Connections among residual strong interaction, the EMC effect and short range correlations

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A linear correlation is shown quantitatively between the magnitude of the EMC effect measured in electron deep inelastic scattering (DIS) and the nuclear residual strong interaction energy (RSIE) obtained from the nuclear binding energy subtracting the Coulomb energy part. The observed correlation supports the recent speculation that the nuclear dependence of quark distributions depend on the local nuclear density. This phenomenological relationship can be used to extract the size of in-medium correction (IMC) effect on deuteron. Most importantly, the EMC slopes $dR_{EMC}/dx$ of nuclei can be predicted with the nuclear binding energy data. The relationship between nucleon-nucleon (N-N) short range correlation (SRC) and RSIE is also presented.

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I. INTRODUCTION

The per-nucleon structure function $F_2^A$ measured on a nucleus ($A > 2$) was first reported to be smaller than that measured on deuterium at intermediate $x_B$ ($0.35 < x_B < 0.7$) by European Muon Collaboration in 1983 [1]. This phenomenon is now commonly referred to as the EMC effect, which was completely unexpected before the experiment. The early expectation was that the per-nucleon lepton DIS cross sections for the nuclear binding energies are subtle compared to the expectation was that the per-nucleon lepton DIS cross sections for the nuclear binding energies are subtle compared to the high momentum components in the nuclear ground-state wave function. Instead of mean-field models, these high-momentum nucleons are produced by the strongly repulsive core of N-N interaction, which are often called the short range correlation. The interpretation for the linear correlation is given that both N-N SRCs and the EMC effect are related to high-momentum (high virtuality) nucleons in the nucleus.

Detailed analysis of the nuclear dependence of the EMC effect and short range correlations is presented in Ref. [10], aimed at testing the possible explanations for the correlation mentioned above. It is proposed that the local density explanation [2] is better than the explanation in terms of high virtuality [7] by comparing the fits to EMC slopes vs $a_2$ and the fits to EMC slopes vs $R_{2N}$. $R_{2N}$ represents the relative probability of a nucleon being part of a short range correlation pair, which is a good description of the average local density. In all, both the high virtuality assumption and the local density explanation hint that the origin of the EMC effect is the N-N residual strong interaction (specifically, the short range correlations). SRCs are from the special and intensive part of the interaction, which can not be explained in the context of the mean field.

As we know, protons and neutrons inside a nucleus are bound together with the residual strong interaction of quarks, which resembles the Van der Waals force between molecules.
The residual strong interaction is so complicated that it cannot be calculated directly from Quantum Chromodynamics (QCD) theory. Fortunately, the strength of residual strong interaction can be weighed by RSIE. In this analysis, RSIE is defined as the energy (mass) loss of nucleons binding together with residual strong interaction. Nuclear binding energy of a nucleus is precisely measured in experiment compared to the EMC and SRC measurements. In order to get the RSIE, the Coulomb repulsive energy needs to be removed from the nuclear binding energy. The residual strong interaction is of short range and it diminishes rapidly with distance. The RSIE is another good description for the local nuclear environment.

Role of nuclear binding in the EMC effect is an important and old issue in the EMC effect study [11, 12]. Usually, the contribution of nuclear binding is believed to be small in the convolution picture [11]. The EMC effect cannot be explained by nuclear binding and nucleon Fermi motion alone. Nevertheless, with new correction to the convolution formula, some [12] argue that the nuclear binding effects may be sufficient to explain the EMC effect at intermediate \( x_B \).

In this paper, the relationships among EMC, SRCs and RSIE per nucleon are investigated.

### II. RESIDUAL STRONG INTERACTION ENERGY AND THE EMC EFFECT

The obtained per-nucleon residual strong interaction energies of various nuclei are shown in Table I. The per-nucleon nuclear binding energies are taken from the world averages of published measurements [13]. The charged protons inside a nucleus repel each other resulting in Coulomb energy, which gives a negative contribution to the nuclear binding. Hence, the RSIE is extracted by the nuclear binding energy removing the Coulomb part.

**TABLE I:** Some of the measured or calculated quantities of studied nuclei. Column 2, 3 and 4 show the data of binding energy per nucleon [13], Coulomb energy per nucleon, RSIE per nucleon, respectively. The last column shows the natural abundance [16] of the nuclide.

