Isoscalar and Isovector Form Factors of ^{3}H and ^{3}He for Q below 2.9 fm^{-1} from Electron-Scattering Measurements

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The ^{3}H and ^{3}He charge and magnetic form factors have been extracted from cross-section measurements in the region $0.3 \lesssim Q \lesssim 2.9$ fm^{-1}. The measurements have random uncertainties of about 2% and systematic uncertainties of about 2% for ^{3}H and 1.5% for ^{3}He. The small systematic uncertainties allow accurate determination of the isoscalar and isovector trinucleon form factors. The isoscalar charge and isovector magnetic form factors are in reasonable agreement with current theoretical models, whereas the isovector charge and isoscalar magnetic form factors show significant deviations from the models.

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The three-nucleon system is an important testing ground for theories of nuclear structure because exact nonrelativistic calculations of the wave function have been done. The wave functions of various groups solving the Faddeev equations in both configuration and momentum space are now in accord[1] and use input from the most realistic two- and three-nucleon interaction models available. Elastic electron scattering provides relatively direct information as regards the trinucleon structure through the charge monopole and magnetic dipole form factors. Calculations of the form factors require, in addition to the wave functions, models of the electromagnetic current. Various attempts have been made to include currents due to meson exchange and nuclear-isobar components in the ground state.[2,3] Recent reviews of electromagnetic properties of the trinucleon ground state may be found in Friar[4] and Hadjimichael and Oelert,[5] and references therein.

The ground states of ^{3}H and ^{3}He form a $T=\frac{1}{2}$ isodoublet. Because, in addition, the charge monopole and magnetic dipole matrix elements are real, the isoscalar and isovector form factors may be determined unambiguously from electron-scattering data. The isospin-separated form factors presented here provide a second valuable projection of the three-nucleon system in isospin space—useful, for example, because only the isovector magnetic meson-exchange currents contribute to the overall current to leading order in a relativistic expansion.[4]

Many measurements of the ^{3}He form factors have been made[6–8]; there are fewer measurements of the ^{3}H form factors[8,9] because of its radioactivity. The experiment described herein was designed to make measurements with both targets under conditions as similar as possible in order to determine accurately the isospin-separated form factors.

The measurements were made at the Massachusetts Institute of Technology (MIT)–Bates Linear Accelerator Center with use of the energy-loss spectrometer system.[10] Cross-section data were taken at two angles covering the range of momentum transfer $0.3 \lesssim Q \lesssim 2.9$ fm^{-1}. Uncertainties in incident charge, spectrometer acceptance, detector efficiency, and target-gas contamination contribute about 0.7% to both the random and systematic uncertainties.[11]

In order to have target systems for ^{3}H and ^{3}He as similar as possible while we maintain the highest target density consistent with safety considerations, cryogenic gas cells were utilized.[11] The operating point of the cells was $T=45$ K and $P=15$ atm. The equations of state for the gases were extrapolated from those of $^1H_2$ and ^{4}He with the principle of corresponding states.[11] Pressure and temperature were measured with transducers located in the respective target gases. The uncertainties associated with the density determination are the largest in the experiment. Random uncertainties in the density amounted to 1.2% for both target gases; systematic uncertainties accruing from four sources including the equation-of-state extrapolation were added in quadrature and amounted to 1.9% for $^3H_2$ and 1.3% for ^{3}He. The total nonstatistical random uncertainties for both ^{3}H and ^{3}He were 1.4%; the total systematic uncertainties were 2.1 and 1.4%, respectively.

Corrections due to electron energy loss and radiative effects were applied to the data. The framework of Mo and Tsai[12] was used to calculate the internal and external radiative corrections. Multiple containment vessels necessary for our handling the ^{3}H amounted to about 0.03 radiation lengths in total. The radiative corrections were typically 40%–50% and divided roughly equal between the two types. The ionization corrections were calculated according to Bergstrom[13] and were relatively small ($\lesssim 3\%$).

The elastic electron-scattering cross section may be written with conventional notation as[14]

$$\frac{d\sigma}{d\Omega}=\frac{\sigma_M}{1+2E_i\sin^2(\frac{1}{2}\theta)/M}\left\{\frac{Z^2F_c^2}{1+\tau}+\tau\mu_A^2F_m^2\left[\frac{1}{1+\tau}+2\tan^2(\tfrac{1}{2}\theta)\right]\right\}, \tag{1}$$

where $\tau=Q^2/4M^2$, $\mu_A=\mu M/M_N$, and M and μ are, respectively, the mass and magnetic moment of the trinucleon. This formula assumes plane-wave electrons in the initial and final state as well as single-photon exchange. The interaction of the electron with the nucleus is, however, significantly more complicated with respect to the accuracy of this experiment. The experimental cross sections were therefore "corrected" to give effective plane-wave cross sections in order to compare with plane-wave theory. The charge and magnetic parts of the cross sections were treated separately with use of the codes of Friar and Negele[15] and Heisenberg,[16] respectively. The largest correction was 6% for ^{3}He at the backward angle and highest momentum transfer.

