Experimental and theoretical results for weak charge current backward proton production

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In this paper, we study deuteron breakup by high energy neutrinos. We present previously unpublished data on neutrino induced backward protons from deuteron targets; we calculate the contributions from both the two-nucleon ($2N$) and six-quark ($6q$) deuteron components, which depend upon the overall normalization of the part that is $6q$; and, we suggest other signatures for distinguishing the $2N$ and $6q$ clusters. We conclude that the $6q$ cluster naturally contributes to the high momentum backward proton spectrum just in the region where the standard $2N$ models lie below the data, and the absolute size of the far backward data is nicely explained if the amount of $6q$ is one or a few percent by normalization of the deuteron.

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I. INTRODUCTION

The deuteron target is our main source of information on the neutron. This is of increasing interest as unexpected results were found for sum rules in which neutron structure functions enter. Examples include the sum rules of Ellis and Jaffe [1,2], Gottfried [3], and Bjorken [4,5]. Assumptions made in most analyses of deuteron data must be reexamined. The deuteron is more than the sum of its proton and neutron parts and the nonadditive portion is important to evaluate by any means available.

Part of the present paper enlarges upon our earlier work [6], which studied deep inelastic ν-d and $\overline{\nu}$-d scattering experiments which saw high momentum backward protons. The shape of the backward proton momentum distribution was consistent with production from a multiquark ($6q$) deuteron component, but difficult to explain with just a conventional two nucleon ($2N$) state.

Here, we will present normalized calculations for the same processes. We need to know the probability of finding the $6q$ configuration in the deuteron, f, and how the residue of the $6q$ cluster recombines into protons. Although there is some uncertainty in the latter, once given f the calculation is reasonably well determined.

From other considerations, f is between 0.01 and 0.07 [7–9]. This range will work here also. We find that conventional $2N$ wave functions are insufficient; another contribution is needed to the rate for fast backward protons. For 500 MeV/c backward protons, e.g., the Paris wave function needs about a 60% additional contribution. Note that speaking only of $6q$ or $2N$ is a simplification; we are mindful of other possibilities (see e.g., Ref. [10]).

Experimentally, Sec. II presents Fermilab E545 neutrino-deuterium 15-ft bubble chamber data (previously unpublished) on backward proton production.

Section III gives the theoretical formulas we use. Comparison with data on backward proton spectra is in Sec. IV. The final section contains further discussion.

II. FNAL E545 NEUTRINO-DEUTERIUM DATA

Previous analyses of the E545 neutrino-deuterium data have concentrated on either extracting νn interaction data, or on the distributions of lepton or hadron variables in νd scattering. A typical analysis would separate the data into even-prong ''νn'' and odd-prong ''νp'' events, where a visible proton spectator is ignored in the prong count. The observed ''νn'' events were assumed to be a sample of νn interactions depleted by ''rescattering'' within the deuteron nucleus. The ''rescattered'' νn events, in turn, would appear in the ''νp'' event sample. In extraction of ratios of νn to νp cross sections the fraction of such rescattered events was estimated to be in the 6–12 % range.

An excess of high momentum proton spectators, compared to standard deuteron wave function predictions, is known to be associated with the ''νn'' event sample. When commented on in previous analyses, it would generally be noted that the origin of this excess is unknown, but given that the excess accounts for less than 1% of the ''νn'' events any effect on the overall distributions or measured quantities would be negligible. In the present analysis, we explicitly examine the νd target fragments in the E545 data, and compare the distribution of backward protons with a deuteron wave function plus a small six-quark component.

Many details of the E545 experiment have been published [11]. The data discussed here were previously presented at an APS meeting [12], where the emphasis was on establishing the existence of a ''rescattering'' phenomena which depleted the observed spectator proton (neutron target) event sample, and in estimating its frequency.

The E545 data are from a 320 000 frame exposure of the deuterium-filled Fermilab 15-ft bubble chamber to a wide-band single-horn focused neutrino beam produced by 4.8

$\times 10^{18}$ 350 GeV/c protons incident on a beryllium oxide target. The antineutrino component of the beam is $\approx 14\%$. The film was scanned twice, and events with two or more charged tracks produced by incident neutral particles in a 15.6 m^3 fiducial volume were accepted for analysis. All charged tracks were digitized and geometrically reconstructed. Topology-dependent weights are applied to the data to compensate for scanning and processing losses and for those events failing geometric reconstruction. The average processing times scanning efficiency is 0.80. Cuts are applied to the two-prong events to remove K^0 and Λ decays and γ conversions from the data.

