High Momentum Transfer $R_{T,L}$ Inclusive Response Functions for $^{3,4}He$

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Inclusive electron scattering cross sections for $^{3,4}He$ have been measured in the quasielastic region at electron energies between 0.9 and 4.3 GeV, and scattering angles of 15° and 85°. Longitudinal (R_L) and transverse (R_T) response functions have been extracted using a Rosenbluth separation at constant $|\mathbf{q}|$ of 1.050 GeV/c. The ratio of the longitudinal to the transverse reduced response functions in the negative y region reaches unity.

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Quasielastic electron scattering has provided over the past decade a powerful tool for investigating the momentum distribution of nucleons in nuclei and their electromagnetic properties. In the quasielastic excitation energy region, the nuclear response function reveals a broad peak approximately centered on the energy transfer of elastic scattering off nucleons at rest with a width that reflects nucleon motion in the nucleus. Partition of the longitudinal (R_L, charge) and transverse (R_T, magnetization and convection current) response functions of medium weight nuclei [1-5] in the region of momentum transfers from 0.30 up to 0.55 GeV/c revealed a surprising "quenching" of R_L. Semiexclusive $(e,e'p)$ experiments with Rosenbluth decomposition [6-8] which explicitly selected the one-nucleon knockout reaction mechanism confirmed the quenching behavior of R_L. This effect was investigated at higher momentum transfer in ^{56}Fe and found to persist but not to display a strong q dependence [9]. The situation for heavy nuclei is still puzzling and needs more attention; while measurements of R_L on ^{238}U show no quenching [10] those of ^{208}Pb display a severe reduction of R_L [11].

Although several ideas on the origin of this quenching have been put forward [12-21], much debate has focused on the lack of a complete description of the initial and final states for heavy nuclei and the validity of the Coulomb distortion correction. To remove a large part of the uncertainty in the interpretation of the data, there are clear advantages to studying light nuclei where sophisticated calculations are becoming available. Interpretations of the low momentum transfer data [22-25] in these nuclei emphasize the important role of correlations in R_L and its corresponding Coulomb sum rule. As an example, the violation of the plane-wave impulse approximation (PWIA) for ^4He at low momentum transfer is revealed in the ratio of the reduced longitudinal to transverse response functions ($R = F_L/F_T$) in the vicinity of the top of the quasielastic peak. Without nucleon-nucleon correlations this ratio is unity while experimentally it is found to be significantly less than 1 [25]. We shall see how the behavior of $R_{L,T}$ for these light nuclei evolves at high momentum transfer.

In this Letter, we present the first measurements of R_L and R_T for $^{3,4}He(e,e')$ at a momentum transfer near 1 GeV/c. The experiment (NE9) was performed at the Stanford Linear Accelerator Center (SLAC). Electron beams with energies ranging from 0.9 to 4.3 GeV were scattered off high-pressure ^3He and ^4He gas targets. Scattered electrons were detected at angles of 15° for incident energies of 2.7, 3.3, 3.6, 3.9, and 4.3 GeV, and 85° for 0.9 and 1.1 GeV, using the 8-GeV/c spectrometer with its associated detection system over a momentum range chosen to cover the quasielastic peak region.

The detection system consists of ten planes of multiwire proportional chambers, a threshold gas Cherenkov counter, a five-layer total absorption lead glass shower counter, and three planes of plastic scintillation counters. This system and the procedures used to obtain the acceptance of the spectrometer at forward and backward angles have been described in detail elsewhere [26]. The target array [27] includes 50-atm ^3He and ^4He targets, a liquid hydrogen target, and two empty-target cells for subtracting the end caps' contributions to the cross section of H_2 and $^{3,4}He$ measurements separately. The high-pressure targets cells were 10-cm-long cylinders with a 4.31-cm inside diameter and a 0.635-mm-thick aluminum wall and outlet window. The inlet window to the cells is 2.54 cm in diameter and 0.58 mm thick. The length of these cells was chosen to be smaller than the spectrometer target length acceptance at 85°. At each kinematical setting separate measurements were performed on the empty cell to determine the yield from the target windows.

