Elastic magnetic electron scattering from ^{13}C at $Q^2 = 1$ GeV$^2/c^2$

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Electron scattering from ^{13}C was measured at a momentum transfer of 5.08 fm^{-1}. No electron events were observed in the vicinity of the elastic peak, giving an upper limit for the elastic cross section of 1.2×10^{-39}cm^2/sr with a confidence level of 90%. At this momentum transfer, the square of the elastic $M1$ form factor apparently continues to fall exponentially with q. Comparison of the data with shell-model calculations indicates that admixtures of $2\hbar\omega$ configurations in the ^{13}C ground state cannot entirely explain the high-q enhancement of the $M1$ form factor relative to $1p$-shell calculations.

Elastic magnetic electron scattering has greatly enhanced our understanding of single-particle aspects of nuclei and of meson exchange currents in nuclei. Measurements of magnetic dipole form factors in few-body nuclei, such as the deuteron, ^{3}H, and ^{3}He, have shown that meson exchange currents (MEC) are an essential ingredient in theoretical descriptions of the data [1–3]. For $1p$-shell and heavier nuclei the current understanding of magnetic dipole ($M1$) form factors nuclei is inferior to that for the few-body systems [4]. In particular, a recurrent problem has been the unexpectedly large $M1$ form factors observed in $1p$-shell nuclei at momentum transfer $q \geq 2$ fm^{-1}.

The $1p$-shell form factor most extensively studied is that for elastic $M1$ scattering from ^{13}C. Least-squares fits within relatively unconstrained $1p$-shell bases succeed in describing the ^{13}C data [5–7] only up to $q \approx 2$ fm^{-1}. The inclusion of MEC, using the same formalism successfully applied to isovector $M1$ cross sections in deuterium, ^{3}H, and ^{3}He, provide scant improvement [6, 8]. Further attempts to resolve this discrepancy have included examinations of $1p$-shell wave functions [6, 8], Nilsson model wave functions [9], core polarization [10], and possible admixtures of Δ-hole configurations [11].

Because none of these interpretations provided a satisfactory account of the data, attempts were made to fit the form factor by introducing phenomenological admixtures of $2\hbar\omega$ configurations [4, 6]. It was soon recognized that admixtures of $(2s1d)^2$ or cross-shell $(1p, 2p)$ matrix elements did little to resolve the difficulty [6]. However, Donnelly and Sick [4] noted the particular importance of the $(2p)^2$ matrix element, which has considerable strength in the region $q \geq 3$ fm^{-1}. Indeed, by including this term with a relatively modest one-body density matrix $|\psi| \approx 0.04$, the data could be fitted adequately up to $q \approx 3$ fm^{-1}.

Support for the importance of $2p$-shell admixtures emerged from a study of the observed suppression of the isovector $E0$ transition matrix element for the reaction ^{13}C$(\gamma, \pi^-)^{13}$N$_{\text{g.s.}}$. Bennhold and Tiator [12] showed that this suppression could be explained by including in the ^{13}C ground state a $2p_{1/2}$ neutron admixture corresponding to a $(2p)^2$ one-body density $|\psi| = 0.06$. Calculations [13] using these densities also provide a good account of cross sections measured for ^{13}C$(\pi^+, \pi^0)^{13}$N$_{\text{g.s.}}$. Contrary to the conclusion of Donnelly and Sick, the most important $2p_{1/2}$-shell matrix element in both these cases was $(1p, 2p)$, not $(2p)^2$. However, the data for both pion reactions lie in the range $q \leq 1.5$ fm^{-1}, a region well below that where the $(2p)^2$ matrix element makes its most evident contribution.

Therefore, despite numerous studies, the origins of the large $M1$ cross sections observed at high momentum transfer in ^{13}C and other $1p$-shell nuclei remain uncertain. The extension of the data to still higher momentum transfers may assist in resolving this problem. For example, the presence of $2\hbar\omega$ configurations in the ^{13}C ground state would, at some level, be expected to introduce additional diffraction minima into the $M1$ form factor at high q. The discovery of such a minimum would provide an important clue in this puzzle. On the most basic level, it is the availability of data over the largest possible q range that imposes the strongest constraints on any theoretical interpretation.

Data on ^{13}C elastic magnetic scattering were taken using the Energy Loss Spectrometer System [14] at the MIT-Bates Linear Accelerator. The incident beam energy and scattering angle were 540 MeV and 150°, corresponding to a three momentum transfer of q = 5.08 fm^{-1} and a four-momentum-transfer squared of Q^2=1.01 GeV$^2/c^2$. This is the highest Q^2 attained to date for an elastic magnetic scattering experiment on a nucleus with mass number $A > 3$. Extrapolations of the known charge form factor indicate that the contribution of the longitudinal cross section should be negligible at this angle and momentum transfer [6]. Approximately 1.73c of electrons was incident on a ^{13}C target [6] of effective thickness 1.35 g/cm^2. In order to optimize resolution, the target was placed in transmission geometry, giving a resolution of approximately 0.4 MeV FWHM in scattered electron energy. The solid-angle defining slits in front of the spectrometer were adjusted to give the maximum usable solid angle of 5.24 msr.

