Longitudinal and Transverse Response Functions in $^{56}Fe(e,e')$ at Momentum Transfer near 1 GeV/c

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(Received 8 October 1990)

Inclusive electron-scattering cross sections have been measured for ^{56}Fe in the quasielastic region at electron energies between 0.9 and 4.3 GeV, at scattering angles of 15° and 85°. Longitudinal and transverse response functions at a q of 1.14 GeV/c have been extracted using a Rosenbluth separation. The experimental Coulomb sum has been obtained with the aid of an extrapolation. The longitudinal response function, after correction for Coulomb distortion, is lower than quasifree-scattering-model predictions at the quasielastic peak and on the high-ω side.

PACS numbers: 25.30.Fj

Quasielastic scattering is one of the main reaction mechanisms in inclusive high-energy electron scattering from nuclei, corresponding to electrons scattering elastically from a moving bound nucleon. The gross features of the quasielastic cross sections have been successfully described by single-particle models, such as shell models[1] and Fermi-gas models.[2] With increasing momentum transfers, excitation of nucleon resonances becomes increasingly important in the quasielastic region. In the last decade, the separate response functions for longitudinal and transverse virtual photons have been extracted for various nuclei at three-momentum transfers q up to 550 MeV/c,[3-7] with the expectation that the resonances make very little contribution to the longitudinal part of the cross section. The results for ^{12}C,[4] ^{40}Ca and ^{48}Ca,[5,6] and for ^{56}Fe,[5-7] show a surprising common feature: The experimental longitudinal response functions R_L are lower than the Fermi-gas calculations by up to 50%. This "quenching" of R_L diminishes when q increases but is still as much as 30% at $q = 550$ MeV/c, the highest momentum transfer for which data have been available. The experimental Coulomb sum, which is the integral of R_L over the energy loss, is also suppressed. The quenching of R_L was also observed in $(e,e'p)$ experiments.[8] This has been one of the most puzzling outstanding problems in nuclear physics.

The problem has motivated considerable theoretical effort. One approach invokes an effective increase in the radius of the nucleon in the nuclear medium (swollen nucleon), resulting from manifestations of the quark substructure (partial deconfinement).[9] The increased nucleon size modifies the nucleon form factors and reduces R_L. Since the modification of the form factors increases with increasing q, so does the reduction of R_L. Other calculations attempt to improve agreement with the data by including final-state interactions, relativistic effects, two- and many-body correlations,[10] and off-shell effects.[11] Recently, relativistic σ-ω-ρ models within the framework of quantum hadrodynamics using the random-phase approximation have been used to calculate R_L, R_T, and the Coulomb sum.[12,13] Although these models reduce the discrepancy between theory and experiment, they generally fail to reproduce both response functions. So far, no single model has succeeded in describing both the longitudinal and the transverse response functions over the full range of the available data. Since the various models have different dependences on momentum transfers, measurements at high momentum transfer can be expected to constrain the models significantly.

In this Letter, we present measurements of R_L and R_T for $^{56}Fe(e,e')$ at a momentum transfer near 1 GeV/c. The experiment (NE9) was performed at the Stanford Linear Accelerator Center (SLAC) with the NPAS (Nuclear Physics at SLAC) facility. Electron beams with energies ranging from 0.9 to 4.3 GeV were scattered from a 6%-radiation-length natural-iron target. Scattered electrons were detected at scattering angles of 15° for incident energies of 2.7, 3.3, 3.6, 3.9, and 4.3 GeV, and 85° for 0.9, 1.1, and 1.25 GeV, using the 8-GeV/c spectrometer with its associated detection system. The momenta of the scattered electrons range from 2 to

4 GeV for 15° data, and from 0.3 to 0.6 GeV for 85° data, covering the quasielastic peak region. The detection system consists of ten planes of multiwire proportional chambers, a threshold gas Čerenkov counter, a five-layer total-absorption lead-glass shower counter, and three planes of plastic-scintillation counters. It has been described in detail elsewhere.[14]

Statistical errors in the measured cross sections are about 1.4% for 20-MeV-wide bins. Extensive efforts were made to minimize systematic errors, with the main uncertainties being the determination of the spectrometer acceptance and background at low momenta ($P < 600$ MeV/c), the absolute normalization, and the radiative corrections.

