JLab Measurement of the ^{4}He Charge Form Factor at Large Momentum Transfers

A. Camsonne,[22] A. T. Katramatou,[11] M. Olson,[20] N. Sparveris,[11,21] A. Acha,[4] K. Allada,[12] B. D. Anderson,[11] J. Arrington,[1] A. Baldwin,[11] J.-P. Chen,[22] S. Choi,[18] E. Chudakov,[22] E. Cisbani,[8,10] B. Craver,[23] P. Decowski,[19] C. Dutta,[12] E. Folts,[22] S. Frullani,[8,10] F. Garibaldi,[8,10] R. Gilman,[16,22] J. Gomez,[22] B. Hahn,[24] J.-O. Hansen,[22] D. W. Higinbotham,[22] T. Holmstrom,[13] J. Huang,[14] M. Iodice,[9] X. Jiang,[16] A. Kelleher,[24] E. Khrosinkova,[11] A. Kievsky,[7] E. Kuchina,[16] G. Kumbartzki,[16] B. Lee,[18] J. J. LeRose,[22] R. A. Lindgren,[23] G. Lott,[22] H. Lu,[17] L. E. Marcucci,[7,15] D. J. Margaziotis,[2] P. Markowitz,[4] S. Marrone,[6] D. Meekins,[22] Z.-E. Meziani,[21] R. Michaels,[22] B. Moffit,[14] B. Norum,[23] G. G. Petratos,[11] A. Puckett,[14] X. Qian,[3] O. Rondon,[23] A. Saha,[22] B. Sawatzky,[21] J. Segal,[22] M. Shabestari,[23] A. Shahinyan,[25] P. Solvignon,[1] R. R. Subedi,[23] R. Suleiman,[22] V. Sulkosky,[22] G. M. Urciuoli,[8] M. Viviani,[7] Y. Wang,[5] B. B. Wojtsekhowski,[22] X. Yan,[18] H. Yao,[21] W.-M. Zhang,[11] X. Zheng,[23] and L. Zhu[5]

(The Jefferson Lab Hall A Collaboration)

[1]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*California State University, Los Angeles, California 90032, USA*
[3]*Duke University (TUNL), Durham, North Carolina 27708, USA*
[4]*Florida International University, Miami, Florida 33199, USA*
[5]*University of Illinois at Urbana Champagne, Urbana, Illinois 61801, USA*
[6]*Istituto Nazionale di Fisica Nucleare, Sezione di Bari and University of Bari, 70126 Bari, Italy*
[7]*Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, 56127 Pisa, Italy*
[8]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Rome, Italy*
[9]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre, 00146 Rome, Italy*
[10]*Istituto Superiore di Sanitá, 00161 Rome, Italy*
[11]*Kent State University, Kent, Ohio 44242, USA*
[12]*University of Kentucky, Lexington, Kentucky 40506, USA*
[13]*Longwood University, Farmville, Virginia 23909, USA*
[14]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[15]*University of Pisa, 56127 Pisa, Italy*
[16]*Rutgers, The State University of New Jersey, Piscataway, New Jersey 08855, USA*
[17]*University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China*
[18]*Seoul National University, Seoul 151-747, Korea*
[19]*Smith College, Northampton, Massachusetts 01063, USA*
[20]*St. Norbert College, De Pere, Wisconsin 54115, USA*
[21]*Temple University, Philadelphia, Pennsylvania 19122, USA*
[22]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[23]*University of Virginia, Charlottesville, Virginia 22901, USA*
[24]*College of William and Mary, Williamsburg, Virginia 23185, USA*
[25]*Yerevan Physics Institute, Yerevan 375036, Armenia*

The charge form factor of ^{4}He has been extracted in the range 29 fm$^{-2} \leq Q^2 \leq 77$ fm^{-2} from elastic electron scattering, detecting ^{4}He recoil nuclei and electrons in coincidence with the high resolution spectrometers of the Hall A Facility of Jefferson Lab. The measurements have uncovered a second diffraction minimum for the form factor, which was predicted in the Q^2 range of this experiment. The data are in qualitative agreement with theoretical calculations based on realistic interactions and accurate methods to solve the few-body problem.

