Magnetic Form Factor of ³He

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The elastic magnetic form factor of ³He has been measured up to $q^2 = 32$ fm^{-2}. Few-body theory fails to explain the location of the diffraction minimum unless nonnucleonic degrees of freedom are explicitly introduced.

Most aspects of the structure of nuclei can be explained within a theoretical framework involving only protons and neutrons and the force between them. However, for an understanding of nuclear structure at a more fundamental or detailed level, the nonnucleonic degrees of freedom must be explicitly included. Of particular importance are the presence of pions associated with the one-boson–exchange nature of the nucleon-nucleon force, and the effect of the Δ and isobars due to the large probability of nucleon excitation via the pion-nucleon interaction. The understanding of the mesonic degrees of freedom is of increasing importance as theories attempt to provide a unified and more fundamental description of nuclei based on quantum chromodynamics.

A great effort has been expended in the search for mesonic degrees of freedom. Nuclear properties as well as reaction mechanisms have to be well understood before mesonic contributions can be clearly identified. To date the measurement of electromagnetic properties of nuclei has provided the least ambiguous information.[1,2] In particular, the magnetic properties are sensitive to the currents produced by the mesons exchanged between nucleons, as well as to the $M1$ transition from the nucleon to the Δ excited state. Historically, the initial efforts to isolate meson

exchange currents (MEC) were concentrated on the calculation of the ³He magnetic moment[3,4] and on the radiative capture[5] of thermal neutrons ($n +p \rightarrow d +\gamma$). In both cases the effect was found to be small, of the order of 10%.

For detailed study of MEC, a much larger relative contribution is desirable. Two cases exhibiting a strong enhancement of the MEC have been found[6-8]: the $M1$ electroexcitation of deuterium to the singlet S state, for which accurate measurements have recently been made,[9] and the magnetic elastic electron scattering cross section for ³He. For these two cases the effect of the MEC is to shift the diffraction minimum to larger q^2; for ³He the magnitude of the cross sections changes by as much as 2 orders of magnitude. Previously available data[10-12] for the ³He magnetic form factor did not reach the region where the diffraction features occur.

In this Letter, we present the results of an elastic electron scattering experiment from the magnetization distribution of ³He. This experiment has covered the region of momentum transfer where meson exchange contributions induce a strong interference effect in the magnetic form factor, shifting the location of its first diffraction minimum by a large amount. The measurements were performed with the Saclay linear accelerator (ALS). For this experiment, the maxi-

mum energy of the accelerator was increased to 720 MeV.

We have used a gaseous ^{3}He target at a pressure of 12 atm, cooled to liquid-hydrogen temperature (22 K). This target, which is shown schematically in Fig. 1, has a cylindrical shape of 150 mm diam with a 50-μm (40-mg/cm^2) stainless-steel window. The geometry of the target was chosen such that the spectrometer acceptance for scattering from the ^{3}He was over a factor of 10^4 greater than the acceptance for scattering from the windows This was important for the suppression of the large cross section for electrons scattered quasielastically from the windows. A fan circulated the 300 l of ^{3}He in the target through a heat exchanger consisting of a grid of sixty copper wires. The primary circuit of the heat exchanger was filled with liquid hydrogen. We were able to use an incident beam intensity of up to 40 μA by defocusing the beam spot to 2 mm $\times$ 3 mm. At an angle of 155° the target thickness seen by the spectrometer was ~50 mg/cm^2. The temperature of the target was continuously monitored at both the entrance and the exit of the heat exchanger.

The scattered electrons were energy analyzed by a 900-MeV/c magnetic spectrometer[13] and detected by two multiwire proportional counters that determined the electron trajectory. The scattered electrons were identified by a coincidence between two planes of plastic scintillators and a Lucite Cherenkov counter. The background was measured to be smaller than 10^{-40} cm^2/sr for a momentum acceptance $\Delta p/p$ of 1%. With an energy resolution $\Delta E/E$ of 10^{-3}, the ^{3}He elastic

peak was well separated from the breakup threshold at 5.5 MeV.