To facilitate the present measurement on ^{13}C, as well as proposed measurements at high Q^2 on other nuclei, the spectrometer focal plane was optimized for background rejection. A brief description of the detectors and background rejection techniques will be presented here; more detailed descriptions will be published later. Figure 1 shows a diagram of the focal plane. Cosmic-ray backgrounds were reduced by applying cuts to particle track angles in the focal plane. Particle trajectories were measured with the vertical drift chamber (VDC) and the two transverse array drift chambers (TA1 and TA2) in the focal plane. Cosmic-ray muons were rejected by placing cuts on the lead-glass shower counter pulse-height spectrum. The lead-glass shower counter was assembled from eight lead-glass blocks into a single layer of lead glass with an electromagnetic absorption length of six radiation lengths. A Hamamatsu 6473 photomultiplier was attached to each block. The Čerenkov counter was used to aid in electron identification. It uses isobutane at atmospheric pressure as the light-producing medium, and has three focusing mirrors near the bottom of the counter to reflect light onto three RCA 8854 photomultipliers mounted on the side of the counter. The pulse-height distribution is consistent with the detection of nine photoelectrons per electron event. After all cuts were applied, the overall efficiency for electron detection was estimated to be 79%. This was checked by measuring the ^{1}H elastic-scattering cross section and comparing it to the results of a fit to previous data, which is of a few-percent accuracy in our kinematic region.

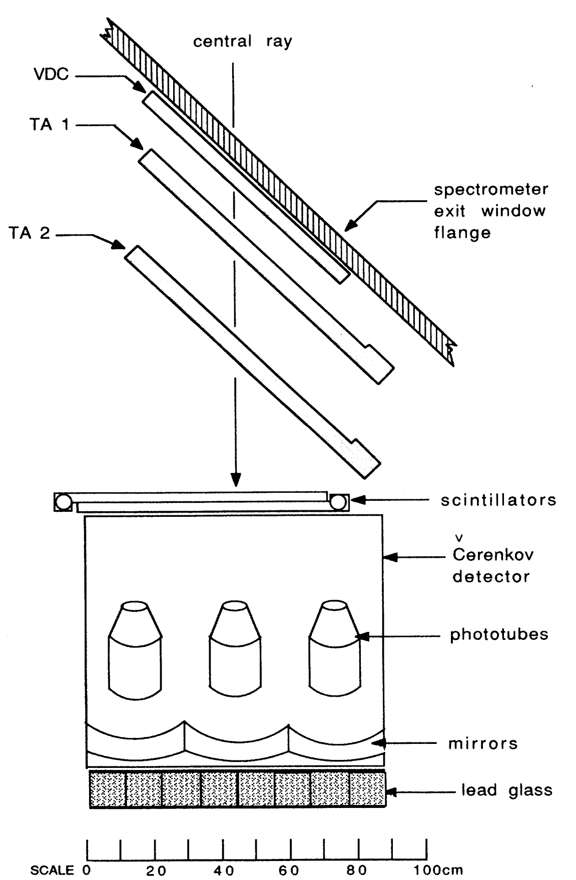

FIG. 1. Diagram of the spectrometer focal plane and detectors used in this experiment.

Only one event satisfied all tests and cuts. In order to establish the excitation energy of the event, the spectrometer was moved to a forward angle and elastic and inelastic scattering on ^{1}H, ^{9}Be, ^{12}C, and ^{16}O were measured. The beam energy and focal plane parameters were determined by observing the different recoil energies of these nuclei. Using this calibration of the beam energy and focal plane, the excitation energy of the event was determined to be 13.8 ± 1 MeV. The origin of this single event is unclear because ^{13}C has many states in this excitation region [15]. Radiative emission during elastic scattering could also produce such an event.

No events were observed in the vicinity of the elastic peak. With a detection efficiency of 79% and a 30% probability for losing scattered electrons by radiative processes, the associated upper limit for the elastic cross section is approximately 1.2×10^{-39} cm^2/sr. This corresponds to a confidence level of 90%, or the detection of approximately two elastic events. Assuming negligible contribution from the longitudinal $C0$ form factor, the upper limit for the squared transverse $M1$ form factor is 5.1×10^{-9}. Figure 2 shows this result in the context of previous measurements [5–7]. It is seen that the elastic magnetic form factor of ^{13}C continues to decline at q = 5 fm^{-1}, giving no evidence for the presence of an additional diffraction minimum.

