Energy Dependence of Dispersive Effects in ^{12}C

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Our investigation of the energy dependence of dispersive effects in elastic electron scattering from ^{12}C has been extended to a beam energy of 690 MeV. The cross section observed in the minimum of the form factor is larger than that predicted using a static charge density obtained by fitting lower-energy data with the customary phase-shift analysis. This "filling in" of the minimum at 690 MeV is even larger than that observed previously at 430 MeV. This indicates an increase in the relative strength of higher-order processes in the minimum with an increase of beam energy; the presence of dispersive effects is the most likely explanation for this effect.

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Generally, nuclear information is extracted from electron-scattering data in the first Born approximation. This one-photon-exchange treatment is improved by taking into account the distortion of the electron wave function by the Coulomb monopole field of the nucleus (Coulomb distortion, see Fig. 1). This leads to the customary partial-wave and distorted-wave Born-approximation techniques for analyzing elastic and inelastic electron-scattering data, respectively, after these have been corrected for radiative effects. The results of this approach (which we refer to as a static analysis) are quite good because multiphoton exchanges are generally suppressed by at least a factor of 137. However, the availability of more precise data and the need to extract ever more accurate nuclear structure information has made it necessary to investigate the size of the contribution from these higher-order processes. The most prominent term in the series of higher-order contributions is probably the dispersive effect, which describes the dynamic effect of virtual excitation of the nucleus during the scattering process. Exact calculations which take the dispersion effects into account are essentially impossible since all intermediate (virtual) nuclear excitations must be included and the calculation must integrate over all possible momentum-transfer values which can be shared between the two exchanged photons. Two different approximations have generally been used:[1] (1) only a few dominant low-lying states are considered, or (2) an average excitation energy is assumed for all levels and closure is invoked to sum over the complete excitation spectrum. Although most calculations[1-3] agree on certain qualitative factors of dispersive effects, (a) that they are largest in diffraction minima, (b) that their relative importance increases with increasing momentum transfer, and (c) that their relative size in the diffraction

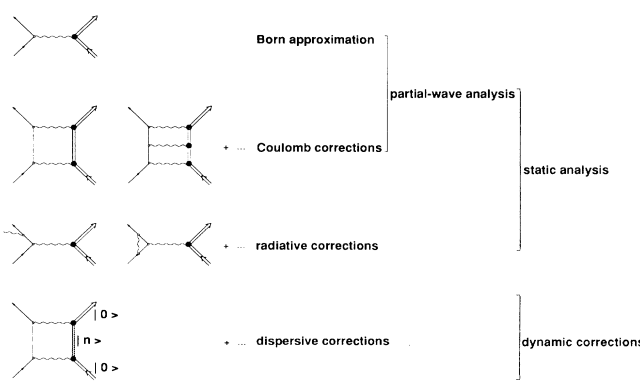

FIG. 1. Feynman diagrams of processes important in electron-nucleus scattering.

minimum decreases with increasing nuclear charge Z, the results of different calculations usually disagree on their magnitude and even on their sign.

One of the ways to observe dispersive effects is to study a diffraction minimum of the elastic cross section at different incident energies. Here, the first-order Born-approximation term goes through zero, so the dispersive effects can in principle be observed directly. Even in a static analysis, however, this diffraction minimum is "filled in" by the Coulomb corrections. Any contribution of higher-order effects should show up first as an energy dependence of the form factor in the region of the diffraction beyond the known energy dependence of the Coulomb and radiative corrections. Because these Coulomb corrections are reduced as Z is reduced, the dispersive effects should be easiest to see in a light nucleus. Because of an abundance of data on its ground-state cross section and its deep diffraction minimum, ^{12}C is a good candidate for such a study.

A recent experiment at NIKHEF-K[4,5] investigated precisely the energy dependence of elastic electron scattering from ^{12}C. A static charge distribution was obtained by analyzing existing low-energy data[6,7] outside the region of the form-factor minimum in conjunction with the 240-MeV NIKHEF data both inside and outside the minimum. This charge distribution was then used to predict the cross section at 431 MeV. The energy dependence manifested itself as a "filling in" of the cross-section minimum at 431 MeV compared to the predictions of the static charge density that fit the lower-energy data. This was the first experiment to show unambiguously the contribution of processes in electron scattering involving multi-(hard)-photon exchanges like dispersive effects. Earlier experiments[6,8] in ^{12}C did not provide conclusive results because the measurements were hampered in the diffraction minimum region by poor energy resolution, backgrounds, or uncertainties in the (large) corrections necessary to unfold the spectrometer acceptance solid angle from the data.

