Future directions for probing two and three nucleon short-range correlations at high energies

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Abstract. We summarize recent progress in the studies of the short-range correlations (SRC) in nuclei in high energy electron and hadron nucleus scattering and suggest directions for the future high energy studies aimed at establishing detailed structure of two-nucleon SRCs, revealing structure of three nucleon SRC correlations and discovering non-nucleonic degrees of freedom in nuclei.

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INTRODUCTION

The short-range nucleon correlations (SRC) for decades were considered to be important though elusive feature of nuclear structure. These correlations lead to presence of the high momentum tail in the nucleus wave function and they are responsible (in medium and heavy nuclei) for $\geq 60\%$ of the kinetic energy of nucleons in the nuclei.

However the SRC are averaged over in the low energy processes and could be hidden in the parameters of the effective 2N, 3N interaction, effective mass of the nucleon, etc. Such averaging leads to successful description of many low energy phenomena - effective field theories. However it results in the wave functions with very small high momentum tails and most of the kinetic energy of nucleons originating from the mean field. This is qualitatively different from the realistic nuclear wave functions with SRCs.

Many attempts to probe SRC in the 50’s and 60’s failed to separate SRC from effects of meson exchange currents, production of $\Delta$ -isobars in the intermediate state, etc. Moreover a no-go theorem was suggested by Amado\(^1\) which states that it is in principle impossible to observe the high momentum component of the nucleus. On the contrary, starting with our first analysis in 1975 \(^2\) we argued that inconclusive results of the previous searches were due to insufficient energy/momentum transfer in the studied reactions, leading to complicated structure of primary interaction, enhancement of the final state contributions. We suggested \(^2,3\) that a way out is to use the processes with large energy-momentum transfer:

$$q_0 \geq 1\text{GeV} \gg |V_{NN}^{SR}|, \bar{q} \geq 1\text{GeV}/c \gg 2k_F. \quad (1)$$

Adjusting resolution scale as a function of the probed nucleon momentum (which is similar to the strategy used in the high energy QCD to probe the parton structure of hadrons) allows to avoid the no-go theorem \(^1\).
Consequently, one can use high energy probes to address fundamental questions of microscopic quark-gluon structure of nuclei and nuclear forces: (i) microscopic origin of intermediate and short-range nuclear forces, (ii) precision of approximation of the bound nucleon wave functions by free nucleon wave functions, (iii) probability and structure of the short-range correlations in nuclei, (iv) presence and structure of non-nucleonic degrees of freedom in nuclei.

WHAT WAS LEARNED ABOUT SHORT-RANGE CORRELATIONS IN THE LAST FEW YEARS

During the last three years a qualitative progress in the study of SRC was reached based on the analysis of the high momentum transfer \((e,e')\) Jlab data \([4, 5]\), the \((p,2pn)\) BNL data \([6, 7]\), the \((e,e'pp)\) \([8]\) and \((e,e'pn)\) Jlab data \([8, 9]\). SRC are not anymore an elusive property of nuclei!

The results of the theoretical analysis of these experimental findings (practically all of which were predicted before the data were obtained) can be summarized as follows (for a detailed review see \([10]\)):

- More than \(~ \sim \sim \sim \sim \sim 90\%\) of all nucleons with momenta \(k \geq 300\) MeV/c belong to two nucleon SRC correlations.
- Probability for a given proton with momenta \(600 \geq k \geq 300\) MeV/c to belong to a \(pn\) correlation is \(~ \sim \sim \sim \sim 18\) times larger than to belong to a \(pp\) correlation.
- Probability for a nucleon to have momentum \(\geq 300\) MeV/c in medium nuclei is \(~ \sim \sim \sim \sim 25\%\).
- \(2N\) SRC mostly build of two nucleons not of six quark configurations, or \(\Delta N, \Delta\Delta\) which constitute no more than \(20\%\) of the \(2N\) SRCs.
- Three nucleon SRC are present in nuclei with a significant probability.