The curves shown in Fig. 2 represent various phenomenological attempts to explain the data. At high q the $M1$ form factor is known to be sensitive to the shape of the radial wave functions [4, 6, 12]. Hence all curves were calculated using Woods-Saxon well parameters of $R = 1.22(A-1)^{1/3}$ fm for the radius and a = 0.75 fm for the diffuseness, values that are consistent with 1p-shell wave functions deduced from $(e, e'p)$ measurements [16]. The dashed curve in the figure is a least-squares fit within a configuration-mixed 1p-shell space. As previously noted, this calculation succeeds in fitting the data

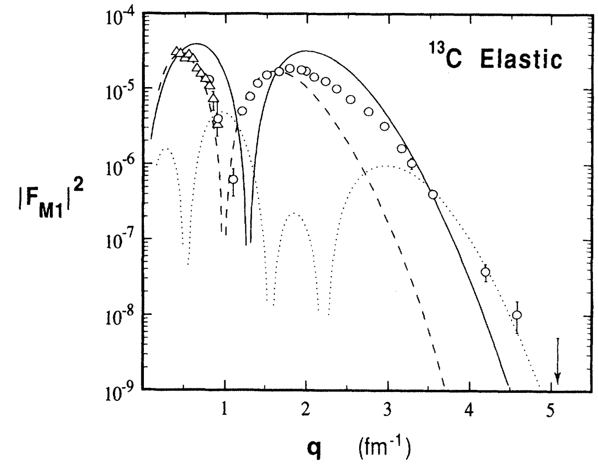

FIG. 2. The ^{13}C elastic $M1$ form factor squared. Triangles represent the results of Lapikas *et al.* [5], and circles the results of Hicks *et al.* [6, 7]. The upper limit at 5.08 fm^{-1} is the result of the present experiment. The dashed curve represents a fit to the data using only configuration-mixed $1p$-shell matrix elements. The solid curve is for the one-body densities of Bennhold and Tiator [12]. The $M1$ form factor corresponding to the $(2p_{1/2})^2$ neutron matrix element only, normalized to fit the data at high q, is indicated by the dotted curve. All calculations rely upon single-particle wave functions derived from a Woods-Saxon well consistent with $(e, e'p)$ results [16].

only to $q \approx 2$ fm^{-1}.

A calculation using the one-body densities of Bennhold and Tiator is shown as the solid curve in Fig. 2. This calculation, which includes $(2p_{1/2})^2$ and $(1p_{1/2}, 2p_{1/2})$ neutron densities, also cannot describe the data. The failure of these densities to properly locate the diffraction minimum is not a major defect; this can be easily corrected by means of small changes in the $(1p)^2$ densities. A more fundamental shortcoming is that, in common with the $1p$-shell fit, the calculations decrease far too steeply at high q.

The $M1$ form factor corresponding to the $(2p_{1/2})^2$ neutron matrix element only is shown as the dotted curve in Fig. 2. In this calculation the form factor is normalized to fit the data at high q. Although the importance of the $(2p)^2$ matrix element at high q is evident, it was not possible to obtain a satisfactory fit to the entire data set with just $(1p)^2$ and $(2p)^2$ matrix elements; the best fit (not shown in the figure) had a χ^2 per degree of freedom of 26. The poor fit was caused by the considerable strength near $q = 1$ fm^{-1} which, by interference with $(1p)^2$ contributions, worsens the overall fit to the data. Given the *ad hoc* nature of this approach, no attempts were made to improve upon the quality of the fit by including other multi-$\hbar\omega$ matrix elements. While it could be argued that the inclusion of such terms may help to rectify problems encountered in the fit at $q < 2$ fm^{-1}, it remains that the normalization of the $(2p_{1/2})^2$ component shown in Fig. 2 corresponds to a one-body density matrix $|\psi| = 0.43$. Such an unreasonably large value suggests that the large $M1$ cross sections observed at $q > 3$ fm^{-1} cannot be simply attributed to admixtures of $2\hbar\omega$ and higher-excited configurations in the ^{13}C ground state.

A more promising suggestion of the origin of the high q strength has been advanced by Blok [17], who showed that a good description of ^{13}C and ^{15}N elastic $M1$ form factors can be obtained by including in the single-particle wave-function high-momentum components resulting from short-range correlations. Although this treatment is phenomenological, the amount of high-momentum strength needed to fit the data is consistent with calculations [18] of nuclear matter and of finite nuclei.

In conclusion, it appears unlikely that a full understanding of these data will rely upon further measurements of this type, which have been pursued about as far as can be reasonably expected. The decisive information may well come from elsewhere. For example, one may seek to study $2\hbar\omega$ admixtures more directly by seeking out transitions in which these configurations provide the leading-order, rather than secondary, contributions. Transitions characterized by such selectivity include those having large angular momentum transfer. Alternatively, information on high-momentum wave-function components could be obtained by measurements of single-nucleon knockout at large missing momentum, such as through the $(e, e'p)$ or (γ, p) reactions.

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