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Transverse quasielastic electron scattering from the deuteron

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Transverse quasielastic electron scattering cross sections have been measured for the deuteron at 180° for incident electron energies of 220, 270, and 320 MeV. At the quasielastic peak the four-momentum transfers squared varied from 3.4 to 6.3 fm^{-2}. The measured spectra include the region from the elastic peak through the entire quasielastic peak. Results are compared with recent calculations incorporating meson-exchange currents and isobar configurations. At large neutron-proton separation energies, the data support the need for the inclusion of large isobar configuration components in the cross section.

Studies of the deuteron, the simplest bound nuclear system, are of prime importance for understanding the interaction between nucleons. High-energy electron scattering with its well-known electromagnetic interaction is especially suitable for these studies. There have been many measurements of elastic electron scattering from the charge and magnetization distributions of the deuteron, and of threshold electrodisintegration, but never a thorough measurement of incoherent quasielastic scattering from its nucleons in which a complete spectrum was separated into longitudinal and transverse components. Previous measurements of quasielastic spectra[1] contained mixtures of the longitudinal and transverse contributions. In these cases, agreement with theory could be purely fortuitous since deficiencies in the theoretical estimates of the longitudinal and transverse parts can cancel in the total cross section. Such was the case for total quasielastic cross sections measured in heavier nuclei before the longitudinal and transverse parts were separated by more detailed experiments, and thus exposed discrepancies with existing theories.[2]

We present here a direct measurement of transverse quasielastic scattering by detecting electrons scattered through 180°. The determination of a transverse cross section in this manner requires only one measurement, whereas a Rosenbluth separation of the transverse from the longitudinal contribution requires several measurements at different scattering angles and incident energies, but at the same momentum transfer. Furthermore, the spectrum of electrons degraded in energy because of bremsstrahlung, the so-called radiation tail, is minimized at 180°.

The measurements were made by using the 180° scattering facility[3] at the MIT-Bates Linear Accelerator Center. This facility deflects back-scattered electrons into an energy-loss spectrometer while maintaining a constant solid angle independent of excitation energy. A 10.5-cm-long liquid-nitrogen cooled gas target cell, with 25 μm Havar[4] foil entrance and exit windows, was pressurized to give deuterium gas thicknesses of up to 50 $\mathrm{mg/cm^2}$. The temperature and pressure in the cell were continuously monitored. The windows could accommodate a momentum-dispersed beam of 3-cm height and of several mm width. Because the beam was dispersed, beam currents as large as 40 μA could be used with no detectable nonlinear effects in scattering from the gas, i.e., the counting rate was directly proportional to the beam current. In order to measure the unavoidable background due to 180° scattering from the foil windows, background targets consisting of stacks of foils and an identical cell filled with natural hydrogen was used. It was found that a linear scaling of the measurements from the foil stacks was sufficient to describe the background. Negative pions produced at high incident electron energies were rejected by an aerogel Cerenkov detector with an index of refraction of 1.05. Because the useful momentum bite $\Delta p/p$ spanned by the spectrometer detection system was approximately 5%, the measurement of a complete spectrum required approximately 30 separate spectrometer magnetic field settings. Final cross sections were extracted by standard analysis procedures[5] and were normalized to elastic proton cross sections[6] measured at each incident energy.

Complete spectra were measured at incident energies $E = 220$, 270, and 320 MeV. Figure 1 shows the spectrum for $E = 270$ MeV, whose most prominent feature is the quasielastic peak. Data are shown both before and after applying corrections for radiative processes. In order to make such corrections to the quasielastic peak, the entire

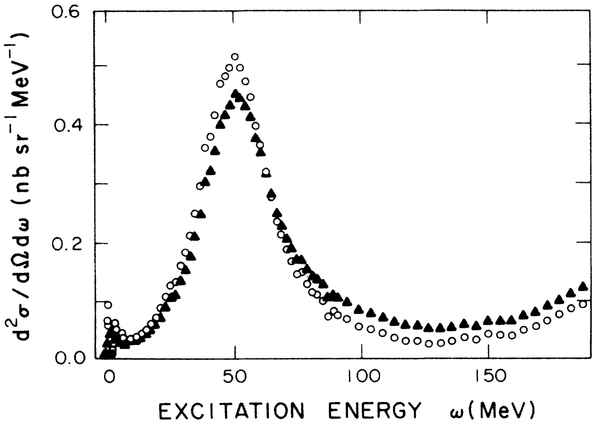

FIG. 1. Excitation energy spectrum measured at 180° for an incident electron energy of 270 MeV. Filled triangles and open circles show data before and after radiative corrections, respectively.

spectrum had to be measured, from the elastic peak through the quasielastic region. For both the elastic and inelastic radiation tails, we have used the formalism of Mo and Tsai.[7] Radiative corrections to the quasielastic continuum were made by using an iterative unfolding procedure[8] which required the interpolation of the measured cross sections at values of the four-momentum transfer intermediate between those of the experiment. To assist in this interpolation, additional data were acquired at $E = 164$, 204, and 248 MeV. The radiatively corrected spectra at 220, 270, and 320 MeV are shown in Fig. 2. These latter spectra were measured to excitation energies greater than the 140-MeV incoherent pion production threshold. The net result of the radiative corrections was to increase the cross sections for elastic scattering and threshold breakup by about 30%, to shift the maxima of the quasielastic peaks to slightly lower excitation energies, and to raise the quasielastic cross section by 8% to 16%. More marked changes were found in the excitation region beyond the quasielastic peak, where the cross section was reduced by 30% to 50%.

