Comment on “Searching for flavor dependence in nuclear quark behavior”

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Weinstein, et. al [1] [PRL 106, 052301 (2011)] and Hen, et. al [2] [PRC 85, 047301 (2012)] observed a correlation between the EMC effect and the amount of short range correlated (SRC) pairs in nuclei which implies that quark distributions are different in SRC pairs as compared with free nucleons. Schmookler, et. al [3] [Nature 566, 354 (2019)] bolstered this by showing that the EMC data can be explained by a universal modification of the structure of nucleons in neutron-proton SRC pairs and presented the first data-driven extraction of this universal modification function (UMF).

Arrington and Fomin [4] [arxiv 1903.12535] attempt to gain insight into the correlation between the EMC effect and SRCs by distinguishing between correlated nucleon pairs at high-virtuality (HV) vs. high local-density (LD). However, there is an inconsistency in their derivations of the UMFs, $F_{LL}$ and $F_{LD}^{uni}$, causing a non-physical difference between them for asymmetric nuclei. In addition, the combinatorial scaling they used to extract high-LD np, pp and nn pairs from measured HV np pairs is contradicted by realistic ab-initio Quantum Monte-Carlo (QMC) calculations.

Ref. [4] attempts to study universal pair modification functions (UMF) for two cases: high-virtuality (HV) np-SRC pairs and SRC pairs at high local density (LD). High-LD NN pairs are defined as having small separation with either high or low relative momenta. HV pairs have both high momentum and small separation, making them a subset of high-LD pairs.

I. UNIVERSAL FUNCTION DERIVATION

Eq. 1 in Ref. [4] was derived in [3] by modeling $F_A^{2n}$ as:

$$F_A^{2n}|_{HV} = (Z - n_{npHV}^{A}) F_{2n}^P + (N - n_{npHV}^{A}) F_{2n}^N$$
$$+ n_{npHV}^A (F_{2n}^{pHV} + F_{2n}^{nHV})$$
$$= Z F_{2n}^P + N F_{2n}^N + n_{npHV}^A (\Delta F_{2n}^{pHV} + \Delta F_{2n}^{nHV}),$$

where $n_{npHV}^A$ is the number of HV np-SRC pairs in nucleus $A$, $F_{2n}^{pHV}$ and $F_{2n}^{nHV}$ are the modified proton and neutron structure functions, and $\Delta F_{2n}^{pHV} = F_{2n}^{pHV} - F_{2n}^P$ (and similarly for the $\Delta F_{2n}^{nHV}$). All of the functions $F$ depend on $x = Q^2/2m\omega$. This assumes that almost all HV (i.e., high momentum) nucleons belong to np-SRC pairs and neglects the contribution of nn and pp pairs. This approximation was shown experimentally and theoretically to be good to better than 10% [5]. The corresponding UMF is given by:

$$F_{uni}^{HV} = n_{npHV}^d \frac{\Delta F_{2}^{pHV} + \Delta F_{2}^{nHV}}{F_2^P}$$
$$= \frac{F_2^A}{F_2} - (Z - N) \frac{F_2^P}{F_2} - N$$

Ref. [4] compares $F_{uni}^{HV}$ with what they claim to be an equivalent expression for the high-LD assumption $F_{uni}^{LD}$. Their function, Eq. 2 of Ref. [4], can be obtained by assuming the UMF is related to the modified EMC-SRC correlation between the slope of $R_A^{EMC}$ for $0.3 \leq x_B \leq 0.7$ and $R_A^{EMC} = \frac{A}{2N} \frac{A - 1}{Z}$. However, there is no theoretical justification for equating this expression with the left-hand side of Eq. 2. Thus, it cannot be consistently compared with $F_{uni}^{HV}$.

