High-Accuracy Comparison of Electron and Positron Scattering from Nuclei

V. Breton,[(1),(a)] P. Bricault,[(1)] L. S. Cardman,[(2)] B. Frois,[(1)] D. Goutte,[(1)] D. B. Isabelle,[(3)] A. J. Linzey,[(2)] G. Masson,[(4)] L. C. Maximon,[(5)] E. A. J. M. Offermann,[(2),(b)] X. H. Phan,[(1)] S. K. Platchkov,[(1)] I. Sick,[(4)] and S. E. Williamson[(2)]

[(1)]*Département de Physique Nucléaire et de Hautes Energies, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette, France*

[(2)]*Nuclear Physics Laboratory and Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*

[(3)]*CERI, Centre National de la Recherche Scientifique, 45071 Orleans, France*

[(4)]*Department of Physics, University of Basel, CH-4056 Basel, Switzerland*

[(5)]*Department of Physics, George Washington University, Washington, D.C. 20052*

(Received 19 November 1990)

We compare the elastic-scattering cross sections for electrons and positrons from ^{208}Pb and ^{12}C. The results demonstrate that the electron-nucleus interaction can be described to good accuracy as a single hard-photon exchange process, and validate the theoretical framework used to interpret electron-scattering data in terms of ground-state charge densities of nuclei.

PACS numbers: 25.30.Bf, 25.30.Hm, 27.20.+n, 27.80.+w

Modern electron-scattering experiments determine the ground-state charge distribution and the transition charge densities to the low-lying excited states of nuclei with statistical and systematic uncertainties as low as 1%. At this level of precision it becomes important to understand the limits of validity of our description of the electron-nucleus interaction. In analyzing spectra from an electron-scattering experiment, one begins by correcting for a variety of radiative effects. The accuracy of these corrections is not well known, but is generally believed to be better than 1%. The "standard" interpretation of the resulting cross sections in terms of the nuclear charge and current densities describes the scattering process using the approximation of a single hard-virtual-photon exchange with a static density, and uses partial-wave analysis (for elastic scattering) and the distorted-wave Born approximation (for inelastic scattering) to account for Coulomb distortion of the electron wave function during the scattering process. Dispersive effects, which correspond to intermediate excitations of the nucleus involving the exchange of two or more hard photons, are neglected.

The contributions of radiative corrections, Coulomb distortion, and dispersive effects to the experimental cross sections varies, in general, with the beam energy E, the scattering angle θ, the nuclear charge Ze, and the charge ze of the incident lepton. The present work provides a careful check on the accuracy of the traditional analysis of electron-nucleus scattering through a high-accuracy comparison of elastic electron and positron scattering from ^{12}C and ^{208}Pb; to the extent that the same static charge density can describe both electron and positron scattering from each of these nuclei we have evidence that effects whose magnitude and sign depend on the sign of the charge of the incident lepton are treated properly in that analysis.

The radiative corrections to the experimental spectra include Landau straggling, thick-target (external) bremsstrahlung, and the Schwinger radiative correction. Most modern electron-scattering experiments are carried out using high beam energies and thin (~ 100 mg/cm^2) targets. Under these conditions the correction for Landau straggling is small ($\sim 0.5\%$), and the differences in Landau straggling for electrons and positrons are calculated[1] to be about an order of magnitude smaller. The bremsstrahlung correction is typically a few percent, but the Coulomb corrections to it contain only even powers of Zze^2, and are therefore identical for electrons and positrons. The Schwinger correction is the largest of the radiative corrections ($\sim 20\%$–30%), and our improved formulation, described below, predicts electron-positron differences as large as 1%; this is the radiative correction tested with the greatest sensitivity by an electron-positron comparison.

While the analysis of elastic-scattering data is carried out using an "exact" phase-shift calculation, the Born approximation provides a useful framework for understanding the sensitivities of an electron-positron scattering comparison to different aspects of the electron-nucleus interaction. The electron-nucleus scattering amplitude can be written as an expansion in powers of Zze^2. The leading term in this expansion, which corresponds to the plane-wave Born approximation (PWBA), is proportional to Zze^2, and will have opposite signs for electrons and positrons. Assuming a static charge density (i.e., no dispersive corrections) the largest correction to PWBA is that due to the Coulomb distortion of the electron wave function by the scattering potential. This leads to correction terms in the amplitude proportional to $(Zze^2)^2$, $(Zze^2)^3$, . . .; the odd terms in this expansion have opposite signs for electrons and positrons. The part of the Coulomb effect associated with the acceleration of the lepton by the Coulomb potential of the nucleus corresponds[2] to the effective momentum ($q_{\rm eff}$)

transferred between the lepton and the nucleus depending on the sign of the lepton's charge; this shifts the apparent location of the diffraction minima. The Coulomb effects predict electron-to-positron cross-section ratios as large as 2:1 for ^{208}Pb at 450 MeV, so our experiment, which is accurate to a few percent, provides a sensitive test of the theory.