The 8-GeV/c spectrometer had been studied extensively at high momenta ($P > 1$ GeV/c),[15] but little was known about its response at low momenta. The momentum dependence of the acceptance was studied using a Monte Carlo simulation. Some test data were taken to check the acceptance at high momentum transfer and to check the Monte Carlo model of the spectrometer. The acceptance at low momenta was determined using the Monte Carlo model, with an estimated uncertainty of 1.5%. The main background at low momenta arises from scattering by the magnet pole tips. Some test data were obtained with effectively all of this background eliminated by inserting a collimator between the two dipole magnets. By comparing these measurements with the measurements without the collimator, we determined that at 85° the background ranged from ~2% at the quasielastic peak to ~5% on the high-energy-loss side. After correction, we estimated that this background contributed an uncertainty of about 1% in the cross sections at 85°.

Elastic-scattering cross sections from hydrogen were measured and compared to a parametrization using a best fit to the measured proton form factors,[16] providing an absolute normalization of the data. The radiative corrections were made using the formulas of Mo and Tsai.[17] The radiative tails from elastic scattering were calculated and found to be negligible for all our data. The procedure of Stein *et al.*[18] was used for continuum radiative corrections, which were up to 30% for the 15° data but were less than 3% for the 85° data. A summary of the systematic errors in the cross sections at the quasielastic peak and their propagation into the determination of R_L and R_T is given in Table I (also see Ref. 14 for more detail).

The longitudinal and transverse response functions were obtained using the Rosenbluth formula with the plane-wave Born approximation (PWBA):

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \sigma_M \left\{ \left(\frac{Q^2}{q^2} \right)^2 R_L(q,\omega) + \left[\frac{1}{2} \left(\frac{Q^2}{q^2} \right) + \tan^2 \left(\frac{\theta}{2} \right) \right] R_T(q,\omega) \right\}, \quad (1)$$

TABLE I. Uncertainties at the quasielastic peak (in %).

Source	$\Delta\sigma/\sigma$ (15°)	$\Delta\sigma/\sigma$ (85°)	$\Delta R_L/R_L$	$\Delta R_T/R_T$
Acceptance	0.2	1.5	10.6	2.3
Pole-tip scattering	0.1	1.0	7.0	1.5
Radiative corrections	1.0	1.0	9.9	1.6
Normalization			7.3	2.5
Other systematic			7.8	1.5
Total systematic			19.3	4.3
Statistical	1.4	1.3	13.4	2.1

where σ_M is the Mott cross section, ω is the energy loss, and $Q^2 = -q_\mu^2 = q^2 - \omega^2$ is the four-momentum transfer squared. The effect of Coulomb distortion of the incident and the scattered electrons was approximated by using an effective-momentum-transfer approach,[2]

$$Q_{\text{eff}}^2 = q_{\text{eff}}^2 - \omega^2 = 4(E - V_C)(E - V_C - \omega)\sin^2(\tfrac{1}{2}\theta), \quad (2)$$

where $V_C = -3Z\alpha/2R$ is the mean value of the electrostatic potential of the nucleus, with $R = (\frac{5}{3})^{1/2}\langle r^2\rangle^{1/2}$ and $\langle r^2\rangle^{1/2}$ being the nuclear rms radius. This correction, to first order, takes the place of a more complicated distorted-wave Born-approximation[19] (DWBA) calculation. A DWBA calculation[20] agrees with the effective-momentum-transfer approach to better than 1% in R_L and R_T at this momentum transfer for ^{56}Fe.

