PHYSICAL REVIEW C VOLUME 57, NUMBER 5 MAY 1998

Dispersive effects from a comparison of electron and positron scattering from ^{12}C

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(Received 14 May 1997; revised manuscript received 29 January 1998)

Dispersive effects have been investigated by comparing elastic scattering of electrons and positrons from ^{12}C at the Saclay Linear Accelerator. The results demonstrate that dispersive effects at energies of 262 MeV and 450 MeV are less than 2% below the first diffraction minimum $[0.95 < q_{\mathrm{eff}}\ (\mathrm{fm}^{-1}) < 1.66]$ in agreement with the prediction of Friar and Rosen. At the position of this minimum $(q_{\mathrm{eff}} = 1.84\ \mathrm{fm}^{-1})$, the deviation between the positron scattering cross section and the cross section derived from the electron results is $-44\% \pm 30\%$. [S0556-2813(98)04405-7]

PACS number(s): 25.30.Hm, 24.10.Ht, 27.20.+n

In a previous paper [1], the validity of the formalism used to describe electron scattering from a rigid and static nucleus has been tested by comparing elastic scattering of positrons and electrons from ^{12}C and ^{208}Pb at 450 MeV incident energy. Data showed that the dispersive effects that are not accounted for by a phase-shift analysis were less than 2% for elastic scattering on ^{12}C in the kinematic regime $1 < q_{\mathrm{eff}}\ (\mathrm{fm}^{-1}) < 1.5$.

The aim of the present paper is to report on a similar experiment which extended the previous experiment to higher momentum transfer up to the first diffraction minimum $(q_{\mathrm{eff}} = 1.84\ \mathrm{fm}^{-1})$.

The Born approximation provides a useful framework to discuss the different aspects of the electron-nucleus interaction. Several corrections must be considered to the first-order term of the electron scattering cross section plane wave Born approximation (PWBA): (i) Coulomb corrections due to the Coulomb field of the target nucleus which causes an acceleration of the incoming and outgoing electrons and are usually treated within a distorted wave Born approximation (DWBA) analysis for inelastic scattering or heavy nuclei [2], (ii) radiative corrections due to energy loss processes [3,4], and (iii) dispersive effects due to virtual excitations of the nucleus at the moment of the interaction (which could become sizable in some particular case, e.g., in minima of form factors [5,6]). The electron-nucleus scattering amplitude can be written as an expansion in powers of αZ. In the framework of the PWBA, the leading term (proportional to αZ) will have opposite signs for electrons and positrons. So if one uses a rigid charge density (e.g., no dispersive effects), the correction to this formalism is essentially due to Coulomb processes adding terms of the order of $(\alpha Z)^2$, $(\alpha Z)^3, \ldots$.

In the case of spin 0 nuclei, Coulomb corrections in elastic scattering are carried out using an exact phase shift calculation with a static electron-nucleus potential. The elastic cross section is then proportional to the phase-shift between the incoming and outgoing electron wave functions.

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Dispersive effects have been investigated by several electron scattering experiments [7–10]. Friar and Rosen [5,6] have calculated dispersive effects on ^{12}C in electron scattering using the harmonic oscillator model for the nucleus. Only the Coulomb component was taken into account to calculate the scattering amplitude in the DWBA. These authors predict that dispersive effects have a smooth energy and momentum dependence: less than 1% outside the first diffraction minimum ($q_{\text{eff}}<1.7\ \text{fm}^{-1}$) and about 2% inside ($q_{\text{eff}}=1.84\ \text{fm}^{-1}$) for energies between 300 and 700 MeV.