The comparison between electron and positron elastic scattering can also provide information on the importance of dispersive effects. These effects require the exchange of at least two hard virtual photons. They are expected[3] to be largest in the region of the diffraction minima, where the contribution of the PWBA one-photon-exchange diagram goes to zero. In the minima, the leading terms in both the dispersive and Coulomb-distortion contributions to the scattering amplitude are proportional to $(Zze^2)^2$, so the interference between them will not change with the sign of the lepton charge. In contrast, in the region outside the diffraction minima the leading term in the static-scattering amplitude is proportional to Zze^2 while the dispersive amplitude is expected to be roughly proportional to $(Zze^2)^2$, so the interference term changes sign as the lepton charge changes sign. It has been suggested[4] that this behavior will provide an experimental signature for the presence of dispersive effects.

The first comparisons[5] of electron- and positron-nucleus scattering were performed in the 1960s on ^{59}Co and ^{208}Bi. Ratios of e^+ to e^- cross sections were found to be compatible with the predictions of a phase-shift calculation to within 10% over the momentum-transfer range studied ($q < 1$ fm^{-1}). These data were obtained with an energy resolution of 20 MeV, which was not sufficient to resolve elastic from inelastic scattering. A related μ^+/μ^- comparison[6] had similar resolution and conclusions. Our experiment used a high-energy positron beam with an energy resolution sufficient to resolve the elastic scattering in order to improve on these earlier results.

The energy dependence of dispersive effects has been studied in the case of elastic electron scattering on ^{12}C. The relative importance of the dispersive effects is expected to be largest in the minima of light nuclei, since Coulomb corrections are much larger in this region for high-Z nuclei. It was found[7] that the experimental cross sections in the region of the diffraction minimum were larger by approximately 10% at 430 MeV and 20% at 690 MeV than the values predicted by a phase-shift calculation assuming a static charge density. The magnitude of the measured effect is larger than theoretical predictions by an order of magnitude. The present experiment provides complementary information due to the interference between the dispersive and static-scattering amplitudes, as discussed above.

The present experiment was performed using the Accelerateur Linéaire de Saclay (ALS), which can provide a 20-nA beam of 450-MeV positrons with a 2×10^{-3} energy resolution. Scattering data were obtained with the high-resolution magnetic spectrometer[8] SP900 ($\delta E/E = 10^{-4}$) and its associated detector, which consists of four multiwire proportional chambers, two layers of plastic scintillators, and a gas Čerenkov counter. The spectrometer SP600 was used as a luminosity monitor. The data were collected using a 100-mg/cm^2 target for ^{208}Pb and a 95-mg/cm^2 target for ^{12}C. The absolute efficiency of the detector was determined by measuring the cross coincidence rates between different elements of the detector.

In order to compare electron- and positron-scattering cross sections with overall uncertainties of the order of a few percent, the physical properties of the beams had to be as identical as possible. The emittance of the ALS positron beam is 6 times larger than that of the normal electron beam. To minimize errors in the electron-positron comparison, the emittance of the electron beam was degraded by installing a 17-μm Al foil after the last section of the accelerator, and the emittance of both beams was defined by the same mechanical slit system. We monitored the beam emittance during the experiment by measuring the beam profiles using a pair of high-sensitivity scanning wire systems.[9]

Special precautions were required to measure the small beam currents (10–20 nA) reliably. The water usually used to cool the Faraday cup induced a leakage current similar in magnitude to the positron current. By draining and drying the Faraday cup its leakage current was reduced to a negligible value. Two ferrite-core induction monitors located upstream of the target and low-noise integrators[9] were also used for a redundant charge determination. The ratio of the charge measurements of the Faraday cup to the induction monitors was stable to $< 0.5\%$.

The elastic-cross-section angular distribution for ^{208}Pb was measured at an incident energy of 450 MeV in 1° or 2° steps for angles between 26° and 53°, corresponding to momentum transfers ranging from 1 to 2 fm^{-1}. The elastic cross sections for ^{12}C were measured at the same energy for five angles: 26°, 29°, 33°, 35°, and 37°, corresponding to momentum transfers between 1 and 1.5 fm^{-1}.

The experimental elastic cross sections were determined by integrating the measured spectra to an excitation energy just below the first excited state and then applying corrections for Landau straggling, thick-target bremsstrahlung, and the Schwinger radiative correction. For Landau straggling the standard analysis has been modified following Heddle and Maximon[1] to incorporate the correct Møller and Bhabba cross sections for electron-electron and positron-electron scattering into the Landau formulation. The standard thick-target bremsstrahlung correction[10] has been modified slightly to correct numerical errors in the original expressions. The Schwinger radiative correction formula of Mo and Tsai[10] has been modified by separating the terms involving the emission of real soft photons and exponentiating them, thereby including Coulomb corrections to these terms to all orders of αZ. Additional corrections were made to make the formula consistent with Schwinger's original expression in the limit of a static potential. The annihilation of positrons in the target and in the spectrometer has been estimated to be negligible ($<0.05\%$). Geometrical corrections due to the spectrometer acceptance and the emittance of the beam were taken into account.

