Electroexcitation of discrete levels in ^{12}C and ^{13}C at high momentum transfers

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Form factors for transverse electron scattering from ^{12}C and ^{13}C have been determined for momentum transfers as high as $q=4.6$ fm^{-1}. Data are presented for the elastic ($M1$), 3.088 MeV ($E1$), and 9.50 MeV ($M4$) transitions in ^{13}C, and for the 15.11 MeV ($M1$), 16.11 MeV ($E2$), and 16.58 MeV ($M2$) transitions in ^{12}C. It is found that calculations in the lowest-order shell-model space fail to account for the measured q dependences of $E1$, $M1$, and $E2$ form factors beyond $q=2$ fm^{-1}. On the other hand, form factor shapes observed for $M2$ and $M4$ multipoles are satisfactorily described to $q=4$ fm^{-1} within the minimal $1\hbar\omega$ configuration space.

I. INTRODUCTION

At momentum transfers of $q>3$ fm^{-1} the wavelength of the virtual photon exchanged in electron scattering is such that nuclear features as small as a few tenths of a femtometer are probed. Moreover, the electromagnetic interaction is relatively weak so that the microscopic depth of field includes the deep interior of the nucleus. Since the electron-nucleus interaction is also well understood, high-momentum-transfer electron scattering is a valuable technique for searching for more complex nuclear interaction effects, such as meson exchange currents.

Although the relative contributions of exchange currents are generally predicted to be greatest at high momentum transfers,[1] form factors in this kinematic region are also influenced by details of nuclear wave functions. For example, in the "core polarization" formalism the wave function is written as a summation of single-particle wave functions extending far beyond the lowest-order configuration space. Many of these highly-excited single-particle states have complex radial wave functions with multiple nodes capable of introducing diffractive features into (e,e′) form factors at high q. Such features cannot be readily separated from contributions arising from the direct coupling of virtual photons to exchange currents. However, since the nuclear wave functions generally extend over larger distances than the exchange currents, the wave function contribution to the form factor is predicted to decrease faster than the exchange part at high q. Thus it is not immediately self-evident that the possibility of exposing exchange current effects should be ruled out by uncertainties in nuclear structure.

On the other hand, the unambiguous identification of these exchange effects has proven extraordinarily difficult. Only for $A=2$ and $A=3$ nuclei are there data acquired at high enough q and sufficient assurance in the nuclear wave functions to identify confidently contributions from exchange currents. These exchange contributions are clearly evidenced in the $M1$ form factors for the threshold electrodisintegration of the deuteron,[2] and for elastic scattering from ^{3}H and ^{3}He, where they provide large enhancements over the predicted one-body terms for $q>2$ fm^{-1}.[3,4] Corresponding evidence for exchange currents in $A\geq 4$ nuclei has been lacking ever since the formulation of the meson field theory of the nucleon-nucleon interaction by Yukawa half a century ago.

This paper reports the extension of data on transverse form factors for ^{12}C and ^{13}C from $q\cong 3$ fm^{-1} to momentum transfers as high as 4.6 fm^{-1}. Motivation for this experiment came from the observation of large (e,e′) form factors at $q\geq 3$ fm^{-1} for $M1$ transitions in ^{6}Li,[5] ^{13}C,[6] ^{14}N,[7] and ^{15}N.[8] Although these high-q enhancements appeared to parallel the effects observed in the light nuclei, standard $1p$-shell structure models[6–8] failed to account for the data even with the inclusion of one-pion exchange contributions evaluated using the same formalism that was successful in the $A=2$ and $A=3$ cases. In ^{13}C, for example, a fit[6] to the elastic $M1$ form factor using $1p$-shell Woods-Saxon wave functions lies below the $q=3.3$ fm^{-1} data by about a factor of 20. Consideration of one-pion exchange currents raises the theoretical result, but only by a factor of 2. The origins of the remaining discrepancy have yet to be established. One candidate is core polarization, discussed earlier. Other speculation centers on the incomplete or inappropriate treatment of non-nucleonic effects, although it is unlikely that such omissions could completely account for the large differences observed. This extension of the data to higher momentum transfers should provide additional clues to the origins of this discrepancy. In addition, transitions of multipolarity other than $M1$ have been measured, which will further constrain theoretical interpretations.