The electromagnetic (EM) form factors of the helium isotopes are, along with the deuteron and tritium form factors, the "observables of choice" [1] for testing the nucleon-meson standard model of the nuclear interaction and the associated EM current operator [2]. They provide fundamental information on the internal structure and dynamics of the light nuclei as they are, in a simple picture, convolutions of the nuclear ground state wave function with the EM form factors of the constituent nucleons. The theoretical calculations for these few-body observables

are very sensitive to the model used for the nuclear EM current operator, especially its meson-exchange-current (MEC) contributions. Relativistic corrections and possible admixtures of multiquark states in the nuclear wave function might also be relevant [2]. Additionally, at large momentum transfers, these EM form factors may offer a unique opportunity to uncover a possible transition in the description of elastic electron scattering by few-body nuclear systems, from meson-nucleon to quark-gluon degrees of freedom, as predicted by the dimensional-scaling quark model (DSQM) and perturbative QCD (pQCD) [3,4].

Experimentally, the few-body form factors are determined from elastic electron-nucleus scattering studies using high intensity beams, high density targets, and large solid angle magnetic spectrometers. There have been extensive experimental investigations of the few-body form factors over the past 50 years at almost every electron accelerator laboratory [5,6], complemented by equally extensive theoretical calculations and predictions [2,6,7].

This work focuses on a measurement of the ^{4}He charge form factor F_C at large momentum transfers, at Jefferson Lab (JLab). The cross section for elastic scattering of a relativistic electron from the spin zero ^{4}He nucleus is given, in the one-photon (between electron and nucleus) exchange approximation, by the formula [8]

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{(Z\alpha)^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)} F_C^2(Q^2), \qquad (1)$$

where α is the fine-structure constant, Z is the nuclear charge, E and E' are the incident and scattered electron energies, θ is the electron scattering angle, and $Q^2 = 4EE' \sin^2(\theta/2)$ is the four-momentum transfer squared.

The few-body EM form factors have been theoretically investigated by several groups, using different techniques to solve for the nuclear ground states, and a variety of models for the nuclear EM current. The most recent calculation of the ^{3}H and ^{3}He EM form factors is that of Refs. [1,9]. It uses the pair-correlated hyperspherical harmonics (HH) method [10] to obtain the few-body nuclear wave functions and goes beyond the impulse approximation (IA), where the electron interacts with one of the nucleon constituents, by including MEC, whose main contributions are constructed to satisfy the current conservation relation with the given Hamiltonian [9]. Part of the present work is the extension of the above method to the ^{4}He charge form factor (see Fig. 1) by using the (uncorrelated) HH expansion to solve for the ^{4}He wave function from the Argonne AV18 [11] nucleon-nucleon (NN) and Urbana UIX [12] three-nucleon ($3N$) interactions, and including MEC contributions arising from π-, ρ-, and ω-meson exchanges, as well as the $\rho\pi\gamma$ and $\omega\pi\gamma$ charge transition couplings. For more details, the reader is referred to Ref. [10] for the HH method, and Refs. [1,9] for the nuclear EM current model. The present experimental and theoretical results are compared to (see below) the Monte Carlo calculations of Refs. [13,14], where the variational Monte Carlo (VMC) and the Green's function
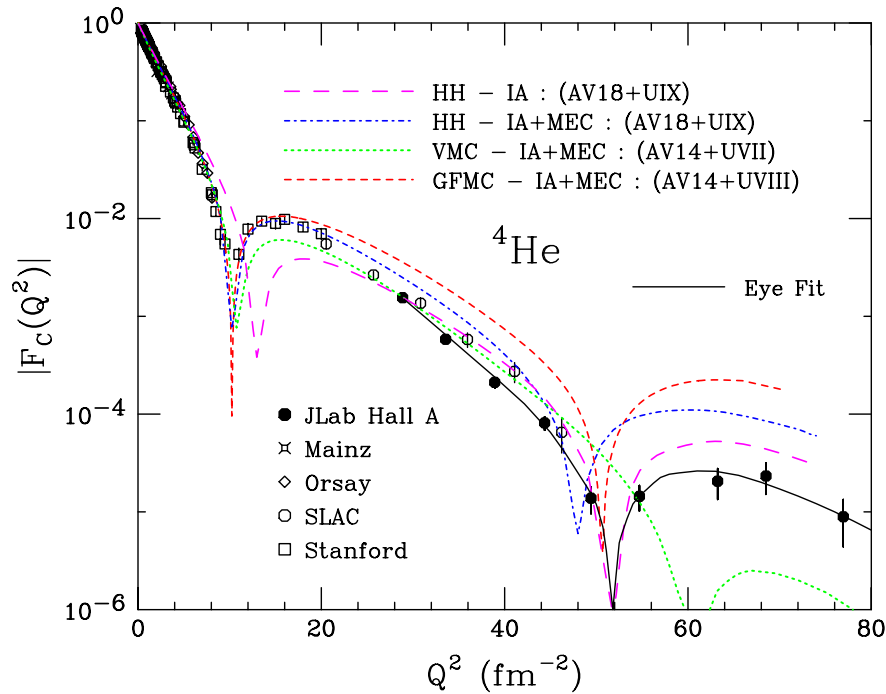

