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Short Range Correlation in Nuclei

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Atomic nuclei are made of protons and neutrons, themselves composed of quarks and gluons. New high-energy electron-scattering studies of close-proximity nucleons in nuclei indicate that their internal quark-gluon structure is different from that of free nucleons.

KEYWORDS: SRC, EMC effect, High-Momentum nucleons, QE, DIS

1. Introduction

The study of short-range correlations (SRC) is a broad subject, covering a large body of experimental and theoretical work, as well as phenomenological studies of the implications of SRCs for other phenomena in nuclear, particle and astro-physics. A full discussion of SRC physics is available in a recent RMP review [1] and a recent theory-oriented review [2]. Here will concentrate on one aspect of the SRC study, its connection to the EMC effect.

Short Range Correlations (SRC) are brief fluctuations of nucleons in nuclei to form pairs with high relative momentum. We show here that the EMC data can be explained by a modification of the structure of nucleons in neutron–proton SRC pairs and present a data-driven extraction of the corresponding universal modification structure function.

The internal quark–gluon substructure of nucleons was originally expected to be independent of the nuclear medium because quark interactions occur at shorter-distance and higher-energy scales than nuclear interactions. However, DIS measurements indicate that quark momentum distributions in nucleons are modified when nucleons are bound in atomic nuclei [1, 3-5], breaking down the scale separation between nucleon structure and nuclear structure. Although evidence for such modification, known as the EMC effect, was first observed over 35 years ago, there is still no generally accepted explanation for its cause.

2. SRC in nuclei

Over the last decade, we have learned a remarkable amount about SRCs from measurements of exclusive hard knockout reactions, A(e, e’N) and A(e, e’pN) [6-10] (here N stands for neutron or proton), from selected nuclei (^{4}He, C, Al, Fe and Pb). The electrons in these reactions interacted with protons or neutrons in the target nucleus via a high-momentum transfer reaction ($Q^2 > 1.7 - 2$ $(\mathrm{GeV}/c)^2$), leading to the knockout of a high-momentum nucleon and, in certain events, the simultaneous emission of a correlated recoil nucleon.

The first such exclusive measurements of SRC pair breakup reactions were performed using hadronic (proton) [11, 12] and electronic [8, 13] probe on Carbon. The main results of these studies are:

- About 20% of all knocked-out protons with missing-momentum (reconstructed initial momentum in the absence of re-interactions) in the range of 300-600 MeV/c, have an associated recoil nucleon with a momentum that balances the missing momentum. These were named "Short-Range Correlated pairs".

- Neutron-proton (np) pairs are nearly 20 times more prevalent than proton-proton (pp) pairs, and by inference, also than neutron-neutron (nn) pairs.

- The relative momenta of the SRC pairs, as reconstructed from the missing and recoil-nucleon momenta, are higher than k_F, while the c.m. momenta are lower (k_F is the nuclear Fermi momentum, typically about 250 MeV/c for medium to heavy nuclei). The latter was observed to be consistent with a Gaussian distribution with characteristic width of about 170 MeV/c [14].

One common interpretation of these results is that the nucleon momentum distribution above k_F is dominated by np-SRC pairs [32, 1, 2, 8, 11-13]. The predominance of np-SRC pairs over pp-SRC pairs suggests that the tensor part of the NN interaction is dominant at the probed distances [1, 2, 29-31]. The tensor interaction is proportional to the total spin of the pair, S. As such, S = 1 states (spin-symmetric states with both spins pointing in the same direction) are preferred over the S = 0 (the equivalent spin-asymmetric) states. As SRC pairs are primarily in a relative S- or D-wave (i.e. even L, symmetric configuration), their isospin must be zero (asymmetric) due to the Pauli principle. Therefore, the tensor force favors np-SRCs, which have an asymmetric isospin component, suppressing contributions from pp-SRC (and nn-SRC) pairs.

3. SRC and EMC

The first experimental evidence supporting the SRC-modification hypothesis as an explanation for the EMC effect came from comparing the abundances of SRC pairs in different nuclei with the magnitude of the EMC effect. They both increase from light to heavy nuclei, with a linear correlation between them [17, 18]. This suggests that the EMC effect might be related to the high-momentum nucleons in nuclei. The later was shown to be dominated by SRC pairs, mainly neutron-proton pairs.

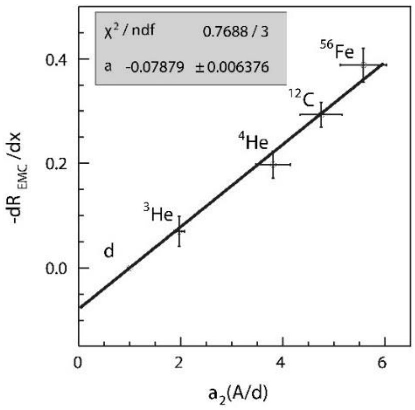

Fig. 1. The EMC slopes versus the SRC scale factors. The uncertainties include both statistical and systematic errors added in quadrature. The fit parameter is the intercept of the line and also the negative of the slope of the line. Figure adapted from [17]. Notice that $a_2(A/d)$ is referred below as a_2.

