Nucleon close encounters

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FIAS/Univ. Frankfurt colloquium, July 1, 2010
Outline

Introduction: Puzzling nuclei - a view from QCD angle - 1975

Why high energies are necessary to probe short-range structure of nuclei

Structure of short-range NN correlations in nuclei and concept of the decay function

Direct observations of short-range correlations using high energy probes

Examples of Implications: neutron stars & heavy ion collisions

Strategies for further studies - with emphasize on current GSI capabilities (fipi, panda-test-facility, HADES) and FAIR (PANDA, CBM,...) potential.
Leonya Frankfurt (LF) and me - both with background in particle physics became interested in nuclei in mid 74. Quarks have been seen - definitively - DIS, J/ψ.

**Where are quarks in nuclei?**

Before QCD - paradox - strength of meson nucleon interaction increases with virtuality in the meson-nucleon field theoretical models: zero charge (Landau) pole is present at rather small virtualities. No trace of this effect in NN and πN interactions. Even without the zero charge pole - interaction is very strong - why nucleus is not a meson soup?

For $r_{NN} < 1.5$ fm difficult to exchange a meson; valence quarks of two nucleons start to overlap.

Perhaps a quark soup for $r_{NN} < 1.2$ fm?

Quark kneading (FS75) became popular under name six quark bags.
Our prime motivation was: quarks were seen in DIS - large momentum transfer processes - can one perform similar program in nuclei and see constituents of the nucleus?

On experimental side: first data on large $Q^2$ momentum transfer reactions with deuteron emerged only a year later. However there was a puzzle in hadronic interactions.

Modern formulation (actual measurements at fixed targets with proton, photon, pion nuclear beams):

Consider collision of nuclei $A_1$ and $A_2$ at a collider - RHIC with $E_A/A=100$ GeV

- nucleons $E_N$ up to 300 GeV are observed
- shape of the spectra for $A=^4$He and $A=^Pb$ are practically same up to 200 GeV
Use hard nuclear phenomena to answer fundamental questions of microscopic quark-gluon structure of nuclei and nuclear forces

- Are nucleons good nuclear quasiparticles?
- Microscopic origin of intermediate and short-range nuclear forces
- Probability and structure of the short-range correlations in nuclei
- What are the most important non-nucleonic degrees of freedom in nuclei?
• Microscopic origin of intermediate and short-range nuclear forces
  - do nucleons exchange mesons or quarks/gluons? Duality?

\[ p_n = \pi^+, \rho^+,... \]

Meson Exchange
extra antiquarks in nuclei

Quark interchange
no extra antiquarks

Prediction \( \bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2 \bigg|_{x=0.05\div0.1} \)

Drell-Yan experiments: \( \bar{q}_A/\bar{q}_N \sim 0.97 \)

A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90. Similar conclusions Eskola et al 93-07 analyses
• Are nucleons good nuclear quasiparticles?

Successes of nuclear physics build on description of nucleus as a multinucleon system - “explanation” of 70’s - treat nucleus as a Landau-Migdal Fermi liquid theory with nucleons as quasiparticles (close connection to mean field approaches) - should work for processes with energy transfer \( \sim E_F \) and momentum transfer \( q \sim k_F \). Nucleon effective masses \( \sim 0.7 \, m_N \), strong quenching for \( A(e,e'p) \) processes: suppression factor \( Q \sim 0.6 \).

Short range correlation (SRC) effects are hidden in parameters of the quasiparticles

Migdal & Khodel told us - SRC could be 10% or 50% does not matter

Similar logic in the chiral perturbation theory / effective field theory approaches - very careful treatment at large distances \( \sim 1/m_{\pi} \), exponential cutoff of high momentum tail of the NN potential
In QCD a hidden parameter (FS 75-81): in NN interactions: direct pion production is suppressed for a wide range of energies due to chiral properties of the NN interactions:

\[
\frac{\sigma(NN \rightarrow NN\pi)}{\sigma(NN \rightarrow NN)} \approx \frac{k_\pi^2}{16\pi^2 F_\pi^2}, \quad F_\pi = 94\text{MeV}
\]

⇒ Main inelasticity for NN scattering for \(T_p \leq 1\) GeV is single \(\Delta\)-isobar production which is forbidden in the deuteron channel.

