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PIONIC CORRECTIONS AND THE EMC ENHANCEMENT
OF THE SEA IN IRON

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ABSTRACT

It is shown that the EMC enhancement in the region $x < 0.3$ can be explained by an increase in the pion field in iron if there is an attractive force which mixes nucleon-hole and delta-hole states at momenta of order 300-400 MeV/c. Some experimental consequences of this explanation are discussed.

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The recent report¹⁾ by the European Muon Collaboration (EMC) of a significant difference between the structure function ($F_2^{\mu N}$) of a "nucleon" in Fe and D, has been confirmed at SLAC²⁾. In view of the enormous range of momentum covered by the two experiments ($3.3 \leq Q^2 \leq 170 \text{ GeV}^2$), this is almost certainly not a higher twist effect. It has been suggested by Llewellyn Smith³⁾ that the observed enhancement of the ratio $F_2(\text{Fe})/F_2(\text{D})$ at small values of x ($= Q^2/2m_N v < 0.3$) could be the result of an increase in the number of pions per nucleon. This suggestion is of considerable interest in medium energy physics where the study of spin-isospin excitations, in particular mediated by the pion, is a central occupation.

Our aim is to investigate this question quantitatively. Let us begin with the observation by Sullivan⁴⁾ that the pion exchange process shown in Fig. 1(a) contributes to $F_2(x)$ for a free nucleon. (The parton which is struck is part of the internal structure of the pion, while the recoiling nucleon remains intact.) For a pion at rest this contribution is restricted to $x < m_\pi/m_N$, but a full calculation gives the following contribution to the nucleon structure function

$$\int F_2^{\mu N}(x, Q^2) = \int_x^1 f(y) F_2^{\mu \pi}(x/y, Q^2) dy, \quad (1)$$

where $F_2^{\mu \pi}$ is the (electromagnetic) structure function of the pion, and $f(y)$ is the probability that the pion carries a fraction y of the momentum of the nucleon in an infinite momentum frame. It is given by^{3,4)}

$$f(y) = \frac{3g^2}{16\pi^2} y \int_{\frac{m_\pi^2 y^2}{1-y}}^{\infty} \frac{t |F(t)|^2 dt}{(t + m_\pi^2)^2}, \quad (2)$$

where $-t = w^2 - \vec{q}^2$ is the four-momentum squared of the exchanged pion, $g = 13.5$ is the coupling constant, and $F(t)$ the form factor, at the $NN\pi$ vertex. We take the latter to be $\exp[-\lambda(t + m_\pi^2)/m_\pi^2]$. (In the Cloudy Bag Model^{5),6)} λ is related to the bag radius R by $\lambda = 0.106 m_\pi^2 R^2$.) It is worth noting that $\delta F_2^{\mu N}$ shows the same scaling properties as $F_2^{\mu \pi}$.

Following the argument of Ref. 3) we observe that Eq. (1) implies that (at $x = 0$)

$$\delta F_2^{\mu N}(0, Q^2) / F_2^{\mu \pi}(0, Q^2) = \int_0^1 f(y) dy = N_\pi, \quad (3)$$

where N_π is the number of pions per (free) nucleon. It is then easily seen that in the nuclear case the EMC enhancement of about 15% at small x ^{*)} would be explained if there were an extra (6 - 10) pions in Fe. (It is natural to attribute the effect to Fe and not D, which is a dilute system.) This possibility seems quite natural to a nuclear physicist.

While the ultimate description of the nucleus will probably be based on QCD ^{5),9)}, the idea that nucleons are close packed but non-overlapping most of the time, suggests that it is their long-range structure - the pion cloud - which will be most distorted. Certainly it is quite a simplification to attribute the whole change in the sea to $q\bar{q}$ pairs in the form of pions. However, there is a qualitative difference in the range of pionic corrections ($m_\pi^{-1} \sim 1.4$ fm) as compared with any other possible fluctuations (mass scale $O(m_\rho^{-1}) \equiv O(2\omega_{1,-1}/R) \sim \sim 0.2$ fm).