II. EXPERIMENT

The experiment was performed at scattering angles of 140° to 160° using the electron scattering facility[9] of the MIT–Bates Linear Accelerator Center. Before moving the spectrometer to large scattering angles, where cross sections are small, beam energies and spectrometer calibrations were precisely determined by utilizing the large cross sections for scattering at forward angles. Sheets of natural graphite served as ^{12}C targets. The ^{13}C targets consisted at 99.05% isotopically enriched ^{13}C powder supported between 0.125 mm thick graphite foils.[10] The largest ^{13}C target provided an effective thickness of 1.41

g cm^{-2}. Targets were placed in transmission geometry[11] to minimize ionization straggling, which limited the attainable resolution. Adequate resolution was important for the separations of background contributions from the data.

Figure 1 shows the excitation spectrum for 415 MeV electrons scattered through 150° from ^{12}C. The peaks observed at 15.11, 16.11, and 16.58 MeV are recognized as the well-known ($J^{\pi}=1^{+};T=1$), ($2^{+};1$), and ($2^{-};1$) levels. The broad peak near 20 MeV is composed of a complex of levels; however, at this high momentum transfer $M4$ excitations[12] should dominate. In addition, a strong and relatively narrow peak is seen at 23.6 MeV. Although a ($1^{-};1$) level has been identified at this excitation energy,[13] it has exhibited little transverse strength in previous electron scattering studies.[14] The measurement of ^{13}C at an incident energy of 485 MeV required two days, during which time 3.13 C of charge was directed onto the target. The spectrum is shown in Fig. 2. Although the ^{13}C elastic peak is apparent, with a cross section of $(7\pm3)\times10^{-39}$ cm^{2} sr^{-1}, the precision with which such small cross sections can be determined is severely compromised by the experimental background at the Bates facility. At lower momentum transfers this background is usually negligible. It arises primarily because of the poor discrimination of the transverse angle of the electron trajectory, i.e., the angle the trajectory makes with the momentum-dispersion plane of the spectrometer. In the transverse plane the spectrometer has close to point-to-parallel imaging. Calculations based on the relevant transfer matrix elements, and which also include multiple scattering processes outside the spectrometer vacuum, indicate that >200 MeV electrons scattered from the target should have transverse angles no greater than 4 mrad.[15] However, the present focal-plane instrumentation is such that a trajectory must have a transverse angle greater than 80 mrad before it is rejected as a background event. The future installation of additional drift chambers will permit the measurement of the transverse angle to a precision of 1 mrad, and thereby reduce the background level by more than a factor of 10.

The raw data were bin sorted and cross sections deduced using a least-squares fitting procedure. Because of the manifestly Poisson character of low count-rate data, bins with small numbers of counts exert disproportionately large weight in a least-squares analysis.[16] Consequent underfitting of spectral peaks was avoided by the application of a simple five-point smoothing of the statistical weights.[16] In the fit shown in Fig. 2, the worst case, peaks were fixed at excitation energies corresponding to known levels in ^{13}C. Only in the case of the elastic peak was a definite cross section obtained, since several known levels cluster near the structures observed at 3.7 and 7.5 MeV. Fits were performed under various background assumptions, and the form factors presented in Sec. IV have errors that reflect both the statistical and the background uncertainties.

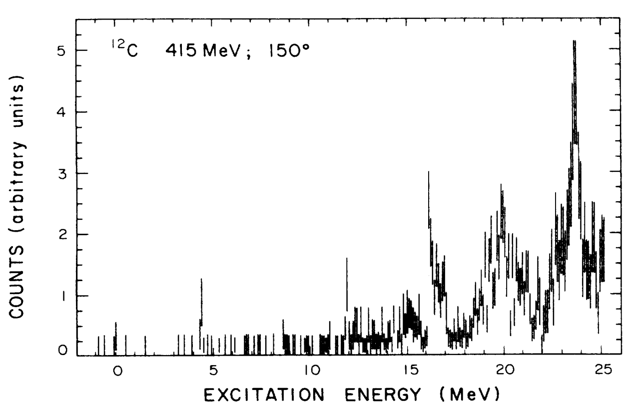

FIG. 1. Excitation spectrum for the inelastic scattering of electrons through 150° from ^{12}C. The incident electron energy was 415 MeV.

