Observation of the EMC effect in $\bar{\nu}$Ne interactions

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Comparison of the x distributions of antineutrino interactions in neon and deuterium from bubble-chamber experiments yields the first piece of evidence for the occurrence of the EMC effect in neutrino reactions.

The European Muon Collaboration (EMC) recently measured the ratio of the structure functions of the nucleon,[1] $F_2^{\rm Fe}(x)/F_2^{\rm D}(x) \cong 1.2 - (0.5 \pm 0.2)x$, in muon scattering by nuclei of iron ($A = 56$) and deuterium at[1)] $9 < Q^2 < 170$ GeV^2. This ratio turned out to be a decreasing function of x, in contrast with the increasing function expected in the standard picture of the Fermi motion of nucleons in an iron nucleus. This "EMC effect" was soon confirmed[2] in electron scattering at smaller values of Q^2, and it has stimulated several theoretical models (see the reviews in Refs. 3 and 4). Attempts to observe the EMC effect in neutrino reactions have not yet been rewarded with definitive results.[5,4]

In this letter we examine the ratio of the x distributions for the interactions of neutrinos in neon ($A = 20$) and deuterium with the transition $\bar{\nu}_\mu \to \mu^+$:

$$R(x) = \left(\frac{1}{N}\frac{dN}{dx}\right)^{\rm Ne} \Bigg/ \left(\frac{1}{N}\frac{dN}{dx}\right)^{\rm D}.$$

According to the quark-parton model we would have $(dN/dx)_{\bar{\nu}} \sim q(x) + 3\bar{q}(x) = F_2 + 2\bar{q}$. The antiquark contribution,[2)] which is dominant at $x \lesssim 0.1$, fades rapidly with increasing x; we have $R(x) \sim F_2^{\rm Ne}/F_2^{\rm D}$, and a direct comparison with Refs. 1 and 2 becomes possible.

The normalization data for deuterium, taken from Ref. 6 and obtained in the BEBC bubble chamber (CERN), are based on 5575 events with $E_{\bar{\nu}} > 10$ GeV and a muon momentum $p_\mu > 4$ GeV ($\langle E_{\bar{\nu}}\rangle = 40$ GeV, $\langle Q^2\rangle = 5.2$ GeV^2), corrected for the p_μ cutoff, radiation effects, the resolution along x, and the detection efficiency. Only single-prong events are lost (some of them, the quasielastic events $\bar{\nu}p \to \mu^+ n$, have the known value $x = 1$).[3)]

To analyze our data, obtained form the 15-foot Fermilab bubble chamber with a heavy Ne-H_2 medium, we selected 5679 events ($\langle E_{\bar{\nu}}\rangle = 35$ GeV, $\langle Q^2\rangle = 4.4$ GeV^2) under the same conditions on $E_{\bar{\nu}}$ and p_μ but also under the condition $\nu > 2$ GeV; these

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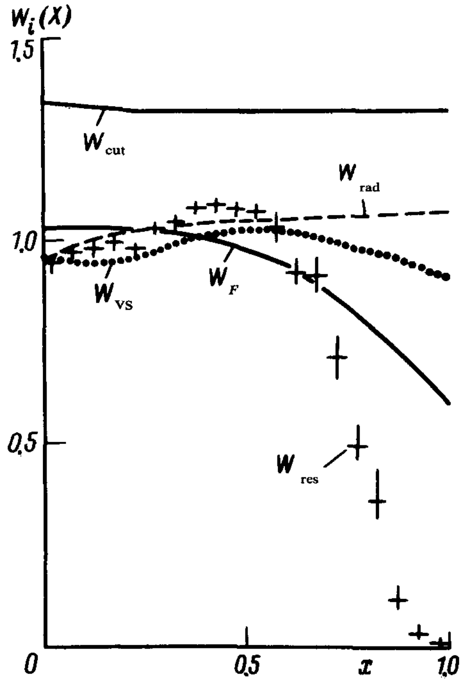

FIG. 1. Monte Carlo corrections to the $\bar{\nu}$Ne x distributions with the following: W_{res}—The resolution (the systematic errors are indicated); W_{rad}—radiation effects; W_{cut}—the cutoff along p_μ and ν; W_{VS}—the violations of scaling at small Q^2; W_F—Fermi motion. The last two corrections have not been applied to the data.