**Correspondence argument:** wave function - continuum ⇒ Small parameter for inelastic effects in the deuteron/nucleus WF, while relativistic effects are already significant since \(v/c \sim 1\)

- Correspondence argument 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.

Logic of quantum mechanics does not map easily to the language of virtual particles - transformational vacuum pairs. At the same time language of QM does not match space-time development of high energy processes which are usually light-cone dominated.

⇒ Relativistic (light-cone) treatment of the nucleus (FS76) - price of switching from nonrelativistic to light-cone quantum mechanics is not very high: in broad kinematic range a smooth connection with nonrelativistic description of nuclei (more complicated structure of the scattering amplitude). Will use relativistic approach when absolutely necessary.

**Use of LC was our biggest mistake - for years frightened many of nuclear theorists**
Best chance to find new physics is to focus on the studies of configuration in nuclei where nucleons are close together and have large momenta - short-range correlations (SRC)

**Popular perceptions about SRC:**

- SRC is elusive feature of nuclei - cannot be observed

  ✓ **Wrong** - problem was due to use of low energy probes

- SRC small correction to any characteristic of nuclei - exotic feature - of no importance

  ✓ **Wrong** - $>60\%$ of kinetic energy of nucleons for $A \geq 50$ is due to SRC, strong influence of the excitation spectrum (more examples in the end of the talk)

- Can predict properties of the core of neutron stars based on studies of nuclei using mean field

  ✓ **Wrong** - Very different strength of pp and pn SRC, practical disappearance of the Fermi step for protons for $\rho(\text{neutron star}) > \rho(\text{nuclear matter})$
Questions:

Probability of SRC?  Isotopic structure  Non-nucleonic components

Dominant contribution for large $k$; 2N SRC: universal (A-independent up to isospin effects) momentum dependence

$$|p_1| < p_F$$  $$|p_2| < p_F$$

Two nucleon SRC

Short-range NN correlations (SRC) have densities comparable to the density in the center of a nucleon - drops of cold dense nuclear matter

Connections to neutron stars:

a) $|l|=1$ nn correlations,
b) admixture of protons in neutron stars $\rightarrow |l|=0$ sensitivity
c) multi-nucleon correlations
Properties of SRCs

Realistic NN interactions - NN potential slowly (power law) decreases at large momenta -- nuclear wf high momentum asymptotic determined by singularity of potential:

\[ \psi^2_D(k)|_{k \to \infty} \propto \frac{V^2_{NN}(k)}{k^4} \]

D-wave dominates in the Deuteron wf for \( 300 \text{ MeV/c} < k < 700 \text{ MeV/c} \)

D-wave is due to tensor forces which are much more important for pn than pp.

Tensor forces are singular enough - in terms of manifestations very similar to shorter range correlations - so we refer to both of them as SRC.

Large differences between in \( n_D(p) = \psi^2_D(p) \) for \( p > 0.4 \text{ GeV/c} \) - absolute value and relative importance of S and D waves between currently popular models though they fit equally well pn phase shifts. Traditional nuclear physics probes are not adequate to discriminate between these models.
Similarly for \( n_A(k) = \int \prod_{i=A}^i d^3 k_i \psi_A^2(k_i) \delta^3(k - k_1) \)

\[
n_A(k)_{k \to \infty} \propto \frac{V_{NN}^2(k)}{k^4}
\]

\[\implies n_A(k) \approx a_2(A) \psi_D^2(k)_{k \to \infty}\]

confirmed by numerical calculations starting ~ 1980

Pieper et al 92
Calculations confirm dominance of tensor forces, but relative contribution of central forces varies from 10 to 20%.

The trend is qualitatively consistent with observed large pn/pp ratios in hard processes.
Consensus of the 70’s: it is hopeless to look for SRC experimentally

NO GO theorem: high momentum component of the nuclear wave function is not observable (Amado 78)

**Theoretical analysis of F&S (75):** results from the medium energy studies of short-range correlations are inconclusive due to insufficient energy/momentum transfer leading to complicated structure of interaction (so called meson exchange currents,...), enhancement of the final state contributions.