Recently, two experiments on ^{12}C have been performed at NIKHEF [10,11] at 240 and 430 MeV and at MIT [12] at 690 MeV for a q_{eff} range of $1<q_{\text{eff}}\ (\text{fm}^{-1})<2.3$. The cross sections were compared to a static phase-shift calculation in order to extract the energy dependence of possible dispersive effects. It was observed that dispersive effects are less than 1% for incident energies lower than 240 MeV but are up to 18% at $q_{\text{eff}}=1.84\ \text{fm}^{-1}$ for an incident energy of 690 MeV. Ouside the minimum, the deviation observed is in good agreement with the prediction of Friar and Rosen [5,6] but they differ drastically in the minimum. Voegler *et al.* [13] in the study of the $\text{O}^+\rightarrow\text{O}^-$ transition of ^{18}O (which is forbidden in the one-photon exchange approximation) have found good agreement with a prediction by Borie and Dreschel [14]. However, the uncertainty is so large that it cannot be regarded as a serious test of the numerous approximations that have been made in the calculation. All the experiments described above have given only an energy dependence of dispersive effects while the comparison of electron and positron cross sections provides information about the sign and the size of the dispersive amplitude. Indeed, outside the diffraction minima, the leading term in the scattering amplitude is proportional to αZ while the dispersive amplitude should be proportional to $(\alpha Z)^2$. The interference term has therefore opposite signs for electrons and positrons. On the other hand, dispersive effects are expected to be largest in the minima of the form factors where the leading terms in both the dispersive and Coulomb distortion contributions to the scattering amplitude are proportional to $(\alpha Z)^2$. The interference between them will not change its sign for electrons and positrons.

The comparison between electron and positron elastic cross sections is therefore a powerful tool for obtaining information on the contribution of dispersive effects [15]. To highlight these effects, one has to use light nuclei because Coulomb corrections become comparably very large for high-Z nuclei. A first experiment performed in Saclay in 1988 [1] showed that dispersive effects were less than 2% for electron elastic scattering on ^{12}C in the kinematic region $1<q_{\text{eff}}\ (\text{fm}^{-1})<1.5$. From NIKHEF [11] and MIT [12], deviation from a static charge analysis of the electron elastic scattering cross section on the same nucleus is larger in the first diffraction minimum, but starts to be significant at $q_{\text{eff}}=1.6\ \text{fm}^{-1}$. These measurements motivated us to extend the measurements of the first experiment at larger q_{eff}.

This experiment was performed at the 700 MeV Saclay Linear Accelerator (ALS) which can provide a 30 nA positron beam with energies up to 600 MeV and a $\Delta E/E$ of 2×10^{-3}. The scattered particles were detected in the HE1 (electron-positron) hall and analyzed by the 900 magnetic spectrometer (SP900) described in [16] (momentum resolution $\Delta P/P_0=2\times10^{-4}$, maximum momentum of 900 MeV/c) equipped with a detector package consisting of (i) two planes (R,Y) of plastic scintillators, (ii) a Čerenkov counter (C) filled with freon gas (index $n=1.0013$) and corresponding to electron and pion thresholds of 10 MeV and 2.7 GeV, respectively, and (iii) two planes of drift chambers both with horizontal and slanted wires. These two planes allow us to extract the scattering angle of the detected electron on an event by event basis as needed for a precise measurement of the cross section. The trigger was given by a RYC coincidence signal eliminating pions. The other spectrometer (SP600) [16] was positioned at 45° with respect to the beam direction and used as a luminosity monitor. The fluctuation of the SP600 monitoring was found to be of the order of 1% and all the runs agree within less than one standard deviation. Three different target thicknesses ($30\times50\ \text{mm}^2$ plane foils) of natural carbon were used: 96, 296, and 500 mg/cm^2. Homogeneous target illumination through rastering of the targets was realized and the uncertainty on the target thickness was 1%.

The positron beam was created by the interaction of a 100 MeV electron beam on a tungsten radiator. Its emittance is 6 times larger than the emittance of the direct electron beam. In order to minimize systematic effects, the electron and positron emittances should be comparable. However, the electron beam cannot be deteriorated using the same method since the beam electrons that did not scatter could not be separated from the electrons created by pair production which are much fewer.

The option to reduce the positron phase space with a collimator produces a beam with a too low current. Because of these considerations, the emittance of the electron beam was degradated by installing a 17 μm aluminum foil after the last section of the accelerator. The emittance of both beams ($\sim2\pi$ mm mrad) was defined by the same mechanical slit system and we monitored the beam emittance during the experiment by measuring the beam profiles using a pair of highly sensitive scanning wire systems. The first one located about 2 m upstream of the target was made out of two perpendicular 300 μm copper wires mounted on a fork. While moving through the beam, secondary emitted electrons produce a signal on the wires that allow us to reconstruct the beam horizontal and vertical profiles with an accuracy of 0.5 mm. The second monitor was located 7.8 m downstream of the target in front of the Faraday cup. A 16×16 array of 300 μm copper wires was used to measure the beam profile with an accuracy of 1 mm.