Figure 1 shows the results of R_L and R_T for ^{56}Fe at $q_{\text{eff}} = 1.14$ GeV/c. Only statistical errors are shown in the plots. The cross-section data were smoothed while performing interpolations using a spline fit. The experimental results are compared with three theoretical calculations. The dashed curve is the relativistic Fermi-gas model of Van Orden.[21] The average separation energy and the Fermi momentum are taken to be 36 MeV and 260 MeV/c, respectively.[22] The solid curve is a PWBA quasifree-scattering calculation, which uses a realistic momentum distribution obtained from a previous SLAC experiment.[23] Both calculations are in agreement with the experimental data for R_L on the low-energy-loss side of the quasielastic peak, but overestimate R_L from the top of the peak to the high-energy-loss side. At this high momentum transfer R_T has large contributions from processes other than quasielastic scattering, such as meson exchange and Δ resonance excitation, and these contributions increase with increasing energy loss. Since the calculations shown include only the quasielastic process, the calculated R_T values are lower than the data as expected, except at the lowest energy transfers. The dotted curve is a calculation by Ji,[12] which uses the local-density random-phase approximation (RPA) to a relativistic σ-ω-ρ model including the vacuum-polarization effect.

Figure 2 shows separated response functions with and without using the effective-momentum-transfer correc-

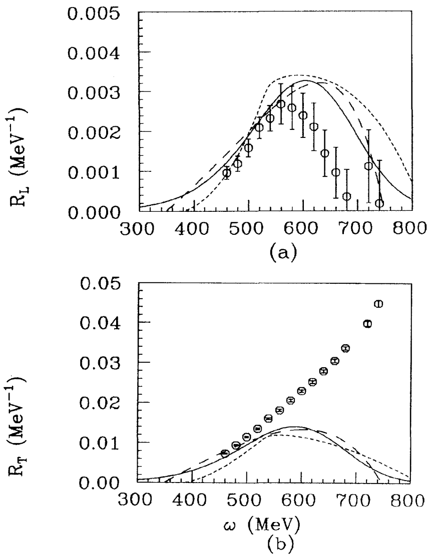

FIG. 1. (a) Longitudinal and (b) transverse response functions for ^{56}Fe at an effective three-momentum transfer $q_{\rm eff}=1.14$ GeV/c (circles), where the use of the effective momentum transfer is an approximate method to include the Coulomb-distortion effect. Only statistical errors are shown. The dashed curves are from a Fermi-gas-model calculation by Van Orden (Ref. 21), and solid curves are from a PWBA quasifree-scattering calculation with a realistic momentum distribution. The dotted curves are from an RPA calculation by Ji (Ref. 12).

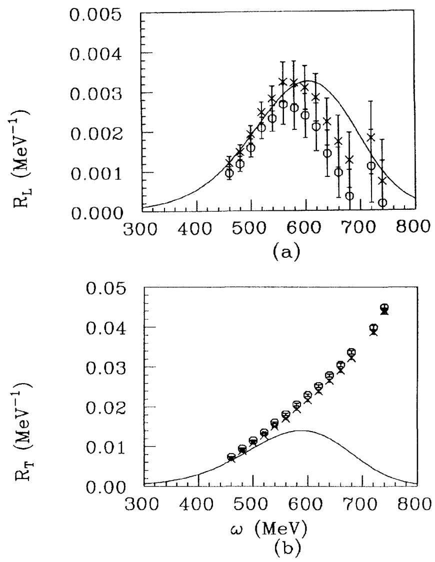

FIG. 2. (a) Longitudinal and (b) transverse response functions for ^{56}Fe at $q=1.14$ GeV/c (crosses) compared with these at $q_{\rm eff}=1.14$ GeV/c (circles). Only statistical errors are shown. The solid curves are the PWBA calculation.

tion. The Coulomb distortion is nearly 20% for R_L at the top of the peak and is only a few percent for R_T.

To obtain the experimental Coulomb sum an integration of R_L is performed at constant three-momentum transfer, after dividing out the nucleon charge form factor with a relativistic correction:[24]

$$C(q)=\int_{\omega_{\rm el}^{+}}^{\omega_{\max}} d\omega \frac{R_L(q,\omega)}{Z[\bar{G}_E(Q^2)]^2}, \quad (3)$$

where $\omega_{\rm el}^{+}$ means that ω starts just above the elastic peak, and $\omega_{\max}$ is the maximum value of the energy loss for which R_L is not zero. The effective nucleon charge form factor is