A kinematic technique which uses only the measured momenta of the charged particles is used to select a sample of charge current events. Only events for which $\Sigma p_L > 5$ GeV/c, where p_L is the component of laboratory momentum in the beam direction and the sum is taken over all charged particles, are included in the analysis. The muon candidate is identified as that negative track in the event with the largest component of momentum transverse to the incident neutrino direction. Those events for which the component of the μ^- candidate's momentum transverse to the vector sum of the momenta of the other charged particles in the event is greater than 1.0 GeV/c are accepted as charge current events.

The incident neutrino energy of the selected charge current events is estimated using transverse momentum balance: $E_\nu = p_L^\mu + p_L^H + |\vec{p}_T^{\,\mu} + \vec{p}_T^{\,H}| p_L^H / p_T^H$, where the symbols p^μ and p^H refer to the muon momentum and the vector sum of the charged hadron momenta, respectively. Only events with $E_\nu > 10$ GeV are accepted for analysis.

A Monte Carlo simulation indicates that the sample selected according to the above criteria includes 79% of the νd charge current events, with the μ^- correctly identified in 98% of the cases, and with a 3% contamination due to νd neutral-current events and 1% due to $\overline{\nu} d$ events.

The corrected number of νd events in the sample is 15 129, with an average neutrino energy $\langle E_\nu \rangle = 50$ GeV. Of these events, 459 have an identified proton with momentum magnitude greater than 160 MeV/c whose direction is backward with respect to the incident neutrino direction. (Significant visibility losses occur for protons with momentum less than 160 MeV/c, and hence are not presented.) The identity of the backward protons was verified by reexamining all such tracks on the scan table. The momentum distribution of the backward protons is given in Table I. This data will be discussed in Sec. III, together with the proton spectrum from a νd and $\overline{\nu} d$ exposure of Big European Bubble Chamber (BEBC) by the WA25 Collaboration at CERN [13].

III. THEORETICAL DISCUSSION

We will give the expressions for the charge current inclusive cross sections of neutrinos hitting a deuteron and producing a backward proton p_B, a forward lepton l^-, and anything else X,

$$\nu + d \rightarrow l^- + p_B + X, \tag{1}$$

TABLE I. Momentum distribution of backward protons in 15 129 νd charge current events from Fermilab experiment E545.

Momentum range (MeV/c)	Number of events
160–200	187
200–240	100
240–280	61
280–320	37
320–360	30
360–400	14
400–440	10
440–480	10
480–520	9
520–560	1
560–600	0

in both the $2N$ and $6q$ models.

The cross section is differential in x, y, α, and p_T. These variables are the struck quark momentum fraction, $x = Q^2/2m_N\nu = Q^2/2m_N(E_\nu - E_l)$; the fractional lepton energy loss, $y = (E_\nu - E_l)/E_\nu$; the backward proton light front momentum fraction,

$$0 \leqslant \alpha = \frac{E_p + p_z}{m_N} \leqslant 2 \tag{2}$$

(with p_z defined positive for backward protons); and the transverse momentum of the proton relative to the direction of the incident neutrino, p_T.

For the $2N$ model, using quark distribution functions appropriate for striking the neutron, with argument $\xi = x/(2-\alpha)$ because the neutron is moving, we find the cross section [14]

$$\frac{d\sigma_{2N}}{dx\,dy\,d\alpha\,d^2p_T} = \sigma_0[D_n(\xi) + S_n(\xi) + (1-y)^2\overline{U}_n(\xi)] \times \frac{(2-\alpha)}{\gamma} |\psi(\alpha, p_T)|^2, \tag{3}$$

where $D_n(\xi)$ is ξ times the distribution function of down quarks in the neutron (n), etc., $\gamma = E_p/m_N$, σ_o is

$$\sigma_0 \equiv \frac{2G_F^2 m_N E_\nu}{\pi}, \tag{4}$$

and ψ is the deuteron wave function normalized by

$$\int d\alpha d^2p_T |\psi(\alpha, p_T)|^2 = 1. \tag{5}$$

The wave function is a light front wave function, which is obtained from a nonrelativistic (NR) wave function by

$$|\psi(\alpha, p_T)|^2 = \frac{E_k}{\alpha(2-\alpha)} |\psi_{NR}(k_z, k_T)|^2 \tag{6}$$

where the arguments of the NR wave function are obtained from $k_T = p_T$ and

$$\alpha = (\sqrt{m_N^2 + \vec{k}^2} + k_z)/\sqrt{m_N^2 + \vec{k}^2}. \tag{7}$$

The NR normalization is $\int d^3k |\psi_{NR}(k_z,k_T)|^2 = 1$.