Way out - use processes with large energy and momentum transfer:

\[ q_0 \geq 1 \text{GeV} \gg |V_{NN}^{SR}|, \quad \bar{q} \geq 1 \text{GeV}/c \gg 2 \ k_F \]

Adjusting resolution scale as a function of the probed nucleon momentum allows to avoid Amado theorem. **Standard trick in QCD**

Actually it is now a standard trick in atomic (10 eV vs 1000 eV) and solid state physics (0.2 eV vs 30 eV) scales.
Comparison of the normalized (e,2e) cross section (momentum profile) for hydrogen with the square of the 1s wave function in the momentum space (Lohmann and Weigrod (1981)]. The solid line represents $(1+p^2)^{-4}$. The measurements were performed at 1200 eV (crosses), 800 eV (circles), and 400 eV (triangles).

Solid state physics:
Angle resolved photo emission spectroscopy (ARPES) $(\gamma e^* \rightarrow e)$ using monochromatic photon beams from synchrotron light source allows to measure distribution over energy binding and momentum of electrons - spectral function in nuclear physics)

Intensity map of the gapless surface state bands $\text{Bi}_{2-x}\text{Mn}_x\text{Te}_3$, D.Hsieh et al, 09
Progress in the study of SRCs of the last 4 years is due to analysis of two classes of hard processes we suggested in the 80’s: nucleus decay after removal of fast nucleus, inclusive scattering in the kinematics forbidden for scattering off free nucleon.

*One group of processes which led to the progress in the studies of SRC at high momentum is A (e,e’) at x> 1, Q^2 > 1.5 GeV^2*

Closure approximation for A(e,e’) at x=Q^2/2q_0m_N > 1, Q^2 > 1.5 GeV^2 up to final state interaction (fsi) between constituents of the SRC.

\[ q = p_e - p_{e’} \text{ is four momentum of virtual photon, } Q^2 = -q^2 \]

In lab frame \( q = (q_0, q_z) \)

- Analog of Ioffe time \( y_1 \rightarrow y_2 \) < 1.2 fm
- FSI only within SRC - may be large for some kinematics - but universal

Corrections could be calculated for large Q using generalized eikonal approximation. For interactions of knocked out nucleon with slow nucleons they are less than few % - LF & Misak Sargsian & MS (08)
A(e,e’) at x>1 is the simplest reaction to check dominance of 2N, 3N SRC and to measure absolute probability of SRC

Define \[ x = \frac{Q^2}{2q_0m_N} \]

x=1 is exact kinematic limit for all Q^2 for the scattering off a free nucleon; x=2 (x=3) is exact kinematic limit for all Q^2 for the scattering off a A=2(A=3) system (up to <1% correction due to nuclear binding)
Only fsi close to mass shell when momentum of the struck nucleon is close to one for the scattering off a correlation. At very large Q - light-cone fraction of the struck nucleon should be close to x (similar to the parton model situation) - only for these nucleons fsi can contribute to the total cross section, though even this fsi is suppressed. Since the local structure of WFs is universal - these local fsi should be also universal.

Scaling of the ratios of (e,e’) cross sections

Qualitative idea - to absorb a large Q at x>j at least j nucleons should come close together. For each configuration wave function is determined by local properties and hence universal. In the region where scattering of j nucleons is allowed, scattering off j+1 nucleons is a small correction.

\[
\sigma_{eA}(x, Q^2)_{x>1} = \sum_{j=2}^{j} A_{j} \frac{a_j(A)}{j} \sigma_j(x, Q^2) \quad \sigma_j(x > j, Q^2) = 0
\]

\[
a_j(A) \cdot \frac{1}{A} \cdot d^3r \cdot j_A(r) \quad a_2 \sim A^{0.15}, \quad a_3 \sim A^{0.22}, \quad a_4 \sim A^{0.27}
\]

for A > 12

\[
\sigma_{A_1}(j - 1 < x < j, Q^2)/\sigma_{A_1}(j - 1 < x < j, Q^2) = (A_1/A_2)a_j(A_1)/a_j(A_2)
\]
Superscaling of the ratios  FS88