The energy dependence observed in the $^{12}C(e,e)$ form factor outside the minimum in the NIKHEF-K experiment agrees qualitatively with the results of the calculations performed by Friar.[1] However, the strongly peaked effect in the minimum is nearly an order of magnitude larger than predicted. For investigation of the inevitable approximations made in the calculations of dispersive effects it is important to extend these measurements to a significantly higher energy than 431 MeV.

In this Letter we report on an experiment performed at the MIT-Bates linear accelerator facility in which an incident energy of 690 MeV was used. The same graphite target used for the NIKHEF-K experiment, which has a density of 93 mg/cm^2 and a natural isotopic composition, was placed in a rotator in order to minimize the effect of target inhomogeneities. Data were taken with the energy-loss spectrometer system (ELSSY).[9] The scattering angle was varied between 26° and 36° in steps of 1° or 2° in such a way that there were overlaps between adjacent settings of the spectrometer angle in the region of the minimum of the form factor (the horizontal angular acceptance of ELSSY is 1.5°). This angular range corresponds to an effective momentum-transfer range of 1.57–2.20 fm^{-1}. In the off-line event-by-event analysis the horizontal angular acceptance of the spectrometer was subdivided into three bins of 8 mrad width. This analysis used the results of a separate study[10] in which the optical transport coefficients of the spectrometer were determined empirically with a solid-angle-defining "sieve" slit using the technique developed earlier at NIKHEF-K.[11] This sieve slit, specially designed and built for ELSSY, is a 2.5-cm-thick slab of Hevimet alloy with an array of 35 holes organized in a 5×7 grid. Figure 2 shows a ϕ spectrum obtained using the sieve slit with all relevant coefficients determined empirically. The transverse angular resolution of ELSSY was found to be better than 2 mrad.

The high momentum resolution of the system ($\Delta p/p \approx 1\times10^{-4}$) allowed a clear separation of scattering from ^{13}C and ^{12}C in the natural carbon target. The energy calibration of ELSSY was determined from the measured positions of elastic and inelastic peaks from a target containing Al and BeO as well as from the ^{12}C target; an accuracy of about 0.5 MeV in the incident energy ($\approx 0.07\%$) was achieved.

For each software-defined acceptance bin of the spectrometer, the cross section for the first 2^+ state of ^{12}C at 4.439 MeV was also analyzed for the purpose of determining the product of solid angle and efficiency for that bin. This inelastic cross section is well suited for this use because, unlike the elastic-scattering cross section, it varies slowly over the q region covered by our measurements. The overall normalization of the MIT-Bates elastic-scattering data was determined from the predictions of the transition charge density for the 4.439-MeV level obtained from an analysis[5] of the data from earlier experiments.

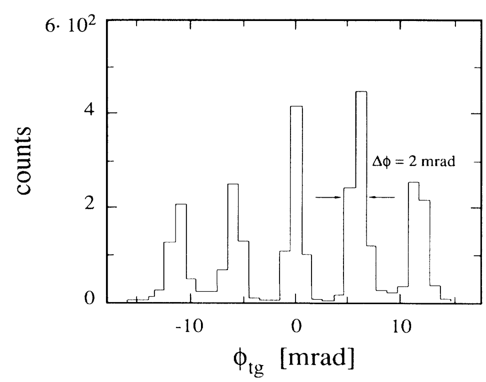

FIG. 2. A typical ϕ spectrum obtained with the solid-angle-defining sieve slit. This measurement was done at a spectrometer angle of 40° and an incident electron energy of 300 MeV. The angular resolution is seen to be better than 2 mrad.

