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RAPID COMMUNICATIONS

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Transverse electrodisintegration of the deuteron in the threshold region at high Q^2

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Cross sections for 180° deuteron electrodisintegration have been measured near threshold for the Q^2 range 1.21–2.77 $(\mathrm{GeV}/c)^2$. The data are compared to several nonrelativistic meson-nucleon and hybrid quark-hadron models. The data are in strong disagreement with the impulse approximation, indicating the importance of non-nucleonic degrees of freedom. None of the models is in good agreement with the data at all values of Q^2. The ratio W_1/W_2 of inelastic structure functions has been extracted using previous forward angle data and is found to decrease strongly near threshold, also indicating the importance of interaction effects.

The deuteron is the most useful nucleus for the study of the nucleon-nucleon interaction and the effects of meson exchange currents (MEC). Of particular interest is the transverse electrodisintegration of the deuteron, where the residual proton and neutron share a low relative energy E_{np}. The diffraction minimum predicted in the impulse approximation (IA) at squared four momentum transfer $Q^2 \approx 0.5$ $(\mathrm{GeV}/c)^2$ is inconsistent with existing data[1,2] averaged over $E_{np} = 0$–3 MeV. The discrepancy is removed by MEC (Ref. 3) and is the firmest evidence to date for their existence. For $Q^2 > 1$ $(\mathrm{GeV}/c)^2$, theoretical predictions which differ by several orders of magnitude have been made both within the meson-nucleon framework,[4–6] and using hybrid quark-hadron models.[7–9] In the latter, the deuteron is represented as a six-quark cluster when the n-p separation is comparable to or less than the nucleon size.

In this Rapid Communication we present new measurements of threshold inelastic scattering from deuterium which, although with poor energy resolution, more than double the Q^2 range of previous data. The new data were obtained as a series of single-arm spectra of electron scattering near 180°. Double-arm measurements of elastic electron-deuteron scattering[10] were taken simultaneously with the single-arm data. The expected small cross sections made it necessary to use long liquid deuterium targets and a large acceptance spectrometer.

The experiment used electron beams of energy $E = 0.73$–1.3 GeV produced by the Nuclear Physics Injector and the Stanford Linear Accelerator (SLAC) with a maximum intensity of 5×10^{11} electrons per 1.6 μsec pulse at a rate of 150 Hz. Energy-defining slits limited the uncertainty in E to $\pm0.35\%$. The beams were transported to a 180° spectrometer system[11] in End Station A and directed into 10 or 20 cm long liquid deuterium cells. Electrons scattered near 180° were momentum analyzed using a set of six wire chambers. A large background of pions was rejected by a threshold gas Čerenkov counter and by measuring the energy deposited in an array of lead-glass blocks.

Radiatively corrected spectra at all eight incident beam energies are shown in Figs. 1 and 2. The 20 cm long liquid deuterium target was used at all energies except the lowest, where the 10 cm target was used. For each spectrum, the spectrometer central momentum E' was set at the deuteron elastic peak, and data were taken in the range $\Delta E'/E' < \pm 3.5\%$. This corresponds to an average range in E_{np} of ± 35 MeV, where E_{np} is the final-state *np* kinetic energy. Corrections were applied for detector inefficiencies of 4-6%, dead-time losses of $< 1\%$, and contributions from target aluminum endcaps. The latter typically ranged from 10% at $E_{np} = 30$ MeV to 100% for $E_{np} < 0$. The absolute solid angle[11] was evaluated to $\pm 2\%$. For $E_{np} > 0$, a correction of $< 4\%$ for pions misidentified as electrons was made by subtracting a scaled pion sample from each spectrum. Small elastic scattering contributions were also subtracted. The momentum calibration[11] of the electron spectrometer was evaluated using elastic scattering from hydrogen for low E' and detailed field maps of the bend magnets for the full range of E'. The resulting uncertainty in E' was $\pm 0.25\%$, which yields an error of $\pm 10\%$ to $\pm 30\%$ in the final cross sections. This was the dominant systematic error.