Compare the ratios for different $Q^2$ at $x$ corresponding to the same momentum of nucleon in nuclei (including effect of excitation of the residual system - best done in the light-cone formalism)

$$\alpha_{tn} = 2 - \frac{q_- + 2m}{2m_N} \left( 1 + \frac{\sqrt{W^2 - 4m^2_N}}{W} \right)$$

where $q_- = q_0 - q_3$, $W^2 = 4m^2_N + 4q_0m_N - Q^2$

Remark for people with a QCD background: This variable is rather close to Nachtmann variable for massive quarks

At $Q^2 \rightarrow \infty$, $\alpha_{tn} = x$
Note - local FSI interaction, up to a factor of 2 for $\sigma(e,e')$, cancels in the ratio of $\sigma$'s

$$\frac{\sigma_{A_1}(x, Q^2)}{\sigma_{A_2}(x, Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn}, p_t) d^2p_t}{\int \rho_{A_2}(\alpha_{tn}, p_t) d^2p_t} = \frac{a_2(A_1)}{a_2(A_2)} |_{1.6>\alpha\geq1.3}$$

$\rho$ - Light-cone density

Masses of NN system produced in the process are small - strong suppression of isobar, $6q$ degrees of freedom.

Frankfurt et al, 93

$k_{min}=0.25$ GeV

Right momenta for onset of scaling !!!
Hall B (Kim Egiyan)

Q^2 > 1.5 GeV^2

Ratio of the cross sections of (e,e’) scattering off a ^56Fe(^12C,^4He) and ^3He per nucleon

The best evidence for presence of 3N SRC. One probes here interaction at internucleon distances <1.2 fm corresponding to local matter densities ≥ 5ρ₀ which is comparable to those in the cores of neutron stars!!!

Note - fsi in the studied Q range and x> 2 is probably very large but it is still local - within SRC

Currently the ratios are the best way to determine absolute probability of SRC - main uncertainty ~20% - deuteron wave function
The second group of processes (both lepton and hadron induced) which led to the progress in the studies of SRC is investigation of the decay of SRC after one of its nucleons is removed via large energy-momentum transfer process.

Nuclear Decay Function

What happens if a nucleon with momentum $k$ belonging to SRC is instantaneously removed from the nucleus (hard process)? Our guess is that associated nucleon from SRC with momentum $\sim -k$ should be produced.

Formal definition of a new object - nuclear decay function (FS 77-88) - 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 $E_r$ (nonrelativistic formulation)

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

General principle (FS77): to release a nucleon of a SRC - necessary to remove nucleons from the same correlation - perform a work against potential $V_{12}(r)$
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: includes not only repulsive core but also tensor force interactions. Prediction of back-to-back correlation.

For 2N SRC we can model decay function as decay of a NN pair moving in mean field (like for spectral function in the model of Ciofi, Simula and Frankfurt and MS91), Piasetzky et al 06

Spectator is released

Emission of fast nucleons “2” and “3” is strongly suppressed due to FSI

Studies of the spectral and decay function of $^3$He reveal both two nucleon and three nucleon correlations

Sargsian et al 2004
The prediction of back-to-back correlation differs from the expectations based on the textbook picture of nuclei:

Nucleons occupy the lowest levels given by the shell model.

What happens if a nucleon is removed from the nucleus?

- Removal of a nucleon
- Residual nucleus in ground or excited state
- Decay product practically do not remember direction of momentum of struck proton

\[ \gamma^* \rightarrow q \]

\[ k_p \approx q \]
First application of the logic of decay function - spectator mechanism of production of fast backward nucleons - observed in high energy proton, pion, photon - nucleus interactions with a number of simple regularities. We suggested - spectator mechanism - breaking of 2N, 3N SRCs. We extracted (Phys. Lett 1977) two nucleon correlation function from analysis of $\gamma(p)\rightarrow^{12}C \rightarrow$ backward p+X processes [no backward nucleons are produced in the scattering off free protons!!!]

We also estimated $a_2^{(12)C} = 4 \div 5$
To observe SRC directly it is far better to consider semi-exclusive processes $e(p) + A \rightarrow e(p) + p + \text{"nucleon from decay" } + (A-2)$ since it measures both momentum of struck nucleon and decay of the nucleus.