| Nucleus | Binding energy per nucleon (MeV) | Coulomb energy per nucleon (MeV) | RSIE per nucleon (MeV) | Natural abundance |
|---------|----------------------------------|----------------------------------|------------------------|------------------|
| Deuteron | 1.112                            | 0.000                            | 1.112                  | 0.0115%          |
| \(^3\)He | 2.573                            | 0.328                            | 2.901                  | 0.000134%        |
| \(^4\)He | 7.074                            | 0.224                            | 7.298                  | 99.999866%       |
| \(^9\)Be | 6.463                            | 0.455                            | 6.918                  | 100%             |
| \(^12\)C | 7.680                            | 0.775                            | 8.455                  | 98.93%           |
| \(^27\)Al | 8.332                           | 1.367                            | 9.699                  | 100%             |
| \(^40\)Ca | 8.551                           | 1.972                            | 10.52                  | 96.94%           |
| \(^56\)Fe | 8.790                            | 2.154                            | 10.94                  | 91.754%          |
| \(^62\)Cu | 8.752                           | 2.300                            | 11.05                  | 69.15%           |
| \(^63\)Cu | 8.757                           | 2.206                            | 10.96                  | 30.85%           |
| \(^107\)Ag | 8.554                           | 3.022                            | 11.58                  | 51.839%          |
| \(^109\)Ag | 8.548                           | 2.948                            | 11.50                  | 48.161%          |
| \(^197\)Au | 7.916                           | 3.817                            | 11.73                  | 100%             |

According to the semi-empirical Bethe-Weizsäcker (BW) mass formula [14, 15], the binding energy of a nucleus of atomic number \( A \) and proton number \( Z \) is described as

\[
B(A,Z) = a_cA - a_sA^{2/3} - a_rZ(Z-1)A^{-1/3} - a_{sym}(A-2Z)^2A^{-1} + \delta
\]

in which \( a_c, Z(Z-1)A^{-1/3} \) is the Coulomb repulsive energy, with \( a_c = 0.71 \text{ MeV} \) from the fit to experimental data of various nuclei. The Coulomb energy is evaluated by taking the nucleus as a liquid spherical charged drop, which is a good approximation. We take the BW mass formula to calculate the Coulomb contribution to the binding. While BW mass formula is of excellent accuracy for heavy nuclei, it fails in describing the very light nuclei and nuclei with magic number. Therefore we take the measured binding energies from experiments in this analysis instead of the calculations from the BW mass formula. Moreover, the measured binding ener-
gies are precise and model independent.

For each chemical element, the binding energy varies with the isotope. In the EMC effect experiments, some of the target elements have more than one stable isotope. For the cases of Cu and Ag, both of the two stable isotopes have big natural abundances (see Table I). The natural abundance data are taken from Ref. [16]. In this analysis, the mean mass numbers and the mean binding energies of Cu and Ag are used.

The strength of the EMC effect is taken as \( dR_{\text{EMC}}/dx \), which is the slope value of the cross section ratio \( R_{\text{EMC}} \) from a linear fit in intermediate \( x_B \) range from 0.35 to 0.7. This definition of the magnitude of the EMC effect is largely unaffected by the normalization uncertainties, which is better than taking the ratio \( R_{\text{EMC}} \) at a fixed value of \( x_B \). The measured EMC slopes of various nuclei in electron DIS at SLAC [5] and Jlab [6] are taken in the analysis, which are listed in Table II. We do not use the data from earlier measurements due to their relatively poor precision or limited \( x_B \) range.

The EMC slopes of different nuclei are shown in Fig. 1(top) as a function of nuclear binding energy per nucleon. The magnitude of the EMC effect is related to the nuclear binding, nonetheless, the correlation between this two quantities is not obvious. A linear fit to the data with the constraint for the deuteron (red dot) is shown in the figure as well. The slope of the linear function is the only free parameter in the fit. The quality of the fit is not good. Fig. 1(bottom) shows the EMC slopes versus per-nucleon RSIEs. Strikingly, a clear linear correlation shows up between this two quantities. The solid line in the plot is a linear fit to the data constrained by the deuteron point. The quality of the fit is good, which has a small \( \chi^2/ndf = 9.4/11 = 0.85 \). The data points of \(^4\)He and Ag are slightly away from the fitted linear line. This is maybe due to the special nuclear structure of \(^4\)He and Ag, or the simple Coulomb energy correction to the RSIE. The slope of the linear relationship is obtained to be \(-0.0393 \pm 0.0014\) from the fit. The formula for the correlation between the EMC slope and the RSIE per nucleon is written as

\[
dR_{\text{EMC}}/dx = \left( \frac{RSIE}{A \, \text{MeV}} \right) - 1.112 \times (-0.0393 \pm 0.0014). \tag{2}
\]

This relationship implies that N-N residual strong interaction plays an important role in the EMC effect.

This amazing correlation allows us to predict the size of the EMC effect for any unmeasured nucleus using the linear relationship from Eq. (2), since the nuclear binding energy is a precisely determined quantity of a nucleus. Further EMC measurements on very light nuclei would be useful to test this correlation.