Because we are dealing with a quasi-free process the exchanged pion in Fig. 1(a) is spacelike ($\omega \sim q^2/2m_N \ll |\vec{q}|$). In addition, the low momentum region contributes only for small y , where $f(y)$ is suppressed by an explicit factor of y . Large momenta are suppressed by the pion propagator and the form factor. Thus the most important momenta for δF_2 are typically 300-400 MeV/c. This is precisely the region where a significant enhancement of the nuclear pion field has been predicted for many years ¹⁰⁾⁻¹²⁾ - so far without experimental confirmation.

In a nucleus the emission of a pion with momentum (300-400) MeV/c can involve more than one nucleon. For example it could be emitted by a correlated pair of nucleons, leaving the nucleus in a state with two particles knocked out of the fermi sea (a two-particle - two-hole, $2p - 2h$, state). Another possibility is that the final nuclear excitation is of the one-particle - one-hole, $1p - 1h$, type, but the emitted pion scatters from a second nucleon before being hit by the photon. In this case it can either lift the nucleon above the fermi sea (Fig. 1(b) - a NN^{-1} excitation) or turn it into a Δ (ΔN^{-1} excitation - Fig. 1(c)). This can happen any number of times, and in the absence of further physics would lead

*) We add the caution that the $x \rightarrow 0$ limit is artificial in this model because we ignore a number of effects there. Processes with a recoiling baryon (e.g., Δ) in Fig. 1(a), which can be large ⁴⁾ for $x < 0.05$ are omitted. Also, shadowing may be important at small x , and this may depend on A ^{7,8)}.

(even at nuclear matter density, $\rho_0 = 0.17 \text{ fm}^{-3}$) to a pion condensed state¹³⁾
 - that is a long range spin-isospin ordering in the region $\omega = 0$, $|\vec{q}| \approx 400 \text{ MeV/c}$.

A more realistic calculation recognizes the existence of repulsive, short-range, NN, $N\Delta$ and $\Delta\Delta$ interactions (see Figs. 1(d) and 1(e)). They are conventionally parameterized as a contact interaction of strength g' , the Landau-Migdal parameter - see Ref. 12). This repulsion kills most of the enhancement that would be generated by the rescattering processes of Figs. 1(b), 1(c) and their iterations. As a consequence the density for pion condensation moves well above nuclear matter density ($\rho_c > 3\rho_0$). Nevertheless some enhancement of the pion field in the region $|\vec{q}| \sim 400 \text{ MeV/c}$ should survive.

All of these processes leading to pion emission, as well as Pauli blocking of final states below the fermi surface, can be incorporated through the longitudinal (i.e. $\vec{\sigma} \cdot \vec{q}$ coupling) spin-isospin response function^{12),14),15)}. We take a nuclear matter description which is expected to be good for inclusive reactions on finite nuclei at large momenta. (Momenta less than 200 MeV/c, where such a description is dubious, are quite unimportant.)

The pion distribution function (per nucleon) in a nucleus then has the form

$$\tilde{f}(y) = \frac{3g^2}{16\pi^2} y \int_{m_N^2 y^2}^{\infty} dq^2 \int_0^{q - m_N y} d\omega \frac{q^2 |F(q^2)|^2 R(q, \omega)}{(t + m_\pi^2)}. \quad (4)$$

Here $R(q, \omega)$ is the response to a longitudinal spin-isospin excitation of momentum q and frequency ω - normalized in such a way that the expression for a free nucleon is recovered in a dilute system. We have made the replacement $t \rightarrow q^2$ ($\omega \ll q$) in order to match pion-nucleus phenomenology. Finally, because the response function guarantees that only on-shell final nuclear states contribute, the limits of integration are simply given by the condition that $q^2 > q_3^2$, where q_3 is the component of pion momentum along the direction of the photon. With $y = (q_3 - \omega)/m_N$ this implies $q > \omega + m_N y$.

In the random phase approximation (R. P. A.), including only $1p - 1h$ excitations, the response function (per nucleon) is^{12),14),15)}

$$R(q, \omega) = -\frac{3\pi}{k_F^3} \text{Im} \left\{ \frac{(2m_N^2/q^2 \Gamma(q^2) q^2) \pi(q, \omega)}{[1 - (g' - q^2/(t + m_\pi^2)) \pi(q, \omega)]} \right\}. \quad (5)$$