Two novel experiments reported results in the last 4 years:

- **EVA BNL** 5.9 GeV protons $(p,2p)n$ $-t = 5 \text{ GeV}^2; t = (p_{in} - p_{fin})^2$

  Based on our proposal of 88-89 (strong enhancement of scattering off fast forward nucleons due to $s^{-10}$ dependence of the elementary cross section)

- $(e,e' pp), (e,e' pn)$ **Jlab** $Q^2 = 2 \text{GeV}^2$
Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei

E. Piasetzky,1 M. Sargsian,2 L. Frankfurt,1 M. Strikman,3 and J. W. Watson4

Analysis of BNL E850 data
\[ \text{pC} \rightarrow \text{ppn} + (A-2) \star \]
at energy and momentum transfer \( \geq 3 \text{ GeV} \)

**spectator mechanism of backward nucleon production**  FS77

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Probabilty to emit neutron is amazingly high
\(~90\%\) after we accounted for the motion of the pair (measured/calculated independently) and detector acceptance

\[ \text{pp scatter at } \theta_{\text{c.m.}}=90^\circ \]

\[ \text{pn/pp > 16; } I=0 \text{ dominance - qualitatively consistent with current calculations of nuclear wave functions} \]

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Analysis using decay function modeled using 2N correlation model (including relativistic effects) - the same approximation as for spectral function in CSFS 91

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**Before collision**
removal of a proton with momentum \( > 250 \text{ MeV/c} \)

**After collision**
\(~90\%\) probability of emission of neutron with similar but opposite momentum
BNL data of 94-98. The correlation between $p_n$ and its direction $\gamma$ relative to $p_i$. The momenta on the labels are the beam momenta. The dotted vertical line corresponds to $k_F=220$ MeV/c.

SRC appear to dominate at momenta $k > 250$ MeV/c - very close to $k_F$. *A bit of surprise* - we expected dominance for $k > 300 - 350$ MeV/c. Naive inspection of the realistic model predictions for $n_A(k)$ clearly shows dominance only for $k > 350$ MeV/c. Important to check a.s.p. - 2 - 4 GeV proton beams are enough - can be done at GSI with available detectors?
Jlab: from study of (e,e’pp), (e,e’pn)~10% probability of proton emission, strong enhancement of pn vs pp. The rate of pn coincidences is similar to the one inferred from the BNL data.
$^{12}\text{C}(e,e'p p)$

Directional correlation

MCEEP Simulation with pair CM motion $\sigma_{CM}=136$ MeV/c

BG (off peak)
Note - BNL and Jlab studied very different kinematics for breakup of 2N SRC - similarity of the numbers is highly non-trivial.

Our analysis of BNL Experiment measurement was $92^{+8}_{-18}\%$

accounting for charge exchange

$\frac{np - SRC}{pp - SRC} = 18 \pm 5$

In Carbon 12
a_2(^3\text{He})=1.7 \ (0.3), \ a_2(^4\text{He})=3.3 \ (0.5), \ a_2(^{12}\text{C})=5.0 \ (0.5),
\ a_2(^{27}\text{Al})=5.3 \ (0.6), \ a_2(^{56}\text{Fe})=5.2 \ (0.9), \ a_2(^{197}\text{Au})=4.8 \ (0.7)

\begin{table}[h!]
\begin{tabular}{|c|c|c|c|c|}
\hline
   & \(a_2(A/^3\text{He})\) & \(a_2N(A)\) \(\%\) & \(a_3(A/^3\text{He})\) & \(a_3N(A)\) \(\%\) \\
\hline
^3\text{He} & 1 & 8.0\pm0.0\pm1.6 & 1 & 0.18\pm0.00\pm0.06 \\
^4\text{He} & 1.96\pm0.01\pm0.03 & 15.6\pm0.1\pm3.2 & 2.33\pm0.12\pm0.04 & 0.42\pm0.02\pm0.14 \\
^{12}\text{C} & 2.51\pm0.01\pm0.15 & 20.0\pm0.1\pm4.4 & 3.18\pm0.14\pm0.19 & 0.56\pm0.03\pm0.21 \\
^{56}\text{Fe} & 3.00\pm0.01\pm0.18 & 24.0\pm0.1\pm5.3 & 4.63\pm0.19\pm0.27 & 0.83\pm0.03\pm0.27 \\
\hline
\end{tabular}
\end{table}