In order to obtain the energy dependence of the cross section in the region of the diffraction minimum we followed the same procedure in analyzing the MIT-Bates data as in our earlier work.[4] First, a model-independent fit using a Fourier-Bessel analysis was made to all the data from NIKHEF-K,[4,5] Mainz,[6] and NBS[7] with energies ranging from 20 to 320 MeV. In the region of the diffraction minimum ($1.6 < q < 2.0$ fm^{-1}), the Mainz data[6] were replaced by the higher-quality data from the NIKHEF-K experiment.[4] The quality of the combined fit was improved slightly by allowing the energy calibration of each data set to vary within its quoted uncertainty. Compared to the previous analysis,[4] a larger data set from NIKHEF-K was available ($1.0 \le q_{\rm eff} \le 2.04$ fm^{-1}); the additional low-energy data are in good agreement with the earlier fit. The ^{12}C ground-state charge-density distribution obtained from this fit was then used to calculate the cross section for the NIKHEF-K data at 419–431 MeV and for the MIT-Bates data at 690 MeV. If higher-order effects are negligible, the (static) charge density deduced from the lower-energy data should predict accurately the elastic-scattering cross section measured over the same range of momentum transfers independent of the beam energy. Figure 3 shows the difference between the new cross sections measured at 690 MeV and those measured earlier at NIKHEF-K at 419–431 MeV and at 238–243 MeV and the cross sections calculated with the ground-state charge density that was determined empirically using the lower-energy data. The shaded error bands in this figure represent the size of the total systematic error, which is predominantly due to the uncertainty in the incident energy. The error bars shown in the figure indicate the statistical error. As shown in the lower part of Fig. 3, the difference between the new data and the prediction of the one-photon-exchange calculation using the previous density is found to peak at $q_{\rm eff} = 1.8$ fm^{-1}, whereas that difference with the 431-MeV data peaks at a slightly larger $q_{\rm eff}$ value. Apparently, higher-order effects influence the position of the diffraction minimum. The height of the peak is much larger at 690 MeV than at 431 MeV suggesting that the relative importance of the higher-order effects increases with increasing beam energy. It is important to note that the energy dependence of the form factor observed between these data and the predictions of the static-density fit to the lower-energy data cannot be removed by a renormalization of the new 690-MeV data.

The relatively good agreement of the earlier NIKHEF-K 240-MeV data with the prediction of the static-charge-density fit to these and earlier data should not be construed as an indication for the 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. However, attempts to find a static density that provided a fit to the new 690-MeV data and the other data outside the region of the diffraction minimum were not successful. The deviations from the best fit were similar to those shown in Fig. 3. This result is consistent with an interpretation of our data as showing a significantly larger dispersive contribution in the region of the diffraction minimum of the 690-MeV data; this contribution is now so large that no static density can come close to providing a reasonable fit to the data.

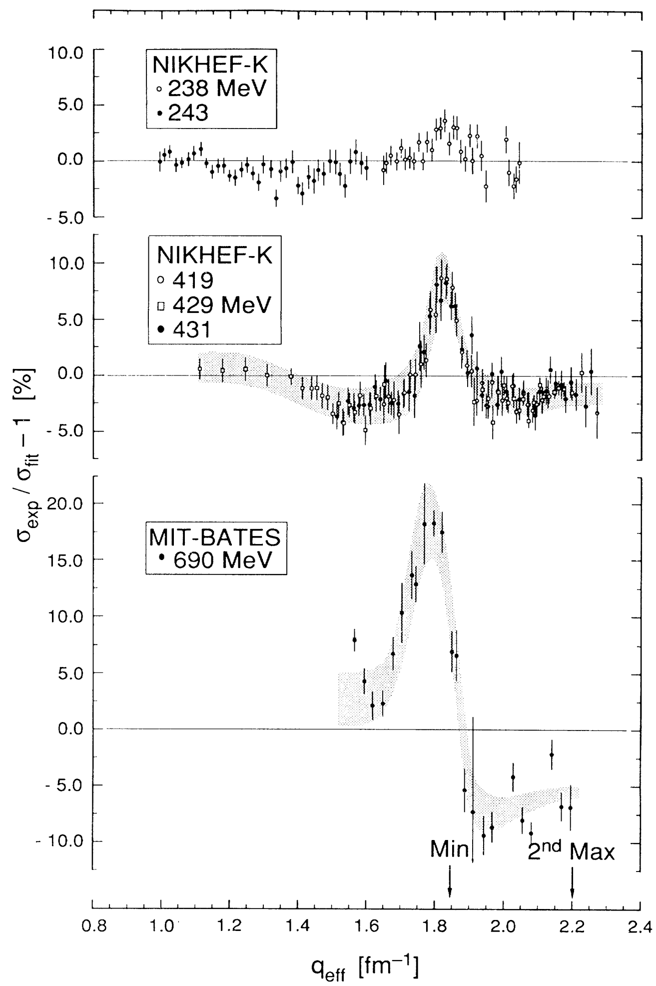

FIG. 3. The differences between the measured cross sections at six incident electron energies (from 238 to 690 MeV) and the corresponding values predicted by the ground-state charge-density parameters obtained from the data at lower energies (see text).