FIG. 1 (color online). ^{4}He charge form factor F_C data from this experiment are compared with the present HH theoretical IA and IA + MEC calculations, using the Argonne AV18 and Urbana UIX Hamiltonian model. Also shown are previous Stanford, Orsay, Mainz and SLAC data, and older VMC and GFMC theoretical calculations (see text). The solid line has been drawn to just guide the eye.

Monte Carlo (GFMC) methods were used to solve for the ^{4}He wave function.

At large Q^2, elastic scattering from few-body nuclear systems like ^{4}He may be partly due to, or even dominated by, contributions from electron interaction with the nucleons' constituent quarks. A purely phenomenological "hybrid quark-hadron" approach includes multiquark states, for overlapping nucleons in the nuclear wave function, which augment the IA approach [15]. The field theory approach of the DSQM, later substantiated within the pQCD framework [4], is based on dimensional scaling of high energy amplitudes using quark counting. This leads to the asymptotic prediction $\sqrt{F_C(Q^2)} \sim (Q^2)^{1-3A}$, where $A = 4$ for the ^{4}He case (see Ref. [3]).

The experiment (E04-018) used the Continuous Electron Beam (100% duty factor) Accelerator and Hall A Facilities of JLab. Electrons scattered from a high density cryogenic ^{4}He target were detected in the Left High Resolution Spectrometer (e-HRS). To suppress backgrounds and unambiguously separate elastic from inelastic processes, recoil helium nuclei were detected in the Right HRS (h-HRS) in coincidence with the scattered electrons.

The energy of the incident beam ranged between 2.09 and 4.13 GeV. The beam current was measured using two resonant cavity current monitors upstream of the target. It ranged, on average for different kinematical settings, between 38 and 82 μA. The two cavities were calibrated against a parametric current transformer monitor (Unser monitor). To reduce beam-induced target density changes and to avoid possible destruction of the target cell, the beam was rastered on the target in both horizontal and vertical directions at high frequency, resulting in an effective beam spot size of 2×2 mm^2.

The target system contained gaseous ^{4}He and liquid hydrogen cells of length $T = 20$ cm. The ^{4}He gas was pressurized to 13.7–14.2 atm at a temperature of 7.14–8.68 K, resulting in a density of 0.102–0.127 g/cm^3. Two Al foils separated by 20 cm were used to measure any possible contribution to the cross section from the Al end-caps of the target cells. This system provided, at the maximum beam current of 110 μA, a record high luminosity of 2.7×10^{38} cm^{-2} s^{-1}, for the ^{4}He target.

Scattered electrons were detected in the e-HRS using two planes of scintillators to form an "electron" trigger, a pair of drift chambers for electron track reconstruction, and a gas threshold Čerenkov counter and a lead-glass calorimeter for electron identification. Recoil nuclei were detected in the h-HRS using normally two planes of scintillators to form a "recoil" trigger and a pair of drift chambers for recoil track reconstruction. The event trigger consisted of a coincidence between the two HRS triggers. Details on the Hall A Facility and all associated instrumentation used are given in Ref. [16].