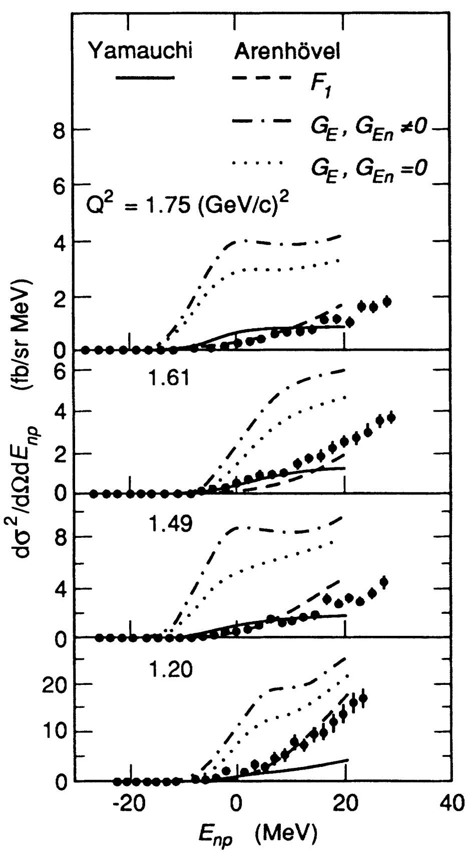

FIG. 1. Electrodisintegration cross sections at 180° vs E_{np} for the four lowest values of the elastic Q^2. The error bars include statistical and systematic uncertainties. The meson-nucleon predictions of Arenhövel (Ref. 4) and the hybrid quark-hadron predictions of Yamauchi (Ref. 8) have been folded with the experimental resolution. Arenhövel's predictions are shown for F_1 and G_E coupling in the MEC, the latter with two parametrizations of $G_{En}(Q^2)$ (see text).

Radiative correction factors were obtained in the Mo and Tsai formalism[12] by convoluting theoretical cross sections[4] with a normalized bremsstrahlung shape. The uncertainty in the radiative correction factors was determined by performing the corrections separately for each of two input models with and without a large enhancement at $E_{np} \approx 0$. The resulting corrected cross sections varied by $\pm 3\%$ to $\pm 8\%$.

Ionization losses, multiple scattering, and the spread in beam energy resulted in a resolution ranging from 12–20 MeV full width at half maximum in E_{np}. In order to make a comparison with previous higher-resolution data and theoretical predictions, resolution effects have been taken into account using two methods. In the first method, nonrelativistic predictions of Arenhövel[4] and Yamauchi[8] were convoluted with resolution functions calculated with a Monte-Carlo simulation[13] and are compared with the data in Figs. 1 and 2. The meson-nucleon calculations of Arenhövel derive the one- and two-body exchange currents directly from the *NN* interaction. The Paris potential[14] is used for the deuteron wave function. The present data lie between predictions using the Dirac electromagnetic form factor $F_1(Q^2)$ for the MEC and those using the Sachs form factor $G_E(Q^2)$. The two predictions with $G_E(Q^2)$ differ in the choice of neutron electric form factor, $G_{En}(Q^2)$, which also has a substantial effect. The Yamauchi predictions are based on a hybrid quark-hadron model with an adjustable parameter R_C governing the division of quark-gluon and meson-nucleon

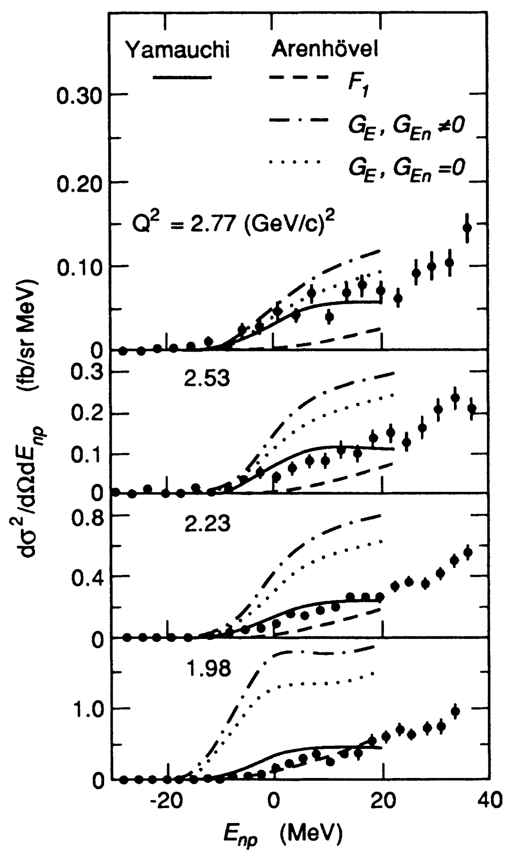

FIG. 2. Same as Fig. 1 except for the four highest Q^2 values of this experiment.

