Tritium Electromagnetic Form Factors

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We have measured the charge and magnetic form factors of tritium for values of the momentum transfer up to 31.3 fm^{-2}. The data are compared with calculations for the three-body system including meson-exchange-current contributions.

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The tritium form factors are an essential piece of information for the understanding of the three-nucleon system. The one-body contribution, coming from three nonrelativistic nucleons, is now believed to be well under control.[1,2] In the magnetic form factors of ^{3}H and ^{3}He, meson-exchange currents (MEC) are dominant at medium and high momentum transfer. The charge form factors are much less sensitive to MEC, and are expected to yield a direct measurement of the nuclear wave function. However, there remains a longstanding difficulty in the explanation of the second maximum of the charge form factor of ^{3}He. Large effects of MEC and three-body forces,[3] as well as quark degrees of freedom,[4] have been proposed to account for this discrepancy. In the case of ^{3}H, the isoscalar and isovector pieces of the MEC contributions are predicted to cancel, leading to a small net effect.[3] Thus, data on the ^{3}H charge and magnetic form factors in the region of the diffraction maximum have been needed. But, whereas the ^{3}He form factors have received much experimental attention,[5,6] there has been a striking lack of data for ^{3}H. The maximum momentum transfer measured for ^{3}H ($q^2 = 8\ \mathrm{fm}^{-2}$) was reached twenty years ago.[5] Recent measurements have been done at very low momentum transfer.[7] The radioactive nature of ^{3}H explains the scarcity of experimental data. Targets suitable for measurements of low cross sections need a large amount of ^{3}H in a reliable container and have to withstand very intense beams.

In this Letter we present the results of an elastic-electron-scattering experiment using a 1-g (10-kCi) liquid ^{3}H target. The experiment has been performed at the Saclay 700-MeV electron linac (ALS). We outline here only the main features of our target; a complete description will be given elsewhere. The target cell is a cylinder, 10 mm in diameter, with two hemispherical end caps. Its total length is 50 mm. This cell is permanently connected to an expansion vessel that has a volume of 160 cm^3. At room temperature, the tritium pressure is 23 bars. When the cell is cooled down to $T = 21.7$ K, with the expansion vessel kept at $T = 300$ K, 98% of the tritium liquefies into the target. The target cell and the expansion vessel together are permanently sealed in the primary container.

The safety requirements are met by enclosing the primary vessel in three additional volumes, in the following sequence: vacuum, helium, vacuum. The innermost vacuum chamber, which ensures thermal insulation, is large enough to hold all the tritium at less than atmospheric pressure. Vacuum is maintained by getters and ion pumps, without exhaust. The intermediate volume provides a permanent leak detection: helium leaking towards the inner or the outer vacuum would indicate the loss of integrity of either envelope. The three innermost enclosures are permanently sealed and vacuum tight. The incident and scattered electrons cross these envelopes through thin stainless-steel windows (50 μm thick each).

The outermost envelope is a container that has all the necessary mechanical strength for transportation and handling. This container is closed and vacuum tight for shipping or whenever someone is present in the experimental hall. It is opened by remote control, by separating the top and bottom half shells by 35 mm. Two independent microprocessors continuously check the vacuum integrity of each of the four envelopes, by means of pressure, temperature, and vacuum gauges. They also check the safety requirements concerning the target and incident beam properties that have to be met for operation of the target.

The scattered electrons were analyzed by use of the 900-MeV/c magnetic spectrometer and its usual detection system.[8] The reaction vertex and the scattering angle within the liquid ^{3}H target were reconstructed by software, with an accuracy of, respectively, 5 mm and 15 mrad FWHM in the worst conditions. A resolution of 2 MeV was achieved after on-line trajectory reconstruction for kinematical broadenings and ionization-energy losses within the target. This resolution allows a clear separation from inelastic scattering. For extreme scattering angles (155°), the target windows were partly located within the spectrometer acceptance. A special collimator attached to the target eliminated their contribution. The target density $\rho = 260 \pm 4$ mg cm^{-3} at zero beam current was taken from tables of saturation properties[9] of ^{3}H. The temperature of the tritium was determined by measurement of the saturation pressure of the liquid hydrogen[9] that cooled the tritium. The variation of the effective target density with beam intensity has been measured at each incident energy. With a beam defocused to 2×2 mm^2, the density was found to decrease by 1.2%/μA, for currents up to 15 μA. The spectrometer acceptance was computed from the geometry of the target cell, the 155° collimator, and the standard spectrometer slits, and measured with a ^{12}C target placed at different positions along the beam axis. The two estimates of the solid angle agree within 0.5%. The efficiency of each counter of the trigger and the wire chambers was determined by redundancy. Thus we have measured absolute cross sections, with a systematic uncertainty of $\pm$ 4.5 %.