Here k_F is the fermi momentum, and $\Pi^0(q, \omega)$ is the self-energy of the pion arising from NN^{-1} and ΔN^{-1} excitations (respectively Π_N^0 , Fig. 1(b), and Π_Δ^0 , Fig. 1(c)). (The effects of anti-symmetrization in the ring approximation (Eq.(5)) must be incorporated in the empirical value of g' .) To be explicit, Π_N^0 is given by

$$\Pi_N^0(q, \omega) = 2 (g^2/4m_N^2) \Gamma(q^2) q^2 \Pi_{FW}^0(q, \omega), \quad (6)$$

where Π_{FW}^0 is given by Fetter and Walecka¹⁶⁾. We have also allowed for an effective vertex function, $\Gamma(q^2)$, in the baryon-baryon interaction, which is not necessarily the same as $F(q^2)$ - the latter being a property of one nucleon. (As usual we take $\Gamma(q^2)$ to be quite hard^{11,12)}, a dipole of mass 1.67 GeV.)

For Π_Δ^0 we have used an approximation from pionic atoms^{17,18)}

$$\Pi_\Delta^0(q, \omega) = -4\pi c_0 \rho \Gamma(q^2) q^2, \quad (7)$$

with $c_0 = 0.22 m_\pi^{-3}$. Because this is purely real, the region of response for $1p - 1h$ excitations in the residual nucleus is restricted to NN^{-1} alone. The ΔN^{-1} excitations which lie about 300 MeV higher are ignored. They also have a many-body character, and could in principle modify F_2 . However the cut-off condition $\omega < q - M_y$ restricts this contribution mainly to small x ($x < 0.05$ for a free nucleon)⁴⁾.

In Eq.(5) we have used a single value of g' , however the forces g'_{NN} , $g'_{N\Delta}$ and $g'_{\Delta\Delta}$ play different roles, and need not be equal. After the ω integration the enhancement of $\tilde{f}(y)$ over $f(y)$ comes mainly because of mixing of the ΔN^{-1} states with NN^{-1} . This is controlled by $g'_{N\Delta}$. The mixing between NN^{-1} states (controlled by g'_{NN}) distorts the response from that of a free fermi gas - enhancing it at small ω and quenching it for large ω . However, because we are far from a pion condensed state the average effect is small. We are therefore mainly sensitive to $g'_{N\Delta}$ and to a lesser extent to $g'_{\Delta\Delta}$. In the final analysis we have adopted a conservative attitude and taken $g'_{N\Delta}$ and $g'_{\Delta\Delta}$ as large as g'_{NN} - that is $g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta} \equiv g' = 0.7$ *). The numerical sensitivity to the input parameters will be discussed later.

The pionic contribution to the effective structure function of a nucleon in a nucleus is given by an equation analogous to Eq.(1), with $f(y)$ replaced by

*) In the process considered here we are sensitive to $q \sim 400$ MeV/c, where the values of g' can differ from those at $q = 0$.

$\tilde{f}(y)$. In principle y could run from x to A in a nucleus, because a single pion could carry all the momentum of the nucleus. However, in practice $\tilde{f}(y)$ is very small for $y \gtrsim 0.5$. The pion structure function^{19,20)} is taken to be constant for $x < 0.3$ and then to go as $(1 - x)^2$.

The results of the calculation are displayed in Fig. 2, which shows the fractional increase in the effective nucleon structure function, together with the experimental data. Both the magnitude and the x dependence of the effect are well reproduced. The value of the fermi momentum of Fe was taken as $k_F = 1.30 \text{ fm}^{-1}$. We have also checked that the deuteron does not contribute by more than 1% to the modification of the ratio. (In the deuteron the major modification arises from the interference term between the probability amplitudes for pion emission by the two nucleons, an interference which vanishes in a spin saturated nucleus.)

The sensitivity of the calculation to the input parameters is fairly strong. Consider first the Landau-Migdal parameters. Lowering $g'_{N\Delta}$ to 0.6 from 0.7 raises $\delta F_2(x)$ uniformly by about 30%. (For $g'_{N\Delta} = 0.4$ the enhancement is doubled.) The sensitivity to g'_{NN} and $g'_{\Delta\Delta}$ is weaker for the reasons given above, lowering either of these to 0.6 gives an increase of only 10% in $\delta F_2(x)$. Finally if g' is raised beyond 0.8 the enhancement is killed.

