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Inelastic lepton-deuteron scattering: Possible coherent effects

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Electron-deuteron data exhibit some unusual secondary peaks in the plots of νW_2 versus Bjorken x. It is our speculation that these peaks are evidence of interference between the three-quark and the six-quark cluster contributions to the inclusive data.

In a previous paper,[1] we have shown that the quark cluster model (QCM) (Ref. 2) reasonably describes the Stanford Linear Accelerator Center (SLAC) E133 (Ref. 3) and E101 (Ref. 4) inclusive inelastic electron-deuteron data with either the Reid soft core (RSC) (Ref. 5) or the Bonn[6] deuteron wave functions. However, there are apparently some unusual peaks in the E133 data, which do not exist in our previous calculations which were based on assumptions of incoherent contributions from three processes: quasielastic nucleon knockout, smeared three-quark (3-q) inelastic and six-quark (6-q) inelastic processes. We present below our phenomenological fit to these secondary peaks based upon assumed interference between a 3-q and the 6-q structure functions. If the 3-q clusters and the 6-q cluster are both present in the deuteron ground state, the quark struck by the photon could be from either a 3-q or the 6-q cluster. Therefore, interference is possible when both processes evolve to the same final state. Such interference is likely only within a certain range of kinematics and inelasticity where the complexity of the inelastic channels is strongly limited.

The issue of whether exotic components of the deuteron are admissible in the light of these same data sets[7,8] has been addressed in the framework of y scaling. Deviations from y scaling represent a nonquasielastic component in νW_2. Our recent reanalysis of this issue has led to the conclusion that these experiments exhibit substantial and systematic violations of y scaling.[8] One view of the results presented in Ref. 1 is that the QCM explains the major deviations from y scaling, and this paper presents results that attempt to improve upon that description by modeling possible coherent effects.

The inclusive inelastic electron scattering cross section from a nucleus when no spin information is retained is usually written as

$$\frac{d^2\sigma}{d\Omega dE'}=\sigma_M[W_2(|\mathbf{q}|,\nu)-2W_1(|\mathbf{q}|,\nu)\tan^2\tfrac{1}{2}\theta]\,, \quad (1)$$

where the Mott cross section σ_M is given by

$$\sigma_M=\frac{\alpha^2}{4E^2}\frac{\cos^2\frac{1}{2}\theta}{\sin^4\frac{1}{2}\theta}\,. \quad (2)$$

Here, θ is the lepton scattering angle, E is the incident energy, E' is the outgoing energy of the electron, $\mathbf{q}$ is the three-momentum transfer, ν is the energy transfer with the quantities expressed in the lab system, and α is the fine structure constant. The square of the four-momentum transfer is $q^2=\nu^2-|\mathbf{q}|^2=-Q^2$. The structure functions W_1 and W_2 appear in the response tensor $W^{\mu\nu}$ which may be written as

$$W^{\mu\nu}=\tilde{g}^{\mu\nu}W_1+\tilde{P}^{\mu}\tilde{P}^{\nu}W_2 =(2\pi)^6\sum_{P_x}\langle P_x|J_\nu^N(0)|P\rangle^*\langle P_x|J_\mu^N(0)|P\rangle \times\delta'(P+q-P_x)\,, \quad (3)$$

with

$$\tilde{g}^{\mu\nu}=g^{\mu\nu}-\frac{q^\mu q^\nu}{q^2}\,, \quad (4)$$

and

$$\tilde{P}^\mu=\left(P^\mu-\frac{P\cdot qq^\mu}{q^2}\right)\frac{1}{M_T}\,. \quad (5)$$

$|P\rangle$ denotes the target state and M_T is the mass of the target.