The cross section for the $6q$ component of the target involves the probability, $D_{p/5q}$, for the residuum of the $6q$ state to fragment into the proton. We have

$$\frac{d\sigma_{6q}}{dx\,dy\,d\alpha\,d^2p_T} = \sigma_0 D_6(x) \cdot \frac{1}{2-x} D_{p/5q}(z,p_T), \tag{8}$$

where we have included just D_6, the down quark distribution for the $6q$ cluster times x, on the grounds that we will need this cross section only for high momenta backward protons. Argument z is the light front momentum fraction of the proton relative to the five quark residuum, $z = \alpha/(2-x)$.

Reported data uses protons from the entire backward hemisphere. Hence, we too integrate over the backward hemisphere, and over x and y also. The term with explicit y dependence gives a small contribution. Then,

$$\frac{E_p}{p^2}\frac{d\sigma_{2N}}{dp} = \int_{bkwd} d\Omega\, dx E_p \frac{d\sigma_{2N}}{d^3p\,dx}$$

$$= \sigma_0 \overline{\xi}_{\nu n} \int_{bkwd} d\Omega\, dx\, \gamma^{-1} \alpha (2-\alpha)^2 |\psi|^2 \tag{9}$$

with

$$\overline{\xi}_{\nu n} = \int_0^1 d\xi (D_n(\xi) + S_n(\xi) + \tfrac{1}{3}\overline{U}_n(\xi)) \tag{10}$$

and

$$\frac{E_p}{p^2}\frac{d\sigma_{6q}}{dp} = \int_{bkwd} d\Omega\, dx\, \alpha D_6(x) D_{p/5q}(z,p_T); \tag{11}$$

$p = |\vec{p}|$ is the backward proton momentum. Finally,

$$\frac{d\sigma}{dp} = (1-f)\frac{d\sigma_{2N}}{dp} + f\frac{d\sigma_{6q}}{dp}. \tag{12}$$

IV. COMPARISON TO DATA

We shall take the Paris and Bonn wave functions [15,16] as representative of sophisticated wave functions (see also Refs. [17,18]). Figure 1 shows what these wave functions produce for the backward proton spectrum.

Some details: The quark distributions for the nucleon are the set CTEQ1L [19]. For the $6q$ cluster, we use the Lassila-Sukhatme model ''B'' quark distributions [20]. These distributions are partly based on quark counting rules and describe the European Muon Collaboration (EMC) data. Models ''A'' and ''C'' are similar and are omitted from the figures to avoid clutter. The fragmentation function for the $5q$ residuum is

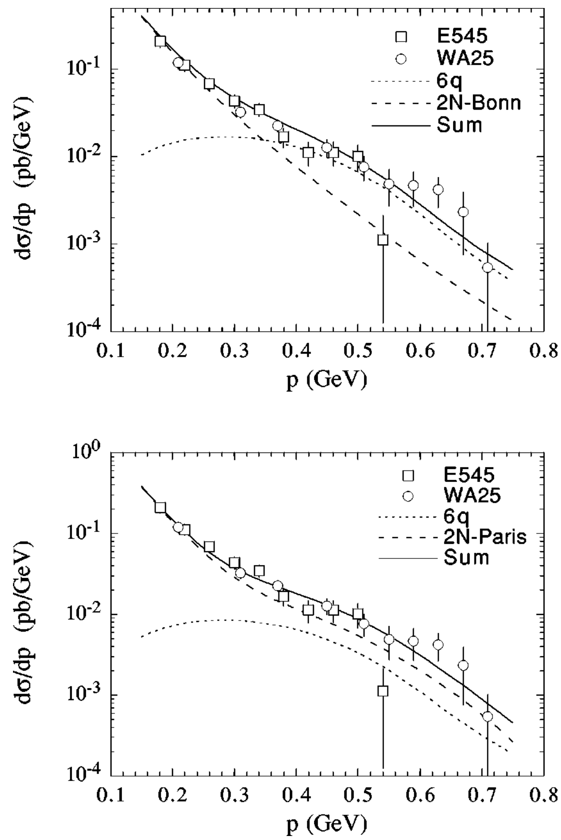

FIG. 1. Comparison of the backward proton spectrum in $\nu + d \to l^- + p_B + X$ to calculations using the Bonn (energy independent OBEPQ) wave function and the Paris wave function, each using a $z^5(1-z)^3$ form in the fragmentation function and with a 2% $6q$ contribution for the Bonn wave function case, 1% for the Paris case.