The findings confirm our predictions based on the study of the structure of SRC in nuclei \([11, 3, 12, 13]\), and add new information about isotopic structure of SRC. In particular, they confirms our interpretation of the phenomenon of the fast backward hadron emission observed in the 70’s-80’s in a number of high energy \(\gamma, \pi, \nu\mu, p,\) nucleus - nucleus experiments as to due to SRC. Thus we can now use information from these experiments for planning new experiments which would allow unambiguous interpretation of \(j \geq 3\) SRCs.

The progress in the studies of SRC which led to the findings summarized above is primarily due to the application of two concepts:

(a) **Validity of the partial closure approximation for the inclusive \((e,e')\) processes at \(x > 1, Q^2 \geq 1.5\, \text{GeV}^2\)**. We find that in this kinematics only final state interactions (fsi) at the longitudinal distances \(\leq 1.2\) fm do not cancel out \([13]\) in the inclusive cross section. At the same time the local fsi’s occur within the SRCs and hence are universal and cancel in the ratios \([3, 13, 10]\). Recently \([10]\) we developed a systematic method to calculate the fsi at large \(Q\) using generalized eikonal approximation (GEA) \([14]\). We find that interactions of knocked out nucleon with slow nucleons changes cross section by less than few \%.
(b) Use of hard exclusive processes where a nucleon of SRC is removed instantaneously. Such processes probe another quantity sensitive to SRC - nuclear decay function [11, 3, 12] - probability to emit a nucleon with momentum \( k_2 \) after removal of a fast nucleon with momentum \( k_1 \), leading to a state with excitation energy \( E_r \). In the nonrelativistic limit the decay function can be defined as

\[
D_A(k_2,k_1,E_r) = |\langle \phi_{A-1}(k_2,\ldots) | \delta(H_{A-1} - E_r) a(k_1) | \psi_A \rangle|^2.
\]

The general principle which governs the properties of the decay function for large momenta of the removed nucleon is that to release a nucleon "1" from say two nucleon SRC it is necessary to remove a nucleon "2" from the same correlation - to perform a work against potential \( V_{12}(r) \).

This property of local singular interactions leads to an operational definition of the SRC: nucleon belongs to SRC if its instantaneous removal from the nucleus leads to emission of one or two nucleons which balance its momentum. Following this definition we include in SRC not only correlations due to the repulsive core but also the ones due to the tensor force interactions. For 2N SRC one can model decay function as decay of the \( NN \) pair moving in mean field (like for spectral function in [15]) [7]. The studies of the spectral and decay functions of \(^3\text{He}\) [16] reveal both 2N and 3N SRC and confirm the pattern of the decay of the correlations described above. It is worth noting here that in the applications to the calculations of the observables it is important to use the light-cone decay functions as they automatically take into account the recoil effects - conservation of the light cone fractions. If nucleon momenta are in the nonrelativistic domain the light-cone decay function is close to nonrelativistic decay function.

So far no methods were developed which would allow to calculate decay functions for \( A > 4 \). However the decay function and another interesting characteristics of the nuclear structure, the two nucleon momentum distribution in the nuclei, which can be calculated for a large range of nuclei [17,18] are close for \( \vec{k}_1 + \vec{k}_2 = 0, k_1 \gg k_F \) though this similarity should break down with increase of \( |\vec{k}_1 + \vec{k}_2| \).

**DIRECTIONS FOR STUDY OF TWO NUCLEON SHORT-RANGE CORRELATIONS IN NUCLEI**

Further 2N correlation studies in inclusive (e,e’) reactions and via study of the decay processes are necessary. In the case of the (e,e’) reactions studies of the isospin dependence of the cross sections would complement the studies of the p/n ratio in the decay reactions. In the decay processes one needs to focus on the high energy kinematics with minimal fsi between nucleons of the 2N SRC. One needs to perform factorization tests for 2N SRC - namely study the removal of a nucleon at different \( Q \) and by different probes and demonstrate that decay function is universal. Experience of BNL and Jlab experiments appears to demonstrate that it is easier to move to larger momentum transfer kinematics with hadronic projectiles. Minimal program would be to study forward - backward correlations for a range of light nuclei \(^3\text{He} \& ^4\text{He}\) in \( A(e,epp) \) and \( A(e,epm) \) at Jlab at \( Q^2 = 2 \div 4\text{GeV}^2 \) and at the proton facilities (J-PARC, GSI) with protons of energies starting at 6 GeV. It will be necessary to investigate the A-dependence of the
pp/pn ratio, its dependence on momentum of the hit nucleon. This would require statistics which is at least a factor of 100 higher than in the current experiments.

