Nucleon mass in nucleon-nucleon short range correlations and the EMC effect

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We determine the nucleon mass in nucleon-nucleon short range correlations (SRC) and the number of pn-SRC pairs in deuterium from the SRC ratio measurements, under the assumption that the nucleon mass in SRC is universal among the different nuclei, for the first time. The nucleon mass in two-nucleon SRC is \( m_{SRC} = 852 \pm 18 \) MeV, and the number of pn-SRC pairs in deuterium is \( n_{SRC}^d = 0.021 \pm 0.005 \). With the nucleon virtuality in SRC pairs determined, the EMC effect of various nuclei are predicted using a \( x \)-rescaling model. The nucleon virtuality in nucleon-nucleon SRC pairs is not enough to explain the EMC effect. The modification of mean-field nucleon or the short-distance configurations formed with more than two nucleons are speculated in order to agree the measured EMC effect of heavy nucleus.

I. INTRODUCTION

Nucleon-Nucleon Short-Range Correlations (NN SRC) depicts the strong overlapping of wave functions of two nucleons, which attracts a lot of experimental interests, for NN SRC is a new phenomenon that is beyond the description of the mean field [1–9]. The nucleons in NN SRC pairs are strongly interacted at a very short-distance of about 0.6 fm. Kinematically, the two nucleons inside SRC pair have big relative momenta, while the center-of-mass (c.m.) momentum of the pair is small which nears the Fermi momentum [3–7]. The nucleons in SRC pairs have big momenta while the mass of SRC pair is limited, hence the nucleons in SRC pairs are of high virtuality. The SRC pairs probably affects the nucleon structure greatly. The experimental evidences come from the exclusive [10, 11] and inclusive measurements [12, 13] of quasi-elastic scattering between the probe and the SRC pair. The exclusive measurements find that about 90% NN SRC pairs are proton-neutron pairs [5, 9, 10, 15], which can explains the high momentum tail in proton-neutron imbalance system.

Furthermore, NN SRC has a connection with the EMC effect. The nuclear EMC effect describes the depletion of the nuclear structure function in the valence region under a high \( Q^2 \) probe [16–18]. The linear correlation [19, 20] between the EMC effect and the NN SRC hints that these two phenomena have the same dynamical origin. A naive speculation is that only the nucleon in SRC pairs has the EMC effect, while the mean-field nucleon is nearly unmodified [14, 22, 23]. Since the nucleon in SRC pairs has high virtuality, a \( x \)-rescaling model is easily performed to the SRC nucleon if the off-shellness is determined [24, 25]. In order to calculate the average nuclear structure function \( F_2 \), we also need to know the number of NN SRC pairs inside the nuclear medium [1, 2, 5, 12].

In this paper, we try to determine the nucleon mass in NN SRC pairs as well as the number of SRC pairs in different nuclei, using some simple approximations (Sec. II). If the virtuality of nucleon matters for the EMC effect, we try to use a \( x \)-rescaling model to predict the EMC effect under the assumption that only nucleons inside SRC pairs are modified (Sec. IV). A short discussion is given in Sec. V.

II. DETERMINATION OF THE NUCLEON MASS IN SRC PAIRS AND THE NUMBER OF SRC PAIRS IN DEUTERON

In the electron-nucleus scattering, the SRC ratio \( a_2 \) connects to the relative number of SRC pairs per nucleon if the scattering at \( x_B \sim 2 \) is only attributed to the scattering between the electron and the SRC pairs. Therefore the number of SRC pairs in a nucleus is expressed as the product of the measured SRC ratio \( a_2 \) and the number of SRC pairs in deuterons, which is shown as Eq. (1):

\[
a_2 = \frac{n_{SRC}^A/A}{n_{SRC}^d/2}, \tag{1}
\]

\[
n_{SRC}^A = A \times a_2 \times \frac{n_{SRC}^d}{2}. \tag{2}
\]

