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Hadron up-down asymmetry in neutrino-neon charged-current interactions

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In charged-current neutrino-neon events (mean energy 100 GeV), fast charged hadrons show an up-down asymmetry with respect to the lepton plane. The asymmetry may be associated with reinteractions in the neon nuclei. For $z > 0.3$ hadrons the asymmetry is -0.054 ± 0.017; for those events showing evidence for reinteractions the asymmetry is -0.111 ± 0.028. For all hadrons the asymmetry is 0.0010 ± 0.0048.

In charged-current neutrino-nucleon interactions, azimuthal symmetry of individual hadrons about the direction of the lepton momentum transfer (i.e., the q vector) is expected in the simple quark-parton model. A small up-down asymmetry due to higher-order QCD processes is predicted by Hagiwara, Hikasa, and Kai.[1] Here "up" and "down" mean above and below the lepton plane (neutrino direction cross muon direction), respectively. The predicted asymmetry is of the order of 1%. A small left-right asymmetry, due to gluon bremsstrahlung[2] and to parton transverse momentum,[3] is also predicted and has been reported in a preliminary study from the present experiment[4] as well as in the analogous muon interactions.[5] The present paper reports on an up-down asymmetry, which is experimentally straightforward to study because the lepton plane is well determined. The target nucleons are mostly (96%) in neon nuclei, so the possibility of reinteractions in the nucleus may complicate the theoretical interpretation.

The data come from an experiment[6] in the Fermilab 15-ft bubble chamber with a two-plane external muon identifier (EMI). The chamber was filled with a neon-hydrogen mix (47% atomic neon) and was exposed to the quadrupole triplet neutrino beam produced by 400-GeV incident protons. The present study used 7482 fully measured charged-current events. Each event has a μ^- with energy $E_\mu > 4$ GeV and a good two-plane match in the EMI, has a primary vertex at least 70 cm from the downstream chamber wall, has a visible hadron energy (excluding identified protons) of at least 5 GeV, and has at least one charged primary hadron that is not identified as a proton. The neutrino energy, which can be estimated typically to $\pm 15\%$ event by event, ranges from 10 to 320 GeV for these events, with a mean value of 100 GeV. The neutrino direction is known to better than 1 mrad event by event. In the bubble-chamber coordinate system, the azimuthal angle of the muon about the neutrino direction is approximately uniformly distributed, so that "above the lepton plane" is approximately equally up and down, or left and right, etc., in the bubble-chamber coordinate system. In all that follows, "neutral hadrons" are e^+e^- pairs or Compton electrons that appear within two radiation lengths of the primary vertex, and V^0's, that point to the primary vertex. Also, "charged hadrons" are primary particles with fractional momentum errors of less than 100%, are not identified protons, and are assigned a pion mass. A proton is identified only if it stops in the bubble chamber (possibly after a scatter). For each event the neutrino energy is estimated via $E_\nu = P_{\mu x} + f(P_{Hx})$, where the x direction is the neutrino direction, H refers to the sum of the charged and neutral hadrons, and the function f is determined from transverse-momentum studies.[6,7] For each hadron, with energy E_h, the variable z is defined as $z = E_h/(E_\nu - E_\mu)$.

For a given sample of events, the up-down asymmetry A is defined as

$$A = (N_u - N_d)/(N_u + N_d) \quad ,$$

where N_u and N_d are the numbers of hadrons above and below the lepton plane respectively. In the following, A is always for charged hadrons. Momentum conservation precludes an overall momentum asymmetry. However, net downward momentum of forward particles, for example, can be compensated by net upward momentum backward. Even overall nonzero A can in principle arise, for example, from forward-backward nonsymmetric parton hadronization or nuclear cascading. If an asymmetry is present at the parton level, particularly if the outgoing struck quark has an asymmetry, then at the hadron level the asymmetry is expected to decrease with decreasing z (see Cahn, Ref. 3, also Ref. 5). The asymmetry A is shown in Fig. 1 in bins of hadron z value, for all events. When all bins are combined the 43 112 hadrons give $A = 0.0010 \pm 0.0048$, i.e., no significant up-down asymmetry. However, the two points with $z > 0.3$ are each more than 2 standard deviations (SD) below zero, and when combined give $A(z > 0.3) = -0.054 \pm 0.017$, which is 3.2 SD from zero. For positive and negative hadrons separately, $A(z > 0.3) = -0.053 \pm 0.020$ and -0.056 ± 0.033, respectively, consistent with being equal within the errors. There are in total 3440 charged hadrons with $z > 0.3$ (2531 positive and 909 negative); 3168 events have one such hadron and 136 events have two. Thus a $z > 0.3$ selection can be viewed generally as a selection of the leading hadron in events where there is a clearly leading hadron.