In the limit of forward angle scattering the cross sections are proportional to the structure functions, νW_2. In the cases of E133 and E101 SLAC data, the cross sections were taken at 8° or 10°, so the data are interpreted as measurements of νW_2. In our previous analysis[1] of deuterium data based on the QCM (Refs. 1 and 2), the contributions to the intermediate states $|P_x\rangle$ could be from the quasifree-knockout nucleon, a 3-q cluster or the 6-q cluster. We treated the summation over these three components as an incoherent sum:

$$\nu W_2^{(D)}=\tilde{p}_3(\nu W_2^{q\text{-}el})+\tilde{p}_3(\nu W_2^{3\text{-}q})+\tilde{p}_6(\nu W_2^{6\text{-}q})\,, \quad (6)$$

where

$$\tilde{p}_3=\int_{2R_C}^{\infty}dr[u^2(r)+w^2(r)]\,, \quad (7)$$

$$\tilde{p}_6=\int_0^{2R_C}dr[u^2(r)+w^2(r)]\,, \quad (8)$$

with $\tilde{p}_3+\tilde{p}_6=1$. The quantities $\tilde{p}_3$ and $\tilde{p}_6$ are the probabilities of finding a 3-q and a 6-p cluster inside a deuteron, respectively. The critical separation of $2R_C$ between two nucleons is the criterion for the formation of the 6-q cluster, and has been treated as the adjustable parameter of the QCM.

According to the parton model, the inelastic nuclear structure function can be written as

$$\nu W_2(\nu,Q^2)=\sum_{\text{quarks } j}e_j^2\frac{x}{A}\mathcal{N}_j(x)\,, \quad (9)$$

where we sum over all quarks in the nucleus, e_j is the charge on the quark j, and $\mathcal{N}_j(x)$ is the probability of finding quark j carrying fraction x/A of the total nuclear momentum P. If we approximate with a properly weighted average of up and down quark distributions, $\mathcal{N}(x)$, we can write

$$\nu W_2(\nu,Q^2) \simeq \sum_{\text{quarks}\, j} e_j^2 \frac{x}{A} \mathcal{N}(x) . \tag{10}$$

According to the model assumptions[2] the quarks are found in an i-quark cluster $(i=3,6,\ldots,3A)$ within a given nucleus with probability $\tilde{p}_i$ so that

$$\mathcal{N}(x) = \sum_{\text{clusters}\, i} \tilde{p}_i \bar{P}_i(x) , \tag{11}$$

where $\bar{P}_i(x)$ is the x distribution of quarks from an i-q cluster in the nucleus. Therefore, if we write

$$\nu W_2^{3\text{-}q} = \sum_{j=1}^{3} e_j^2 \frac{x}{A} \bar{P}_3(x) , \tag{12}$$

$$\nu W_2^{6\text{-}q} = \sum_{j=1}^{6} e_j^2 \frac{x}{A} \bar{P}_6(x) , \tag{13}$$

then the deuteron inelastic structure function is written as in Eq. (6). The nucleon (3-q) structure function, $\nu W_2^{3\text{-}q}$, which involves additional integrals over the deuteron wave functions, and the "6-q structure function," $\nu W_2^{6\text{-}q}$, are given in Ref. 1.

In the $Q^2=4$ GeV^2 deuterium data set there exist two small peaks between $x\sim 1.2$ and 1.35 as seen in Figs. 1 and 2. At these two peaks the data rise about two times as large as our previous theoretical results. To indicate the potential size of the interference effects, we have performed some simple phenomenological estimates in which we make a crude attempt to fit the two secondary peaks in this data set. We *select* the probability of the 6-q cluster, $\tilde{p}_6$, to be 7.4% for both the RSC and Bonn wave functions. This value of $\tilde{p}_6$ was fixed so that in the RSC case the magnitudes of the 3-q cluster and of the 6-q cluster contributions are equal at the $x\sim 1.3$ peak. For comparison, in the QCM description of all the E133 and E101 data, we found[1] an acceptable description emerged with $R_C=0.5$ fm for either the RSC or Bonn wave functions. This value of R_C implies $\tilde{p}_6=4.7\%$ for RSC and $\tilde{p}_6=5.4\%$ for Bonn. In addition, we choose the relative phase angle between the 3-q and 6-q contributions to be 0° at this peak.