The πNN form factor $F(q^2)$ also plays a crucial role. In Fig. 2 we show the effect of increasing λ from 0.026 to 0.035 (i.e. from $R = 0.7$ to 0.8 fm). This leads to a 25% reduction of the effect. Notice that if the last $NN\pi$ vertex ($F(q^2)$) were made as hard as the effective vertex function $\Gamma(q^2)$ the effect would be more than doubled. However, such hard vertex functions for a single nucleon are ruled out by deep-inelastic scattering data²¹⁾. We consider the results for $R \sim (0.7 - 0.8) \text{ fm}$ the most reliable.

We have also estimated the role of the $2p - 2h$ excitations discussed earlier. Since these have no counterpart for a free nucleon they certainly participate in the enhancement of F_2 . In order to estimate this effect we have used the relationship between $2p - 2h$ excitations and the absorptive part of the p wave pionic atom potential discussed in Ref. 22). Using a reasonable extrapolation of this parameter with energy and momentum, we find that the $2p - 2h$ excitations can easily provide an extra enhancement of 50% over that obtained with the standard parameter set. More details of this estimate will be given in a longer report²³⁾.

In this study of the EMC effect we have concentrated entirely on the small x enhancement. The large x region is both exciting and intrinsically more difficult to deal with. For example, the fermi motion corrections are extremely model dependent^{1),3)}. In addition, as observed by Llewellyn Smith³⁾, because of momentum conservation the presence of additional pions in the nucleus must soften the valence quark distribution. Finally, Jaffe has suggested that the presence of six-quark bags in nuclei would modify the large x behaviour in a way which agrees qualitatively with the data²⁴⁾.

Let us now summarize. We have shown that the EMC enhancement in the region $x < 0.3$ can be explained if there is an attractive force which mixes NN^{-1} and ΔN^{-1} states at momenta of order 300-400 MeV/c. Although it has long been anticipated there has hitherto been no experimental hint that this attractive force exists. Experiments in preparation at LAMPF on the polarization transfer in $(\vec{p}, \vec{p}')$ inclusive scattering should help resolve this issue²⁵⁾.

In the meantime one important test of this mechanism would be provided by its A dependence. Since π_{Δ}^0 is linear in the density, we expect that the enhancement should also be roughly linear. For example, in Fig. 2 we show the effect of lowering k_F to 1.1 fm^{-1} , which is appropriate²⁶⁾ for ^{12}C . This cuts the enhancement in half. Even for ^{20}Ne ($k_F \sim 1.2 \text{ fm}^{-1}$)²⁶⁾ the enhancement is reduced by some 30 %.

We also note that the enhancement of the sea proposed here is in the form of pions and therefore is not $SU(3)_F$ invariant. (This has been used in Ref. 21) to put limits on the cut-off parameter, λ (or R), for a free nucleon.) The CDHS data²⁷⁾, which suggest a greater excess of $\bar{u}$ and $\bar{d}$ over $\bar{s}$ in Fe than in hydrogen, are consistent with this²¹⁾, but the errors are too large to permit a firm conclusion. Finally, we note that in nuclei with a large neutron excess (e.g. ^{208}Pb), the isovector character of the πN interaction means that $\bar{u}d(\pi^-)$ pairs are favoured over $u\bar{d}(\pi^+)$. This may have a signature in inclusive hadron production.

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Figure captions

Fig. 1 Illustration of (a) the basic pion contribution to the nucleon structure function (the $\gamma^* \pi$ vertex involves the structure function of the pion itself); (b) and (c) other coherent processes involving pion rescattering in the nucleus which lead to enhancement for $|\vec{q}| \sim 300\text{--}400 \text{ MeV}/c$; (d) and (e) the phenomenological short-range repulsion which damps the enhancement arising from (b) and (c).

Fig. 2 The fractional increase in the ratio of the structure function in Fe compared with D, as a function of $x (= Q^2/2m_N v)$, caused by the multi-nucleon pion emission graphs of Figs. 1(b) - (e). The data are from the EMC collaboration¹⁾, and the shaded area indicates possible systematic errors. The standard input (solid curve) for Fe is $k_F = 1.30 \text{ fm}^{-1}$, $g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta} = 0.7$, a bag radius of 0.7 fm in $F(q^2)$, and $\Gamma(q^2)$ is a dipole of mass 1.67 GeV. We show in the other curves the effect of altering any single one of these parameters.

- Figure 1 -

- Figure 2 -