Thus a cut at $z = 0.3$ is appropriate if any asymmetry in the struck quark should be best revealed by the leading hadrons. The exact value 0.3 is arbitrary, however. Selections of other minimum z values yield asymmetries of

$$A(z > 0.25) = -0.028 \pm 0.014 \quad (4830 \text{ hadrons})$$

and

$$A(z > 0.35) = -0.057 \pm 0.020 \quad (2462 \text{ hadrons}) \quad .$$

A minimum z value anywhere in the range 0.28 to 0.38

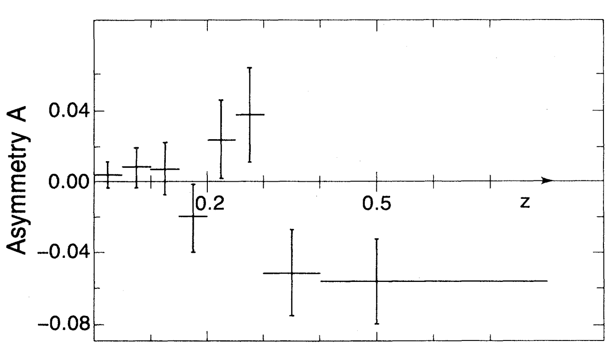

FIG. 1. The up-down asymmetry A of charged hadrons, in z bins.

yields an asymmetry that is more than 2.6 SD from zero. The experimental uncertainty in z is typically $\pm 20\%$, due primarily to the uncertainty in the total-hadron-energy estimate.[8] We conclude that while the cut $z > 0.3$ is appropriate to select leading hadrons, its exact value is not critical.

Extensive studies were carried out to eliminate the possibility that the asymmetry noted above for $z > 0.3$ charged hadrons is due to some instrumental bias, as follows: (1) The events were divided into three parts in several different ways, according to the event-vertex coordinates and the lepton-plane orientation in the bubble-chamber coordinate system. No region and/or orientation was found that was responsible for most or all of the asymmetry. (2) The median momentum of charged hadrons with $z > 0.3$ is 15 GeV/c. The asymmetries of such hadrons with momenta less than and greater than 15 GeV/c are -0.051 ± 0.024 and -0.057 ± 0.024, respectively. In comparison, the asymmetry for charged hadrons with $z < 0.3$ and momenta greater than 15 GeV/c is -0.002 ± 0.025. Hadrons with $z < 0.3$ and momenta > 15 GeV/c on average make a smaller angle with the lepton plane than hadrons with $z > 0.3$ and momenta < 15 GeV/c and hence would be more sensitive to any systematic bias. Therefore (at the 2-SD level) the asymmetry cannot be due to a simple bias in high-momentum charged particles. (3) In the 3304 events with one (or more) charged hadrons with $z > 0.3$, the up-down asymmetry of P_s, the vector sum of the momenta of charged hadrons with $z < 0.3$, is 0.044 ± 0.018. Therefore (at the 2.5-SD level) any instrumental bias must have opposite effects on the fast ($z > 0.3$) and slow ($z < 0.3$) components of an event. (4) Within the statistical errors, the asymmetry is independent of the measured length and the fractional momentum error of the $z > 0.3$ hadrons, and is independent of the institution where the events were measured and of the geometrical-reconstruction program (TVGP or HYDRA) used. (5) As mentioned above, the positive and negative hadrons have asymmetries of the same sign. Therefore the asymmetry is unlikely to be due to a simple charge-dependent bias.

The conclusion is that the asymmetry is very unlikely to be caused by an instrumental bias.