The ^{3}H and ^{3}He form factors were determined with use of Eq. (1) from cross sections measured at 54° and 134.5°. A comparison of form factors determined in this experiment and those of other recent measurements is shown in Figs. 1 and 2 (with random uncertainties only). All form factors in these figures have been determined directly from experimental cross sections (i.e., no distortion corrections have been applied). In each case the data sets are divided by a fit to the present data (with a Fourier-Bessel expansion of the nuclear current density) in order to illustrate the comparison more clearly. Agreement among the experimental ^{3}He form factors is good (Fig. 2). The present data are, however, systematically about 10% higher at intermediate values of Q than the recent preliminary results of Juster *et al.*[9] for ^{3}H (here only a sample of their data[17] is reproduced with the points spaced at 0.25-fm^{-1} intervals). The Juster *et al.* data are being reanalyzed but the cross sections are not expected to change by more than a few percent.[17] Therefore the difference between the data sets is not currently understood.

The trinucleon isoscalar and isovector form factors are written[18]

$$F_c^{S,V}=\tfrac{1}{2}\{Z(^3\mathrm{He})F_c(^3\mathrm{He})\pm Z(^3\mathrm{H})F_c(^3\mathrm{H})\},$$
$$F_m^{S,V}=\tfrac{1}{2}\{\mu(^3\mathrm{He})F_m(^3\mathrm{He})\pm \mu(^3\mathrm{H})F_m(^3\mathrm{H})\} \tag{2}$$

[the normalizations implicit in Eq. (1) are $F_{c,m}(Q=0)=1$]. The separated isospin form factors from the present experiment are presented in Table I. They have been extracted from the effective plane-wave cross sec-

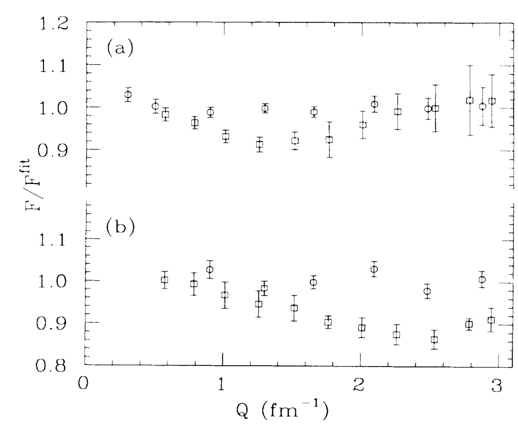

FIG. 1. Comparison of ^{3}H data (divided by fit to present data) for (a) F_c and (b) F_m. Circles, present experiment; squares, Ref. 9.

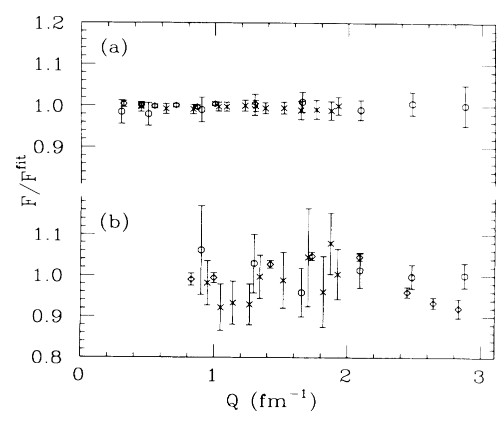

FIG. 2. Comparison of ^{3}He data (divided by fit to present data) for (a) F_c and (b) F_m. Circles, present experiment; lozenges, Ref. 6; plusses, Ref. 7.

TABLE I. Effective plane-wave form factors with total random uncertainties.

Q (fm^{-1})	F_c^S	F_c^V	F_m^S	F_m^V
0.300	1.419 ± 0.028	0.433 ± 0.027		
0.501	1.283 ± 0.024	0.388 ± 0.024		
0.900	0.955 ± 0.019	0.265 ± 0.019	0.312 ± 0.075	-1.726 ± 0.075
1.298	0.622 ± 0.010	0.151 ± 0.010	0.219 ± 0.031	-1.088 ± 0.031
1.654	0.381 ± 0.006	0.088 ± 0.006	0.186 ± 0.016	-0.661 ± 0.016
2.092	0.182 ± 0.003	0.035 ± 0.003	0.108 ± 0.007	-0.357 ± 0.007
2.479	0.082 ± 0.002	0.0116 ± 0.0016	0.054 ± 0.003	-0.186 ± 0.003
2.874	0.029 ± 0.001	0.0010 ± 0.0010	0.029 ± 0.001	-0.088 ± 0.001

tions described above.