LIGHT-CONE WAVE FUNCTIONS OF NUCLEI

There is a price to pay for use of high energy processes: high energy process develops along the light cone (LC). Hence similar to the perturbative QCD the amplitudes of the processes are expressed through LC wave functions of the probed system. At the same time for the nonrelativistic momentum component in nuclei and for 2N SRC correspondence with nonrelativistic wave functions is unambiguous and rather simple due to the angular condition \[19, 3, 12\]. Many features of nonrelativistic quantum mechanics hold - number of degrees of freedom and dynamic variables remain the same, though the relations between wave functions and the amplitudes become somewhat different. At the same time logic of quantum mechanics does not map easily to the language based on the virtual particles - transformational vacuum pairs lead to extra degrees of freedom. For example, in the LC model the deuteron is described by two (S- and D-) wave functions while in the Bethe-Salpeter model one has to introduce four (for one nucleon off shell) wave functions.

One can define the single nucleon LC wave function \( \rho_A(\alpha, p_t) \) where \( \alpha \) is the LC fraction carried by a nucleon scaled to \( A (\sum_{i=1}^{A} \alpha_i = A) \). One can also define LC spectral function, \( \rho^N_A(\alpha, p_t, M^2_{rec}) \) which after account of the angular momentum conservation (angular condition) depends on two variables like the nonrelativistic spectral function. The LC spectral function enters into description of \( (e, e') \) at large \( Q^2 \) and \( x > 1 \). Early validity of the closure for \( x < 2 \) leads to possibility to use the relation \( \int d^2 M^2_{rec} \rho^N_A(\alpha, p_t, M^2_{rec}) = \rho^N_A(\alpha, p_t) \). Also for production of fast backward nucleon in the high energy hadron - nucleus scattering we find

\[
\frac{d\sigma^{h+A \rightarrow N+X}}{d\alpha d^2p_t} = \kappa_h A \sigma_m^N \rho^N_A(\alpha, p_t), \tag{3}
\]

where factor \( \kappa_h \sim 1 \) which is a weak function of \( \alpha \) accounts for local screening effects in the interaction of the projectile with the SRC.

Since the NN interaction is sufficiently singular for large nucleon momenta, \( \rho^N_A(\alpha, p_t) \) can be expanded over contributions of j-nucleon correlations as \[12\]:

\[
\rho^N_A(\alpha > 1.3, p_t) = \sum_{j=2}^{A} \rho_j(\alpha, p_t), \tag{4}
\]

where \( \rho_j(\alpha, p_t)(j-\alpha)^{(j-1)+j-2} \) and \( \rho_j(\alpha, 0) \propto (2 - \alpha)^n \). Note that the LC density matrix behavior at large \( \alpha \geq 2 \) is determined by multinucleon correlations while in the nonrelativistic case the \( k \rightarrow \infty \) asymptotic of the the momentum distribution, \( n(k) \) is due to two nucleon correlations.
DIRECTIONS FOR STUDY OF THREE NUCLEON SHORT-RANGE CORRELATIONS IN NUCLEI

Current evidence for the presence of the three nucleon correlations comes from the study of the production of fast backward nucleon production at $\alpha \geq 1.5$ and from the scaling of the ratios of the $(e,e')$ cross sections at $3 > x > 2$ for $^3\text{He}/^4\text{He}$ [12] and for a wider range of nuclei in [4]. Also, the theoretical studies of the three nucleon wave functions have revealed configurations in the spectral and decay functions which are determined by the three nucleon correlations [16, 10].