$$[\bar{G}_E(Q^2)]^2=\{[G_E^p(Q^2)]^2+(N/Z)[G_E^n(Q^2)]^2\} \times\frac{1+Q^2/4M_N^2}{1+Q^2/2M_N^2}, \quad (4)$$

where M_N is the nucleon mass. Z and N are the numbers of protons and neutrons in the nucleus, respectively. The dipole form factor is used for $G_E^p(Q^2)$, the proton electric form factor. $G_E^n(Q^2)=0$ is used for the neutron electric form factor. The use of other parametrizations of the form factors, for instance, Höhler's[25] parametrization 8.2, will change the Coulomb sum by no more than 5%. Since the data do not cover the whole peak, extrapolations into the unmeasured region were performed. The contribution to the Coulomb sum from the unmeasured tails at both sides was estimated to be about 10% by using exponential extrapolation. The results, along with a comparison to the Fermi-gas calculation, are shown in Table II.

To better compare with the results at low momentum transfers, a Coulomb sum defined as a simple integration of R_L over energy loss along constant three-momentum transfer was also computed:

$$C(q)=\int_{\omega_{\rm el}^{+}}^{\omega_{\max}} R_L(q,\omega)d\omega. \quad (5)$$

Figure 3 presents the result along with the previous measurements and the Fermi-gas calculation. The Coulomb sum continues to be lower than the calculation at this high momentum transfer by about 30%, with an uncertainty of about 20%.

In conclusion, R_L and R_T at $q=1.14$ GeV/c were obtained for quasielastic scattering from ^{56}Fe. Except on the low-energy-loss side of the peak, R_T includes large effects from the Δ and higher nucleon resonances. The measured longitudinal response R_L is lower than the calculation at the top and on the high-ω side of the peak.

TABLE II. Coulomb sum.

	Data	Error (±)	Fermi gas	RPA model
$q=1.14$ GeV/c	0.95	0.29	1.10	1.16
$q_{\rm eff}=1.14$ GeV/c	0.76	0.23	1.10	1.16

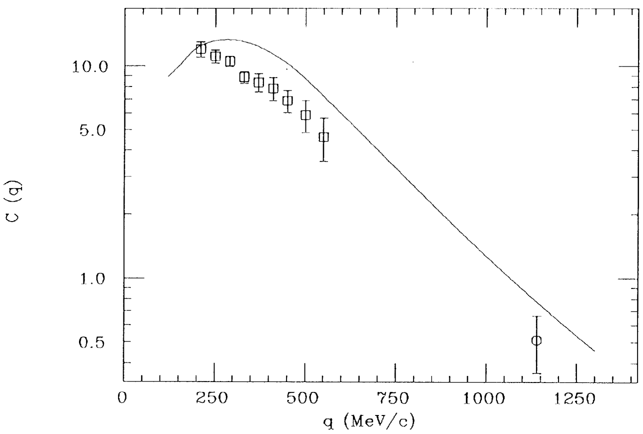

FIG. 3. Coulomb sum for ^{56}Fe. The circle is the result of this experiment at $q_{\rm eff}=1.14$ GeV/c. Total error, including both statistical and systematic errors, is shown. The squares are the Saclay (Ref. 6) and Bates (Ref. 7) data. The solid curve is from the Fermi-gas calculation.

The experimental Coulomb sum, with a rather large uncertainty, is lower than the Fermi-gas calculation. The R_L quenching persists at this high momentum transfer, showing no strong q dependence. Within 1 standard deviation, the R_L strength missing at this q is no more than 50%. Since R_L is a linear combination of the nucleon form factors squared, this result constrains swollen-nucleon models to have no more than 30% reduction in the nucleon form factors at this high momentum transfer.

We acknowledge the support of the SLAC staff. We thank Dr. X. Ji and Dr. M. Traini for providing us with their calculations. This work was supported by U.S. Department of Energy Grants No. DE-FG05-86ER40-261 and No. DE-FG05-88ER40390 (University of Virginia) and No. DE-FGO3-88ER40439 (Stanford University), National Science Foundation Grants No. PHY-88-17296 (Caltech) and No. PHY-89-10648 (Florida State University), and the Commonwealth of Virginia Center for Nuclear and High Energy Physics.

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