### Table II: The extracted EMC slopes \( dR_{\text{EMC}}/dx \), SRC scaling factors \( a_2(A/d) \) and SRC ratios \( R_{2N}(A/d) \). The SRC ratios \( R_{2N}(A/d) \) are all corrected for c.m. motion of the pair, and the isoscalar corrections applied to earlier extractions are excluded.

| Nucleus | \( dR_{\text{EMC}}/dx \) (JLab [6]) | \( dR_{\text{EMC}}/dx \) (SLAC [5]) | \( a_2(A/d) \) (JLab [9]) | \( a_2(A/d) \) (SLAC [17]) | \( R_{2N} \) (E02-019 [9]) | \( R_{2N}(A/d) \) (SLAC [17]) | \( R_{2N}(A/d) \) (CLAS [18]) |
|---------|----------------------------------|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(^3\)He | -0.070±0.029                    | 1.7±0.3                         | 2.13±0.04       | 1.93±0.10       | 1.8±0.3         |                  |                  |
| \(^4\)He | -0.199±0.029                    | -0.191±0.061                    | 3.3±0.5         | 3.60±0.10       | 3.02±0.17       | 2.8±0.4         | 2.80±0.28       |
| Be      | -0.271±0.029                    | -0.207±0.037                    | 3.91±0.12       | 3.37±0.17       |                  |                  |                  |
| C       | -0.280±0.029                    | -0.318±0.040                    | 5.0±0.5         | 4.75±0.16       | 4.00±0.24       | 4.2±0.5         | 3.50±0.35       |
| Al      | -0.325±0.034                    | 5.3±0.6                         |                  | 4.4±0.6         |                  |                  |                  |
| Ca      | -0.350±0.047                    |                                 |                  |                  | 5.21±0.20       | 4.33±0.28       |                  |
| Fe      | -0.388±0.032                    | 5.2±0.9                         |                  | 4.3±0.8         | 3.90±0.37       |                  |                  |
| Cu      | -0.496±0.051                    |                                 |                  |                  | 5.16±0.22       | 4.26±0.29       | 4.0±0.6         |
| Ag      | -0.409±0.039                    | 4.8±0.7                         |                  |                  |                  |                  |                  |

This correlation also allows us to extract significant information about the deuteron itself. In the EMC effect measurements, the deuteron is viewed as an approximation to a free proton and neutron system, for the deuteron is loosely bound. However, the deuteron is not a free \( pn \) system accurately. The in-medium correction (IMC) effect, defined as \( a_2^{(A)} = \langle M_{pn}^2 \rangle \), is extracted for the deuteron using the correlation between the EMC effect and SRCs [7, 8, 10]. Similarly, the deuteron IMC effect can be extracted from the extrapolation of the EMC effect to the free \( pn \) pair where the residual strong interaction energy is zero. The intercept is extracted to be \( dR_{\text{EMC}}^{\text{free \( pn \)}}/dx = 0.044 ± 0.002 (RSIE = 0) \) from the linear fit to the correlation between the EMC effect and RSIE per nu-
FIG. 1: The top plot shows the EMC slopes versus the per-nucleon nuclear binding energies, and the bottom plot shows the EMC slopes versus the per-nucleon RSIEs. The solid lines are the linear fits with a constraint for the deuteron.

The ratio \( R_{2N}(A/d) \) represents the contribution of 2N-SRCs to the nuclear wave function, relative to the deuteron, which is extracted after removing the smearing effect of the center-of-mass (c.m.) motion of the 2N-SRC pairs in the nucleus. Most of the observed 2N-SRC pairs are \( pn \) pairs [19]. If \( pp \), \( pn \), and \( nn \) pairs all have equal probability to form high local density configurations, then a good description of high local...
density is \( R_{2N}(A/d)N_{tot}/N_{iso} \), in which \( N_{tot} = A(A - 1)/2 \) and \( N_{iso} = NZ \).

The SRC ratios \( R_{2N}(A/d)N_{tot}/N_{iso} \) with isoscalar correction applied are shown in Fig. 3(top) as a function of per-nucleon nuclear binding energy. The quality of a linear fit to the data with the constraint for the deuteron is not good. The data point of \(^4\text{He}\) is largely away from the fitted line. Fig. 3(bottom) shows \( R_{2N}(A/d)N_{tot}/N_{iso} \) versus the per-nucleon RSIEs. \( R_{2N}(A/d)N_{tot}/N_{iso} \) is roughly correlated to the RSIE per nucleon, from a linear fit with the constraint for the deuteron having \( \chi^2/ndf = 62/14 = 4.4 \). The big \( \chi^2/ndf \) is mainly attributed to the data points of \(^9\text{Be}\) and \(^4\text{He}\). The per-nucleon residual strong interaction energy of \(^9\text{Be}\) is slightly smaller than that of \(^4\text{He}\), however, the SRC ratio \( R_{2N}(A/d)N_{tot}/N_{iso} \) of \(^9\text{Be}\) is bigger compared to that of \(^4\text{He}\).