Particles in the e-HRS were identified as electrons on the basis of a minimal pulse height in the Čerenkov counter ("Čerenkov cut") and the energy deposited in the calorimeter, consistent with the momentum as determined from the drift chamber track using the spectrometer's optical properties ("calorimeter cut"). Particles in the h-HRS were identified as ^{4}He on the basis of their energy deposition in the first scintillator plane ("helium cut"). Electron-^{4}He (e-^{4}He) coincidence events, consistent with elastic kinematics, were identified using the relative time-of-flight between the electron and recoil triggers after imposing these three cuts. To check the overall normalization, elastic electron-proton (e-p) scattering was measured at several kinematics with solid angle Jacobians similar to those for e-^{4}He elastic scattering. The e-p measured cross section values were found to be in excellent agreement (to within $\pm 2.0\%$) with values calculated using a proton form factor fit [17] based on all existing e-p elastic cross section measurements.

The elastic e-^{4}He cross section values were calculated using the formula

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{N_{\mathrm{er}}C_{\mathrm{cor}}}{N_b N_t (\Delta\Omega)_{\mathrm{MC}} F(Q^2,T)}, \qquad (2)$$

where N_{er} is the number of electron-recoil ^{4}He elastic events, N_b is the number of incident beam electrons, N_t is the number of target nuclei/cm^2, $(\Delta\Omega)_{\mathrm{MC}}$ is the effective coincidence solid angle (which includes most radiative effects) from a Monte Carlo simulation, F is the portion of the radiative corrections that depends only on Q^2 and T (1.10 on average) [18], and $C_{\mathrm{cor}} = C_{\mathrm{det}}C_{\mathrm{cdt}}C_{\mathrm{rni}}C_{\mathrm{den}}$. Here, C_{det} is the correction for the inefficiency of the Čerenkov counter and the calorimeter (1.01) (the scintillator counter hodoscopes were found to be essentially 100% efficient), C_{cdt} is the computer dead-time correction (between 1.05 and 1.17), C_{rni} is a correction for losses of recoil nuclei due to nuclear interactions in the target cell and vacuum windows [1.10 (1.03) at the lowest (highest) Q^2], and C_{den} is a correction to the target density due to beam heating effects (ranging between 1.03 at 38 μA and 1.06 at 82 μA). There were no contributions to the elastic e-^{4}He cross section from events originating in the target cell end caps, as determined from runs with the empty replica target. The e-p elastic cross section values were determined similarly.

The effective coincidence solid angle was evaluated with a Monte Carlo computer code that simulated elastic electron-nucleus scattering under identical conditions as our measurements [18]. The code tracked scattered electrons and recoil nuclei from the target to the detectors through the two HRS systems using optical models based on magnetic field measurements and precision position surveys of their elements. The effects from ionization energy losses and multiple scattering in the target and vacuum windows were taken into account for both electrons and recoil nuclei. Bremsstrahlung radiation losses for both incident and scattered electrons in the target and

TABLE I. Kinematics, elastic e-^{4}He cross section and ^{4}He charge form factor results from this experiment, and total errors (statistical and systematic added in quadrature).

Q^2 (fm^{-2})	E (GeV)	θ (degree)	$d\sigma/d\Omega$ (cm^2/sr)	$|F_C|$
28.9	2.091	30.52	$(2.04 \pm 0.18) \times 10^{-36}$	$(1.55 \pm 0.07) \times 10^{-3}$
33.6	2.091	33.20	$(1.99 \pm 0.22) \times 10^{-37}$	$(5.77 \pm 0.32) \times 10^{-4}$
38.9	2.091	36.11	$(1.69 \pm 0.42) \times 10^{-39}$	$(2.01 \pm 0.23) \times 10^{-4}$
44.4	4.048	19.25	$(9.51 \pm 2.76) \times 10^{-39}$	$(8.01 \pm 0.12) \times 10^{-5}$
49.4	4.048	20.40	$(2.14 \pm 1.01) \times 10^{-40}$	$(1.36 \pm 0.32) \times 10^{-5}$
54.7	4.048	21.56	$(1.87 \pm 0.88) \times 10^{-40}$	$(1.42 \pm 0.33) \times 10^{-5}$
63.2	4.127	22.86	$(2.84 \pm 1.91) \times 10^{-40}$	$(2.02 \pm 0.68) \times 10^{-5}$
68.5	4.127	23.90	$(2.97 \pm 1.99) \times 10^{-40}$	$(2.26 \pm 0.76) \times 10^{-5}$
77.0	4.127	25.50	$(3.31 \pm 3.38) \times 10^{-41}$	$(8.67 \pm 4.43) \times 10^{-6}$

vacuum windows, as well as internal radiative effects, were also taken into account. Monte Carlo simulated spectra of scattered electrons and recoil nuclei were found to be in very good agreement with experimentally measured spectra.