The Fermi motion of the struck nucleon, and random uncertainties in the neutrino, muon, and hadron directions, will lead to incorrect up or down assignments for some hadrons, and, in general, to a measured asymmetry smaller in magnitude than the true asymmetry. Monte Carlo studies showed that on average 4% of $z > 0.3$ charged hadrons get the wrong up or down assignment, with 66% of the wrong assignments being for hadrons with $|P_n| < 0.05$ GeV/c. Here P_n is a hadron's momentum component perpendicular to the lepton plane. The corresponding corrections to the present data are small, and have been neglected. The P_n distribution for $z > 0.3$ charged hadrons is shown in Fig. 2(a). The mean value of P_n is -0.027 ± 0.008 GeV/c. The asymmetry shows no strong dependence of P_n; for $|P_n|$ below and above the median value of 0.28 GeV/c the asymmetries are -0.037 ± 0.024 and -0.072 ± 0.024, respectively.

While the available theory predicts that z is the relevant variable correlated with parton-level asymmetry, one may ask whether A is correlated also with other variables. Of course, other variables such as x_F and y, which are essentially longitudinal, would be expected to show, and do show, roughly the same asymmetry structure as does z. An indica-

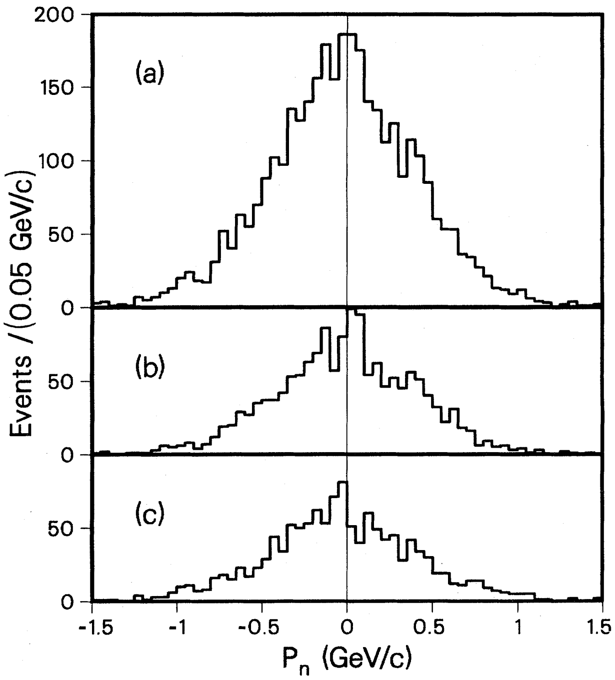

FIG. 2. Distributions of P_n; P_n = momentum transverse to the lepton plane, for charged hadrons with $z > 0.3$. (a) All events, (b) events showing no evidence for reinteractions in the neon nucleus, and (c) events showing evidence for reinteractions.

tion of Q^2 dependence of the asymmetry was found in addition, where Q^2 is the negative of the four-momentum transfer squared from the neutrino to the muon. For events with Q^2 below and above the median value of 11.2 GeV^2/c^2 the asymmetries are -0.087 ± 0.024 and -0.021 ± 0.024, respectively. Within Q^2 bins, there is no strong dependence on E_ν or on the total hadron mass W. Not surprisingly, the dependence on the related scaling variable x, is similar to that on Q^2. We know of no predictions of up-down-asymmetry dependence on these other variables.

The asymmetry could be related to the neon nuclei that contribute 96% of the target nucleons. Therefore the events were divided into three classes: "no-reinteraction," "reinteraction," and "unknown." An event was called "reinteraction" if there was evidence for reinteraction in the struck nucleus (i.e., evidence that at least two nucleons in a neon nucleus were involved). Such evidence was taken to be any of the following:[9] (1) net observed hadron charge Q_H not equal to 1 or 2, (2) two or more identified protons, (3) a charged hadron with Feynman-x value < -1.0. For these three criteria, identified protons were excluded if their momenta were less than 200 MeV/c and included if greater than 200 MeV/c (the proton range in the bubble chamber was 1 cm at 200 MeV/c; detection and measurement inefficiencies become appreciable below 200 MeV/c). An event was called "unknown" if it satisfied neither (2) nor (3) above and if a primary hadron's charge was undetermined. The numbers of events in each class, some of their properties, and the asymmetries are given in Table I. The separation into "no-reinteraction" and "reinteraction" events is not expected to be perfect, of course.