We have found that our beam spots were positioned about 5 mm under the point that corresponds to the crossing of the line defined by the center of the rotation of the spectrometer and the central ray of the spectrometer collimator due to misalignment in the beam tuning. This brings a correction of 0.5% on the solid angle for both the two spectrometers of the HE1 hall.

Special precautions were required to measure the small ($\simeq30$ nA) beam current. The water used to cool the Faraday cup induced a leakage current similar in magnitude to our mean beam current. By draining and drying the Faraday cup, its leakage current was reduced to $\simeq30$ pA. A ferrite-core induction monitor located upstream of the target was used for a redundant charge determination. The charge measurements of both the Faraday cup and the ferrite-core monitor were in agreement within 2%.

Electron cross sections were extracted for a $q_{\rm eff}$ range from 1.14 $\rm fm^{-1}$ to 1.66 $\rm fm^{-1}$ at 450 MeV incident energy and positron cross sections for the same $q_{\rm eff}$ range at the same incident energy and from 0.95 $\rm fm^{-1}$ to 1.54 $\rm fm^{-1}$ at 262 MeV. The scattering angles covered a region from 29° to 72°. One point in the minimum ($q_{\rm eff}=1.84\ \rm fm^{-1}$) was extracted in positron scattering at the kinematical setting (450 MeV, 48°). Our experimental cross sections were corrected for dead time which contributes to 11% at 450 MeV and 14% at 262 MeV. Pair annihilation (for positrons) was found to be negligible. Radiative corrections were accounted for using the method developed by Mo and Tsai [3,4]: the measured spectra were corrected for Landau straggling, thick target bremsstrahlung, and Schwinger corrections. Coulomb corrections to the radiative corrections were taken into account using the effective momentum approximation (EMA).

Radiative corrections never contribute more than 20% to our elastic cross sections for both electrons and positrons. Overall systematic effects were estimated to 2% compared to an average systematical uncertainty of 1%.

After performing the geometrical corrections due to the spectrometer acceptance and including the emittance of the beams, we compared our experimental data to a fit of all known data using a phase-shift calculation [17]. A sum of Gaussian (SOG) parametrization of static charge density was used [18]. A study of these cross sections ($\sigma_{\rm SOG}$) shows that a 100 keV variation in the incident energy gives its biggest systematic effect — about 1% — inside the diffraction minimum at 450 MeV. This effect is very small compared to our statistical uncertainty. Measurements at $q_{\rm eff}=1.14\ \rm fm^{-1}$ corresponding to a 29° scattering angle were done repeatedly throughout the experiment to make sure the overall spectrometer efficiency remained stable.

In the region $1.14<q_{\rm eff}\ (\rm fm^{-1})<1.66$, the experimental cross sections extracted from the electron runs at 450 MeV incident energy have an overall normalization of 1.013 ± 0.013 compared to the prediction from the $\sigma_{\rm SOG}$ fit of the carbon charge density. Using the same fit to compute positron elastic cross section, the positron runs at both incident energies (262 and 450 MeV) have an overall normalization of 1.025 ± 0.003.

Figure 1 shows the ratio of the electron and positron cross sections in the region $1<q_{\rm eff}<1.7\ \rm fm^{-1}$ for the two Saclay experiments. The two experiments agree within the statistical error bars. Our experiment extends up to $q_{\rm eff}=1.66\ \rm fm^{-1}$, the conclusion being that dispersive effects are below 2%, in agreement with the calculation by Friar and Rosen.

Our point in the first diffraction minimum ($q_{\rm eff}=1.84\ \rm fm^{-1}$), which was extracted only for positron scattering, is compared to other electron data [9,11–13] in Fig. 2. There is deviation up to 18% at 690 MeV between electron scattering experiments and a static phase-shift calculation as a function of the incident energy. At this momentum transfer, the prediction of Friar and Rosen [5,6] shows no energy dependence and a magnitude of about 2%. There is very poor agreement between the theory and electron scattering results.