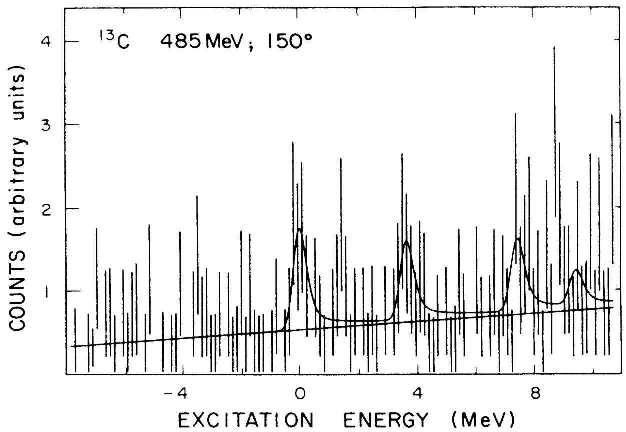

FIG. 2. Excitation spectrum measured at a scattering angle of 150° for 485 MeV electrons incident on ^{13}C. The curves represent one of several fits performed under different background assumptions. In this case the background was independent of excitation energy.

The overall efficiency of the apparatus was calibrated by measurements of elastic scattering from the proton, for which the absolute cross section is well known.[17] The longitudinal CO content in the elastic ^{13}C cross section was computed in distorted-wave Born approximation using the experimentally deduced[18] ground-state charge distribution. Longitudinal contributions to inelastic ^{13}C cross sections were assessed by extrapolating data measured at forward scattering angles.[12,19] Such contributions, estimated to be less than 5% for $q>3.5$ fm^{-1}, were removed from the data. The data are included in documents available from the Physics Auxiliary Publication Service.[20]

III. THEORY

As mentioned earlier, standard $1p$-shell models fail to account for $M1$ form factors of $1p$-shell nuclei above $q\cong2.5$ fm^{-1}, even when meson exchange currents are included. Large-basis shell model calculations in a $2\hbar\omega$ basis space also predict form factors which fall too quickly at high q.[6-8] A Nilsson model treatment for ^{13}C by Lin and Zamick[21] gave results quantitatively similar to, and with the same deficiencies as spherical-basis shell model calculations. Consequently, a description of the data in terms of conventional structure models would require the extension of the basis space to include even higher-excited shells, as in the core polarization model. Although the core polarization formalism is basically sound, unresolved questions remain concerning the appropriate form of the core-particle effective interaction, the convergence of the calculations at high momentum transfers, and whether or not it is necessary to go beyond first-order perturbation theory.

Of the several existing core polarization treatments, first-order perturbation calculations have been made by Suzuki, Osterfeld, and Speth,[22] as well as by Suzuki and co-workers.[23] Although the former calculation included $6\hbar\omega$ excitations, the computed form factors continued to decrease too steeply at high q. The calculations of Suzuki *et al.*[23] extended to $12\hbar\omega$ transitions and provided reasonable representations of $M1$ form factors in ^{13}C and ^{15}N, at least to $q = 3$ fm^{-1}. However, a similar calculation for the 15.11 MeV $M1$ transition in ^{12}C still fell much too quickly for $q > 2$ fm^{-1}. For the large momentum transfer range of the present measurements, it is likely that even higher-excited configurations need to be considered. For example, Desplanques and Mathiot[24] found it necessary to calculate to $38\hbar\omega$ in excitation to achieve convergence at $q = 3$ fm^{-1} in $A \cong 90$ nuclei.

Recently, Blunden and Castel[25] have performed second-order perturbation calculations within a $12\hbar\omega$ model space for ^{15}N and other nuclei. It was shown that the second-order core polarization and meson exchange effects have opposite signs, and tend to cancel one another. It was therefore considered unlikely that the high-q enhancements seen in the $M1$ form factors of the $1p$-shell nuclei could be attributed to second-order core polarization.