The next issue to address is how the relative phase changes with the kinematics. It is natural to introduce the phase angle in terms of its dependence upon some invariant quantities, like Bjorken x, and Q^2. Since the Bjorken limit has not been reached at this kinematic regime, we choose the phase angle to be a simple linear function of the more general Nachtmann variable ξ:[9]

$$\phi(\xi) = \tfrac{3}{2}\pi + 4\pi \left(\frac{\xi-\xi_1}{\xi_2-\xi_1} \right) , \tag{14}$$

where ξ_1 and ξ_2 are free parameters which are adjusted only for the RSC case until the peaks coincide with the data: $\xi_1=0.96$ and $\xi_2=1.05$. The Nachtmann variable is

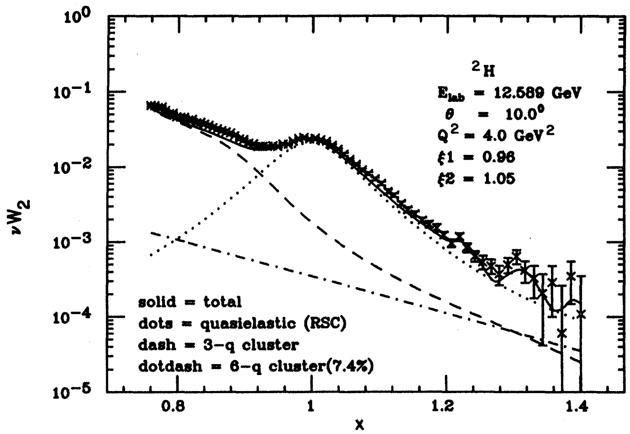

FIG. 1. Comparison of data and quark cluster model for the deuteron inelastic structure function, νW_2, as a function of Bjorken x. The data are from Ref. 3. Only the cases for the kinematics indicated are shown. The QCM components are calculated using the Reid soft core wave function for deuterium with the 6-q cluster probability set at 7.4%. The dotted curve represents $\nu W_2^{q\text{-}el}$. The dashed curve represents $\nu W_2^{3\text{-}q}$ and the dotted-dashed curve represents $\nu W_2^{6\text{-}q}$. The solid curve specifies the total νW_2 including the coherent effects between the 3-q and 6-q cluster contributions as discussed in the text.

given by

$$\xi = \frac{2x}{1+(1+Q^2/\nu^2)^{1/2}} . \tag{15}$$

For ξ values outside the $[\xi_1,\xi_2]$ range, the 3-q component is again 90° out of phase with the 6-q component, thereby yielding an incoherent result.

Figure 1 shows that this procedure yields an improved description of the E133 data in the $x>1$ region with the RSC wave function.

For simplicity, we take the *same* value of $\tilde{p}_6$ and the *same* $\phi(\xi)$ along with the Bonn wave function results as

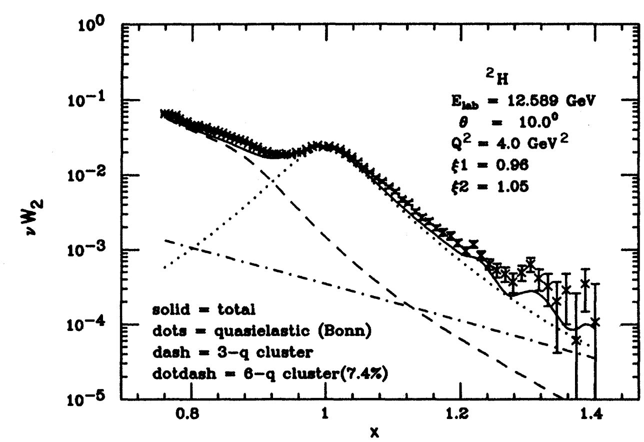

FIG. 2. The same quantities as plotted in Fig. 1 with the exception that the Bonn wave function for deuterium is employed in the QCM calculations.

another illustration of possible coherent effects. These results are shown in Fig. 2 along with the same data. The peaks in the calculation are again of about the right magnitude which is satisfying since we have made no attempt to optimize the calculated results in Fig. 2.

The other data sets from E133 do not show indications of such secondary peaks to the same degree as the $Q^2=4$ GeV^2 set we address here. We are not able to present predictions for additional interference effects since the phase function has been introduced phenomenologically as a function of Nachtmann ξ. Additional Q^2 dependence is possible but would have to be fixed by additional data. To fix the phase function from theoretical considerations requires a quantum mechanical model for the parton physics. Current models under development could be very useful in this regard.[10]

More precise inclusive experiments and/or exclusive measurements such as $(e,e'\pi)$ are necessary to confirm this phenomena. If confirmed, these coherent effects could provide a powerful tool for elucidating details of the quark cluster model.

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