Search for Dispersive Effects in Elastic Electron Scattering from ^{12}C

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A significant energy dependence was observed in the region of the first diffraction minimum of the form factor for elastic electron scattering from ^{12}C between 238 and 419 (and 431) MeV. This effect might be attributed to dispersive (two-step) processes.

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Two-step processes (or dispersive effects) play an important role in nuclear scattering of hadrons and heavier particles. Consequently, it has been necessary to develop phenomenological techniques in order to extract nuclear matrix elements from measured scattering cross sections. As a result of the weakness of the electromagnetic interaction, two-step processes are expected to be much less important in electron scattering. On the other hand, the nuclear-structure information to be extracted from electron scattering is often of great quantitative precision, implying that these effects must be calculated with higher accuracy. These effects are also important in an accurate comparison of electron-scattering and muonic-atom results. In the absence of convincing theoretical calculations and clear experimental evidence, dispersive effects have generally been neglected in the analysis of electron-scattering data. We report here the first measurement of an unambiguous energy dependence in an elastic-electron-scattering form factor. Dispersive effects are the most likely cause of this energy dependence.

Friar[1] has reviewed the practical difficulties in performing accurate calculations of dispersive (or virtual nuclear excitation) effects in elastic electron scattering. These calculations are quite involved, since both a sum over an infinite set of virtual nuclear excitations, each with its particular transition energy and form factor, and an integral over the division of the momentum transfer between the two exchanged photons must be evaluated. One of two possible approximations has been applied in most calculations performed to date: (1) a summing over a few low-lying states that are expected to dominate the integral, or (2) neglect of the excitation energy of the intermediate state and application of closure (or even better a closure expansion). Only Coulomb excitations have been considered in most calculations performed to date. The results of such calculations differ dramatically; they often disagree on even the sign of the correction. Many calculations have displayed a strong sensitivity to a delicate cancellation between contributions of the various excited states and the center-of-mass correction. Most calculations, however, do agree on a number of qualitative, systematic trends: (a) Dispersion corrections are most important in the region of diffraction minima where the first-order Born approximation goes through zero; the relative importance of dispersive effects tends (b) to increase with increasing momentum transfer, and (c) to decrease with increasing nuclear charge Z. The validity of the different approximations used in these calculations could be tested if experimental measurements of dispersion effects became available. In the past a number of attempts have been made to attribute anomalies observed in isotopic charge-distribution differences[2,3] or in diffraction minima[4,5] of the elastic form factor of ^{12}C to dispersive effects. All of the results reported to date are ambiguous. Later experiments[6-9] indicated that the bulk of the isotopic charge-density differences observed was due to errors in the cross-section normalization of the experiments, while the ^{12}C minimum measurements suffered from limitations of the experimental apparatus used, as discussed below.

Two other avenues are available to experiment. The direct excitation of a 0^- state in a nucleus with a 0^+ ground state by inelastic electron scattering is forbidden as a single-step process; hence its observation would constitute a direct manifestation of two-step processes in electron scattering. This would not, however, give a measure of the dispersion correction as applied to elastic electron scattering. A comparison of elastic electron and positron scattering would also be sensitive to dispersive effects, because the leading-order dispersion correction depends on the sign of the projectile charge. Neither of these approaches has yielded a conclusive signal to date.[10,11] There is a general consensus that the most fruitful way to observe dispersive effects in electron scattering would be to study a diffraction minimum of the elastic cross sec-

tion for a light nucleus at different incident energies.

The first diffraction minimum in the form factor for elastic electron scattering from ^{12}C is very deep, which makes it an excellent testing ground for dispersion corrections. This region has been examined in two previous experiments. The model-independent analysis[5] of elastic-electron-scattering data on ^{12}C from Mainz, which covered a momentum-transfer range of 0.5 to 2.75 fm^{-1}, yielded a result in good agreement with previous data[12,13] at low (<1 fm^{-1}) momentum-transfer values. However, systematic deviations between the data and the Fourier-Bessel fit were observed in the first minimum of the form factor. The experimental data[5] measured in that region at 320 MeV exceed the prediction of the best-fit charge density by $(5 \pm 2)\%$. In an earlier experiment[4] at Stanford, the minimum was observed to be filled in by $(12 \pm 5)\%$ at 375 MeV. Both of these observations have been tentatively ascribed to dispersive effects. Unfortunately, possible uncertainties due to target impurities, backgrounds, and the unfolding of the spectrometer acceptance solid angle, could not be ruled out in either of these earlier experiments. In both measurements the angular acceptance of the spectrometer was comparable to the angular width of the diffraction minimum.