In contrast to the perturbation calculations in an extended basis space, Delorme *et al.*,[26] and Toki and Weise[27] have calculated core polarization to all orders by constructing effective spin operators for use within a restricted $1p$-shell basis. The calculations differ in the description of the particle-hole and Δ-hole interactions responsible for the polarization effects. Delorme *et al.* employed π- and ρ-exchange currents as well as a short-range repulsive term with strength given by the Migdal parameter g', but still failed to generate sufficient strength for $q > 2.5$ fm^{-1}. Toki and Weise substituted two-pion exchange currents for ρ exchange and in this way were able to fit the $M1$ form factor of the 15.11 MeV transition in ^{12}C up to $q = 3$ fm^{-1}. Unfortunately, since ^{12}C was the only case calculated by Toki and Weise, the consistency of their technique remains to be tested.

Despite these efforts, at this time there exists no global understanding of the $M1$ form factors measured for $1p$-shell nuclei at $q > 2.5$ fm^{-1}. A defect exhibited to greater or lesser degrees by all theoretical treatments is that the calculated form factors decrease too steeply compared to the data at high q. It is not clear if the discrepancies should be attributed to incomplete or inappropriate treatments of non-nucleonic effects, or more simply, to unexpectedly large contributions from high-lying single-particle orbits.

In the absence of an accepted model, the results have in part been interpreted using a simple phenomenological procedure,[6–8] whereby the data were fitted with an expression of the form

$$F(q) = q^X e^{-y} f_{\mathrm{c.m.}} f_{\mathrm{sn}} Z^{-1} (A_0 + A_1 y^1 + A_2 y^2 + \cdots) \,.$$

In this expression $f_{\mathrm{c.m.}}$ and f_{sn} are the shell-model center-of-mass and nucleon finite-size terms. For magnetic transitions, $X = L$, the multipolarity of the form factor. In the case of electric transitions, $X = L - 1$. For harmonic oscillator orbitals $y = b^2 q^2/4$, where b is the oscillator size parameter and the degree of the polynomial is fixed by the configuration space. For example, only terms up to the order of y^1 exist for an $M1$ transition within the $1p$-shell harmonic oscillator shell model. The parameter b and the polynomial coefficients A_0, A_1, $A_2, \ldots$ were determined by fitting the Lth nuclear moment and the measured form factor. Such an analysis give some insight into the minimum configuration space required to understand the data and also provides a limited quantitative point of reference for the comparison of the different form factors.

IV. RESULTS

Figure 3 shows transverse form factors measured for the 15.11 MeV ($M1$), 16.11 MeV ($E2$), and 16.58 MeV ($M2$) excitations in ^{12}C. The high-q points obtained in the present experiment have been combined with data previously reported by Hicks *et al.*,[28] Flanz *et al.*,[29,30] and Deutschmann *et al.*[31] The 15.11 MeV form factor displays features representative of other $M1$ transitions in $1p$-shell nuclei. Any model restricted to the $1p$-shell space can account for the data only as far as $q \cong 2$ fm^{-1}. In order to successfully fit data at higher momentum transfers the model space must, at the very least, be extended to include sizeable single-particle matrix elements within the $2p$-$1f$ shell. A similar result is apparent for the 16.11 MeV $E2$ transition, demonstrating that the relative enhancement of transverse form factors at high momentum transfer is not confined to $M1$ excitations. On the other hand, the $M2$ excitation to the 16.58 MeV level can be satisfactorily described as a transition within the lowest-order configuration space extending to the $2s$-$1d$ shell. The result is not inconsistent with the recent investigation by Castel, Johnstone, and van Hees[32] into the reduction of $M2$ strength in ^{12}C compared to predictions of 1p-1h shell models. Castel *et al.* attributed this quenching primarily to components in the ^{12}C ground state that have two particles in the *sd* shell. Although these 2p-2h correlations deplete the calculated $M2$ strength, they give no additional one-body matrix elements which could modify the shape of the $M2$ form factor.