![Graph](image)

**FIG. 3:** The top plot shows the isoscalar corrected SRC ratios \( R_{2N}(A/d)N_{tot}/N_{iso} \) versus the per-nucleon nuclear binding energies, and the bottom plot shows \( R_{2N}(A/d)N_{tot}/N_{iso} \) versus the per-nucleon RSIEs. The solid lines are the linear fits with a constraint for the deuteron.

| Nucleus | EMC slope | Nucleus | EMC slope |
|---------|-----------|---------|-----------|
| \(^3\text{H}\) | -0.067 ± 0.003 | \(^{10}\text{B}\) | -0.237 ± 0.009 |
| \(^3\text{He}\) | -0.070 ± 0.003 | \(^{11}\text{B}\) | -0.251 ± 0.009 |
| \(^4\text{He}\) | -0.243 ± 0.009 | \(^{12}\text{C}\) | -0.289 ± 0.011 |
| \(^{6}\text{Li}\) | -0.181 ± 0.007 | \(^{40}\text{Ca}\) | -0.370 ± 0.014 |
| \(^{7}\text{Li}\) | -0.189 ± 0.007 | \(^{40}\text{Ca}\) | -0.358 ± 0.013 |
| \(^{9}\text{Be}\) | -0.228 ± 0.009 | \(^{60}\text{Cu}\) | -0.391 ± 0.014 |

**IV. SUMMARY AND DISCUSSIONS**

It is shown that the magnitude of the EMC effect is linearly related to the RSIE per nucleon. This correlation hints that the quark distributions in bound nucleon is modified by the N-N residual strong interaction. With this assumption, the EMC slope of an unmeasured nucleus can be calculated from the precisely measured nuclear binding energy. The approved JLab E12-10-008 [20] and E12-10-103 [21] Experiments for the 12 GeV physics program will measure the nuclear EMC effect from very light to medium heavy nuclei. These provide a good opportunity to test the correlation between the EMC slope and the RSIE. By applying the correlation, the predicted EMC slopes of various nuclei which will be measured at Jlab are shown in Table III. The EMC effect for \(^3\text{H}\) and \(^3\text{He}\) mirror nuclei will be measured in E12-10-103 experiment. The predicted EMC slope of tritium is very close to that of \(^4\text{He}\). A comparison of the EMC effect on \(^{40}\text{Ca}\) and \(^{48}\text{Ca}\) will be made in E12-10-008 experiment for the first time. From the EMC-RSIE correlation, the EMC slope of \(^{48}\text{Ca}\) is slightly smaller than that of \(^{40}\text{Ca}\).

The magnitude of IMC effect on deuteron is extracted, which is in consistent with the value obtained from local density explanation fit. The local density assumption for the origin of the EMC effect is favored. The obtained IMC slope on deuteron is 0.044 ± 0.002, which is smaller than early extrapolation from correlation between \( a_2(A/d) \) and the EMC effect.

What is the role of the RSIE in the EMC effect? As we know, the total modification of the nuclear parton distribution functions can not be explained by the binding model, for the binding energy per nucleon is small. Furthermore, the average nuclear binding peaks at \( A = 56 \), while the EMC effect continues to grow in heavier nuclei. In the latter binding models the nucleon has an average separation energy \( < \epsilon > \) and a momentum \( \beta \). The separation energy can be subsumed into
an effective nucleon mass, thus causing a shift in the scaling variable $x_B = Q^2/(2M\nu)$ towards higher values. However this approach is criticized for two problems: the incorrect normalization of the relativistic spectral function and the method of $\langle \epsilon \rangle$ determination [2–4]. Afterwards, it was found that there is no significant binding effect in relativistic mean field models by Birse [22] and Miller [23]. We find that it is the strong interaction part of the binding that the magnitude of the EMC effect scales with, by comparing the fit to EMC slopes vs nuclear binding energy and the fit to EMC slopes vs RSIE. The EMC effect is a QCD effect rather than the binding effect.

The linear correlation between the per-nucleon RSIE and the N-N short range correlation is not obvious. Note that the uncertainty of Coulomb energy correction is not considered. There may be a rough correlation between RSIE per nucleon and $R_{2N}(A/d)N_{tot}/N_{iso}$. The RSIE is one of the basic properties of a nucleus, which is a general and global description of the N-N strong interaction. The N-N SRCs are the special and intense part of it. The poor linear correlation between this two quantities is not unexpected.

Various correlations related to the EMC effect are observed. We should be careful when we try to explain these correlations. The N-N residual strong interaction plays an important role in the EMC effect. The RSIE per nucleon is a good description for the average local density, since residual strong interaction is of short range. RSIE represents the magnitude of the nuclear force, which is powerfully attractive between nucleons at distances of about 1 femtometer and decreases rapidly with distance increasing. The linear correlation between the RSIE and the EMC slope supports that the local nuclear environment is an important factor for the EMC effect.

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