K. Egiyan, et al 2005

Amazingly good agreement between two analyses for \(a_2(A)\)

Compare also to the analysis of EVA data on \((p,2p)\) - \(a_2(C) \sim 5\) \quad Yaron et al 02

Our first result of 77 \ from backward proton production \(a_2(C) \sim 4 \div 5\)

Puzzle of fast nucleon production is solved!!!
Due to the findings of the last 4 years at Jlab and BNL SRC are not anymore an elusive property of nuclei!!

**Summary of the findings**

- Practically all nucleons with momenta \( k \geq 300 \) MeV belong to two nucleon SRC correlations  
  - BNL + Jlab +SLAC

- Probability for a given proton with momenta \( 600 > k > 300 \) MeV/c to belong to pn correlation is \( \sim 18 \) times larger than for pp correlation  
  - BNL + Jlab

- Probability for a nucleon to have momentum \( > 300 \) MeV/c in medium and heavy nuclei is \( \sim 25\% \)  
  - BNL + Jlab 04 +SLAC 93

- Three nucleon SRC are present in nuclei with a significant probability  
  - Jlab 05

The findings confirm our predictions based on the study of the structure of SRC in nuclei (77-93), and add new information about isotopic structure of SRC. Possible to use information from experiments of 70’s for planning new experiments which would allow unambiguous interpretation.
Some implications for neutron stars

Our focus is on the outer core where nucleon density is close to nuclear one:
\[ \rho \sim (2 \div 3) \rho_0; \quad \rho_0 \approx 0.16 \text{nucleon/fm}^3 \quad \text{and} \quad \text{p/n} \sim 1/10 \]

Neutron gas heats proton gas due to large pn SRC

Practical disappearance of the proton Fermi surface

Large enhancement of neutrino cooling of the neutron stars at finite temperatures

Suppression of the proton Fermi surface leads to the suppression of proton superconductivity, etc
SRCs and heavy ion collisions

Need to generate nucleon configuration in nuclei leading to

- correct single nucleon density $\rho_A(r)$
- correct spacial NN correlations

otherwise - fluctuations are either overestimate (no correlations) or underestimated (hard core with sequential algorithm)

Baym, Blattel, Frankfurt, Heiselberg, MS 1993

Algorithm to generate correct configurations - M. Alvioli, H. Dreshel, MS 09

http://www.phys.psu.edu/~malvioli/eventgenerator
Example: Fluctuations of gluon density in lead on event by event basis

Heavy nuclei are not large enough to suppress fluctuations - A=200 nucleus for gluons is like a thin slice of Swiss cheese.

Far from the A →∞ limit.
Relativistic heavy ion collisions

Unique feature of RHIC - determination of the reaction plane. Becomes interesting to take another look at the process of formation of the spectator system in the heavy ion collision (discussed in FIAS in particular in the framework of the abrasion - ablation model).

What happens when a piece of the nucleus is chopped off? How the residual system decays?

With our configuration generator + Glauber model we can perform more microscopic treatment.
**Lead - Lead collision event at b=6 fm**

Using event generator of Alvioli and MS which generates correct SRC between nucleons in the colliding nuclei.

- protons
- neutrons
- spectator nucleons which were near wounded nucleons
Estimate of the total excitation energy - generalization of the Koltun sum rule for the excitation of the nucleus in the (e,e’p) reactions.

Excitation energy of spectator system

\[ \text{Excitation energy of spectator system} = - \sum_{s,w} V_{sw} \]

\[ s=\text{spectator nucleons}; \ w=\text{wounded nucleons}; \]

\[ \sum_{s,w} V_{sw} \text{ is dominated by np SRCs.} \quad \langle V_{pp} \rangle : \langle V_{nn} \rangle : \langle V_{pn} \rangle = 1:1:9 \]

Correct nuclear configurations in MC are critical for calculation of

\[ - \sum_{s,w} V_{sw} \]
Potential Energy $< V >$ transferred to target - $^{208}\text{Pb} - ^{208}\text{Pb}$

$0 \leq b \leq 16 \text{ fm}$

energy transfer localized on the interaction surface!
FIG. 7: Transferred energy in $^{208}\text{Pb}-^{208}\text{Pb}$ collisions at $P_{\text{lab}} = 160 \text{ GeV}$, calculated within our model at different impact parameters.