The results for the elastic $M1$ form factor of ^{13}C are shown in Fig. 4. Independent of the use of either harmonic oscillator or Woods-Saxon radial wave functions, an otherwise unconstrained $1p$-shell calculations[6] can account for the data only to $q \cong 2$ fm^{-1}. As in the case of the 15.11 MeV $M1$ transition in ^{12}C, the extension of the harmonic oscillator model space to include the $2p$-$1f$

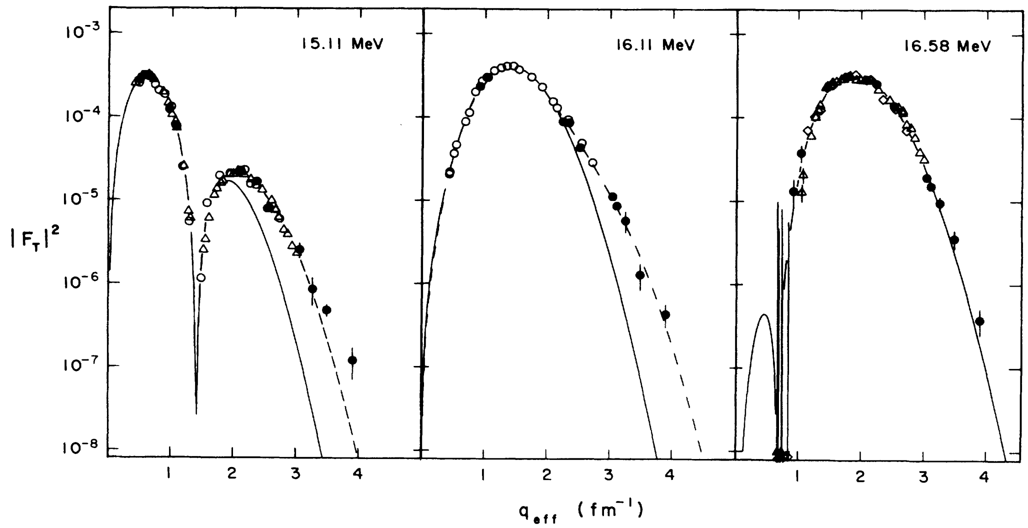

FIG. 3. Transverse form factors for the 15.11 MeV ($M1$), 16.11 MeV ($E2$), and 16.58 MeV ($M2$) transitions in ^{12}C. The results of this experiment are denoted by solid circles. Other data are from Bates [open circles (Refs. 29 and 30) and diamonds (Ref. 28)] and Mainz (Ref. 31) (triangles). The curves are phenomenological fits. In the case of the 15.11 and 16.11 MeV excitations, the continuous curves represent fits made in a restricted $1p$-shell harmonic oscillator model space and the dashed curves are for the full harmonic oscillator space up to the $2p$-$1f$ shell. For the 16.58 MeV excitation, the continuous curve is for a $1p$ to $2s$-$1d$ shell transition with harmonic oscillator wave functions. The best-fit curves correspond to the following parameter sets. 15.11 MeV: $b=1.67$ fm, $A_0=0.293$, $A_1=-0.264$, $A_2=0.0598$, $A_3=-0.0132$; 16.11 MeV: $b=1.50$ fm, $A_0=0.0383$, $A_1=0.315$, $A_2=-0.0932$, $A_3=0.0184$; 16.58 MeV: $b=1.49$ fm, $A_0=-0.0389$, $A_1=0.158$.

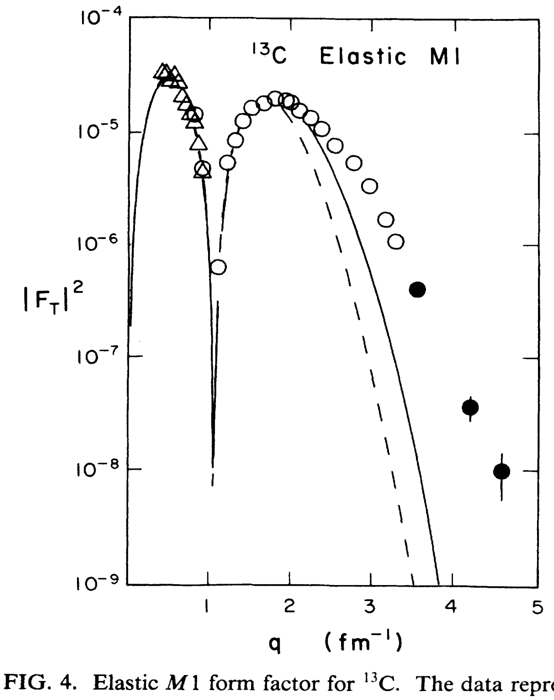

FIG. 4. Elastic $M1$ form factor for ^{13}C. The data represented by the triangles were measured by Lapikas *et al.* (Ref. 33). Open circles are the work of Hicks *et al.* (Ref. 6). The new data are denoted by solid circles. All data have been corrected for Coulomb distortion effects, as described in Ref. 6. The dashed curve is the result of a $1p$-shell calculation using harmonic oscillator wave functions ($b=1.76$ fm). The continuous curve is for $1p$-shell Woods-Saxon wave functions derived in a potential well given by radius parameter $R_0=1.25$ fm and surface diffuseness $a=0.60$ fm.