Currently a dedicated Jlab experiment is approved to study 3N correlations for $x > 2$. The range of the $Q^2$ will be rather limited and accuracy of the scaling relations in the kinematics of the experiment requires further theoretical studies.

FIGURE 1. Quasielastic scattering of electron (proton) off 3N SRC with production of two backward nucleons.

One of the possible ways to study 3N correlations would be to investigate processes where a projectile knocks out a forward moving nucleon of the nucleus and one detects two nucleons emitted backward (Fig.1).

One expects (i) $\alpha_1^\text{Back.Nucl} + \alpha_2^\text{Back.Nucl}\alpha_3^\text{Forw.Nucl} \approx 3$, (ii) similar rate of $ppn$ and $nnp$ events (when corrected for a different elementary cross section of projectile proton / neutron interaction) and much smaller rate for $nnn$ and $ppp$ events due to dominance of the $I = 0$ 2N correlations which build up 3N correlations (similar trend is expected due to the contribution of the three nucleon forces), (iii) strong correlation of the transverse momenta of the backward nucleons - the transverse angle $\psi$ between directions of the transverse momenta $k_1$ and $k_2$ of two backward nucleons. Most of the events should have $\psi \sim \pi$, while the yield for $\psi \sim 0$ should be strongly suppressed because for the parallel emission of two backward nucleons the LC invariant mass for the three nucleon system is much larger.

The last expectation is in a qualitative agreement with the studies of the inclusive process $p + A \rightarrow pp + X$ at $p_{\text{inc}} = 7.5$ GeV/c where correlation function

$$R_2 = \frac{1}{\sigma_{pA}^{\text{in}}} \frac{d\sigma(p + A \rightarrow pp + X)/d^3p_1d^3p_2}{d\sigma(p + A \rightarrow p + X)/d^3p_1d\sigma(p + A \rightarrow p + X)/d^3p_2}$$

was measured for a fixed azimuthal angle $\theta = 120^\circ$. $R_2$ was found to drop strongly for the angles $\psi$ deviating from $\pi$. A detailed analysis of these data will be presented elsewhere.
HOW TO DISCOVER THE STRUCTURE OF NONNUCLEONIC BARYONIC DEGREES OF FREEDOM IN NUCLEI

What is the domain in momentum space where description of NN correlations in terms of nucleonic degrees of freedom maybe justified? If this momentum range is small and too many states should be included in the decomposition over hadronic states, the Fock representation

$$|D\rangle = |NN\rangle + |NN\pi\rangle + |\Delta\Delta\rangle + |NN\pi\pi\rangle + \ldots$$

would be useless.

In view of limited knowledge of details of the dynamics of the off shell NN interactions we have to use experimental information on NN interactions at energies below few GeV and the chiral dynamics combined with the following general quantum mechanical principle - *relative magnitude of different components in the wave function should be similar to that in the NN scattering at the energy corresponding to off-shellness of the component.*

Important simplification of the dynamics is due to the structure of the final states in NN interactions: direct pion production is suppressed for a wide range of energies due to chiral properties of the NN interactions [12]:

$$\frac{\sigma(NN \rightarrow NN\pi)}{\sigma(NN \rightarrow NN)} \approx \frac{k_N^2}{16\pi^2F_{\pi}^2}, F_{\pi} = 94\ \text{MeV}. \quad (5)$$

Consequently, the main inelasticity for NN scattering for \(T_p \leq 1\) GeV is single \(\Delta\)-isobar production which is forbidden in the deuteron channel where inelastic threshold corresponds to production of two \(\Delta\)-isobars i.e. to \(k_N = \sqrt{m_{\Delta}^2 - m_N^2} \approx 800\) MeV/c ! For the I=1 channel the single \(\Delta\) production threshold corresponds to \(k_N \approx 500\) MeV/c. (Note that the correspondence argument for connection between wave functions of bound state and continuum is not applicable for the cases when the probe interacts with rare configurations in the bound nucleons due to the presence of an additional scale.)