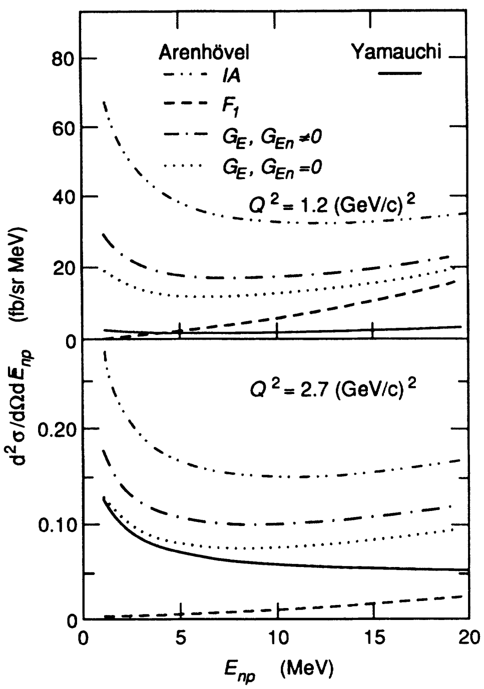

FIG. 3. Predictions of Arenhövel (Ref. 4) and Yamauchi (Ref. 8) at 180° as a function of E_{np} with no resolution smearing at the lowest and highest Q^2 values of this experiment. Calculations of Arenhövel are shown in the IA and including MEC using F_1 coupling and G_E coupling with two choices for $G_{En}(Q^2)$.

degrees of freedom. They are in fair agreement with the data for $Q^2 > 2$ $(\mathrm{GeV}/c)^2$, but lie below the data at lower Q^2.

Previous data[1,2] have generally been better described by models using F_1. This has motivated several theoretical arguments[15] in favor of its use. It has been pointed out[16-18] that the choice of F_1 and G_E for the MEC cannot be made unambiguously in a nonrelativistic framework. It has also been shown[17] that the choice of deuteron wave function, for example using the Bonn potential[19] with its relatively low D-state probability compared to the Paris potential, can give variations in the cross sections as large as those arising from the choice of F_1 or G_E coupling in the MEC.

In order to investigate the effects of the experimental resolution smearing, in Fig. 3 we have plotted the theoretical curves of Arenhövel and Yamauchi with no resolution smearing at the lowest and highest Q^2 of this experiment. It can be seen that in the impulse approximation at both values of Q^2 there is a strong enhancement near threshold due to the influence of the quasibound $^1S_0$ state. This causes a peak in the cross section near $E_{np} = 1$ MeV, decreasing to an approximately constant value above $E_{np} = 5$ MeV. The effect of MEC in Arenhövel's calculations is to decrease the cross section in the threshold region. Using G_E coupling preserves the threshold peak, but using F_1 coupling causes it to vanish almost completely. The model differences remain large even at $E_{np} = 10$ MeV, where they differ by a factor of 3 (at low Q^2) to 6 (at high Q^2). Folding these theoretical curves with the experimental resolution, as shown in Figs. 1 and 2, somewhat smears out the threshold peak, but the large differences in shape and magnitude remain between the curves using G_E and F_1 coupling.

In the second method of comparing the present data with predictions and previous data, a model-dependent procedure was used to extract resolution-unfolded cross sections averaged over E_{np} from 0–10 MeV. Polynomial models of maximum order 3–5 were used to represent the true cross sections since they can reproduce the shapes of all available theoretical cross sections. The range of 0–10 MeV was chosen to be comparable to the experimental resolution and much larger than the uncertainty in E'. The effect of the momentum uncertainty was evaluated by repeating the fits for central momentum shifts of $\pm 0.25\%$. This yielded errors on the averaged cross sections of typically $\pm 35\%$, while systematic errors due to the choice of polynomial order were $\pm 5\%$.