It should be noted that the two-photon exchange effect [19] is not included in the radiative corrections implementation. A very recent analytic calculation [20] for ^{4}He, extending previous work for the pion [21], has shown that this effect is small (changing $d\sigma/d\Omega$ by less than 0.8%), at least for the elastic channel without excitation of an intermediate state, and can be neglected without introducing a sizable form factor error.

The extracted ^{4}He charge form factor (absolute) values are listed in Table I, and shown in Fig. 1 along with previous Stanford [22], Orsay [23], SLAC [24], and Mainz [25] data. In the figure, the error bars represent statistical and systematic uncertainties added in quadrature, and the solid curve labeled as "eye fit" is a line drawn just to guide the eye. The new data suggest the existence of a second diffraction minimum for the ^{4}He charge form factor at $Q^2 = (51.7 \pm 0.2)$ fm^{-2}. The existence of the minimum is confirmed by the momentum distribution of the observed e-^{4}He elastic events for the two Q^2 points about the minimum, 50 and 55 fm^{-2}: for the former (latter) point, the distribution is indicative of a fast falling (rising) form factor with Q^2. It is also evident from Fig. 1 that the new JLab data are in significant disagreement with the existing SLAC data. The latter data were taken with the medium resolution 8 and 20 GeV/c spectrometers, for recoil and electron detection, respectively, using a hardware coincidence between their event trigger signals. The JLab and SLAC experiments were similar with the exception of not measuring at SLAC (i) the actual time-of-flight difference between the electron and recoil triggers, and (ii) the momentum and recoil angle of the recoil particles, due to the lack of a suitable tracking device. Both of the above measurements were critical for the unambiguous identification of e-^{4}He elastic events at JLab.

The data in Fig. 1 are compared to the HH variational calculation performed using the AV18 NN and Urbana UIX

$3N$ interactions. Also shown are the VMC results of Ref. [13], using the older AV14 NN and UVII $3N$ interactions, and the GFMC results of Ref. [14], using the AV14 and UVIII $3N$ interactions. It can be seen that all three calculations, which include MEC, are in qualitative agreement with the new JLab data and do predict, though at different locations, a second diffraction minimum for $Q^2 > 40$ fm^{-2}. The present HH calculation for the ^{4}He F_C is in a qualitatively better agreement with the data when compared with the older Monte Carlo studies of Refs. [13,14]. To better illustrate this aspect, we also show the HH calculation without MEC (IA only). Of note is that the lower Q^2 data are in good agreement with the HH IA + MEC calculation, while the higher Q^2 data are in better agreement with the HH IA-only calculation. This observation may be indicative of a possible diminishing role of MEC with increasing Q^2 required to bring the theory into better agreement with the data. The inadequacy of the above theoretical approach to describe well the entire Q^2 range of the ^{4}He F_C may also indicate the need for a truly covariant relativistic framework, which has been successful in describing all deuteron form factor data [6]. In fact, we would like to remark that the second diffraction minimum is in a range of Q^2 where the applicability of the standard nonrelativistic nuclear physics approach presented here may be questionable.

The diffractive pattern of the new data is clearly incompatible with the asymptotic-falloff DSQM prediction [3]. It is evident that our data support the conclusion of Ref. [26] that the onset of asymptotic scaling must be at a Q^2 value greater than 100 fm^{-2} (25 fm^{-2} per nucleon), not presently accessible at JLab for ^{4}He.

In summary, we have measured the ^{4}He charge form factor in the range 29 fm$^{-2} \le Q^2 \le 77$ fm^{-2}. The new data have uncovered a second diffraction minimum for this form factor. They constrain inherent uncertainties of the theoretical calculations and lead, together with previous large Q^2 data on the deuteron, ^{3}He and tritium elastic form factors [24,27,28], to the development of a consistent hadronic model describing the internal EM structure and dynamics of few-body nuclear systems.

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