We analyzed experimental data taken using CLAS (CEBAF Large Acceptance Spectrometer [19] at the Thomas Jefferson National Accelerator Facility (Jefferson Laboratory). A 5.01-GeV electron beam impinged upon either a liquid deuterium target or foils of either C, Al, Fe or Pb. The scattered electrons were detected in CLAS over a wide range of angles and energies, which enabled the extraction of both quasi-elastic (QE) and deep inelastic scattering (DIS) reaction cross-section ratios of nucleus A to deuteron over a wide kinematical region. The results are shown in Fig. 2.

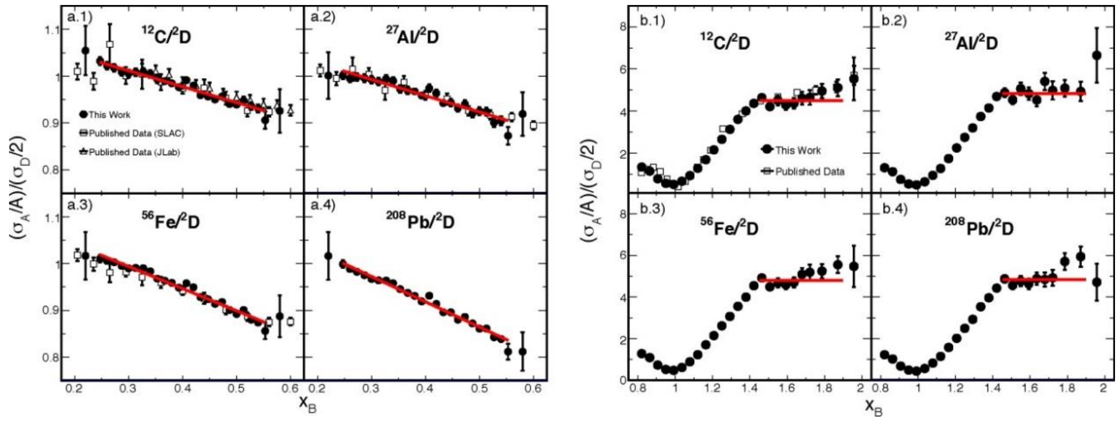

Fig. 2. DIS and QE (e,e′) cross-section ratios. **a1) – a4),** Ratio of the DIS per-nucleon electron scattering cross-section of nucleus A ($0.2 \leq x_B \leq 0.6$ and $W \geq 1.8$ GeV). Solid points are measurements of [20], the open squares – SLAC data [27] and the open triangles show Jefferson Laboratory data [28]. The red lines show a linear fit.
b1) – b4) are corresponding ratios for QE kinematics ($0.8 \leq x_B \leq 1.9$). The solid points - data obtained in [20] and the open squares the data of ref. [22]. The red lines show constant fit. The error bars shown include both statistical and point-to-point systematic

uncertainties, 1σ or 68% confidence level. The figure was adapted from [20].

The DIS cross-section on a nucleon can be expressed as a function of a single structure function, $F_2(x_B, Q^2)$. In the parton model, x_B represents the fraction of the nucleon momentum carried by the struck quark. $F_2(x_B, Q^2)$ describes the momentum distribution of the quarks in the nucleon.

Motivated by the correlation between the magnitude of the EMC effect and the SRC-pair density ratio (a_2), we model the modification of the nuclear structure function, F_2^A for nucleus A, as entirely caused by the modification of np SRC pairs in that nucleus.

$$F_2^A = Z \cdot F_2^p + N \cdot F_2^n + n_{SRC}^A \cdot (\Delta F_2^p + \Delta F_2^n) \quad (1)$$

where n_{SRC}^A is the number of np SRC pairs in nucleus A, F_2^p, F_2^n are the free-proton and free-neutron structure functions, ΔF_2^p, ΔF_2^n are the average modified structure functions for protons and neutrons in SRC pairs, which are assumed to be the same for all nuclei.

Since there are no model-independent measurements of the neutron structure function, we then rearrange equation (1) to depend on the deuteron structure function

$$\frac{n_{SRC}^d \cdot (\Delta F_2^p + \Delta F_2^n)}{F_2^d} = \frac{\frac{F_2^A}{F_2^d} - (Z-N) \cdot \frac{F_2^p}{F_2^d} - N}{(A/2) \cdot a_2 - N} \quad \textbf{(2)}$$

Where F_2^p / F_2^d has been previously extracted [21] and a_2 is the measured per-nucleon cross-section ratio shown by the red lines in Fig. 2b.1-4. Here we assume that a_2 approximately equals the per-nucleon SRC-pair density ratio between nucleus A and deuterium [1, 22-26].

Because $\Delta F_2^p + \Delta F_2^n$ is assumed to be nucleus-independent, our model predicts that the left-hand side of the equation above should be a universal function (that is, the same for all nuclei). This means that the nucleus-dependent quantities on the right-hand side of the equation above combine to give a nucleus-independent result.