shell allows the data to be fitted to $q=3.5$ fm^{-1}, but even that fails at the highest momentum transfers. As discussed elsewhere,[6] consideration of meson exchange currents increases the $M1$ form factor by about 20% at the second diffraction maximum, and by a factor of 2–3 for $q>3$ fm^{-1}. Reanalysis of the data with exchange currents included yields little change in the fitted curves, since the one-body terms simply readjust to accommodate the exchange contributions.[6]

Figure 5 shows longitudinal[19] and transverse form factors for the pure $E1$ 3.088 MeV transition in ^{13}C. The dominant component of this excitation is the promotion of a neutron from the $1p_{1/2}$ to the $2s_{1/2}$ orbit. The comparison of the data with shell model calculations by Millener[34] embodies most of the difficulties encountered in the shell model description of the form factors of $1p$-shell nuclei. Whereas, the theoretical prediction underestimates the magnitude of the longitudinal form factor at the maximum and then decreases too slowly at high q, exactly the opposite occurs for the transverse form factor. Despite these difficulties the calculation correctly describes the diffractive structure of the form factors. Core polarization effects strongly modify longitudinal form factors primarily through the agency of the isoscalar operator. Since it is the isovector operator which provides the dominant contribution to most transverse form factors, these form factors are sensitive to an aspect of core polarization only weakly manifest in longitudinal form factors.

In Fig. 6 are the results for the 9.50 MeV $M4$ excitation to the $(\frac{9}{2}^+;\frac{1}{2})$ level in ^{13}C. In general, the data are satisfactorily represented by the "stretched" $(1d_{5/2},1p_{3/2}^{-1})_{M4}$ matrix element, with Woods-Saxon wave functions being preferred.[12] The curves show the predict-

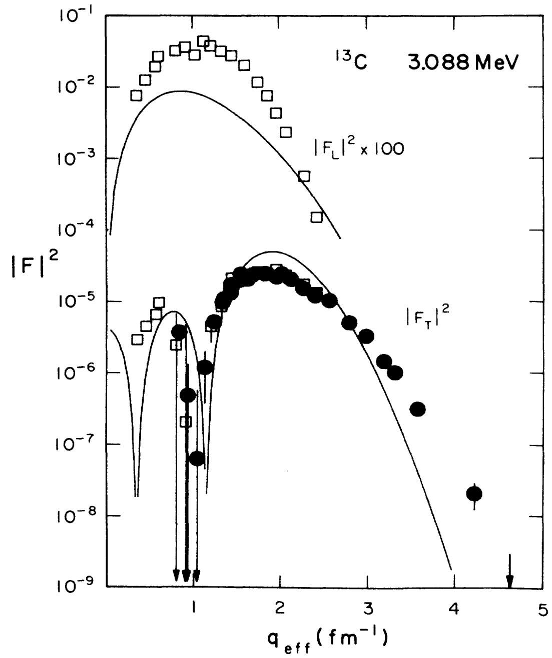

FIG. 5. Form factors for the 3.088 MeV ($E1$) excitation in ^{13}C. The squares denote data obtained by Crannell *et al.* (Ref. 19). The present measurements are represented by solid circles. The curves show the results of large-basis shell model calculations by Millener (Ref. 34) using harmonic oscillator wave functions with $b = 1.65$ fm. Bare charges and magnetic moments were employed.