Resolution-unfolded data from this experiment averaged over E_{np} from 0–10 MeV are shown on the right-hand side of Fig. 4 with similarly averaged predictions by Arenhövel and Yamauchi. The errors shown are the total statistical and systematic errors, dominated by the error from the uncertainty in E'. Shown on the left-hand side of Fig. 4 are ≈ 1 MeV resolution data[2] averaged over $E_{np} = 0$–3 MeV along with similarly averaged predictions of Arenhövel and the predictions of Yamauchi at $E_{np} = 1.5$ MeV. The differences due to averaging the predictions over 0–3 vs 0–10 MeV are indicated by the small discontinuities in the curves at $Q^2 = 1.1$ $(\mathrm{GeV}/c)^2$ in

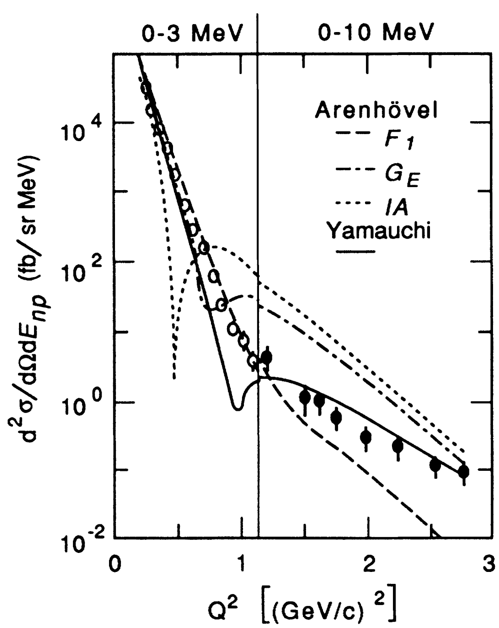

FIG. 4. Threshold electrodisintegration cross sections at 180° vs Q^2. Arenhövel's meson-nucleon predictions (Ref. 4) using the Paris potential are shown in the IA and with meson exchange currents using both F_1 and G_E (with $G_{En} \neq 0$) coupling. A hybrid quark-hadron model by Yamauchi (Ref. 8) is also shown. All predictions and present data above $Q^2 = 1.1$ $(\mathrm{GeV}/c)^2$ are averaged over E_{np} from 0 to 10 MeV. Below $Q^2 = 1.1$ $(\mathrm{GeV}/c)^2$, previous data (open circles, Ref. 2) and predictions of Arenhövel are averaged over 0–3 MeV, while the calculation of Yamauchi is at $E_{np} = 1.5$ MeV.

Fig. 4. These differences are illustrated over the full Q^2 range of this experiment for three theoretical models in Fig. 5. The differences are comparable to the errors on our data and are much smaller than the differences between the models, except for the Arenhövel calculation using F_1 coupling, where the minimum is washed out with the 0–10 MeV average. This shows that even with relatively poor resolution in E_{np} and the resulting systematic errors from resolution unfolding, the present data can be used to discriminate between the available models. The data indicate a change in slope versus Q^2 around 1–1.5 $(\mathrm{GeV}/c)^2$, which is qualitatively consistent with that indicated by all of the models.

The new data support the main conclusion from the earlier data at lower Q^2 that the IA is in strong disagreement with the measurements. Adding MEC improves the agreement when F_1 coupling is used but with G_E coupling the models disagree with the data over the full Q^2 range. The MEC model with F_1 coupling gives excellent agreement in the Q^2 range below 1.1 $(\mathrm{GeV}/c)^2$, and is often cited as clean evidence for MEC. We now see that it diverges from the new data at higher Q^2. This indicates that, while MEC may be important in this range, it is not yet understood how to calculate them. The hybrid quark model of Yamauchi is close to the new data above 1.1 $(\mathrm{GeV}/c)^2$, but a diffraction feature at lower Q^2 is not seen in the data. Other hybrid quark models[7,9] have been produced, but results are available only for $E_{np}=1.5$ MeV and are not shown.

Another method of looking for interaction effects beyond the IA is to compare the present backward angle data with similar data taken at forward angles. The cross section can be written in terms of two structure functions,

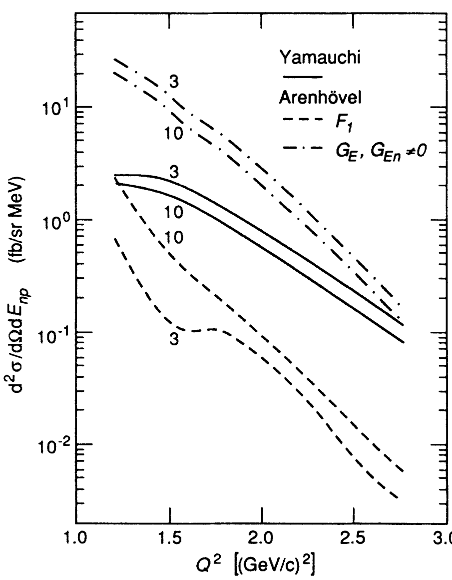

FIG. 5. Effect of averaging theoretical cross sections over E_{np}. Two models of Arenhövel (Ref. 4) and the model of Yamauchi (Ref. 8) are averaged over $E_{np}=0$–3 and 0–10 MeV (curves labeled 3 and 10, respectively). The variation between the different averages is small compared to the differences between the models, allowing the present ≈ 10 MeV resolution data to discriminate between the models.