Measurements were taken at thirteen different energies between 200 and 700 MeV. The magnetic data were determined by measuring elastic cross sections at a scattering angle of 155°. The absolute detection efficiency was calibrated by elastic scattering measurements at forward angles corresponding to momentum transfers between 1 and 4 fm^{-2}. Corrections have been made for dead-time losses and for the variation of the target thickness as a function of the incident electron beam current. The data were also corrected for radiative effects and the finite acceptance of the spectrometer. The magnetic contribution to the 155° measurements has been determined in an iterative procedure. Earlier experiments at forward angles[11,12] provided charge scattering cross sections uncorrected over our momentum transfer range for a small magnetic contribution. As a first approximation, a fit to these data was used to estimate the charge scattering contribution to our measurements. A fit to the resulting magnetic cross sections was used to deduce and subtract the magnetic contribution to the forward-angle data of Refs. 11 and 12, yielding a closer approximation to the charge scattering cross section. A second iteration of this procedure was sufficient to achieve a self-consistent separation of charge and magnetic contributions in our meas-
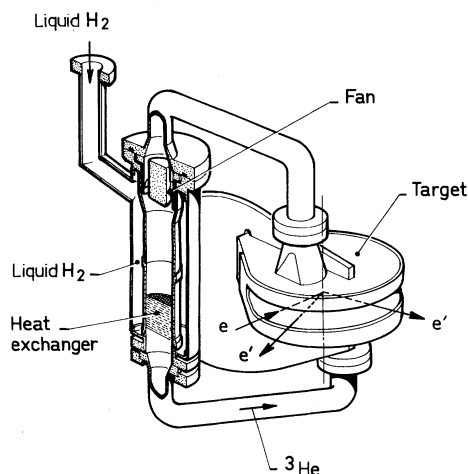

Liquid H$_2$

Fan

Target

Liquid H$_2$

Heat exchanger

e

e'

e'

e'

^{3}He

FIG. 1. Schematic view of the ^{3}He gas target.

TABLE I. Experimental results for the magnetic form factor measurement of ^{3}He at a scattering angle of 155.05°. The incident electron energy, E, momentum transfer squared, q_μ^2, and the deduced plane-wave Born-approximation magnetic form factor, $F_M^2(q_\mu^2)$, are tabulated.

E (MeV)	q_μ^2 (fm^{-2})	$F_M^2(q_\mu^2) \pm \Delta F_M^2(q_\mu^2)$
300.5	7.34	$(1.39 \pm 0.05) \times 10^{-3}$
325.5	8.50	$(5.45 \pm 0.31) \times 10^{-4}$
350.4	9.72	$(2.41 \pm 0.15) \times 10^{-4}$
375.7	11.01	$(9.08 \pm 0.88) \times 10^{-5}$
400.5	12.35	$(2.83 \pm 0.38) \times 10^{-5}$
420.8	13.49	$(1.14 \pm 0.19) \times 10^{-5}$
450.3	15.21	$< 2 \times 10^{-6}$
514.1	19.19	$< 2 \times 10^{-7}$
568.3	22.83	$< 8 \times 10^{-7}$
584.9	23.98	$(1.54 \pm 0.50) \times 10^{-6}$
603.9	25.33	$(1.87 \pm 0.48) \times 10^{-6}$
629.6	27.20	$(7.13 \pm 3.20) \times 10^{-7}$
659.3	29.41	$(7.48 \pm 3.00) \times 10^{-7}$
688.9	31.67	$(7.03 \pm 2.39) \times 10^{-7}$

urements.

In order to extract a Born form factor, as defined in Ref. 11, from the magnetic cross sections, we have unfolded the effect of the Coulomb distortion of the incoming electron wave. This calculation was done in a phase-shift analysis using the high-accuracy distorted-wave Born-approximation code HADES.[14] Our experimental data are presented in Table I and plotted in Fig. 2. In the low-q^2 region, the present data agree reasonably with the results of the previous experiments.[10-12] Our data clearly define the diffraction minimum. In the minimum ($q^2 = 18$ fm^{-2}), the error bars are quite large because of the subtraction of the charge contribution which has its diffraction maximum at this momentum transfer. The position and the amplitude of the second maximum are rather well determined. A desirable extension of these measurements towards higher q^2 has to await the availability of electron beams with energies higher than 700 MeV.

In Fig. 2 we have compared our experimental data with the predictions of two recent theoretical calculations.[17,18] The calculation of Riska was
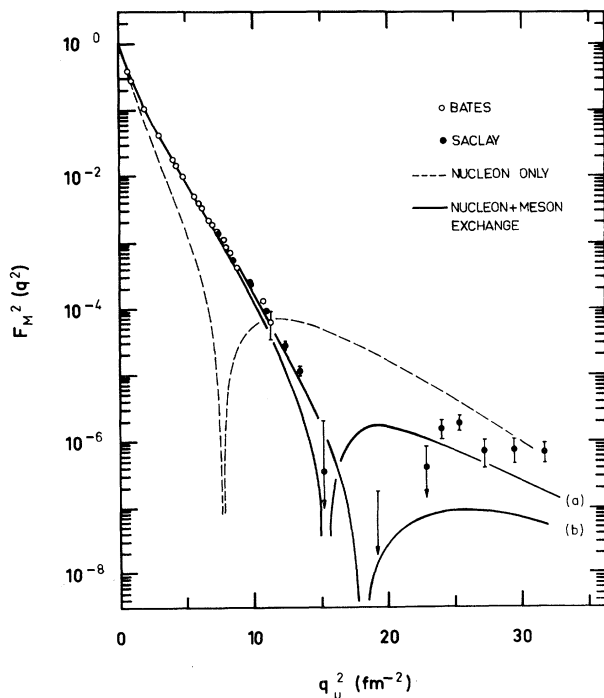