The statistical distribution of the measured cross sections repeated at the same scattering angles shows that there was an unidentified common random error in the determination of the experimental cross sections of 0.5% for ^{12}C and 0.7% for ^{208}Pb for both positrons and electrons; these errors were folded in quadrature with the identified statistical uncertainties.

The measured ^{208}Pb cross sections are shown in Fig. 1, where they are compared with the results of a phase-shift calculation,[11] which provides an exact solution for elastic scattering from a spherically symmetric, static charge distribution; the charge distribution used was determined[12] from a model-independent analysis using several sets of electron-scattering data collected for momentum-transfer values up to 3.8 fm^{-1}. The effects of Coulomb distortion and differing q_{eff} for electrons and positrons are clearly visible; the locations of the diffraction minima are shifted between electrons and positrons due to the change in q_{eff}, and the magnitudes of the cross sections at the same q_{eff} differ due to differences in the Coulomb distortion. Clearly, an electron-positron comparison is highly sensitive to Coulomb-distortion effects, and the calculation is in general agreement with the data.

For each incident energy and scattering angle we determined the ratio $R=\sigma^+(E,\theta)/\sigma^-(E,\theta)$ for both the data and the theoretical calculation; many possible experimental errors cancel in these ratios. In the PWBA this ratio would be unity. The lower half of Fig. 1 displays the experimental and theoretical values of R for ^{208}Pb; the measured ratios are generally in good agreement with those obtained from the phase-shift calculation.

Figure 2 displays the experimental cross sections and their ratios for the ^{12}C data compared to the predictions of a phase-shift calculation using the static charge density of Ref. 13. The agreement between experiment and theory for the ^{12}C data is excellent.

To provide increased sensitivity to small discrepancies between experiment and theory, Fig. 3 displays the *differences* between the calculated and measured ratios of positron and electron cross sections for both ^{12}C and ^{208}Pb. The ^{12}C ratios agree with the theoretical predictions to within the experimental error bars, indicating that dispersive effects in ^{12}C are smaller than 2% for momentum transfers from 1 to 1.5 fm^{-1}. This result suggests that the *change* in the dispersive effect with beam energy measured in previous electron-scattering experiments[7] is close to the absolute size of this effect.

The ^{208}Pb ratios display a tendency to differ systematically from the theoretical predictions, although the magnitude of the discrepancies is near the limit of our experi-

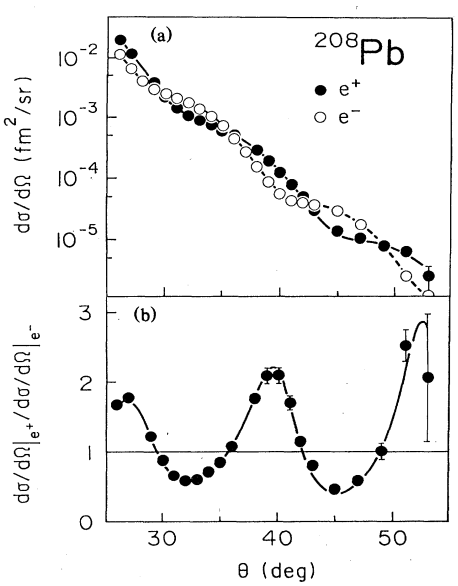

FIG. 1. (a) Measured electron and positron elastic-scattering cross sections and (b) their ratios for ^{208}Pb compared with phase-shift calculations of the cross sections and ratios using a static charge density (Ref. 12).

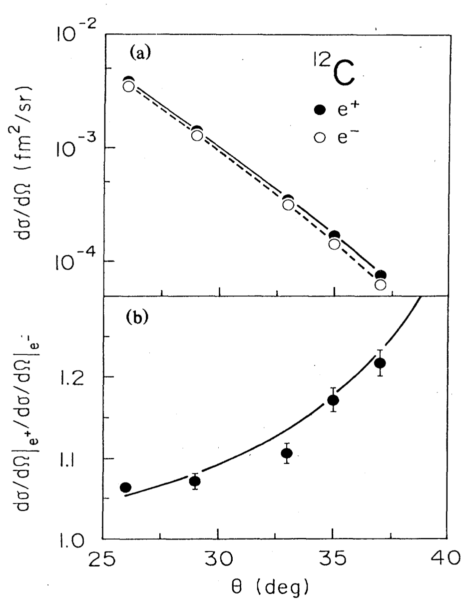

FIG. 2. (a) Measured electron and positron elastic-scattering cross sections and (b) their ratios for ^{12}C compared with phase-shift calculations of the cross sections and ratios using a static charge density (Ref. 13).