This is shown in Fig. 3. The left panel of Fig. 3 shows the per-nucleon structure-function ratio of different nuclei relative to deuterium. The approximately linear deviation from unity for $0.3 \le x_B \le 0.7$ is the EMC effect, which is larger for heavier nuclei. The right panel shows the relative structure modification of nucleons in np SRC pairs, extracted using the right-hand side of the equation above.

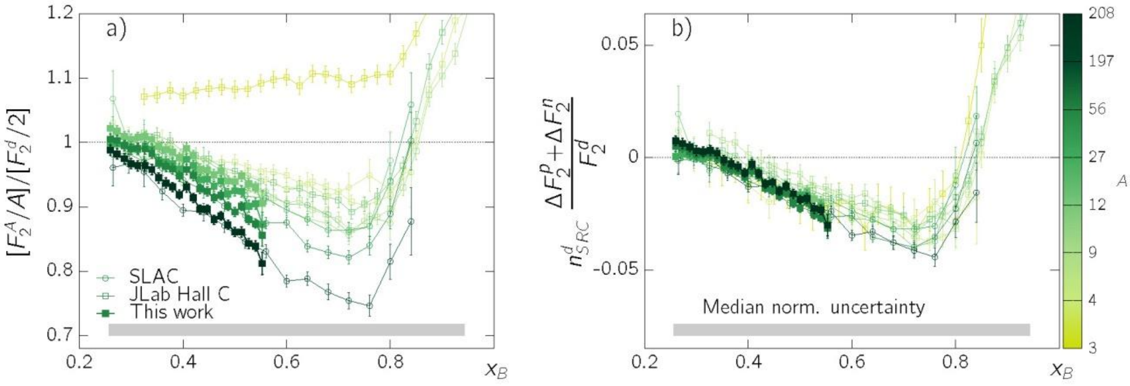

Fig. 3. Universality of SRC-pair quark distributions. a), b) The EMC effect for different nuclei, as observed as a function of x_B (a), and the modification of SRC pairs, as described by the equation above (b). Different gray levels correspond to different nuclei, as indicated by the gray scale on the right. The open circles show SLAC data [27] and the open squares show Jefferson Laboratory data [28]. The nucleus independent (universal) behavior of the SRC modification, as predicted by the SRC-driven EMC model, is clearly observed. The error bars show both statistical and point-to-point systematic uncertainties, both at the 1σ or 68% confidence level. The grey bands show the median normalization uncertainty at the 1σ or 68% confidence level. Figure adapted from [20].

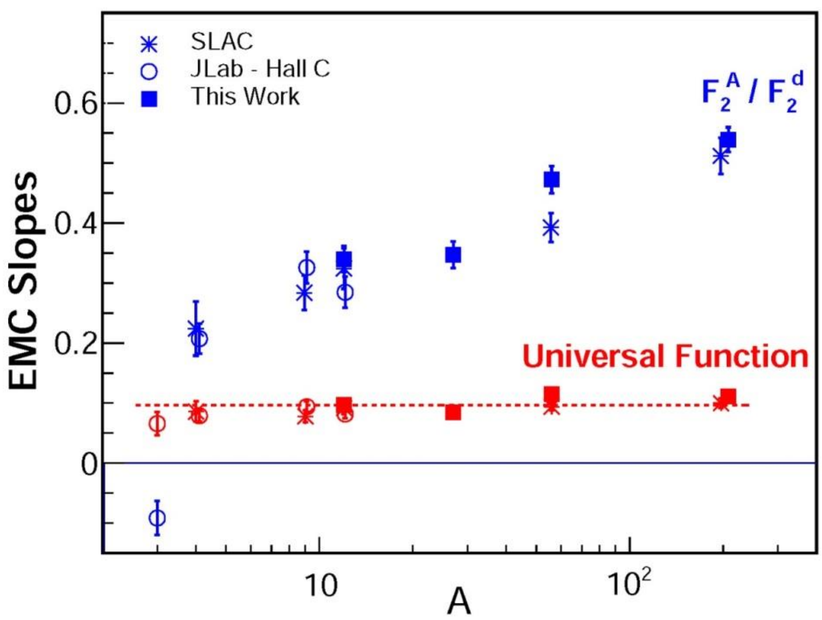

Fig. 4. EMC and universal modification function slopes. The slopes of the EMC effect for different nuclei from Fig. 2a and of the universal function from Fig. 2b. The error

bars shown include the fit uncertainties at the 1σ or 68% confidence level. Figure adapted from [20].

The EMC slope for all measured nuclei increases monotonically with A whereas the slope of the SRC-modified structure function is constant within uncertainties. Thus, we conclude that the modification function is in fact universal. This universality appears to hold even beyond $x_B = 0.7$.

4. Conclusion

The association of the EMC effect with SRC pairs implies that the EMC is a dynamical effect. Most of the time, nucleons bound in nuclei have the same internal structure as that of free nucleons. However, for short time intervals during which two nucleons form a temporary high-local-density SRC pair, their internal structure is briefly modified. When the two nucleons disassociate, their internal structure again becomes similar to that of free nucleons. This dynamical picture differs markedly from the traditional static modification in the nuclear mean field, which has been previously proposed as an explanation for the EMC effect.

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