The comparison of rms radii deduced from electron scattering and from muonic x-ray experiments may provide additional evidence for dispersive processes. Ruckstuhl *et al.*[14] have performed an extremely accurate measurement of muonic transition energies in ^{12}C with a bent-crystal spectrometer. They obtain a value for the rms radius of 2.4829(19) fm, which is nearly two standard deviations larger than the value of 2.464(12) fm obtained by Reuter *et al.*[5] without dispersion corrections. Although this cannot be considered a serious discrepancy, it is striking that in many cases where rms radii deduced accurately from muonic transitions have been compared with those deduced from elastic electron scattering, the result from the muonic-atom experiment is larger by up to 20 am.

In this Letter we present the results of a careful study of the form factor for elastic electron scattering from ^{12}C in the region of the first diffraction minimum at three different energies, 238, 419, and 431 MeV. The experiment was performed at the 500-MeV electron-scattering facility[15] of NIKHEF-K. Scattered electrons were analyzed with the high-resolution quadrupole–double-dipole (QDD) spectrometer and its associated detection system. The properties of this setup permit a determination of the scattering angle for each scattered electron. The solid-angle acceptance of the spectrometer can thus be divided into bins small enough that the folding over the solid angle results in a small ($\leq 2\%$) and accurately calculable correction to the measured cross section. The angular resolution of the QDD spectrometer was measured to be ± 2 mrad in the scattering plane, its angular acceptance is 80 mrad. The data were histogrammed into 8-mrad bins, which resulted in nine data points at a single setting of the spectrometer [Fig. 1(a)]. The spectrometer was moved in steps of 30 mrad, so that overlapping of data points was obtained. The excellent momentum resolution of the apparatus (30 keV at 238 MeV and 50 keV at 419 and 431 MeV) allowed a clean separation of the ^{12}C elastic-scattering peak from the contributions of ^{13}C and other target impurities. A graphite target, 93 mg/cm^2 thick and of natural isotopic composition, was rotated in the beam in order to average out possible target inhomogeneities. At each incident energy an effective momentum-transfer range of at least 1.6 to 2.1 fm^{-1} was covered. Standard corrections were applied for the wire-chamber efficiencies and dead-time losses. Since data were collected on an event-by-event basis, corrections for spectrometer aberrations could be optimized off line. These aberrations were studied carefully through the use of a special solid-angle defining

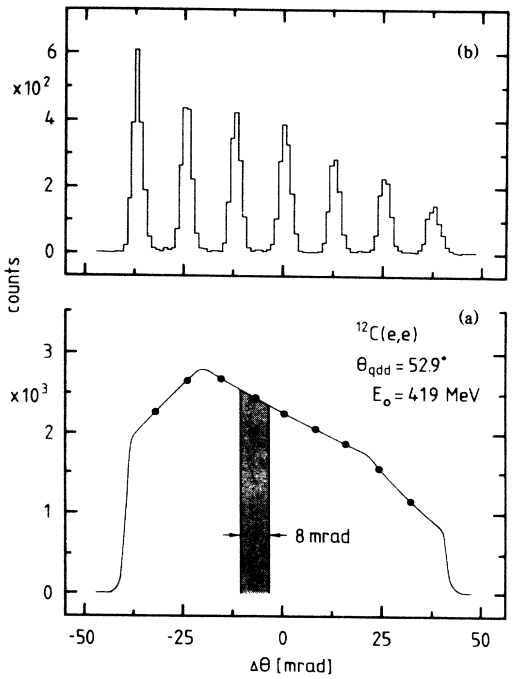

FIG. 1. (a) Angular spectrum in the scattering plane of 419-MeV electrons, scattered elastically from ^{12}C and observed with the QDD spectrometer set at a nominal scattering angle of 52.9°. The gray band indicates the 8-mrad bin into which the data have been histogrammed. The slope in the center of the curve is caused by the angular dependence of the cross section, while the sudden slope changes at ± 20 mrad are caused by the octagonal shape of the solid-angle defining slit. (b) The angular spectrum obtained from the seven small apertures of the sieve slit that lie in the scattering plane (see text). The ± 2-mrad angular resolution of the QDD spectrometer is clearly evident.

slit,[16] consisting of a 2-cm-thick stainless-steel plate with a grid of small holes of 3-mrad angular acceptance at equal distances corresponding to 12-mrad angular separation. This procedure permitted us to determine the angular resolution of the spectrometer [see Fig. 1(b)] and also allowed a check on the alignment of the beam spot on the target, and therefore on the scattering angle, at each spectrometer setting. The variation of the spectrometer acceptance over the solid angle was calculated with a Monte Carlo simulation. This calculation was later checked with the elastic-scattering cross sections measured simultaneously with the second, large-solid-angle spectrometer, the quadrupole-dipole-quadrupole which shares a pivot with the QDD spectrometer, and with the data obtained simultaneously on inelastic electron scattering from the 2^+ level at 4.439 MeV.