The experiment has been performed at fifteen different energies, ranging from 190 to 685 MeV. The scattering angles cover the region from 25° to 104°, and a backward scattering angle of 155°. We have measured 185 cross sections, which span ten decades, down to 3.4×10^{-39} cm^2 sr^{-1}. The background was always negligible. The experiment was continuously monitored to within a few percent by repetitive measurements at forward angle. Radiative corrections

TABLE I. Tritium charge and magnetic form factors normalized to unity and expanded as a sum of Gaussians following Eq. (6) of Ref. 11. The Q_i parameters are best-fit values. The rms radius of all Gaussians is 0.8 fm, which corresponds to $\gamma = 0.6532$.

R_i (fm)	Q_i (Charge)	Q_i (Magnetic)
0.01	0.035 952	0.001 315
0.20	0.027 778	0.093 538
0.50	0.131 291	0.150 007
0.80	0.221 551	0.156 982
1.20	0.253 691	0.246 090
1.60	0.072 905	0.130 560
2.00	0.152 243	0.137 359
2.50	0.051 564	0.055 848
3.00	0.053 023	0.029 534

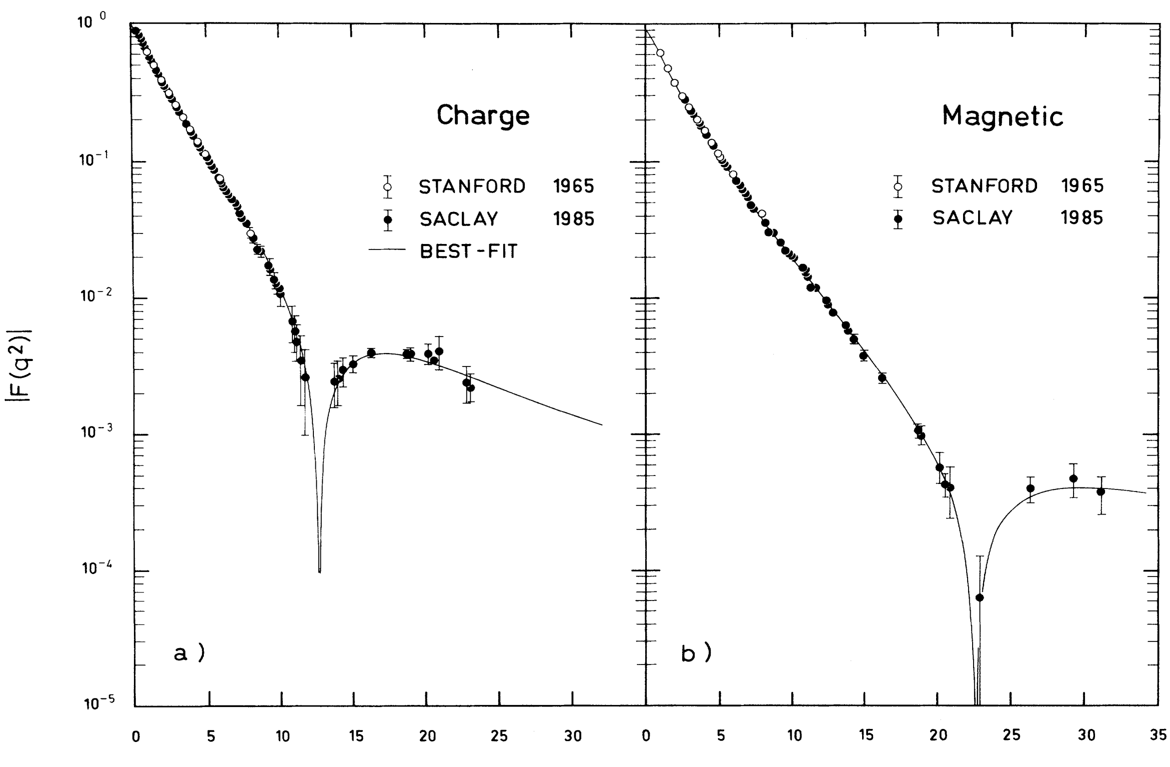

FIG. 1. (a) Charge and magnetic (b) form factors of ^{3}H. The solid curve corresponds to the best fit of Table I. Open circles are data from Refs. 5 and 7; solid circles, from this work.