To consistently compare $F_{uni}^{HV}$ and $F_{uni}^{LD}$, Eq. 1 needs to be re-written for high-LD pairs, which include nn $(n_{nn}^{A,LD})$ and pp $(n_{pp}^{A,LD})$ pairs:

$$F_{2n}^{A}|_{LD} = (Z - n_{npld}^{A} - 2n_{ppld}^{A}) F_{2n}^P +$$
$$\quad (N - n_{npld}^{A} - 2n_{npld}^{A}) F_{2n}^N +$$
$$n_{npld}^{A} (F_{2n}^{ppld} + F_{2n}^{npld}) + 2n_{ppld}^{A} F_{2n}^{ppld} + 2n_{npld}^{A} F_{2n}^{npld}$$

$$\quad = Z F_{2}^P + N F_{2}^N +$$
$$\quad n_{npld}^{A} [(1 + \frac{Z - 1}{N}) \Delta F_{2}^{ppld} + (1 + \frac{N - 1}{N}) \Delta F_{2}^{npld}],$$

where $n_{npld}^{A} = n_{npld}^{A} \frac{Z(Z-1)}{2NZ}$, $n_{npld}^{A} = n_{npld}^{A} \frac{N(N-1)}{2NZ}$. As $\Delta F_{2}^{ppld}$ and $\Delta F_{2}^{npld}$ have different nucleus-dependent coefficients, unless one assumes a constant relation between them, Eq. 3 cannot be used to extract
an equivalent UMF to $F_{univ}^{HV}$ (i.e. equation that has the same left-hand side as Eq. 2).

If instead we assume symmetric nuclei ($N = Z$) we get Eq. 2 of Ref. [4]:

$$F_{univ}^{LD} = n_{nPLD}^d \frac{\Delta F_{p}^{PLD} + \Delta F_{n}^{PLD}}{F_{2}^{d}} = \frac{E_{A}^{4}/A^{2} - 1}{2NZ R_{2}} (4)$$

Therefore, the difference between $F_{univ}^{HV}$ and $F_{univ}^{LD}$ comes primarily from the use of Eq. 4 (that is only comparable to $F_{univ}^{HV}$ for symmetric nuclei) for asymmetric nuclei. This is done by defining the isoscalar-corrected EMC ratio $R_{EMC}^{A} = E_{A}^{4}/A^{2}/\chi_{isospin}$ and assuming that $R_{EMC}^{A}$ for asymmetric nuclei equals $E_{A}^{4}/A^{2}$ for a symmetric nucleus with the same $A$ but $Z = A/2$.

This assumption is unjustified, especially if the EMC effect in asymmetric nuclei is flavor-dependent. Moreover, it is not consistently applied to $F_{univ}^{HV}$, which leads to an artificial difference between $F_{univ}^{HV}$ and $F_{univ}^{LD}$. This difference is largely driven by the $(Z - N)E_{pp}^{4}/F_{2}^{d}$ term that was artifically removed from $F_{univ}^{LD}$, but not from $F_{univ}^{HV}$. This is inconsistent with the flavor dependence being studied and casts doubt on the entire HV LD comparison of Ref. [4].

In addition, Arrington and Fomin logarithmically fit the $A$-dependence of the slopes of $F_{univ}^{HV}$ and $F_{univ}^{LD}$ (Fig. 3 [4]) in order to show which one is more consistent with $A$-independence. However, they failed to note that a one-parameter constant fit to $dF_{univ}^{HV}/dx$ already gives a $\chi^{2}$/dof of 0.83 and their two-parameter over-fitting gives $\chi^{2}$/dof of 0.34 (Fig. 1). For $F_{univ}^{LD}$ constant and logarithmic fits give reduced $\chi^{2}$/dof of 1.3 and 1.5 respectively, again indicating that a constant fit is more appropriate [7].

II. COMBINATORIAL SCALING

The combinatorial relations assumed for $n_{nPLD}^{d}$, $n_{nPLD}^{n}$, and $n_{ppPLD}^{A}$ are also questionable. LD and HV correspond to different dynamical pictures as HV pairs are predominantly $D$-wave while high-LD have increased $S$-wave contributions.

Ref. [4] assumes the high-LD ratio of $np$ pairs to $pp$ pairs, $\rho_{np}^{A}(r)/\rho_{pp}^{A}(r)$, equals $NZ/[Z(Z - 1)]/2 \approx 2$ for symmetric nuclei. However, ab-initio calculations for $^{12}$C, $^{16}$O and $^{40}$Ca [3,9] indicate that this ratio is only 2 at large-$r$ ($> 3$ fm), but increases at small-$r$ ($< 1$ fm) by a factor of 2 to 4 (see Fig. 2), implying a much smaller $pp$ and $nn$ pair contribution at small-$r$.