FIG. 2. Experimental ^{3}He magnetic form factors from the present experiment (filled circles) and Ref. 15 (open circles). Also shown are the results of an impulse-approximation calculation (Ref. 16) including only nucleonic degrees of freedom, and two calculations including MEC: curve a, Ref. 17 and curve b, Ref. 18.

performed with a phenomenological wave function with parameters adjusted to fit various ^{3}He properties. He investigated in detail the role played by different effects (percentage of ^{3}He D state, ρ meson exchange, vertex form factors). The calculation by Bornais, Goulard, and Hadjimichael is based on the Faddeev wave function of Torre, Benayoun, and Chauvin.[16] Their calculation shows the extent to which the experiment can be reproduced by using some of the best theoretical wave functions presently available.

When only the nucleon degrees of freedom are taken into account,[16] the diffraction minimum of the ^{3}He magnetic form factor occurs at $q^2 = 8$ fm^{-2} (Fig. 2). This minimum occurs at a q^2 much lower than for the charge form factor, as a result of the interference of the matrix elements connecting the ^{3}He S and D states. The value of the magnetic form factor depends strongly on the D-state wave function at large q^2. In contrast to the charge form factor, the magnetic form factor of ^{3}He is not very sensitive to the details of the wave functions at short range. Accordingly, calculations of rather different character[17-19] give similar predictions for the purely nucleonic magnetic form factor. At high momentum transfers, these calculations fail to explain the experimental data by an order of magnitude (Fig. 2).

The introduction of MEC brings the calculations into reasonable agreement with experiment (Fig. 2). The data up to $q^2 \sim 10$ fm^{-2} are very well reproduced, in accordance with the expectation that MEC terms of order q/M should be reliably determined by the theory. In this intermediate region, the diagrams corresponding to pair current, the pionic current, and Δ-resonance excitation give the dominant contribution. In the very-large-momentum-transfer region, higher-order effects such as vertex form factors and additional diagrams involving ρ or ω exchange play an increasingly important role.

Our new data for the magnetic form factor of ^{3}He show a large effect due to nonnucleonic degrees of freedom. They should serve as a touchstone for theories of the underlying structure of nucleons in nuclei.

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Production of K^+ Mesons in 2.1-GeV/Nucleon Nuclear Collisions

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K^+ meson production by 2.1-GeV/nucleon Ne, d, and p projectiles on NaF and Pb targets has been measured. The cross sections depend exponentially upon the kaon energy in the nucleon-nucleon c.m. frame, with an inverse slope T_0 larger than the values obtained from comparable proton and π^- spectra. The angular distribution in this frame is approximately isotropic. We find that $\sigma(\mathrm{Ne} + \mathrm{Pb} \to K^+ X)/\sigma(\mathrm{Ne} + \mathrm{NaF} \to K^+ X) > \sigma(d + \mathrm{Pb} \to K^+ X)/\sigma(d + \mathrm{NaF} \to K^+ X)$. Data are compared with theoretical predictions.

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Recently the study of strange-particle (K^+, Λ, K^-) production[1-3] in collisions of relativistic heavy ions has begun. The K^+ mesons are of particular interest since they have an extremely small cross section for absorption and, at low energies, a small cross section, ≈ 13 mb, for scattering on a nucleon. Thus, they may be relatively undistorted by thermalization or multiple scatterings and may, therefore, be more reliable messengers of the early, perhaps very compressed and hot stage of the nuclear collision.

We have measured the inclusive cross section for production of K^+ mesons in collisions of 2.1-

GeV/nucleon Ne, d, and p projectiles on NaF and Pb targets. We have compared these data with a simple model based on a superposition of elementary nucleon-nucleon collisions.[4] We find that certain features of the data are not consistent with such a model when conventional internal momentum distributions are assumed. In particular, the number of K^+'s produced with large momentum in the nucleon-nucleon center-of-mass system (NN c.m.s.) is much larger than predicted by this model. Also, the dependence of the K^+ production cross sections on the target and projectile masses is not reproduced.