In an approximation, we assume that both the nucleon mass in SRC pairs (\( m_{SRC} \)) and the nucleon mass in mean-field (\( m_{MF} \)) are universal values for any nuclei. Then the nucleon mass is decomposed into two terms (see Eq. (2)). Eq. (3) shows the decomposition in terms of the per-nucleon nuclear mass.

\[
M(A, Z) = 2n_{SRC}^A m_{SRC} + (A - 2n_{SRC}^A) m_{MF}. \tag{3}
\]
\[ M(A, Z) / A = m_{MF} + a_2 n^d_{SRC}(m_{SRC} - m_{MF}). \tag{3} \]

For deuteron, the SRC ratio \( a_2 \) is one, hence we have a constraining condition, the Eq. (4), for the nuclear mass decomposition Eq. (5).

\[ \frac{M^d}{2} = m_{MF} + n^d_{SRC}(m_{SRC} - m_{MF}). \tag{4} \]

From Eq. (4), we get \( m_{MF} \) as an expression of \( n^d_{SRC} \) and \( m_{SRC} \). Substituting \( m_{MF} \) with the expression of \( n^d_{SRC} \) and \( m_{SRC} \) to Eq. (6), finally we get the per-nucleon nuclear mass as a function of \( a_2 \), in terms of two parameters, \( n^d_{SRC} \) and \( m_{SRC} \) (see Eq. (5)).

\[ \frac{M(A, Z)}{A} = \frac{M^d}{2(1 - n^d_{SRC})} - \frac{n^d_{SRC}}{2} m_{SRC} \]
\[ + a_2 \left[ \frac{n^d_{SRC}}{1 - n^d_{SRC}} m_{SRC} - \frac{M^d n^d_{SRC}}{2(1 - n^d_{SRC})} \right]. \tag{5} \]

The nuclear mass as a function of \( a_2 \) is shown in Fig. 1. The nuclear masses are taken from Refs. [26, 27], and the \( a_2 \) data are taken from the combination of the two analyses [14, 20]. A linear fit is performed to the mass-\( a_2 \) correlation using Eq. (5). All the present measured data are more or less sit around the fit. The quality of the fit is obtained to be \( \chi^2/N = 95/9 = 10.5 \). The nucleon mass in SRC pair is obtained to be \( m_{SRC} = 0.915 \pm 0.019 \ u = 852 \pm 18 \ MeV \), and the number of SRC pairs in deuteron is obtained to be \( n^d_{SRC} = 0.021 \pm 0.005 \). Applying Eq. (4), we get the mean-field nucleon mass \( m_{MF} = 1.009 \pm 0.005 \ u = 939.9 \pm 5 \ MeV \). We guess there are two reasons that the quality of the fit is not good. The first is that the mean-field nucleon mass is not a universal value for all the nuclei. The second is that there are more terms in addition to the nuclear mass decomposition in Eq. (2), such as the nucleon mass in multiple nucleon short range correlations (more than two nucleons). If we exclude the data of \(^3\)He and \(^4\)He in performing the fit, the quality of the fit is \( \chi^2/N = 9.1/7 = 1.3 \).

The number of SRC pairs in deuteron is an interesting quantity, which tells us the probability of the nucleon being in a SRC configuration. From our fit, the nucleon in deuteron has the around 21% probability forming into a SRC pair. This value is also given by the calculation using AV18 nucleon-nucleon potential. We adopt \( n^d_{SRC} = 0.022 \) from calculations with the momentum distribution above 2 \( fm^{-1} \) (394 MeV/c) by using AV18. Using Eq. (1), we calculate the number of pn-SRC pairs in \(^{12}\)C to be \( n^A_{SRC} = 0.58 \), with the obtained \( n^d_{SRC} = 0.021 \). Based on our analysis, there are 10% of the nucleons in \(^{12}\)C that are in the SRC configuration, which is about the half of the previous estimation [3][12]. We find that the number of nucleons in SRC pairs is defined as the number of nucleons of high momenta \( k > k_F \approx 275 \ MeV/c \). In this definition, there may be a small fraction of mean-field nucleons miss-regarded as the SRC nucleons.