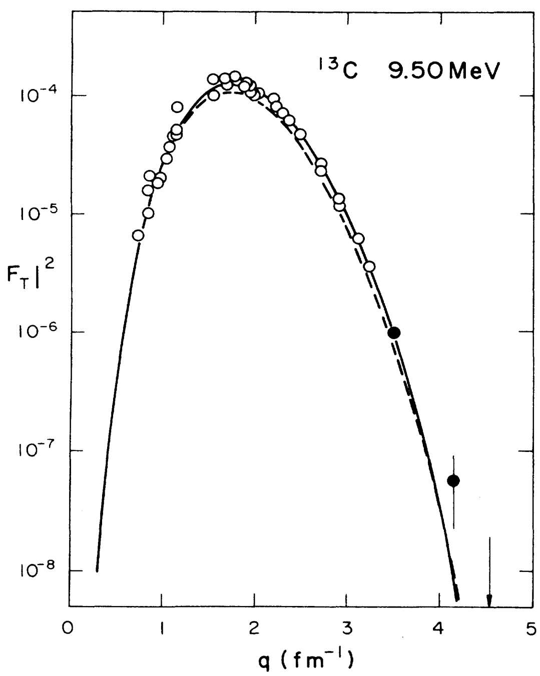

FIG. 6. Form factor for the 9.50 MeV ($M4$) excitations in ^{13}C. Open circles were measured by Hicks *et al.* (Ref. 12). The new data are represented by solid circles. All data have been corrected for Coulomb distortion effects. The curves show the form factor evaluated for the $(1d_{5/2}, 1p_{3/2}^{-1})_{M4}$ single-particle matrix element with Woods-Saxon radial wave functions ($R_0 = 1.16$ fm, $a = 0.60$ fm). One-pion exchange current contributions, computed using harmonic oscillator wave functions with $b = 1.55$ fm, are included in the continuous curve, but not in the dashed curve.

ed enhancement from one-pion exchange currents, calculated using harmonic oscillator wave functions.[35] For this transition the calculated one-body and exchange current terms have very similar q dependences in the kinematic range of the existing data, so no clear signature for exchange effects can be discerned.

V. SUMMARY

In this study, from factors for discrete levels in ^{12}C and ^{13}C have been measured at momentum transfers higher than previously investigated. It was found that restricted-basis shell model calculations cannot account for the observed q dependences of low multipole $E1$, $M1$, and $E2$ form factors beyond $q \cong 2$ fm^{-1}. Order-of-magnitude discrepancies exist for $q > 3$ fm^{-1}, where the transverse form factors are strongly enhanced relative to proposed theoretical descriptions. In recent years much attention has been given to the reduction in magnetic excitation strength at low q compared to model predictions. The explanation appropriate for this quenching is still uncertain. The appearance of excess strength in (e,e′) cross sections at high q may be another manifestation of the processes responsible for the quenching, and hence may provide guidance for the resolution of this problem.

Of particular merit are measurements of electric transitions for which there exist two form factors, longitudinal and transverse. At least for $E1$ and $E2$ transitions, core polarization effects strongly modify these two form factors, but in different senses. At the present time, however, there have been few theoretical attempts to explain simultaneously these contrasting effects.

For the $M2$ and $M4$ multipoles we have found that the observed form factor shapes can be satisfactorily described as simple transitions between the $1p$ and $2s$-$1d$ shells. Moreover, very recent measurements to $q = 4$ fm^{-1} of $M3$ form factors in ^{10}B and ^{11}B gave results that are entirely consistent with $1p$-shell Woods-Saxon wave functions.[36] In these cases there is no apparent need for higher-lying components in the wave functions, nor for any other mechanism, to contribute directly to (e,e′) form factors.

Finally, except for the possible existence of a rare pathological case, it may be unreasonable to expect to find convincing evidence for exchange current effects in the $M1$ form factors of $1p$-shell nuclei, as has been identified in the $A = 2$ and $A = 3$ nuclei. At the present time it appears that undefined structure effects modify $M1$ form factors to an extent that far exceeds the compass of predicted exchange current contributions. It might in fact be argued that it would be more propitious to search for exchange current effects in higher multipole transitions (such as $M3$ and $M4$ excitations in $1p$-shell nuclei), where conservation of angular momentum severely restricts the number of contributing single-particle matrix elements, so that nuclear structure uncertainties pose less severe problems. However, as has been seen in the case of the 9.50 MeV $M4$ excitation in ^{13}C, the exchange current contributions are calculated to have a q dependence very similar to that of the one-body terms, and hence no distinctive signature of meson aspects can be expected in the range of the existing data.

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