To summarize: pn and pp correlations are predominantly build of nucleons with an 10\(\div\)20 % accuracy. Thus exotic components (6q, \(\Delta\) -isobars) should be corrections even in SRC where energy scale is larger than for the mean field configurations and internucleon distances are < 1.2 fm.

The EMC effect for 0.3 < \(x\) < 0.7 unambiguously indicates presence of non-nucleonic degrees of freedom in nuclei. (Claims to the opposite are due to the violation of baryon or energy-momentum conservation or both). Also the Drell-Yan experiments observe no enhancement of the pion field. Hence it appears that looking for exotic baryonic degrees of freedom is the most promising strategy.

According to the correspondence logic for large nucleon momenta admixture of configurations containing \(\Delta\)-isobars should not be too small as the energy denominators for NN and \(N\Delta\) intermediate states become comparable. The hard probes should resolve intermediate states with \(\Delta\)’s which are usually hidden in the definition of the NN potential.

Few possible strategies for looking for baryonic non-nucleonic degrees of freedom are
(a) looking for spectator $\alpha_\Delta \geq 1$ production. Selection of events with $x > 0.1$ leads to a very strong suppression of two step mechanisms [3]. In fact the best limit on the probability of $\Delta^{++}\Delta^-$ component in the deuteron $< 0.2\%$ comes from the neutrino experiment performed in this kinematics [21]. The study of $\Delta$ production in the $\alpha \geq 1$ kinematics provides the only possible experimental evidence for presence of the spectator $\Delta$'s in nuclei. The experiment was performed using DESY AGRUS data on electron - air scattering at $E_e=5$ GeV [22]. The $\Delta^{++}/p, \Delta^0/p$ ratios for the same light cone fraction $\alpha$ were measured:

$$\frac{\sigma(e+A \rightarrow \Delta^0 + X)}{\sigma(e+A \rightarrow \Delta^{++} + X)} = 0.93 \pm 0.2 \pm 0.3,$$

$$\frac{\sigma(e+A \rightarrow \Delta^{++} + X)}{\sigma(e+A \rightarrow p + X)} = (4.5 \pm 0.6 \pm 1.5) \cdot 10^{-2}.$$

Clearly, CLAS is in a good position to check this result and get by far superior data.

(b) Knock out of $\Delta^{++}$ isobars in electron scattering at sufficiently large $Q^2$. Examples of good channels are $e + ^2H \rightarrow e + \text{fast } \Delta^{++} + \text{slow } \Delta^-$, $e + ^3He \rightarrow e + \text{fast } \Delta^{++} + \text{slow } nn$.

One can perform similar studies using hadronic projectiles in the kinematics where projectile experiences a large angle elastic scattering off a constituent of the nucleus, for example $p+A \rightarrow \Delta^{++} + p + (A-1)$. An important tool for analysis of this process and for separation of the one step and two step processes is measurement of the $\alpha_\Delta$ distribution which is much broader for the one step processes of scattering off exotic components off the nucleus.

## CONCLUSIONS

Impressive experimental progress of the last three years - discovery of strong short range correlations in nuclei with strong dominance of I=0 SRC, proves validity of the strategy of using high momentum transfer processes for probing SRCs. It provides a solid basis for further experimental studies.

There are many theoretical challenges in the studies of the SRC including calculation of the decay functions, study of the isotopic effects for SRC, calculating admixture of isobars, study of the relativistic effects. Further investigations are also necessary of the fsi dynamics. This would allow to find optimal kinematics for probing SRCs, and understanding the role of the color transparency effects. The Generalized Eikonal Approximation (GEA) (see review in [23]) provides a good starting point for such analyses. GEA allows also include in a consistent way fsi of the produced isobars. It would be important to perform experimental tests of GEA in the kinematics where isobar fsi’s are maximal.

Several experiments to probe SRC are under way/ been planned for 12 GeV. One would need also more coherence in the program and complementary studies using hadron beams.

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