Operated at a temperature of 21 K these targets have thicknesses near 650 mg/cm^2 for ^{3}He and 920 mg/cm^2 for ^{4}He. Constant monitoring of pressure and temperature allowed us to obtain the time average density of these targets. The loss in density along the beam path due to beam heating was studied by varying the instantaneous current intensity and/or the repetition rate of the incident electron beam. This study was important for the large-angle data where, because of the low cross section, the highest available current was used during the experiment. The correction for density loss, although negligible at the forward angle, was about 5% for ^{3}He and 2% for ^{4}He at the large angle.

Elastic scattering cross sections from a hydrogen target were measured when the central momentum of the spectrometer was set for the ^{3,4}He quasielastic centroid. These cross sections were compared to calculations that used a fit to the experimentally measured proton form factors, providing an absolute normalization to our data. At all energies the peak position for elastic electron scattering from hydrogen was checked against the expected energy peak position and was found to agree to within 0.5×10^{-3}. This check is essential in order to exclude systematic effects in the Rosenbluth separation of $R_{T,L}$ from a relative energy miscalibration between the forward and the large-angle cross-section measurements. Extensive efforts were made to minimize systematic errors. In the region near the top of the quasielastic peak, the total relative systematic uncertainties for both nuclei are about 19.5% in R_L and 5.5% in R_T.

The standard procedure of Stein *et al.* [28], following the formalism of Mo and Tsai [29], was used to perform the continuum radiative corrections, which are up to 30% of the cross sections for the 15° data but are less than 3% for the 85° data. In order to perform the radiative corrections at backward angle we used additional inclusive spectra measured at Saclay at the same angle (85°) but lower incident energy ($E_i=600$ MeV). We estimated the systematic uncertainty to be 1.5% at both scattering angles. The radiative tail from elastic scattering off ^{3,4}He was found to be negligible in the measured kinematic region.

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

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

where σ_M is the Mott cross section, ω is the energy loss, and $Q^2=-q_\mu^2=\mathbf{q}^2-\omega^2$ is the four-momentum transfer squared.

Figure 1 shows values, with statistical uncertainties only, of R_L and R_T for ^{3,4}He extracted at $|\mathbf{q}|=1.050$ GeV/c using interpolated cross sections among spectra at different incident beam energies but the same scattering angle. In contrast to heavy nuclei, the quasielastic peaks of these light nuclei still dominate the cross section at this high momentum transfer in both R_L and R_T. The calculations shown in Fig. 1 which include quasielastic and inelastic contributions are those of Meier-Hajduk *et al.* [30] for ^{3}He and Ciofi degli Atti *et al.* [31] for ^{4}He. R_L is reasonably well reproduced while R_T still misses strength in the "dip region." If one assumes that the PWIA describes the quasielastic region, where the reaction mechanism is the knockout of one nucleon leaving a spectator recoil nucleus (spectator model), and rewrites Eq. (1) so that the electric and magnetic contributions of the electron-nucleon cross section [30,32] are explicitly separated, we obtain R_T and R_L in terms of the reduced response functions F_T and F_L:

$$R_T(q,\omega)=\eta\frac{-q_n^2}{2E_kE_{k'}}\tilde{G}_M^2F_T(q,y), \tag{2}$$

$$R_L(q,\omega)=\eta\left\{\tilde{G}_E^2\frac{(E_k+E_{k'})^2}{4E_kE_{k'}(1-\tau)}F_L(q,y)-\frac{1}{2E_kE_{k'}}\left[\mathbf{q}^2-\frac{\tau(E_k+E_{k'})^2}{2(1-\tau)}\right]\tilde{G}_M^2F_L(q,y)\right\}. \tag{3}$$

In Eqs. (2) and (3) q_n^2 is the four-momentum transfer evaluated from the nucleon side as $q_n^2=(E_k-E_{k'})^2-\mathbf{q}^2$. (E_k,k) and $(E_{k'},k')$ are respectively the energy-momentum four vectors of the struck and outgoing nucleons, $\tau=q_n^2/4M^2$, and η is a kinematical factor defined in Refs. [33,34]. The effective form factors $\tilde{G}_{E,M}^2=ZG_{E,M}^{p2}+NG_{E,M}^{n2}$ are expressed in terms of the electric and magnetic Sachs form factors of the nucleon, and y is the minimal momentum of the struck nucleon, satisfying energy conservation for the process

$$\omega+M_A=(M^2+q^2+y^2+2yq)^{1/2}+(M_{A-1}^{*2}+P_{A-1}^2)^{1/2},$$

where M is the nucleon mass, P_{A-1} is the recoil nucleus momentum, and M_A and M_{A-1}^* are the total masses of the initial and the excited recoil nucleus, respectively. The spectator model imposes $\mathbf{P}_{A-1}=-\mathbf{k}$ and $F_L(q,y)=F_T(q,y)$ which can be tested experimentally and if not