Rawitscher [15] predicts the same sign and amplitude for both electron and positron. The deviation obtained from a static charge density in positron scattering is $-44\% \pm 30\%$. The magnitude of the error bar is mainly due to statistical error. As a result of time constraints, measurement of the cross section at the same $q_{\rm eff}$ point in electron scattering was not possible. Since the cross section is very sensitive to any systematic uncertainty inside the minima, no definitive conclusion about the absolute sign and amplitude of dispersive effects in positron scattering inside the first diffraction minimum of ^{12}C can be made.

The present experiment confirms that the errors that one introduces by not taking dispersive corrections into account is small for a four-momentum range between 1 and 1.66

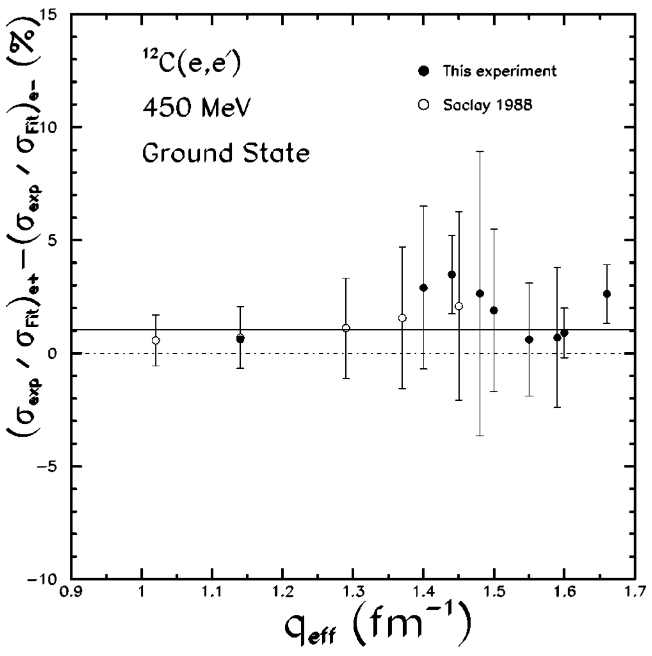

FIG. 1. Comparison of electron and positron cross sections for elastic scattering from ^{12}C at 450 MeV for $1<q_{\rm eff}<1.7\ \rm fm^{-1}$.

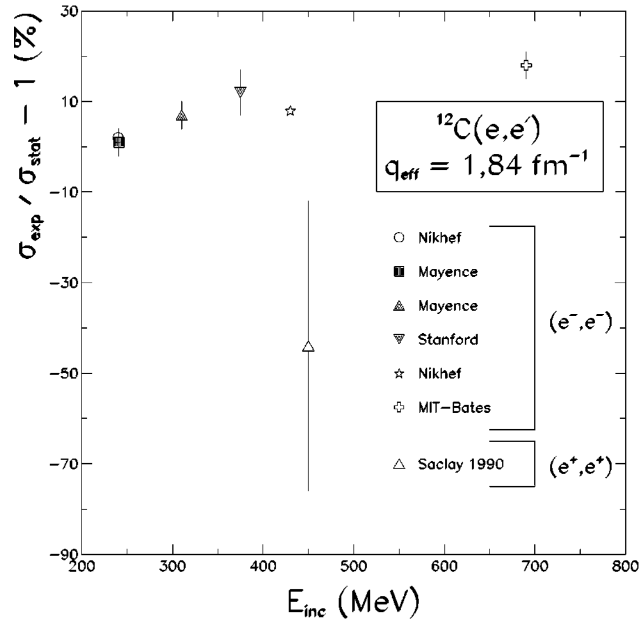

FIG. 2. The energy dependence of the experimental cross sections on ^{12}C in the first diffraction minimum at $q_{\rm eff}=1.84\ \rm fm^{-1}$. $\sigma_{\rm stat}$ is the cross section calculated with a static charge density using a Fourier Bessel (electron scattering) and a sum of Gaussian (positron scattering) parametrization of the charge distribution.

fm^{-1}, below the first diffraction minimum of ^{12}C. However, since the contribution of dispersive effects seem to increase with higher incident energies and higher momentum transfer, other experiments using electron and positron beams in these kinematical regions on light nuclei will be interesting to obtain more precise information concerning the size and the sign of dispersive effects. Inside the diffraction minima, simultaneous measurement of electron and positron cross sections is proved to be the best way to extract this information. New experiments with better statistical error bars will be helpful to confirm or deny the potential sign difference which has been observed in this experiment.

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