$W_1(E_{np},Q^2)$ and $W_2(E_{np},Q^2)$. In the IA the ratio W_1/W_2 is approximately unity independent of E_{np} and Q^2. The ratio is insensitive to the choice of wave function and nucleon form factors. Any measured deviations from this behavior would indicate the influence of interaction effects.

The present 180° threshold data and quasielastic[20] data, yielding the transverse W_1 structure function, were compared with previous data[21] at 8°, essentially proportional to W_2. The forward-angle data were resolution-unfolded and interpolated to common values of E_{np} and Q^2.

The ratios W_1/W_2 at three values of average Q^2 are shown in Fig. 6. In each case W_1/W_2 is approximately unity for $E_{np}>50$ MeV but decreases as $E_{np}\to 0$, in agreement with earlier results[22] at lower Q^2. This shows that the quasifree mechanism is dominant above $E_{np}\approx 50$ MeV. Near threshold, interaction effects are important over the entire Q^2 range.

The curves in Fig. 6 represent calculations using wave functions from the Paris potential by Laget[23] and

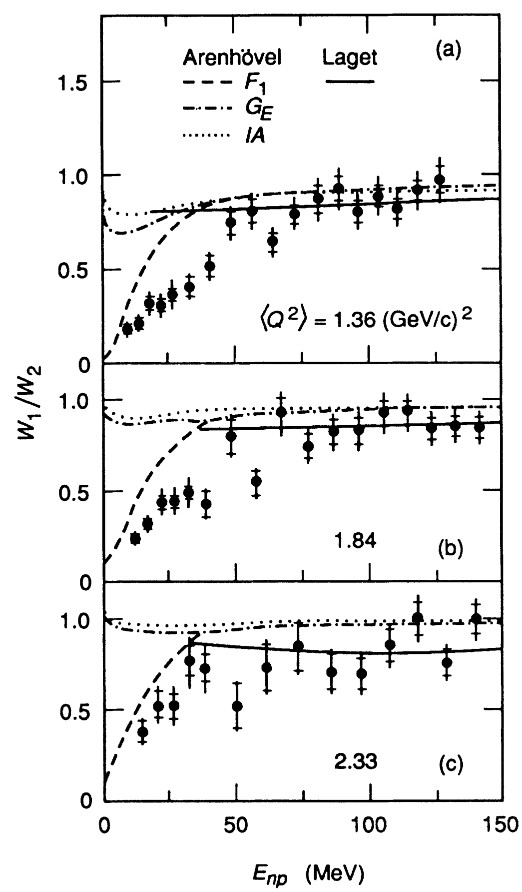

FIG. 6. Values of the ratio W_1/W_2 vs E_{np} extracted for three values of average Q^2 from the present 180° data and forward angle data of Ref. 21. The inner error bars are statistical only, and outer error bars include systematic uncertainties. The meson-nucleon predictions of Arenhövel (Ref. 4) using the Paris potential are shown in the IA and with meson exchange currents using both F_1 and G_E (with $G_{En}\neq 0$) coupling. Also shown are meson-nucleon predictions of Laget (Ref. 23).

Arenhövel[4] with final-state interactions, MEC, and isobar configurations. With the exception of Arenhövel's model using F_1 coupling for the MEC, all calculations fail to reproduce the decrease in W_1/W_2 observed near threshold. The choice of $G_{En}(Q^2)$ has little effect on the predictions.

In summary, it has been found that threshold-inelastic cross sections measured at 180° show clear evidence for scattering mechanisms beyond the IA. However, none of the presently available models agree with the data now that it has been extended to $Q^2=2.77$ (GeV/c)^2. Threshold data with higher resolution would be useful in looking for a diffraction minimum predicted by some of the models, and to examine the E_{np} dependence at each value of Q^2. Our new data should stimulate development of theoretical models in a region where the deuteron wave function, non-nucleonic degrees of freedom, and relativistic effects are all important.

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