Quasielastic peak measurements provide good tests of impulse approximation calculations since interaction effect such as meson exchange currents (MEC), and isobar configurations (IC), are predicted[9,10] to be relatively small in this region, e.g., only about 4% or 5% near the maximum of the peak. Conversely, in order to have confidence in the identification of interaction effects, which are more significant away from the peak's maximum, it is important that the impulse approximation predictions be consistent with the experimental observations. A comparison of quasielas-

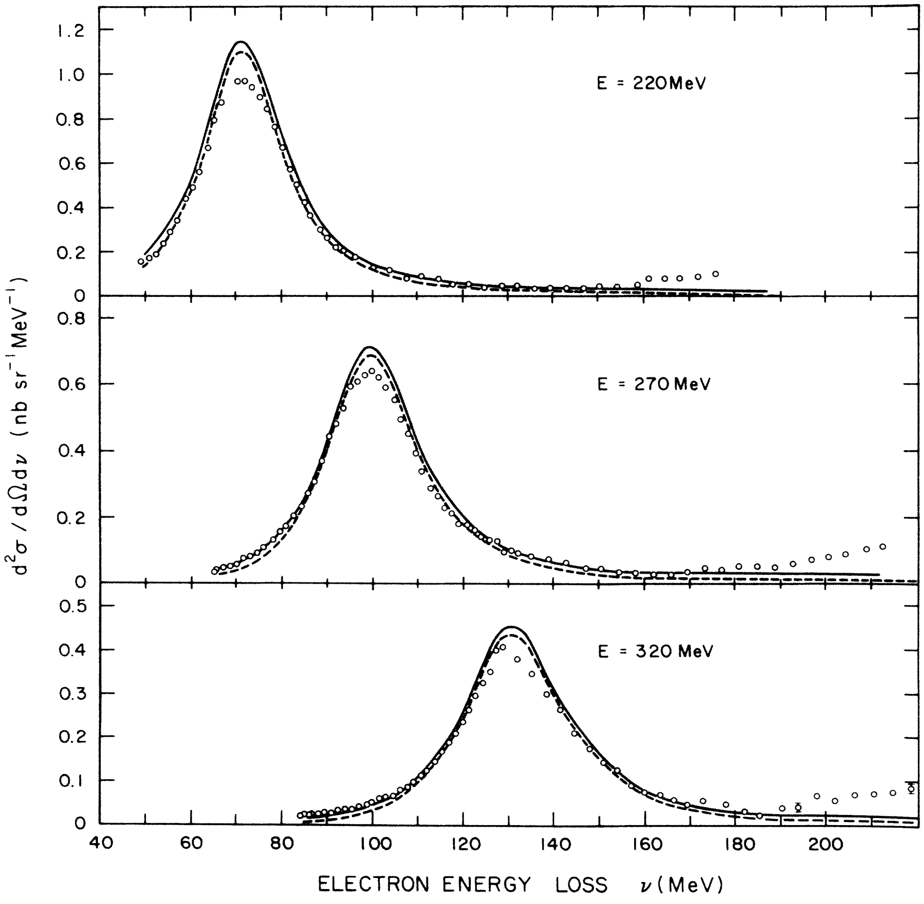

FIG. 2. Radiation corrected quasielastic cross sections measured at 180° for incident electron energies of 220, 270, and 320 MeV. The dashed curves were calculated in the impulse approximation. The continuous curves include contributions due to meson exchange currents and isobar configurations according to Ref. 11.

tic data with the predictions of Fabian and Arenhovel[10] was made by Simon *et al.*[1] Excellent agreement was obtained with the minor exception of the peak's maximum, where the theory is 2% to 3% higher than the experiment. However, the forward-angle quasielastic data of Simon *et al.*[1] contained a mixture of comparable longitudinal and transverse contributions and therefore the comparison with theory is not completely definitive.

Figure 2 shows a comparison of our 180° quasielastic data with the theoretical predictions of Liedemann and Arenhovel.[11] In this work gauge-invariant nucleon form factors were used, and the deuteron wave functions were derived from the Paris potential. Unlike previous treatments[12] the evaluation of one-pion exchange currents included those connecting to isobar admixtures in the ground state wave function. These calculations are in accord with the observed shape of the quasielastic peak, although the predicted magnitudes are about 12% too high at the maximum. When the quasielastic cross sections are integrated as far as the 140-MeV pion production threshold, the theoretical predictions exceed the data for $E = 220$, 270, and 320 MeV by 11%, 7%, and 6%, respectively. A similar discrepancy has been observed in ^{3}He, where plane-wave impulse approximation calculations[13] are 25% larger than data taken by McCarthy *et al.*[14] at $E = 500$ MeV and a scattering angle of 60°. In this case, however, the cross section contains both transverse and longitudinal components.