Figure 4 shows the results of a calculation[3] of the dispersion correction for two different energies: This calculation uses a closure expansion to sum over the excitation spectrum. There is qualitative agreement between the data and the prediction of this theory: (a) The energy dependence of the dynamic cross section peaks sharply in the region of the diffraction minimum (see lower half of Fig. 4), and (b) the energy dependence has the opposite sign on either side of the diffraction minimum from that in the minimum. Quantitatively, however, the

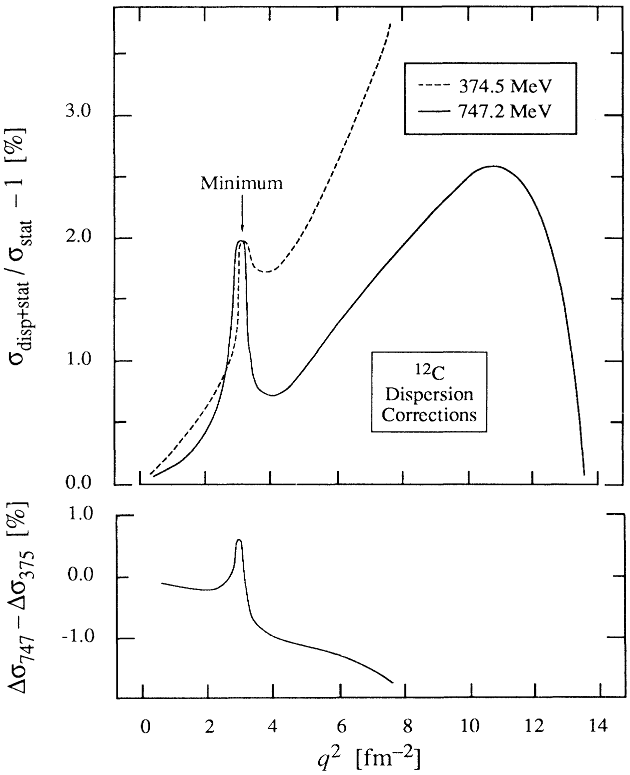

FIG. 4. Results of the calculation of Ref. 3 for the dispersion effects on elastic scattering of electrons with energies of 374.5 and 747.2 MeV from ^{12}C.

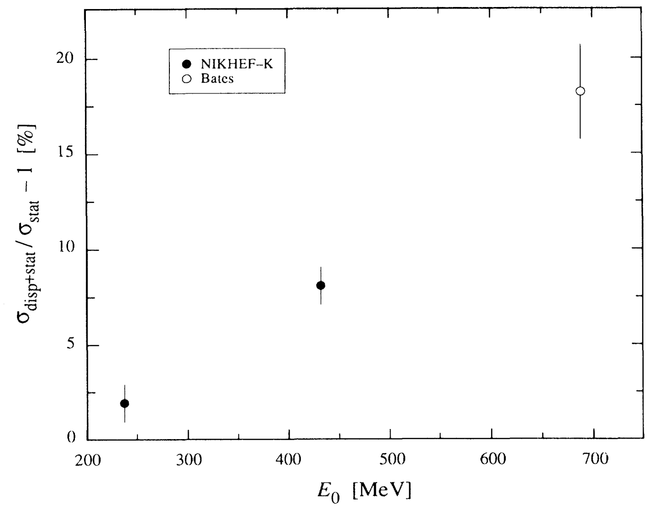

FIG. 5. The energy dependence of the filling of the form-factor minimum. The results are from different laboratories; NIKHEF-K: solid circles; MIT-Bates: open circle.

agreement between theory and experiment is rather poor; the observed effect is nearly an order of magnitude larger than the predictions of Friar. This discrepancy is not surprising in view of the rather crude approximations applied in the calculations.

At all energies considered, a distinctive peak is observed in the difference between the measured and predicted cross sections at the location of the minimum of the cross section. Figure 5 shows the strength of these peaks at different energies. An increase in the relative strength of the higher-order processes is observed as the incident electron energy is increased.

In conclusion, careful measurements performed with high-energy electrons at the MIT-Bates laboratory yield a clear signal for an energy dependence of the form factor in the region of the first diffraction minimum of the ^{12}C elastic cross section. This energy dependence is most probably due to higher-order processes such as dispersive effects, the same conclusion as drawn in the earlier work at NIKHEF-K. However, comparison with the earlier work shows that the signal is even stronger at the higher incident electron energy. A concerted experimental and theoretical effort is needed before these effects will be well understood.

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