Nuclear Dependence of Dimuon Production at 800 GeV

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A precise measurement of the atomic mass dependence of dimuon production induced by 800 GeV protons is reported. Over 450,000 muon pairs with dimuon mass $M \geq 4\ GeV$ were recorded from targets of ^2H, C, Ca, Fe, and W. The ratio of dimuon yield per nucleon for nuclei versus ^2H, $R = Y_A/Y_{^2H}$, is sensitive to modifications of the antiquark sea in nuclei. No nuclear dependence of this ratio is observed over the range of target-quark momentum fraction $0.1 < x_t < 0.3$. For $x_t < 0.1$ the ratio is slightly less than unity for the heavy nuclei. These results are compared with predictions of models of the EMC effect.

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The European Muon Collaboration (EMC) observed a modification of the quark structure of nucleons bound in heavy nuclei by studying the deep-inelastic scattering (DIS) of leptons.[1] The original EMC effect has been confirmed[2,3] in the region of fractional quark momenta $0.3 < x < 0.6$. The region $x \leq 0.1$, however, remains a subject of active experimental[4,5] and theoretical[6] activity.

After many years of intense effort, there is no consensus on the origin of the EMC effect. Continuum dimuon production in high-energy hadron collisions, known as the Drell-Yan[7] (DY) process, provides an independent measure of the modification of the quark structure of nuclei.[8] Proton-induced DY production, for fractional longitudinal momentum (Feynmann x), $x_F \geq 0.2$, is dominated by the quark-antiquark annihilation subprocess

$$q_p + \overline{q}_t \rightarrow l^+ l^-,$$

where p and t indicate the beam proton and target nucleon, respectively. Although there are large QCD corrections to the simple DY electromagnetic vertex, the factorization property of the next-to-leading order QCD calculation ensures a DY dimuon yield proportional to the antiquark content of the target nucleon.[9] Thus proton-induced DY production is complementary to DIS where both quarks and antiquarks contribute.

Previous studies of the A dependence of the DY process performed at Fermilab and CERN[10,11] lack the statistical precision of the nuclear DIS data. In this paper we report the results of Fermilab experiment 772, a 450,000 event measurement of DY dimuon production from nuclei in a kinematic regime that is sensitive to the antiquark distribution in the target nuclei.

Experiment 772 used a modified version of the large spectrometer in the Meson-East beamline at Fermilab which was originally constructed for experiment 605.[12] The magnetic fields of the three dipole magnets of the spectrometer were configured to optimize acceptance for three different regions of dimuon mass. The spectrometer was used in a closed-aperture configuration. A thick hadron absorber in front of the first active detector permitted incident proton intensities of 10^{11} protons per second at the high-mass setting and $3 * 10^{10}$ at the low-mass magnet setting. A total luminosity of $3.5 * 10^{41} cm^{-2}$ was recorded.

The 800 GeV proton beam, 8 mm wide by ≤ 2 mm high at the target, was monitored by position sensitive RF cavities and ion chambers; position stability was typically better than 1 mm. Beam intensity was monitored by two secondary-emission detectors and a quarter-wave RF cavity. Two four-element scintillator telescopes viewing the target at 90° monitored the luminosity, the beam duty factor, and the data acquisition livetime.

The dimuon yields were measured for five targets, ^2H, C, Ca, Fe, and W. Care was taken to achieve a very accurate target-to-target relative normalization. Long-term drifts were cancelled by interchanging the solid targets with the ^2H target every few minutes. The solid targets consisted of 7.28 cm diameter disks[13] distributed over a length of 50 cm, the length of the liquid deuterium cell. Target thicknesses, ranging from 6%(W) to 15%(^2H) of an interaction length, were chosen to equalize rates in the spectrometer. Elemental assays of the targets and beam attenuation were included in the luminosity calculation.

The electronic trigger consisted of a pair of triple hodoscope coincidences having the topology of a $\mu^+\mu^-$ pair from the target. This trigger reduced the primary background of low p_T muons from the target and beam dump. Typically 50 events per second were recorded of which ~ 1 was a valid dimuon event from the target. Electronic livetime was kept above 98%.

Track reconstruction was performed on a Fermilab Advanced Computing Project parallel processor. Track reconstruction efficiency averaged $\sim$ 91%; the inefficiency was proportional to the instantaneous luminosity. Target-to-target rate dependent corrections in reconstruction efficiency were applied. A small contamination ($\sim$ 3%) of random muon coincidences was subtracted by studying like-sign muon pairs. Target-out backgrounds were measured and found to be negligible.

One million muon pairs were tracked through a complete Monte Carlo simulation of the spectrometer to study the acceptance. The acceptance for the solid targets was slightly larger than that with the liquid deuterium cell; a correction (0.9%) for this effect was applied to the data .

The systematic error in the ratio of yields from the solid targets versus deuterium is dominated by the uncertainty in the rate dependence (1.5%), acceptance (0.4%), deuterium thickness (0.4%), and beam attenuation (0.3%). All other contributions are negligible. This results in a total systematic error in the ratios of less than 2%. In the figures shown below only statistical errors are indicated.

