.877	0.593	122.3	1.295	22.79	0.419	5.17
45.0	0.877	0.566	140.0	1.360	15.50	0.436	6.00

Table 2: Backward elastic electron-triton kinematics in the Q^2 range from 23 to 45 fm^{-2}, where E is the incident electron energy, E' and Θ are the scattered electron energy and angle, and Θ_r, P_r and β_r are the angle, momentum and speed of the recoil triton. The last column is the Jacobian transformation of the ratio of the scattered electron and recoil triton solid angles.

FORWARD ELECTRON SCATTERING RUN PLAN

Q^2 (fm^{-2})	F_C	F_M	Cross Section (cm^2/sr)	Time (hr)	Counts	ΔF_C ($\pm$%)
23.0	$3.1{\times}10^{-3}$	$2.7{\times}10^{-5}$	$3.6{\times}10^{-36}$	4.8	136	6.4
26.0	$2.5{\times}10^{-3}$	$3.1{\times}10^{-4}$	$1.8{\times}10^{-36}$	7.2	117	6.4
29.0	$2.1{\times}10^{-3}$	$4.7{\times}10^{-4}$	$5.3{\times}10^{-36}$	7.2	116	8.8
33.0	$1.6{\times}10^{-3}$	$4.7{\times}10^{-4}$	$2.6{\times}10^{-36}$	4.8	41	14.3
37.0	$1.2{\times}10^{-3}$	$3.6{\times}10^{-4}$	$1.1{\times}10^{-36}$	4.8	19	20.0
41.0	$8.5{\times}10^{-4}$	$2.4{\times}10^{-4}$	$4.6{\times}10^{-37}$	9.6	17	21.5
45.0	$6.1{\times}10^{-4}$	$1.5{\times}10^{-4}$	$1.9{\times}10^{-37}$	14.4	11	23.1
Total				52.8		

Table 3: Run plan scenario with cross section and counting rate estimates for the forward electron-triton scattering measurements, using the two HRS systems to detect both scattered electrons and recoil tritium nuclei in coincidence. The rate estimates assume a 25 cm long gas tritium target with density 0.00325 g/cm^3, a beam current of 20 μA, a nominal solid angle of 5.0 msr for HRS, and a radiative correction factor of 0.8. Also given is the total uncertainty in the extraction of the charge form factor F_C.

BACKWARD ELECTRON SCATTERING RUN PLAN

Q^2 (fm^{-2})	F_C	F_M	Cross Section (cm^2/sr)	Time (hr)	Counts	ΔF_M ($\pm$%)
23.0	3.1×10^{-3}	2.7×10^{-5}	1.9×10^{-37}	9.6	52	NM
26.0	2.5×10^{-3}	3.1×10^{-4}	7.4×10^{-38}	31.2	68	21.5
29.0	2.1×10^{-3}	4.7×10^{-4}	1.7×10^{-37}	28.8	146	21.7
33.0	1.6×10^{-3}	4.7×10^{-4}	9.8×10^{-38}	9.6	27	19.6
37.0	1.2×10^{-3}	3.6×10^{-4}	4.4×10^{-38}	7.2	9	22.0
41.0	8.5×10^{-4}	2.4×10^{-4}	2.3×10^{-38}	22.8	15	23.5
45.0	6.1×10^{-4}	1.5×10^{-4}	7.8×10^{-39}	33.6	8	25.1
Total				142.8		

Table 4: Run plan scenario with cross section and counting rate estimates for recoil triton detection measurements using the Right HRS system. The rate estimates assume a 25 cm long gas tritium target with density 0.00325 g/cm^3, a beam current of 20 μA, a spectrometer nominal solid angle of 5.0 msr, and a radiative correction factor of 0.8. Also given is the total uncertainty in the extraction of the charge form factor F_M (NM means not measurable).

References

[1] *Measurement of the F_2^n/F_2^p and d/u ratios and $A = 3$ EMC effect in deep inelastic scattering off the tritium and helium mirror nuclei*, JLab Proposal PR-12-10-103, J. Arrington et al., The JLab MARATHON Collaboration, 2010.

[2] F.-P. Juster *et al.*, Phys. Rev. Lett. **55**, 2261 (1985).

[3] A. Amroun *et al.*, Phys. Rev. Lett. **69**, 253 (1992); Nucl. Phys. **A579**, 596 (1994).

[4] H. Collard *et al.*, Phys. Rev. Lett. **11**, 132 (1963); Phys. Rev. **138**, B57 (1965).

[5] D. H. Beck *et al.*, Phys. Rev. **C30**, 1403 (1984); Phys. Rev. Lett. **59**, 1537 (1987).

[6] L. E. Marcucci, D. O. Riska and R. Schiavilla, Phys. Rev. **C58**, 3069 (1998);

[7] J. Carlson and R. Schiavilla, Rev. Mod. Phys. **70**, 743 (1998).

[8] L. E. Marcucci *et al.*, Phys. Rev. **C72**, 014001 (2005).

[9] L. I. Schiff, Phys. Rev. **133**, B802 (1964).

[10] M. Garçon and J. W. Van Orden, Advances in Nucl. Phys. **26**, 293 (2001).