The energy calibration and cross-section normalization were determined carefully. At each spectrometer setting data were also accumulated from a BN and a BeO target. From the positions of a large number of peaks in the spectra measured from these two targets the energy of the incident electrons was determined with a typical accuracy of 0.05%. The absolute accuracy of the NIKHEF electron-scattering system has been estimated[15] to be $\pm 2.5\%$. In Table 6 of Ref. 15 the contributions of the various error sources are listed. A significant number of these error sources, such as the uncertainties in the solid angle and in the target thickness, are energy independent and therefore cancel in a comparison of data sets taken at different energies. The efficiency of our multi-wire-chamber detector was monitored on line during the experiment by observation of the number of events rejected as a result of inefficiencies in the individual chambers. For the present experiment, the normalization uncertainty has been reduced to less than $\pm 2\%$ by a careful recalibration of the scattering angle scale, a detailed study of the ^{12}C target thickness and uniformity, and improvements in the spectrometer's energy calibration. The stability of the measurement apparatus is even better; repeated measurements of cross sections at a fixed beam energy agreed to within their statistical uncertainties (typically less than 1%), as do cross sections at a given scattering angle measured with different settings for the central angle of the QDD spectrometer.

We performed a Fourier-Bessel analysis of the complete 238-MeV data set (sixty data points at 8-mrad intervals) in conjunction with the data from earlier experiments by Reuter *et al.*[5] and Cardman *et al.*,[13] which were taken at energies ranging from 20 to 320 MeV. Data from the experiment of Reuter *et al.*[5] taken in the region of the diffraction minimum ($1.6 < q < 2.0$ fm^{-1}) were omitted in this analysis because they were replaced by the higher-quality data from the present experiment. The quality of the combined fit could be improved slightly with respect to the fit[5] to the data of Reuter *et al.*[5] alone by adjusting the incident energies of those data slightly within the quoted error of 0.1%. This implies that the form-factor minimum was observed at the same momentum-transfer value in the present data set as in that from Reuter *et al.*,[5] so that the energy calibrations of both experiments are in mutual agreement. The ground-state charge distribution extracted from the present Fourier-Bessel analysis was essentially identical to that resulting from the analysis of Reuter *et al.*[5] Next, this charge distribution was used to calculate the cross section at each of the other two energies, 419 and 431 MeV. If dispersion effects are negligible, the (static) charge density deduced from the lower-energy data should allow an accurate prediction of the elastic-scattering cross section obtained over the same momentum-transfer range, irrespective of the incident energy. The deviation between the predicted and measured values is shown in Fig. 2. Clearly, the form-factor minimum measured at the two higher energies is filled in with respect to the prediction based on the lower-energy data sets by as much as 7.5%. Furthermore, the form factor drops below the predicted values on both sides of the minimum. It is important to note that the agreement of the new 238-MeV data with the prediction of the static-charge-density fit to these and earlier data

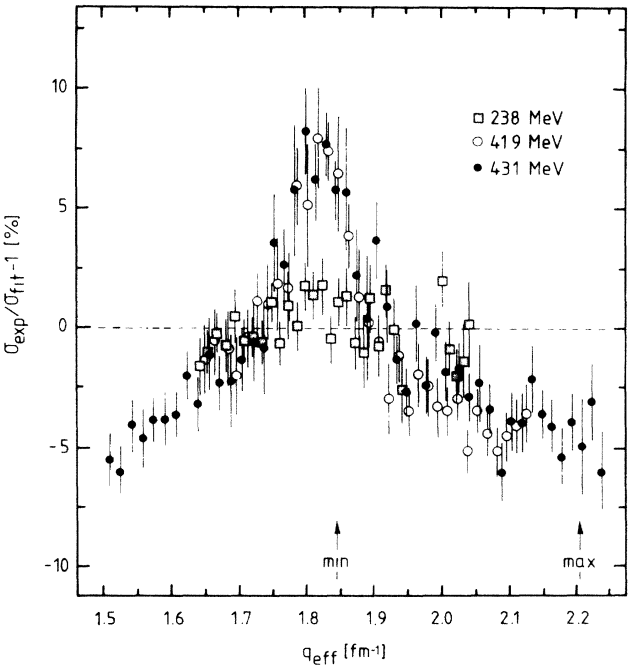

FIG. 2. The experimental data taken at 238, 419, and 431 MeV compared to the cross section calculated from the result of the Fourier-Bessel fit (dashed line) to the data at 238 MeV and the earlier data of Reuter *et al.* (Ref. 5) and of Cardman *et al.* (Ref. 13).