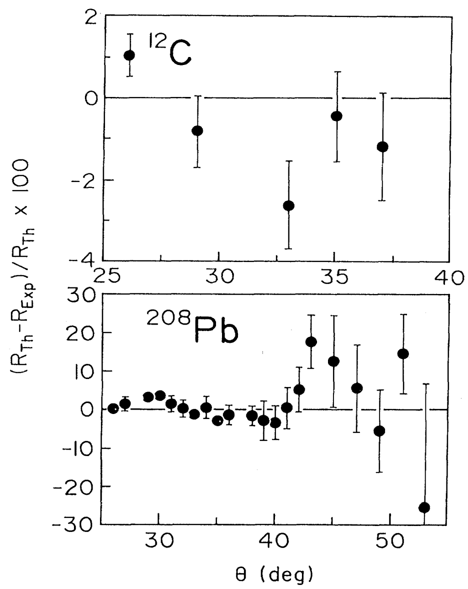

FIG. 3. Deviations of the measured electron/positron ratios from the predictions of phase-shift calculations using static charge densities.

mental accuracy of a few percent. The discrepancies are most significant in the low-q region where the experimental accuracy is highest. Renormalization of the cross sections, which corresponds to a vertical translation of the x axis in this figure, will not remove these discrepancies, nor will a change in the energy calibration of the spectrometer. The differences observed could be due to errors in the radiative corrections, the Coulomb corrections, or the omission of dispersive effects in the analysis of the data; our experiment cannot distinguish between these possibilities. We note, however, that the discrepancies are at the level of a few percent, where their contribution to the uncertainty in the charge density inferred from a typical electron-scattering experiment would be comparable to or smaller than other sources of uncertainty.

The validity of the treatment of radiative corrections, Coulomb corrections, and dispersive effects had never been tested at the level of precision needed to verify the theoretical treatment used for the extraction of nuclear charge-density distributions from the present generation of electron data. The present experiment provides clear evidence that errors in this treatment are no larger than a few percent in ^{12}C and ^{208}Pb for the momentum-transfer range we have investigated, and provides a firmer foundation for confidence in the charge-density distributions of spherical nuclei deduced from high-energy electron elastic-scattering data.

This work was supported in part by the U.S. NSF under Grant No. PHY-89-21146 (L.S.C., A.W.L., E.A.J.M.O., and S.E.W.), by the U.S. Department of Energy under Grant No. DE-FG05-86-ER40270 (L.C.M.), and by the Swiss NSF (I.S. and G.M.).

[a]Present address: Laboratoire de Physique Corpusculaire, Universite Blaise Pascal–Institut National de Physique Nucléaire et de Physique des Particules, F63177 Aubiere CEDEX, France.

[b]Present address: Institut für Kernphysik der Universität Mainz, 6500 Mainz, Germany.

[1]D. P. Heddle and L. C. Maximon, Phys. Rev. C **40**, 1632 (1989); Phys. Rev. C **41**, 3120(E) (1990).

[2]D. R. Yennie, F. L. Boos, Jr., and D. G. Ravenhall, Phys. Rev. **137**, B882 (1965).

[3]J. L. Friar and M. Rosen, Ann. Phys. (N.Y.) **87**, 289 (1974).

[4]G. H. Rawitscher, Phys. Rev. **151**, 846 (1966).

[5]J. Goldemberg *et al.*, Phys. Rev. **132**, 406 (1963); A. Browman *et al.*, Phys. Rev. **143**, 899 (1966).

[6]R. O. Stenerson and R. W. Williams, Phys. Rev. **137**, B266 (1965), and references therein.

[7]I. Sick and J. S. McCarthy, Nucl. Phys. **A150**, 631 (1970); W. Reuter *et al.*, Phys. Rev. C **26**, 806 (1982); E. A. J. M. Offermann *et al.*, Phys. Rev. Lett. **57**, 1546 (1986); N. Kalantar-Nayestanaki *et al.*, Phys. Rev. Lett. **63**, 2032 (1989).

[8]Ph. Leconte, Ph.D. thesis, Université de Paris, Orsay, 1976.

[9]V. Breton, Ph.D. thesis, Université de Paris-Sud, 1990.

[10]L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).

[11]D. G. Ravenhall, R. Herman, and B. C. Clark, Phys. Rev. **136**, B589 (1964).

[12]B. Frois *et al.*, Phys. Rev. Lett. **38**, 152 (1977).

[13]L. S. Cardman *et al.*, Phys. Lett. **91B**, 203 (1980); W. Reuter *et al.*, Phys. Rev. C **26**, 806 (1982).