[11] R. Gilman and F. Gross, J. Phys. **G28**, R37 (2002).

[12] I. Sick, Prog. Part. Nucl. Phys. **47**, 245 (2001).

[13] F. Gross and A. Stadler, Few Body Syst. **49**, 91(2011).

[14] S. Bacca and S. Pastore, J. Phys. **G41**, 123002 (2014).

[15] L. E. Marcucci *et al.*, JLAB-THY-15-2030/arXiv:1504.05063, April 2015, submitted to J. Phys. **G**.

[16] E. Hadjimichael, in *International Review of Nuclear Physics*, Vol. 3, World Scientific, Singapore (1985).

[17] S. J. Brodsky and B. T. Chertok, Phys. Rev. **D14**, 3003 (1976); B. T. Chertok, Phys. Rev. Lett. **41**, 1155 (1978).

[18] R. Schiavilla, V. R. Pandharipande and D. O. Riska, Phys. Rev. **C40**, 2294 (1989); R. Schiavilla and D. O. Riska, Phys. Lett. **B244**, 373 (1990).

[19] R. Schiavilla, V. R. Pandharipande and D. O. Riska, Phys. Rev. **C41**, 309 (1990).

[20] R. B. Wiringa, Phys. Rev. **C43**, 1585 (1991).

[21] M. J. Musolf, R. Schiavilla and T. W. Donnely, Phys. Rev. **C50**, 2173 (1994).

[22] J. Carlson, Phys. Rev. **C38**, 1879 (1988).

[23] D. O. Riska, Phys. Rep. **181**, 207 (1989).

[24] V. V. Burov and V. K. Lukyanov and A. I. Titov, Z. Phys. **A318**, 67 (1984); V. V. Burov and V. K. Lukyanov, Nucl. Phys. **A463**, 263c (1987).

[25] M. A. Maize and Y. E. Kim, Phys. Rev. **C31**, 1923 (1985).

[26] L. S. Kisslinger, W.-H. Ma and P. Hoodbhoy, Nucl. Phys. **A459**, 645 (1986); W.-H. Ma and L. S. Kisslinger, Nucl. Phys. **A531**, 493 (1991).

[27] H. Dijk and M. Beyer, Phys. Lett. **B237**, 323 (1990).

[28] T. Katayama, Y. Akaishi and H. Tanaka, Prog. Theor. Phys. **67**, 236 (1982).

[29] J. S. McCarthy, I. Sick and R. R. Whitney, Phys. Rev. **C15**, 1396 (1977).

[30] M. Bernheim *et al.*, Lett. Nuovo Cimento **5**, 431 (1972).

[31] J. M. Cavedon *et al.*, Phys. Rev. Lett. **49**, 987 (1982).

[32] I. Nakagawa *et al.*, Phys. Rev. Lett. **86**, 5446 (2001).

[33] P. C. Dunn *et al.*, Phys. Rev. **C27**, 71 (1983).

[34] C. R. Ottermann *et al.*, Nucl. Phys. **A436**, 688 (1985).

[35] R. G. Arnold *et al.*, Phys. Rev. Lett. **40**, 1429 (1978).

[36] A. Camsonne *et al.*, *JLab Measurements of the ^{3}He Form Factors at Large Momentum Transfers*, to be submitted to Phys. Rev. Lett. (in preparation).

[37] *Elastic electron scattering off ^3He and ^4He*, JLab Proposal PR-04-018, J. Arrington *et al.*, The JLab Hall A Collaboration, 2004.

[38] A. Camsonne *et al.*, Phys. Rev. Lett. **112**, 132503 (2014).

[39] R. B. Wiringa, V. G. J. Stoks and R. Schiavilla, Phys. Rev. **C51**, 38 (1995).

[40] B. S. Pudliner *et al.*, Phys. Rev. Lett. **74**, 4396 (1995).

[41] H. Henning, P. U. Sauer and W. Theis, Nucl. Phys. **A537**, 367 (1992).

[42] G. Rupp and J. A. Tjon, Phys. Rev. **C45**, 2133 (1992).

[43] A. Stadler, F. Gross and M. Frank, Phys. Rev. **C56**, 2396 (1997).

[44] F. Gross, A. Stadler and M. T. Peña, Phys. Rev. **C69**, 034007 (2004).

[45] F. Gross, in *Modern Topics in Electron Scattering*, ed. B. Frois and I. Sick (World Scientific, Singapore, 1991).

[46] S. A. Pinto, A. Stadler and F. Gross, Phys. Rev. **C79**, 054006 (2010); Phys. Rev. **C81**, 014007 (2011).

[47] F. A. Baroncini, E. Pace and G. Salmè, Few Body Syst. **43**, 173 (2008).

[48] R. F. Frosch *et al.*, Phys. Rev. **160**, 874 (1967).

[49] J. P. Repellin *et al.*, Phys. Lett. **16**, 169 (1965).

[50] *A conceptual design of a tritium gas target for Jefferson Lab*, R. J. Holt *et al.*, April 2010.

[51] A. T. Katramatou, Kent State University preprint KSU-CNR-14-11, December 2011.

[52] W. Alahmade, M.S. Thesis, Kent State University, 2015.