Acceptance-corrected mass spectra from the three spectrometer settings are shown for the ^2H target in Fig. 1. Also shown is a calculation of the DY cross section in the leading-log approximation($q(x) \rightarrow q(x, M^2)$) which was normalized to the data. The calculation, which employed the structure functions (set 1) of Eichten et al.,[14] gives an excellent account of the shape of the DY continuum. Figure 2 shows the $Fe/^2H$ ratio as a function of dimuon mass, x_F, and transverse momentum. It is evident that the mass regions dominated by quarkonium resonances ($M \leq 4$ GeV and $9 \leq M \leq 11$ GeV) have very different A dependences than the DY continuum; the A dependence of J/ψ, ψ', and Υ production will be described in a forthcoming publication. The dependence on transverse momentum is similar to that seen by NA10[11] at 280 GeV, but significantly less than that observed at 140 GeV.

Figure 3 shows the ratios of Drell-Yan yield per nucleon for each heavy target versus ^2H, $Y_A/Y_{^2H}$, as a function of x_t for muon pairs with positive x_F. Mean values of x_F and transverse momentum are 0.26 and 0.95 GeV/c, respectively . The x_t ratios are based on mass regions free of contribution from decay of the quarkonium states, specifically, $4 \leq M \leq 9\ GeV$ and $M \geq 11\ GeV$. With these cuts the above calculation predicts that the fraction of the accepted DY events due to $q_p\overline{q}_t$ annhilation is ~ 0.95 at $x_t = 0.05$ and ~ 0.75 at $x_t = 0.3$.

No nuclear dependence of the antiquark ratio is observed over the range $x_t > 0.1$. A slight, but experimentally significant depression of the ratio is seen in the heavier targets for $x_t < 0.1$. Figure 3 compares present data for $W/^2H$ to the F_2 ratio $Sn/^2H$ from the EMC group.[4] The lepton scattering data exhibit a more pronounced shadowing at small x_t. It is clearly of interest to know whether this difference can be understood in terms of current models of shadowing.[6] It is worth noting that $Q^2 \geq 16\ GeV^2$ for our data, which is significantly larger than in DIS.

Many of the theoretical attempts to calculate the EMC effect fall into three general categories: pion-excess models, quark-cluster models and rescaling models. These models can also be used to predict the nuclear dependence of DY dimuon production. The acceptance of the E772 spectrometer was taken into account in each of the following calculations.

The pion-excess model in its earliest forms[15−17] predicted a rise in the $F_2^{Fe}/F_2^{^2H}$ ratio at small x_t as well as a depletion for $x_t \geq 0.2$. The small enhancement in the pion cloud surrounding a bound nucleon arises from a conjectured attractive p-wave $\pi - N$ interaction in nuclear matter. The strength of this interaction is often characterized by the Landau-Migdal parameter g_0'; typical values found in the literature range around $g_0' \sim 0.6 - 0.7$. Figure 3 compares the results of a calculation[18] (using the structure functions of Ref.

14) with $g_0' = 0.6$ to the present $Fe/^2H$ DY data; it is completely inconsistent with the data. The pion-excess model of Ref. 17, which uses a different pion distribution function, predicts a similar enhancement in the antiquark content of nuclei, in disagreement with our data.

Quark-cluster models view the nucleus as composed of a combination of ordinary nucleons plus some fraction of multiquark ($6q$, $9q$, and higher) clusters formed by the overlap of nucleons. The uncertainties in these models come from the essentially unknown structure functions of multiquark clusters. In the model of Carlson and Havens[19], for example, the parton structure functions were parameterized according to constituent counting rules. The gluon momentum fraction for the $6q$ cluster was constrained to be the same as for the free nucleon. This results in a significant enhancement of the sea even for a modest 15% $6q$-cluster fraction. The calculated DY ratio (Fig. 3) is in significant disagreement with the present data. An alternate but plausible assumption,[20] that the momentum fraction sea/glue in $6q$-clusters is the same as it is for nucleons, leads to a smaller enhancement of the DY ratio. However such a calculation is still in disagreement with our data.

The rescaling model assumes that nuclear binding results in a phenomenon similar to the scaling violation associated with gluon emission.[21] Comparisons to the present DY data are made on the basis of the scale change of structure functions $f(x_t, Q^2) \rightarrow f(x_t, \xi Q^2)$, where $\xi \sim 2$ over the Q^2 range of our data. The calculation, shown in Fig. 3, yields a scaling violation similar to DIS.[5] It approximately fits the DY data, except in the range $x_t < 0.1$ where the approximations made in this model are known to break down.

In summary, this experiment has shown almost no nuclear dependence in the production of continuum dimuon pairs. In the context of the DY description of dimuon production this implies no modification of the antiquark sea in the range, $0.1 < x_t < 0.3$. Models of the EMC effect which postulate a significant pion excess or antiquark enhancement in multiquark clusters are apparently ruled out. The Q^2 rescaling model is consistent with the present data. A slight, but experimentally significant, depletion of the yield is seen in the heavier targets for $x_t < 0.1$.

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Figure Captions

FIG. 1. Acceptance corrected mass spectra at the three spectrometer settings for the ^2H target. The solid curves are calculations of the Drell-Yan cross section, normalized to the data, using the structure functions of Eichten et al.[14]

FIG. 2. Ratios of the dimuon yield per nucleon for $Fe/^2H$ versus dimuon mass, p_T, and x_F. The p_T and x_F ratios only include data from the pure continuum mass region, $4 \leq M \leq 9$ GeV and M $\geq$ 11 GeV.

FIG. 3. Ratios of the Drell-Yan dimuon yield per nucleon, $Y_A/Y_{^2H}$, for positive x_F. The curves shown for $Fe/^2H$ are predictions of various models of the EMC effect. Also shown are the DIS data for $Sn/^2H$ from the EMC group.[4]