conditions are introduced because of the uncertainty regarding the resolution in terms of ν (and thus x) at small values of[4] ν. A general description of the experiment and a description of the procedures for extracting the muon and for allowing for the imperfect scanning efficiency are given in Ref. 7. The apparent hadron energy is corrected in accordance with $\nu = 0.65$ GeV $+ 1.14\nu_{app}$; we then write $E_{\bar{\nu}} = E_\mu + \nu$. Final corrections to the x distribution of the weight function, $W(x)$, calculated by the Monte Carlo method in the scaling model for $\bar{\nu}N$ interactions are made on the basis of the Field-Feynman quark distributions.[8] Radiative effects,[9] the experimental resolution in terms of p_μ and ν, and the p_μ and ν cutoffs are taken into account. The contributions of these effects are shown separately in Fig. 1 ($W = W_{rad} W_{res} W_{cut}$). We restrict the discussion here to the region $x < 0.7$, where the resolute correction is $\lesssim 10\%$. The value of W_{res} is calculated in a self-consistent manner, since (a) the model x distribution reproduces the experimental distribution well[5], while (b) W_{res} is essentially independent of the variations of the former within the errors of the latter. The systematic errors specified here reflect these variations, along with the statistical errors in the calibration ν-resolution functions. For our purposes, the 3.8% excess of protons over neutrons in the Ne–H_2 mixture is unimportant.

Figure 2a shows normalized x distributions of $\bar{\nu}D$ and $\bar{\nu}$Ne events. The former has an integral equal to 0.90 because of the loss of single-prong events, while the second has an integral of 0.94, in accordance with our estimate of a 6% contribution of the

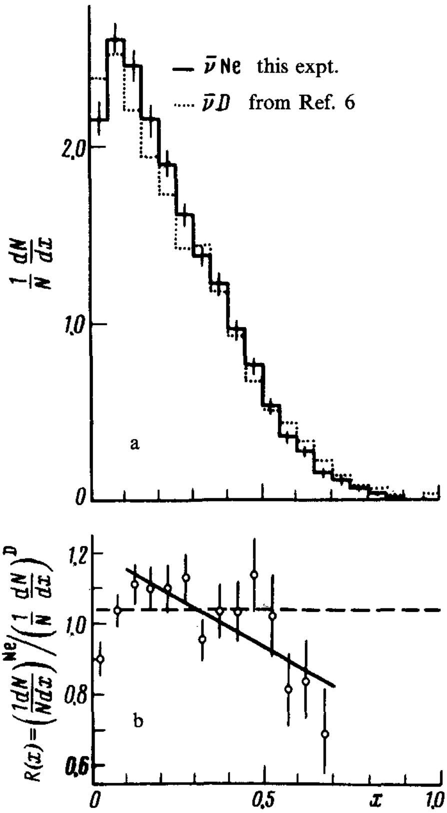

FIG. 2. a—The x distributions of $\bar{\nu}$Ne and $\bar{\nu}$D events, normalized to 0.94 and 0.90. No correction has been made for the Fermi motion; b—ratio of the distributions at $x<0.7$ (the errors are statistical). Dashed line) Ratio of integrals; solid line) result of a fit at $0.1<x<0.7$.

quasielastic channel at $x=1$. Figure 2b shows the ratio of these distributions. A fit with a straight line $R(x)=a(1-bx)$—as in the EMC experiment—leads to a value of 25/12 for χ^2 per degree of freedom with $b=0.17\pm0.10$. The values of χ^2 is large because of the dip at small values of x. Furthermore, in the same region $R(x)$ is not proportional to $F_2^{\rm Ne}/F_2^{\rm D}$, and Q^2 is particularly small in comparison with the EMC result ($\langle Q^2\rangle$ varies roughly linearly from ~1 GeV^2 for the bin with $x<0.05$ to ~12 GeV^2 at $x=0.7$). The restriction $x>0.1$, which leads to a more direct comparison with the EMC data, improves the quality of the fit (χ^2 per degree of freedom is 8.9/10) and gives us