were made following the procedure described by Auffret *et al.*[10]

In order to determine the charge and magnetic form factors $F_C(q^2)$ and $F_M(q^2)$, the whole set of cross sections, including data from previous experiments,[5-7] has been analyzed simultaneously. The cross sections have been fitted by expansion of the charge and magnetic form factors as a sum of Gaussians.[11] A standard fitting procedure was used to determine the values of the amplitudes of the Gaussians (nine per form factor). The result of the best fit is quoted in Table I, and is shown as a solid line in Figs. 1(a) and 1(b). The total χ^2 is 476 for 248 data points. The data of this experiment alone have a total χ^2 of 211 for 180 data points. The fitting procedure provides a thorough treatment of all the statistical and systematical errors. This fit value is the best representation of our experimental results. However, this presentation does not convey any information on the number, the density, and the dispersion of the data points leading to the fit. Thus, we have separated each experimental cross section into a charge and a magnetic form-factor value, using the charge/magnetic ratio obtained from the fit. By doing so, we have used the fact that our experiment provides a high density of data points. This permits a determination of the ratio F_C/F_M for a specific data point by use of a fit to all of the data (but the one of interest). The form factors extracted with this procedure are shown in Figs. 1(a) and 1(b), with error bars including proper propagation of the error both of the experimental point and of the F_C/F_M ratio. We have also performed a standard Rosenbluth separation of the data which agrees perfectly with the results of the fitting procedure.

The magnetic form factor has been measured from $q^2 = 3.1$ to $31.3\ \mathrm{fm}^{-2}$. The charge contribution to the three highest-momentum cross sections is small (< 10%) and is safely subtracted by use of the extrapolation of the fit to F_C. The measurement of the charge form factor has been limited to the range $q^2 = 0.3$–$22.9\ \mathrm{fm}^{-2}$. Our data agree within 8% with the previous values of Collard *et al.*[5] The charge and