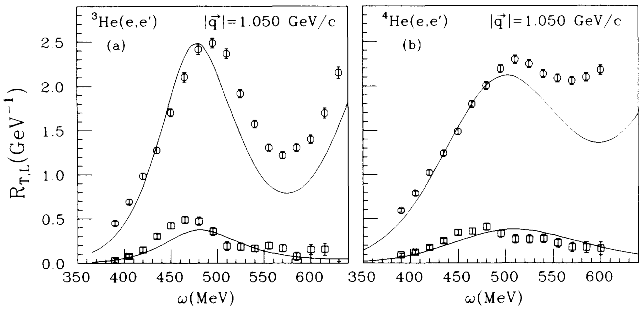

FIG. 1. R_L (open squares) and R_T (open circles) response functions for (a) ^{3}He and (b) ^{4}He at $|\mathbf{q}|=1.050$ GeV/c. Only statistical errors are shown. The calculations are those of Meier-Hajduk *et al.* [30] for ^{3}He and Ciofi degli Atti *et al.* [31] for ^{4}He. In R_T the quasielastic and inelastic processes are evaluated while R_L contains only the quasielastic process.

satisfied would be a good measure of the violation of the PWIA.

Figure 2 shows $F_L(q,y)$ and $F_T(q,y)$ for ^{3}He and ^{4}He extracted according to Eqs. (2) and (3). The low momentum transfer data at $|\mathbf{q}|=0.50$ GeV/c from Saclay [22] and Bates [25] as well as those of this experiment at $|\mathbf{q}|=1.050$ GeV/c are displayed. In the definition of y we assumed breakup of a two-body system (proton-recoil nucleus) and used 7.7 MeV for the two-body breakup energy of ^{3}He and 20.0 MeV for that of ^{4}He. First, we notice that at high momentum transfer and in the negative-y region near the quasielastic peak, the ratio $R=F_L/F_T$ is about 1 for both ^{3}He and ^{4}He. At low momentum transfer the ratio R is unity for ^{3}He while for ^{4}He the results differ from the present data since clearly $R\simeq 0.75$. This result is supported by the momentum dependence trend observed between 0.40 and 0.65 GeV/c for the fully corrected longitudinal (S_L) over transverse (S_T) exclusive response functions of the two-body breakup channel of ^{4}He measured at Saclay [35,36]. It would be of importance to confirm this result by extending the exclusive ^{4}He$(e,e'p)$ measurement from $|\mathbf{q}|=0.65$ GeV/c to a momentum transfer of about 1 GeV/c or more. Second, we notice a shift in the peak position between $F_L(q,y)$ and $F_T(q,y)$. At this high momentum transfer F_T contains a large contribution from exchange currents to the three-body breakup and the electroproduction of pions through the Born and Δ resonant terms. This would explain part of the F_T peak position shift to larger y values.

In order to further investigate the charge response of these nuclei an integration of R_L is performed at constant three-momentum transfer, after dividing out the nucleon charge form factor with a relativistic correction. This is known as the Coulomb sum and is expressed as

$$C(q)=\int_{\omega_{el}^+}^{\omega_{max}} d\omega\, \frac{R_L(q,\omega)}{Z[\bar{G}_E(Q^2)]^2}\,, \tag{4}$$

where ω_{el}^+ means that ω starts just above the elastic peak,

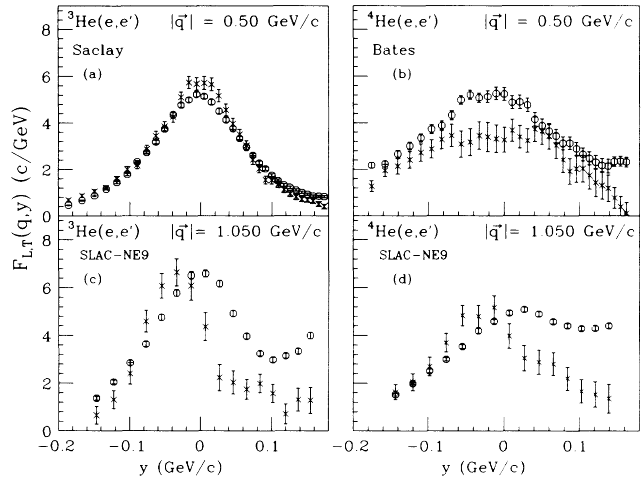

FIG. 2. F_L (crosses) and F_T (open circles) reduced response functions for (a) ^{3}He (Ref. [22]), (b) ^{4}He (Ref. [25]) at $|\mathbf{q}|=0.50$ GeV/c and (c) ^{3}He, (d) ^{4}He at $|\mathbf{q}|=1.050$ GeV/c. Only statistical errors are shown.