$$D_{p/5q}(z,p_T) = \frac{2(N+4)!}{\pi\lambda^2 N!3!}\frac{z^N(1-z)^3}{(1+p_T^2/\lambda^2)^3}, \tag{13}$$

where $\lambda = 310$ MeV. For $z \to 1$, the $(1-z)^3$ is given by the counting rules. Barring effects outside the $5q$ residuum, the average proton should have 3/5 its momentum, giving $N = 5$. The struck quark could pull the proton more forward. This would reduce N above. Using $N = 3$ roughly doubles the f needed.

Both $2N$ models give cross sections below the data for high momentum backward protons. At 500 MeV/c, the Bonn model needs an increase of 350% and for the Paris model, an additional 62% is needed. The logarithmic scale needed for $d\sigma/dp$ squashes differences, but it is clear that the Paris curve is below most of the data error bars. More compellingly, we can calculate the squares of the differences between the center of the data points and the dashed Paris and solid Paris$+6q$ curves divided by the error bar squared for the momentum range $0.2 < p < 0.5$ GeV. The result is χ^2 per data point of 0.8 for the solid curve and and 3 for the dashed curve, corresponding to confidence levels of 0.5 and 0.003, respectively.

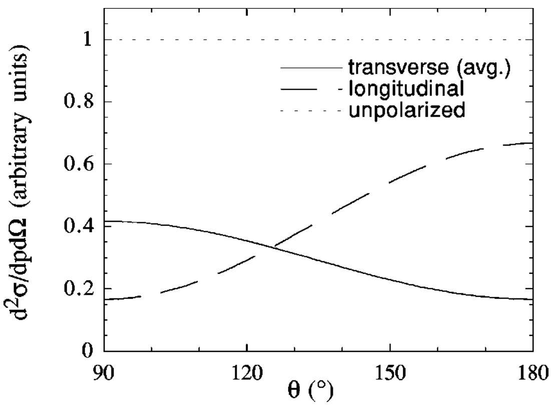

FIG. 2. Angular distribution of backward protons assuming a polarized deuteron, the $2N$ model, and a momentum at which the D state dominates.

V. DISCUSSION AND CONCLUSION

We have seen that a small amount of $6q$ cluster in a deuteron can explain the backward proton data. It is of interest to find other signatures to signal the presence of $2N$ or $6q$ states. We will mention two possibilities.

If a polarized deuteron target is available, the $2N$ model leads to a definite backward proton angular distribution at momenta where the D state dominates (about 400 MeV for the Paris wave function). Figure 2 shows this angular distribution for longitudinally polarized deuterons and for the average of the two transverse polarizations. Hall B CEBAF experiment (E-94-102) will measure backward protons from inelastic electron-deuteron interactions. Also, polarized targets have been used in Hall B, though present hardware does not allow backward going particles from the polarized target to be seen [21].

If we can bin data in both x and p, we can define a ratio of the observed cross section, off a d with backward proton production, to the cross section for a plain neutron (at an appropriate momentum). Explicitly,

$$R_2 = \frac{\sigma_{meas}(x,y,\alpha,p_T)}{\sigma_{nX}(x,y,\alpha,p_T)}, \tag{14}$$

with denominator $\sigma_{nX} = (d\sigma/dxdy)(\nu n \to \mu^- X)$.

If the $2N$ model is correct, $R_2 = |\psi(\alpha,p_T)|^2$. Thus, for the $2N$ model, R_2 would be x independent for fixed α and p_T. If the $6q$ cluster dominates at some fixed backward proton momentum, it gives a curve for R_2 vs x that varies by a factor of roughly two from peak to valley, as we have shown in an electromagnetic case [22].

This ratio test seems feasible since the capability of making it with neutrinos existed during the heyday of the bubble chamber. For example, with the original data, it would be possible to separate the events in each of the lowest bins, at least, of our Table I into 2–3 bins in p_T. (The ν and $\bar{\nu}$ films from the Fermilab and CERN bubble chambers were sent to Moscow a decade ago.)

In conclusion, we have presented some previously unpublished data on, and studied theoretically, the production of backward protons in ν-d and $\bar{\nu}$-d scattering [23]. We believe we have good indications that $6q$ configurations exist in the deuteron and can be observed.

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