Dashed line: potential energy due to removing of nucleons with no other effects taken into account; solid line: transferred energy after i) subtraction of kinetic energy of emitted high-momentum nucleons ii) emission of soft nucleons from the interaction surface iii) extra energy gained from absorbed elastically scattered nucleons.

Dashed curve - Effects of SRC emission and surface evaporation are subtracted & elastic NN scattering included.
Spectator emission

Qualitative expectations:

- **Average kin. energy/ nucleon drops with increase of b**
- **Asymmetry of nucleon emission v₁; Correlation of asymmetries from two nuclei**
- **For small b the emission spectrum is close to momentum distribution in the nucleus (near the surface)**
Perspectives of studies of short-range nuclear structure

Jlab plans

Quantifying and extending recent studies (current numbers have 20% errors)

(e,e'), (e,e’NN) experiments approved for 6 GeV; data mining initiative CLAS, \(x > 1\) for 12 GeV

Discovering new phenomena

- Direct observation of 3N SRC
- Direct observation of non-nucleonic degrees of freedom in nuclei
Is there an evidence for deviations from the many nucleon picture of the nucleus with bound nucleons having the same properties as free ones?

- EMC effect - spectrum of fast quarks in nucleus is softer than in free nucleons
- Enhancement of valence quarks and gluons at $x \sim 0.1$
- Bound nucleon e.m. form factors are different from free ones Jlab - observed effect linear in virtuality (confirms our prediction) ⇒ should be enhanced in SRCs

Analysis of the data provides implicit prove of presence of non-nucleonic degrees of freedom in nuclei with increased role for these effects with increase of the nuclear density/nucleon momenta
What can be done at GSI before FAIR & at FAIR?

High precision experiments with statistics orders of magnitude higher than the BNL experiment.

Need large $-t$. For $90^\circ$ c.m. $-t=T_p m_N$.

Hence proton beams of 4 GeV are fine. Angles of two forward protons emitted back to back are $\sim \theta \approx 16^\circ$. For 3 GeV - $\theta \approx 18^\circ$.

Possible to study transition from mean field to SRC regime - probe momenta $p$ upto 500MeV/c? For wide range of angles both forward and backward. Range of nuclei

Investigate down to what energies factorization works as a function of the momentum of the struck nucleon. For $p < 400$MeV/c probably down to $T_p=2$ GeV. 

↓

use of ion beams - r3b
Exotics - $\Delta$-isobars

Large angle knockout of $\Delta$-isobars

\[ pA \rightarrow \Delta^{++} + p + (A - 1)^* \]

♫ FAIR facility

PANDA detector will be able to collect in one year of running (3 months with protons) > $10^3$ higher statistics than the one collected by EVA BNL (p,2pn) experiment. Very interesting to compare antiproton and proton induced reactions - for example J/$\psi$ production off bound nucleons - will be sensitive to nucleon modification in nuclei.

♫ Look for effects of SRCs including 3N correlations - comparison on pn, pp channels,...
♫ non-nucleonic degrees of freedom - discover $\Delta$'s?.
♫ Color & chiral transparency effects, ...
Conclusions

Impressive experimental progress of the last several years - discovery of strong short range correlations in nuclei with strong dominance of $I=0$ SRC - has proven validity of general strategy of using hard nuclear reactions. It provides solid basis for further studies.

Direct observation of 3N SRCs, nonnucleonic degrees of freedom in nuclei which are of direct relevance for neutron stars core dynamics are among top aims of future studies. Would be highly beneficial to have parallel programs of studies with electron beams (Jlab 6) and hadron beams in the next few years. Will prepare ground for 12 GeV Jlab program and programs at future (anti) proton machines.

A number of theoretical challenges including a) calculation of the decay functions for $A>3$, b) isotopic effects for SRC, c) isobars, d) relativistic effects, e) studies of FSI dynamics - optimizing for signal of SRC, understanding the role of color transparency effects.