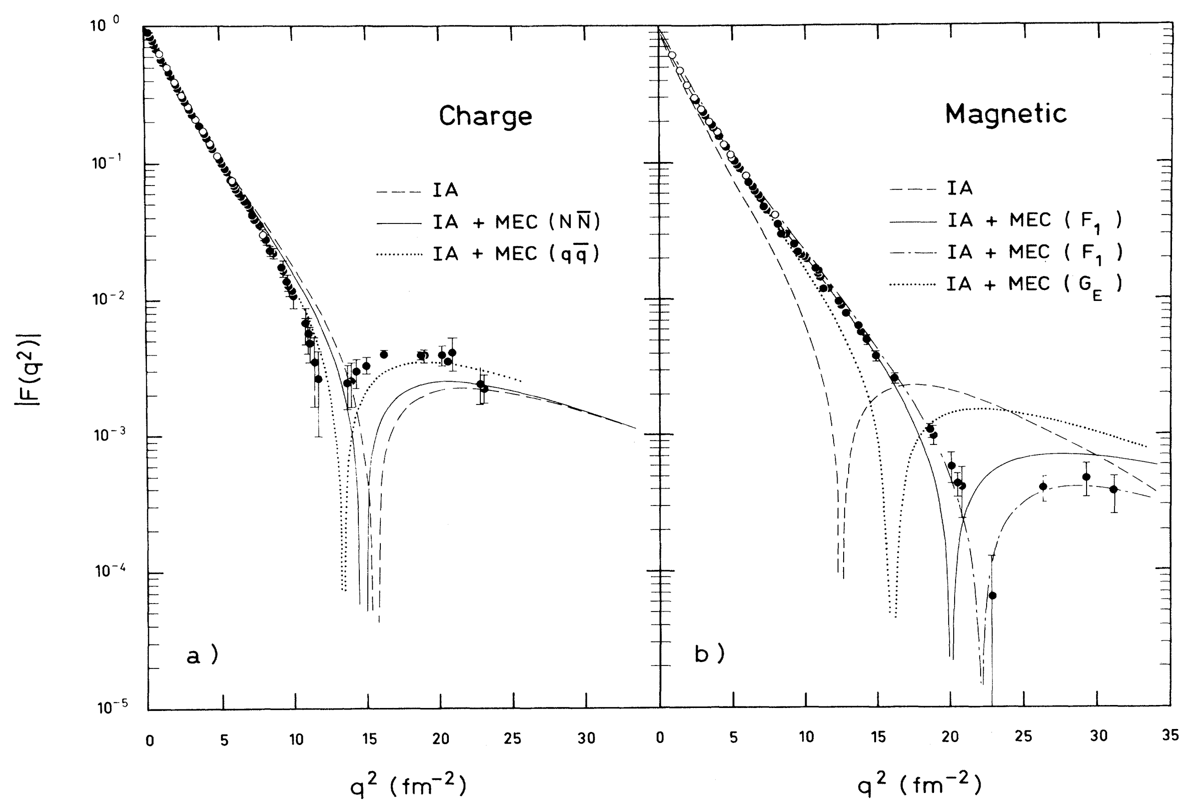

FIG. 2. Theoretical calculations: (a) Charge form factor. The dashed curve (IA) is the impulse-approximation result. The solid curve (IA+MEC) is obtained after inclusion of meson-exchange currents. Calculations from Refs. 2 and 12 are nearly identical and are shown by a single curve. The dotted curve (IA+MEC $q\bar{q}$) corresponds to the coupling of the virtual photon to a $q\bar{q}$ pair (Ref. 14). (b) Magnetic form factor. Impulse-approximation result (dashed curve), and IA+MEC using G_E (dotted curve) or F_1 (solid curve) form factor (Ref. 2). The dash-dotted curve (Ref. 12) includes MEC, with the use of F_1.

magnetic diffraction minima are found at $q^2 = 12.6 \pm 0.4$ fm^{-2} and $q^2 = 22.5 \pm 0.5$ fm^{-2}, respectively. The corresponding rms radii are $r_C = 1.76 \pm 0.04$ fm and $r_M = 1.72 \pm 0.04$ fm.

Figure 2 is a comparison of our results to theoretical predictions. These predictions[2,12] are based on solutions of Faddeev equations and include meson-exchange currents computed with pseudoscalar coupling. Strueve and co-workers[2] account for the three-body force by including Δ-isobar components directly in the nucleonic wave functions, while Hadjimichael, Goulard, and Bornais[12] use an explicit three-body force in addition to the wave functions of Torre, Benayoun, and Chauvin.[13] They also compute a more extended set of exchange diagrams, including ρ and ω exchange.

Figure 2(b) shows that meson-exchange effects dominate F_M at medium and large momenta. The present data confirm that, as previously observed[6,10] for M1 isovector transitions, good agreement with the data is achieved. One of the calculations[12] reproduces the data, while the other[2] deviates at high-momentum transfers. The use of the Sachs form factor $G_E(q^2)$ instead of the $F_1(q^2)$ Dirac form factor leads in all cases to a very poor result. This is similar to what has been observed previously for the ^{3}He magnetic form factor; the long-range part of MEC is well understood, but ambiguities remain for short-range processes. The ^{3}H charge form factor is shown in Fig. 2(a). Both calculations[2,12] underestimate the data by about 40% in the region of the secondary diffraction maximum. The absolute amount of this disagreement is almost identical to the difference between theory and experiment for the ^{3}He nucleus. This observation indicates possible inadequacies in the isoscalar contribution to the three-nucleon charge form factors. Recently Beyer *et al.*[14] have computed $F_C(q^2)$ using, for the exchange piece, a quark constituent model in which the virtual photon couples to a quark-antiquark pair, rather than to a nucleon-antinucleon pair. This prediction fits the ^{3}H data, but no longer reproduces the ^{3}He data so well. Calculations performed with pseudovector πNN coupling[12] give almost identical results.