Several effects could influence the magnitude of the theoretical cross sections at the level of a few percent. For example, relativistic effects are omitted in the treatment of Leidemann and Arenhovel,[11] and there are experimental uncertainties in the nucleon form factors. In the kinematic range of this experiment the absolute magnitude of the proton magnetic form factor is known to an accuracy of about 2%. Less well known, however, is the magnetic form factor for the neutron. A decrease of 5% in the neutron form factor would provide approximate agreement between the magnitudes of the observed and calculated cross sections.

Beyond the high excitation side of the quasielastic peak, the largest contributions due to IC are expected[9] along the kinematic line $E_{\mathrm{np}} \cong 60 q^2_{\mathrm{c.m.}}$, where E_{np} is the relative separation energy of the neutron and proton in MeV and $q_{\mathrm{c.m.}}$ is the momentum transfer in the center-of-mass frame in fm^{-1}. Unfortunately, data satisfying this relationship extend beyond the 140-MeV pion production threshold. Thus only a limited comparison with theory is possible, since the calculation of Ref. 11 does not include pion production. We have therefore chosen to make a comparison at $E_{\mathrm{np}} = 40 q^2_{\mathrm{c.m.}}$, where the IC effects are still appreciable and pion production poses less of a problem. Leidemann and Arenhovel[11] predict that the IC effects are about two times larger than MEC effects for this kinematical condition and, as seen in Fig. 3, give a large enhancement over the impulse approximation calculation. Although the radiative corrections are large, reducing the raw data by 30% to 50%, and have accumulated uncertainties due to corrections in other portions of the spectrum, the data support such large IC contributions.

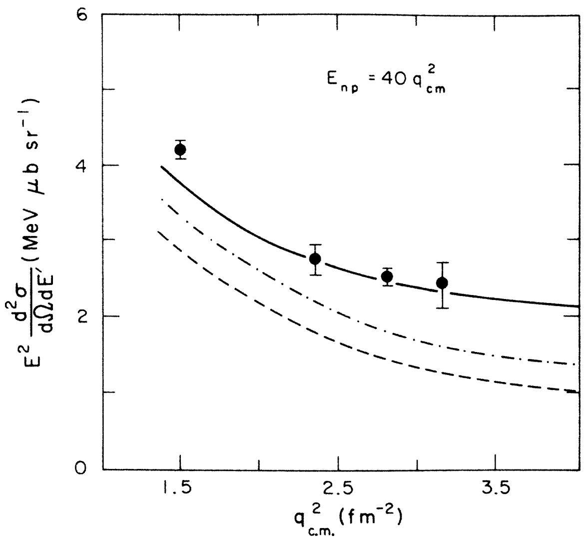

FIG. 3. Quasielastic cross section multiplied by E^2 for the kinematic condition $E_{\mathrm{np}} = 40 q^2_{\mathrm{c.m.}}$. The cross section is differential in the scattered electron energy E' and the solid angle Ω for scattering. The curves represent the theoretical predictions of Fabian and Arenhovel (Ref. 10) and Leidemann and Arenhovel (Ref. 11). The dashed curve is the IA calculation, the dash-dot curve includes MEC contributions, and the solid curve is the total including IC.

The deuteron transverse cross sections in the dip region on the high excitation side of the quasielastic peak, as shown in Fig. 2, are small for the kinematic conditions of this experiment. In contrast, considerably larger dip region cross sections per nucleon are observed for heavier nuclei,[2,15-17] and even for nuclei as light as ^{3}He and ^{4}He.[18] These results, when taken together, may indicate the presence of two-nucleon correlations in complex nuclei.[19]

Also measured in this experiment was the transverse elastic cross section in the four-momentum transfer region $q_\mu^2 = 1.6$–10.2 fm^{-2}, and the transverse break-up cross section at threshold in the region $q_\mu^2 = 2.3$–7.8 fm^{-2}. These were used for the radiation corrections to regions of the spectra at high excitation energies and also as systematic checks. Our results are in accord with recent Saclay measurements of the elastic magnetic[20] and threshold[21] cross sections, although our results are statistically less accurate. Averaged over the range $E_{\mathrm{np}} = 0$ to 1.5 MeV, the data for the break-up threshold lie in reasonably good agreement with theoretical predictions[11] which, in this region, are increased by about a factor of 2 due to MEC contributions. The experimental observation[21] of this enhancement over an extensive q_μ^2 range remains as the most credible demonstration of our understanding of meson exchange currents in nuclei.

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