$$b = 0.45 \pm 0.11\ (\text{stat.}), \qquad 0.1 < x < 0.7\,. \tag{1}$$

This result is distorted both by the methodological errors in the Ne and D results themselves and by the physical differences between the sets of data. We have examined the following sources of systematic errors: (A) uncertainties in the correction for the resolution ($W_{\rm res}$) lead to errors $\Delta b = \pm0.05$ because of the ν resolution and $^{+0.02}_{-0.03}$ because of the variations of the Monte Carlo model. (The correction $W_{\rm res}$ by itself would change b by only -0.04.) The corresponding systematic error for the D data was not given in Ref. 6, but it can be hoped that it is of the same order of magnitude and thus has little effect on the results. (B) The Ne data have been corrected for the discarded region, $\nu < 2$ GeV. The scaling approach is not completely suitable here (because of the small values $Q^2 = 2M_N \nu x \lesssim 4x$ GeV^2), and there is a problem in the accuracy with which the violation of scaling is described. From the W_{VS} curve in Fig. 1 we can estimate the necessary correction. It is found by introducing an empirical fit of the violation of scaling[10] in the Monte Carlo calculations at small values of Q^2; this empirical fit gives a reasonable description of the low-energy data.[11] The correction changes b by -0.13. (C) The D data have a harder energy spectrum. The weighting of the Ne events by the ratio of the CERN $\bar{\nu}$ spectrum[12] to the Fermilab spectrum changes b by $+0.09$. (D) From the Ne data we need to single out the analogs of single-prong events in D (additional positive tracks can appear in Ne because of rescattering in the nucleus), and we also need to consider single-prong events at $\nu < 2$ GeV. After determining the fraction of such events as a function of x separately for $\nu > 2$ GeV and $\nu < 2$ GeV, we find that b changes by $+0.09$ and $+0.03$. Summing the errors of each sign in (A)–(D), we find the maximum systematic error in (1) to be $\Delta b^{\max}_{\text{syst}} = {}^{+0.28}_{-0.21}$.

The observed decrease in $R(x)$ with increasing x contradicts the expected effect of Fermi motion (the corresponding correction, estimated by the curve W_F in Fig. 1, simply increases b to 0.57) and is a new piece of evidence in favor of the EMC effect. The slope parameter (1) agrees with the corresponding results obtained from the scattering of charged leptons.[1,2]

At $x < 0.1$ we see a change in the behavior of $R(x)$. Using $r = R(x < 0.05)/R(0.10 < x < 0.25)$, for example, as a numerical measure of the depth of the dip, we find $r = 0.81 \pm 0.06^{+0.068}_{-0.005}$. A similar tendency at small values of x has been observed previously in $\sigma_{eA}(x)/\sigma_{eD}(x)$ for A = Al and Cu in electron scattering at small Q^2 (Ref. 2).

In summary, this study of the ratio $R(x)$ of the x distributions of $\bar{\nu}$Ne and $\bar{\nu}$D interactions reveals an EMC effect for the Ne nucleus at $0.1 < x < 0.7$ and $\langle Q^2 \rangle \cong 5$ GeV^2. Furthermore, there is an indication of a change in the behavior of $R(x)$ at small x.

We wish to thank the physicists at Fermilab and the University of Michigan for their inestimable contribution to our experiment in its first stage.

[1)]In the lepton-nucleon scattering $l + N \to l' +$ everything, $Q^2 = -(p_l - p_{l'})^2$ is the square of the 4-momentum transfer, $\nu = E_l - E_{l'}$ is the energy transfer, and $x = Q^2/2M_N\nu$.

[2)]The (anti)quark structure functions of the nucleon are q, $\bar{q} = (F_2 \pm xF_3)/2$.

[3)]Allasia *et al.*[6] give normalized x distributions for $\bar{\nu}n$ and $\bar{\nu}p$ interactions, $n(x)$ and $p(x)$ (without single-prong events in the case of the $\bar{\nu}p$ sample). Using $\sigma_{\bar{\nu}n}/\sigma_{\bar{\nu}p} = 0.51$ and 10% for the fraction of single-prong events, we find $dN/dx = 0.34n(x) + 0.56p(x)$, where we are writing the errors under the assumption that this is a distribution of 5575 unweighted events.

[4)]The hadron-energy resolution functions are known from calibration measurements of the interactions of π^- mesons in the chamber at $E_\pi = 1$–50 GeV.

[5)]The Field-Feynman x distribution was actually altered at $x < 0.1$ to reach agreement with the data; the alteration changes W_{res} only at $x < 0.05$ and then by only 2%.

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