### III. THE EMC EFFECT FROM THE PN-SRC PAIRS

With the nucleon mass in NN-SRC pairs obtained, we apply a \( x \)-rescaling model to evaluate the EMC effect of various nuclei. A naive assumption is that only the valence quark distributions inside NN-SRC pairs are modified, while the valence quark distribution in the mean-field nucleon is the same as that in the free nucleon. The second assumption is that the valence quark distributions of NN-SRC inside different nuclei are the same distributions, which means that the NN-SRC configuration is an universal structure. This is suggested by the scaling observed in the region of \( 1.4 < x_B < 2 \) [28]. With this simple picture, the nuclear structure function is written as,

\[ F_2^A = \left[ n^A_{SRC} F_2^{p \text{ in SRC}} + n^A_{SRC} F_2^{n \text{ in SRC}} \right] + \left( Z - n^A_{SRC} \right) F_2^p + \left( A - Z - n^A_{SRC} \right) F_2^n / A, \tag{6} \]

in which \( n^A_{SRC} \) can be estimated using Eq. (1). \( F_2^p \) is provided by a lot of global analyses such as CT14 [29] and CJ15 [30]. \( F_2^n \) is easily got from parton distributions of proton under the isospin symmetry between the proton and the neutron, as \( u^p = d^n \) and \( d^p = u^n \). For the convenience of discussion, we refer the above model that only SRC nucleon is modified as the model-1.

The structure function of the nucleon in SRC pairs is predicted with the \( x \)-rescaling model. The momentum fraction \( (x = Q^2/(2m^*\nu)) \) of the quark inside the SRC nucleon is different from the Bjorken scaling variable \( x_B = Q^2/(2m\nu) \) in experiments. \( m^* \) is the effective nucleon mass inside SRC pairs, and \( m \) is the free nucleon.
mass. In a $x$-rescaling model, the momentum fraction of the quark equals to the Bjorken variable times a rescaling factor, i.e., $x = x_B^\eta$ with $\eta = m/m^* \ [24]$. Therefore, the structure function of the nucleon in SRC pairs is written as,

$$F^p_{2 \text{ in SRC}}(x, Q^2) = F^p_2(x\eta, Q^2),$$

$$F^n_{2 \text{ in SRC}}(x, Q^2) = F^n_2(x\eta, Q^2).$$

(7)

With the nucleon mass in SRC pairs determined in Sec. II, the $\eta$ for NN-SRC is 1.1.

The predictions of the EMC ratios of light nuclei are shown in Fig. 2. The experimental data is from JLab Hall C \[31]\). $Q^2$ is 5.3 GeV$^2$ in the calculations to be consistent with the experiment.

FIG. 2. The predicted EMC ratios from a $x$-rescaling model are shown with the experimental data (light nuclei). The experimental data is from JLab Hall C \[31]\). $Q^2$ is 5.3 GeV$^2$ in the calculations to be consistent with the experiment.

IV. THE EMC EFFECT FROM THE PN-SRC PAIRS AND THE MEAN-FIELD NUCLEONS

As the modification of pn-SRC pairs only is not enough to produce the EMC effect, we come up with the model that both the SRC nucleon and the mean-field nucleon are modified. To calculate the EMC effect, we also apply the $x$-rescaling to the mean-field nucleon. Different from the situation for SRC nucleon, the rescaling factor $\eta_{MF}$ for mean-field nucleon inside different nuclei are different, for the densities of different nuclei are different. In order to get the rescaling factor $\eta_{MF}$, we perform the least square fits to the EMC effect data in the range of 0.35 < $x_B$ < 0.65. The obtained $\eta_{MF}$ are listed in Table I. For the convenience of discussion, we refer the model that both SRC nucleon and mean-field nucleon are modified as the model-2. In model-2, $\eta_{MF}$ of deuteron is simply one. The $\eta_{MF}$ of $^{208}$Pb is determined to be 1.022, and it is much smaller than the rescaling factor of SRC nucleon. The EMC effect predictions of model-2 are shown in Figs. 2 and Fig. 3. Obviously, the model-2 explains the EMC effect successfully.