and ω_{max} is the maximum value of the energy loss for which R_L is not zero. The effective nucleon charge form factor $[\bar{G}_E(Q^2)]^2$ as suggested by de Forest [37] and justified by Donnelly *et al.* [38] to account for relativistic effects due to the motion of the nucleon in the nucleus is given by

$$[\bar{G}_E(Q^2)]^2=\{[G_E^p(Q^2)]^2+(N/Z)[G_E^n(Q^2)]^2\} \times \frac{1+Q^2/4M_N^2}{1+Q^2/2M_N^2}\,, \tag{5}$$

where M_N is the nucleon mass. Z and N are the numbers of protons and neutrons in the nucleus, respectively. The dipole form is used for the proton electric form factor

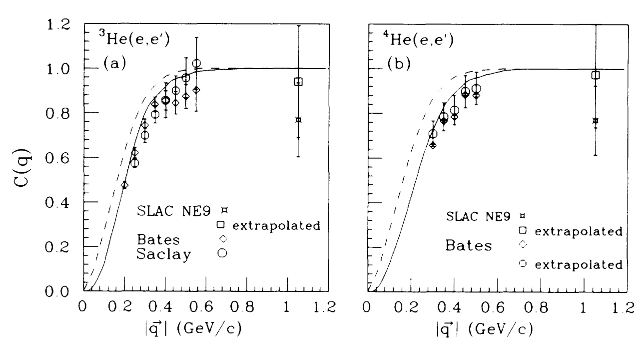

FIG. 3. Coulomb sum rule for (a) ^{3}He and (b) ^{4}He. The crosses (nonextrapolated) and squares (extrapolated) are data of this experiment at $|\mathbf{q}|=1.050$ GeV/c. In (a) the open circles and diamonds are the low momentum transfer extrapolated data from Saclay [22] and Bates [23,25], respectively. Unextrapolated data are not shown for clarity. In (b) only Bates low momentum transfer unextrapolated and extrapolated data are shown. For the calculations see text. Total (statistical and systematic) errors are shown.

TABLE I. Coulomb sum rule.

$\|\mathbf{q}\|=1.05$ GeV/c	Data	Stat. error (±)	Syst. error (±)	Extrapolation	Total error
^{3}He	0.77	0.04	0.16	0.94	0.24
^{4}He	0.77	0.04	0.15	0.97	0.25

$G_E^p(Q^2)$ while the neutron electric form factor $G_E^n(Q^2)$ is set to zero. The use of other parametrizations of the form factors, for instance, parametrization 8.2 of Höhler *et al.* [39], will change the Coulomb sum by more than 10%. Figure 3 presents the Coulomb sum for (a) ^{3}He and (b) ^{4}He along with the low momentum transfer measurements from Bates [23,25] and Saclay [22]. The solid curve is a calculation by Schiavilla *et al.* [40], and the dashed curve is the no-correlation limit. Since the data of R_L do not cover the whole peak, exponential tail extrapolations into the unmeasured region were performed using the last five data points as a constraint. The results are shown in Table I.

Contrary to the results for ^{56}Fe, the Coulomb sum for light nuclei seems to saturate to the expected value within an uncertainty of ±25%.

In conclusion, for the first time R_L and R_T have been obtained for ^{3,4}He at high momentum transfer. In contrast to the low momentum transfer data the ratio F_L/F_T is close to 1 for the low-energy-loss side of the peak and a relative peak position shift between R_L and R_T is observed. As for the experimental Coulomb sum, in converse to the case of the ^{56}Fe nucleus, it saturates to the expected value, although with large uncertainty. A measurement of inclusive and exclusive response functions with high precision in the intermediate region of momentum transfer at CEBAF would be extremely valuable in the future.

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