Therefore the contribution of high-LD $pp$ and $nn$ pairs should be reduced from the simplistic combinatorial calculation by a factor of 2 to 4, reducing the difference between $F_{univ}^{HV}$ and $F_{univ}^{LD}$ from a factor of 2.5 to about 1.5. Furthermore, in the spin-0 channel, even for asymmetric nuclei, calculations show the same abundances of small-$r$ $nn$, $pp$, and $np$ pairs, contrary to combinatorial expectations [11].

Recent work [12] even showed that $NN$-pair scaling coefficients at small-$r$ are the same for a remarkable range of $NN$ potentials (i.e. they are scale- and scheme-independent) and consistent with measured values of $a_{2}(A/d)$ without requiring any combinatorial scaling.

III. PAIR C.M. MOTION CORRECTIONS

Ref. [4] also distinguish between scaling of HV and high-LD pairs by defining separate scale factors: $a_{2}$ (HV) and
$R_2$ (high-LD). The two are related by a multiplicative factor arising from the center of mass (c.m.) motion of SRC pairs.

c.m. motion effects can increase the measured $(e,e)$ cross-section ratio that is used to extract $a_2$. Correcting for this enhancement is reasonable. However, it should be applied in the extraction of the relative number of either high-LD or HV pairs and requires detailed modeling of the nuclear spectral function $^{[13]}$. The application of this correction only for the high-LD case, again, leads to an artificial difference between the two approaches.

Quantitatively, Ref. $^{[10]}$ estimated the c.m. correction to be 20% for medium and heavy nuclei, using a simplistic one-dimensional smearing of the deuteron momentum distribution. This procedure ignored the three-dimensional nature of the problem and, most importantly, the phase-space correlations that significantly affect the measured electron scattering cross section. A more detailed study $^{[15]}$, accounting for these and other effects, suggested a 70% correction factor.

IV. HV VS. LD SCALING

QMC calculations extract pair distributions in both coordinate ($\rho^{NN,\alpha}_{N,N,\alpha}(r)$) and momentum space ($\eta^{NN,\alpha}_{N,N,\alpha}(k)$). These densities were shown to both factorize as $^{[10]}$, $^{[11]}$, $^{[14]}$ $^{[16]}$ $^{[22]}$:

$$\eta^{NN,\alpha}_{N,N,\alpha}(k > k_F) = C^{A}_{NN,\alpha} \times |\psi_{NN,\alpha}(k)|^2,$$
$$\rho^{NN,\alpha}_{N,N,\alpha}(r < 1 fm) = C^{A}_{NN,\alpha} \times |\psi_{NN,\alpha}(r)|^2,$$

where $\alpha$ marks the pair spin-isospin state and $\psi_{NN,\alpha}$ are zero-energy solutions of the two-body Schrodinger equation for state $\alpha$. Their $k$- and $r$-space representations are related by a Fourier transform that does not change their normalization. $C^{A}_{NN,\alpha}$ are nucleus-dependent scale factors that (A) account for the many-body dynamics and (B) are the same in both $k$- and $r$-space for all spin-isospin channels. This single scaling factor at both small distance and large momentum is inconsistent with the Ref. $^{[4]}$ concept of small-$r$, low-$k$ correlated pairs.

Eq. $^5$ was shown $^{[10]}$, $^{[11]}$, $^{[14]}$ to reproduce QMC calculations at high-$k$ and small-$r$ to 10% for $A = 4, 40$ nuclei and describes electron-scattering data using the same scaling factors $C^{A}_{NN,\alpha}$ as obtained from the QMC calculations.

Therefore, ab-initio calculations do not support the existence of different high-$k$ and small-$r$ scaling factors as used by Ref. $^{[4]}$, shown complete physical equivalence in the many-body dynamics of HV and high-LD pairs.

V. CONCLUSIONS

The underlying cause of the EMC effect is an open question with far reaching implications for our understanding of QCD effects in the nuclear medium. The original observations of the EMC-SRC correlation $^{[1]}$ and UMF extraction $^{[3]}$, raises an interesting and relevant question about the mechanism driving this physics.

We explained that inclusive electron scattering data fundamentally cannot answer this question and pointed to a collection of quantitative issues with the analysis of Ref. $^{[4]}$.

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