Furthermore, let’s take a look at the nuclear dependence of the rescaling factor $\eta_{MF}$ for the mean-field nucleon. The correlations between $\eta_{MF}$ and $ln(A)$, $\eta_{MF}$ and the nucleon density, $\eta_{MF}$ and the proton density are shown in Fig. 3. The nucleon density and proton density are calculated using $A/(\frac{1}{2} \pi R^3)$ and $Z/(\frac{1}{2} \pi R^3)$ respectively, in which $R$ is the charge radius of a nucleus. The data of nuclear charge radii are taken from Ref. [32]. Since the radius of the neutron distribution in the nucleus may not be the same as the charge radius, that is why we also plot the correlation between $\eta_{MF}$ and the proton density of the nucleus. Although the linear correlation is not perfect, the rescaling factor $\eta_{MF}$ of the mean-field
nucleon is more or less correlated with the nucleon density.

TABLE I. The rescaling factor $\eta_{MF}$ for the mean-field nucleon (not in Short-Range Correlation) are listed. In this model, modifications of both the SRC nucleon and the mean-field nucleon generate the EMC effect. The error comes only from the fit to the EMC effect data. The uncertainty of $n_{SRC}^0$ and $a_2$ are not included.

| nucleus     | $\eta_{MF}$       | nucleus     | $\eta_{MF}$       |
|-------------|--------------------|-------------|--------------------|
| $^4$He       | 1.008 ± 0.001      | $^6$Be      | 1.005 ± 0.002      |
| $^{12}$C     | 1.016 ± 0.002      | $^{27}$Al   | 1.021 ± 0.002      |
| $^{56}$Fe    | 1.027 ± 0.001      | $^{208}$Pb | 1.022 ± 0.002      |

FIG. 4. The correlations among the rescaling factor $\eta_{MF}$ of mean-field nucleon, $\ln(A)$, the nucleon density, and the proton density.

FIG. 5. The predicted EMC ratios from a $x$-rescaling model are shown with the experimental data (heavy nuclei), with $n_{SRC}^0 = 0.041$ [12] and that the mean-field nucleons are not modified. The experimental data is from CLAS [14]. $Q^2$ is 2 GeV$^2$ in the calculations to be consistent with the experiment.

result suggests there are 10% nucleons that are in pn-SRC configurations, for the nucleus $^{12}$C.

In addition to the extraction of the NN-SRC mass, we also studied the EMC effect taking the nucleon mass in SRC pairs in a $x$-rescaling model. However the modified valence structure in NN-SRC is not enough to explain the EMC effect observed in experiments, if the $x$-rescaling model is correct. We find that the number of pn-SRC pairs in deuteron is estimated to be $n_{SRC}^d = 0.041$ by K. S. Egiyan et al. [12], which is much larger than the value from our analysis. In Fig. 5 we show the predicted EMC ratios using the $x$-rescaling model, assuming only the nucleons in pn-SRC pairs are modified, and taking the SRC $a_2$ data from experiments [14, 20] and $n_{SRC}^d = 0.041$ [12]. The predicted EMC slopes are smaller than the data by CLAS collaboration. Therefore, based on either our estimation on SRC numbers or the estimation by K. S. Egiyan et al., the pn-SRC nucleons only are not enough to interpret the EMC effect. We speculate that more origins of modified nucleon from short-distance configurations are necessary, such as 3N-SRC and $\alpha$ clusters. Another possible interpretations are either the mean-field nucleon is noticeably modified, or the NN-SRCs in different nuclei have different structures. For a preliminary exploration, We have shown that the EMC effect can be explained if we just assume that the mean-field nucleon is also modified.

V. DISCUSSIONS AND SUMMARY

We have obtained the nucleon mass in NN-SRC pairs, which shows that the nucleon in SRC has a big virtually around 87 MeV. Moreover, we also get the number of NN-SRC pairs in deuteron to be 0.021, from the correlation between the nuclear mass and the SRC ratio $a_2$. Our

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