The asymmetries in the "no-reinteraction" and "reinteraction" events differ by 2.9 SD with that in the former being consistent with zero. In the "unknown" events, the intermediate asymmetry is consistent with these events being a mixture of the other two classes. For each of the "no-reinteraction" and reinteraction" classes, further investigation revealed no subclass that had an asymmetry significantly different from the remainder of the class.[10] The distribution in P_n for the "no-reinteraction" and "reinteraction" event classes are shown in Figs. 2(b) and 2(c). In these figures there is a suggestion that the asymmetry near $P_n = 0$ depends on P_n. However, with an average resolution in P_n of $\approx \pm 0.05$ GeV/c, and with limited statistics, no conclusion on this structure is evident. In Fig. 2(a) where all classes are included, no such P_n dependence is apparent. In summary, a tentative conclusion is that the asymmetry is correlated with reinteractions.

If most or all of the asymmetry is indeed due to reinteractions, then the QCD test proposed by Hagiwara, Hikasa, and Kai[1] would be obscured in a nuclear target. Also, as in the effect observed by the European Muon Collaboration,[11] there is a caution here that there may be differences between lepton-nucleon and lepton-nucleus interactions. We know of no theoretical prediction of azimuthal asymmetry correlated with reinteraction in nuclei. However, one may speculate, for example, that reinteraction might convert a polarizaton into an asymmetry, or that asymmetry might be present in multiparton final states which should tend to have larger reinteraction cross sections than simpler states. (The latter view is not unexpected in the model of Ref. 1.)

TABLE I. Event properties and up-down asymmetries A of $z > 0.3$ charged hadrons, in three event classes.

Class	"No-reinteraction"	"Reinteraction"	"Unknown"
No. of events	3265	2860	1357
$z > 0.3$ charged hadrons/event	0.47	0.44	0.48
$\langle Q^2 \rangle$ (GeV^2/c^2)	16.6 ± 0.3	19.0 ± 0.4	21.9 ± 0.7
$\langle P_n^2 \rangle$ (GeV^2/c^2)	0.18 ± 0.01	0.21 ± 0.01	0.21 ± 0.01
A	-0.001 ± 0.026	-0.111 ± 0.028	-0.069 ± 0.039

In any case, an asymmetry correlated with reinteractions may shed new light on the problem of hadron formation inside a nucleus (e.g., see Ref. 12, and references therein).

Conclusions. There is an up-down asymmetry in fast charged hadrons from neutrino-neon interactions; for $z > 0.3$ the asymmetry is -0.054 ± 0.017. The asymmetry may be associated with reinteractions within the neon nuclei; for the class of events where there is clear evidence for reinteraction, the asymmetry (for $z > 0.3$) is -0.111 ± 0.028. For all charged hadrons the asymmetry is 0.0010 ± 0.0048, i.e., consistent with zero.

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[4]M. D. Sokoloff *et al.*, Bull. Am. Phys. Soc. **27**, 512 (1982).

[5]J. J. Aubert *et al.*, Phys. Lett. **130B**, 118 (1983).

[6]H. C. Ballagh *et al.*, Phys. Rev. D **21**, 569 (1980).

[7]The explicit expression for $f(P_{Hx})$ used here is $1.33P_{Hx} + 0.79 - 0.0018P_{Hx}^2$, P_{Hx} in GeV/c.

[8]Many neutrino experiments use another method of estimating E_ν, as described in H. G. Heilmann, Bonn Internal Report No. WA21-INT-1 1978 (unpublished); J. Blietschau *et al.*, Phys. Lett. **87B**, 281 (1979). If that method is used here, resulting asymmetries are $A(z > 0.3) = -0.043 \pm 0.016$ (3744 hadrons) and $A(z > 0.4) = -0.074 \pm 0.022$ (1968 hadrons). The z values get shuffled around somewhat with different E_ν estimates, but a significant asymmetry remains.

[9]Of the 2860 events assigned to the "reinteraction" class, 644 satisfy only criterion (1), 55 only (2), 827 only (3), 63 (1) and (2), 412 (1) and (3), 329 (2) and (3), and 530 all three. Of the 827 satisfying only (3), 288 satisfy the more conservative criterion of having a proton emittted backwards in the laboratory.

[10]For the subclass of events that move from the reinteraction class to one of the other two classes when the proton momentum cut is altered from 200 to 400 MeV/c (874 such events), $A(z > 0.3) = -0.120 \pm 0.050$.

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