Figures 3 and 4 show the effective plane-wave isoscalar and isovector form factors from this experiment compared with three theoretical models. All three models use wave functions generated by solution of the Faddeev equations. The calculations of Hadjimichael, Goulard, and Bornais[3] and Friar *et al.*[18] use the Reid soft-core two-nucleon potential, whereas the Strueve, Hajduk, and Sauer[2] calculation uses the Paris potential. The Hadjimichael, Goulard, and Bornais[3] and the Strueve, Hajduk, and Sauer[2] models both include meson-exchange currents, whereas the Friar *et al.*[18] model does not. The model of Ref. 2 includes virtual Δ isobars in the ground state explicitly (i.e., they represent an extra degree of freedom in the Faddeev equations). The models of Refs. 3 and 18 incorporate some of the same physics by including a "three-body" potential in the Faddeev Hamiltonian. The model of Ref. 18 uses a complete version of the Coon and Glockle[19] three-body potential, whereas the model of Ref. 3 uses only an approximate form.

The isoscalar charge form factor is best represented by the Hannover calculation with very good agreement over the entire range of momentum transfer. The Friar *et al.*[18] calculation lies significantly above the data for all but the lowest momentum transfer. Both the Strueve, Hajduk, and Sauer[2] and the Friar *et al.*[18] calculations lie systematically above the isovector charge form factor while the Hadjimichael, Goulard, and Bornais[3] calculation lies below by about the same amount.

The isoscalar magnetic form factor differs significantly from theory. All three calculations have shapes different from that of the data near 1.5 fm^{-1}, deviating by a maximum of about 20% (systematically 2 or 3 standard deviations). This is to be contrasted with the isovector magnetic form factor where again the calculation of Ref. 2 is in excellent agreement. It should be noted that when the Juster *et al.*[9] ^3H data are combined with the present ^3He data the resulting isoscalar magnetic form factor is in reasonable agreement with the calculations.

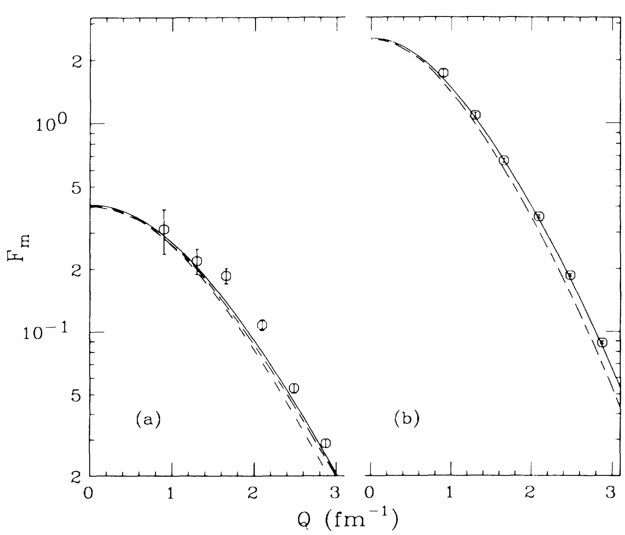

FIG. 3. Comparison of theory and the present data for (a) F_c^S and (b) F_c^V. Circles, present experiment; long-dashed line, Ref. 3; solid line, Ref. 2; short-dashed line, Ref. 18.

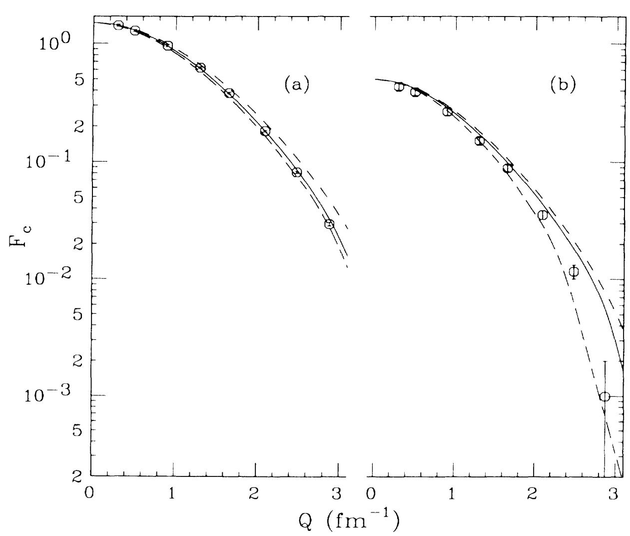

FIG. 4. Comparison of theory and the present data for (a) F_m^S and (b) $|F_m^V|$. Circles, present experiment; long-dashed line, Ref. 3; solid line, Ref. 2; short-dashed line, Ref. 18.

In summary it would appear that the inclusion of three-body potentials or explicit Δ isobars in theoretical models of the three-nucleon system does not result in complete agreement with experiment even at low momentum transfers (even though they improve the agreement with the observed binding energy). The Friar *et al.*[18] calculation lies significantly above the isoscalar charge form factor. The sensitive difference form factors—the isovector charge and the isoscalar magnetic—are not well represented by either the Strueve, Hajduk, and Sauer[2] or Friar *et al.*[18] calculations. In the one case where meson-exchange currents enter in a consistent manner in a relativistic expansion—the isovector magnetic form factor—at least the calculations of Ref. 2 is in excellent agreement with the data.

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