In conclusion, our experiment has extended the knowledge of the ^{3}H charge and magnetic form factors up to the region of the second diffraction maximum. The magnetic form factors are reasonably well described in terms of nucleons and mesons. Our new measurement on the ^{3}H charge form factor shows that the region of the secondary maximum of the three-nucleon form factors is not yet fully understood. A satisfactory explanation of both ^{3}H and ^{3}He is now a clear challenge to theory.

The success of this experiment is due to the cooperation of technical groups of Commissariat à l'Energie Atomique, Saclay, and Commissariat à l'Energie Atomique, Bruyères-le-Châtel, which have designed, built, filled, and operated the tritium target. Our warmest thanks go to all of the people that have made our project possible, and in particular to P. Colnet, A. Godin, B. Hervieu, and M. Maurier. We are grateful to W. Strueve for kindly providing results prior to publication.

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[1]J. L. Friar, B. Gibson, and G. L. Payne, Ann. Rev. Nucl. Part. Sci. **34**, 403 (1984); J. Carlson, V. R. Pandharipande, and R. B. Wiringa, Nucl. Phys. **A401**, 59 (1983); S. Ishikawa *et al.*, Phys. Rev. Lett. **53**, 1877 (1984); C. R. Chen *et al.*, Phys. Rev. Lett. **55**, 374 (1985); J.-L. Ballot and M. Fabre de la Ripelle, Ann. Phys. (N.Y.) **127**, 62 (1980).

[2]W. Strueve, C. Hajduk, and P. U. Sauer, Nucl. Phys. **A405**, 620 (1983); C. Hajduk, P. U. Sauer, and W. Strueve, Nucl. Phys. **A405**, 581 (1983); W. Strueve, Ph.D., thesis, Hannover 1985 (unpublished), and private communication.

[3]W. M. Kloet and J. A. Tjon, Phys. Lett. **61B**, 356 (1976); D. O. Riska, Nucl. Phys. **A350**, 227 (1980); E. Hadjimichael, B. Goulard, and R. Bornais, Phys. Rev. Lett. **48**, 583 (1982).

[4]P. Hoodbhoy and L. Kisslinger, Phys. Lett. **146B**, 163 (1984); M. A. Maize and Y. E. Kim, Phys. Rev. C **31**, 1923 (1985); J. P. Vary, S. A. Coon, and H. J. Pirner, in *Few Body Problems in Physics,* edited by B. Zeitnitz (Elsevier, New York, 1984), Vol. II.

[5]H. Collard *et al.*, Phys. Rev. **138**, B 57 (1965).

[6]M. Bernheim *et al.*, Nuovo Cimento Lett. **5**, 431 (1972); J. S. McCarthy *et al.*, Phys. Rev. C **15**, 1396 (1977); Z. Szalata *et al.*, Phys. Rev. C **15**, 1200 (1977); R. G. Arnold *et al.*, Phys. Rev. Lett. **40**, 1429 (1978); A. V. Gunten, thesis, Institut für Kernphysik, Darmstadt, 1982 (unpublished); J. M. Cavedon *et al.*, Phys. Rev. Lett. **49**, 986 (1982); P. C. Dunn *et al.*, Phys. Rev. C **27**, 71 (1983); C. R. Ottermann *et al.*, Nucl. Phys. **A436**, 688 (1985).

[7]D. H. Beck *et al.*, Phys. Rev. C **30**, 1403 (1984).

[8]P. Leconte *et al.*, Nucl. Instrum. Methods **169**, 401 (1980).

[9]H. M. Roder *et al.*, U. S. National Bureau of Standards Technical Report No. NBS-641, 1973 (unpublished); P. C. Souers, Lawrence Livermore Laboratory Report No. UCRL-52628, 1973 (unpublished); L. Guizouarn, Commissariat à l'Energie Atomique–Centre d'Etudes Nucléaires Grenoble Report No. CENG/ASP 65-11, 1965 (unpublished).

[10]S. Auffret *et al.*, Phys. Rev. Lett. **55**, 1362 (1985).

[11]I. Sick, Nucl. Phys. **A218**, 509 (1977).

[12]E. Hadjimichael, B. Goulard, and R. Bornais, Phys. Rev. C **27**, 831 (1983).

[13]J. Torre, J. J. Benayoun, and J. Chauvin, Z. Phys. A **300**, 319 (1981).

[14]M. Beyer *et al.*, Phys. Rev. Lett. **122B**, 1 (1983).