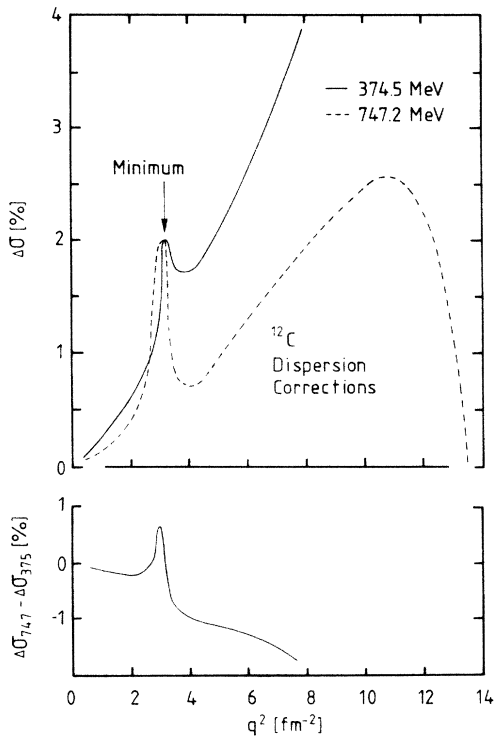

FIG. 3. Results of the calculations of Ref. 1 for dispersion corrections to elastic scattering from ^{12}C at 374.5 and 750 MeV.

should not be construed as indicating the complete absence of dispersive effects at lower energies. The extent to which dispersive effects present in these data have been absorbed into an incorrect static charge density is unknown. The cross section for scattering from the "true" ^{12}C charge density in the absence of dispersive effects may well disagree with both low- and high-energy data (see, e.g., the calculations of Friar,[1] shown in Fig. 3). It is also important to note that the energy dependence we observe in the momentum-transfer dependence of the ^{12}C elastic form factor cannot be removed by a renormalization of our 419- and/or 431-MeV data. Such a renormalization (which we estimate to be $\leq 2\%$) could only alter the relative magnitude of the discrepancies observed in the minimum and on each side of it.

The energy dependence observed in the ^{12}C(e,e) form factor agrees qualitatively with the result of the calculations performed by Friar,[1] as shown in the lower part of Fig. 3. A strongly peaked effect in the diffraction minimum and an energy dependence of opposite sign on either side of the minimum is both observed and predicted. Quantitatively, however, the agreement is rather poor; the observed effect is nearly an order of magnitude larger than the predictions of Friar. In view of the rather crude approximations applied in the calculations; this discrepancy is not surprising.

Reuter *et al.*[5] have estimated that the dispersion corrections as calculated by Friar would result in an increase of approximately 4 am in the rms radius deduced from their experiment. If the energy dependence observed in the present experiment is caused by dispersive effects, application of a correction scaled according to the present results would improve significantly the agreement between the rms-radius values deduced from elastic electron scattering and muonic x-ray data.

In conclusion, the present data provide unambiguous evidence for an appreciable energy dependence of the elastic electron scattering form factor, most probably due to dispersive effects. Certainly the present results indicate the need for more elaborate calculations of two-step processes in electron scattering.

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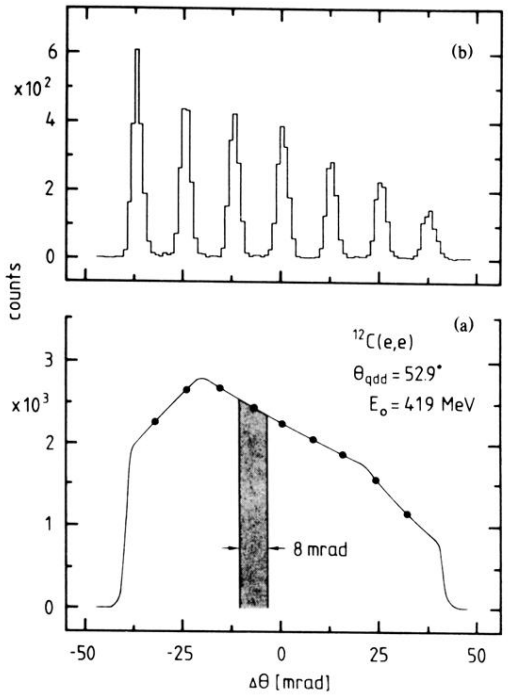

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