The Transparent Nucleus

Unperturbed inverse kinematics nucleon knockout measurements with a carbon beam


Physics Colloquium,
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Tel Aviv beach Saturday 9 May 2020 during a short Covid break
Nuclei are the densest matter on earth

Even denser nuclear systems in nature:

In the Lab:

HI collision

SRC are nuclear density fluctuations

Cold dense nuclear matter

\[ \rho = 2 - 5 \rho_0 \]
Neutron Star Equation-of-State

Compilation by Jeremy Holt
The Nuclear challenge

Nuclei are the densest objects on earth.

The interaction between nucleons is strong and complicate.

SRC and neutron stars.
Nuclear Physics

- Many-Body Hamiltonian:

\[ H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i<j=1}^{A} V_{2N}(i, j) + \sum_{i<j<k=1}^{A} V_{3N}(i, j, k) + \ldots \]

\( A, \ Z, \ N \)
Nuclear Physics: extremely simple, almost correct

**IPM: Independent Particle Model**

- **Many-Body Hamiltonian:**

\[ H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i<j=1}^{A} V_{2N}(i, j) + \sum_{i<j<k=1}^{A} V_{3N}(i, j, k) + \]

- **Mean-Field Approximation:**

\[ H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i=1}^{A} V(i) \]

E. Wigner, M. Mayer, and J. Jenson, 1963 Nobel Prize
Nuclear Physics: extremely simple, almost correct

IPM: Independent Particle Model

Mean Field Approximation

Results in an “atom-like” shell model:

- Ground state energies
- Excitation Spectrum
- Magic numbers
- Abundances of isotopes in the universe
Nuclear Physics: another extremely simple almost correct

In momentum space

FG: Fermi Gas

$k_F \approx 250 \text{ MeV/c}$
Single-nucleon removal experiments are well known method to explore the single-particle structure of nuclei.

The excitation levels of $^{39}$K are shown, with various single-nucleon removal experiments, such as $^{40}\text{Ca}(e,e'p)^{39}\text{K}$. The missing-energy spectrum of the reaction $^{40}\text{Ca}(e,e'p)^{39}\text{K}$ at $p_m = 140$ MeV/c is shown, highlighting the knockout of $1d_{3/2}$ and $2s_{1/2}$ levels. Fig. 7 illustrates the experimental momentum distributions for transitions in the reaction $(e,e'p)$.
Nucleons in well defined shells are not the full story

Missing correlations

L. Lapikas, NPA 553 (1993)
Short-Range Nucleon Correlations (SRC)

Nucleon pairs that are close together in the nucleus

**Momentum space:** *high relative* and *low c.m. momentum*, compared to the Fermi momentum ($k_F$)

\[ k_1 > k_F, \quad k_2 > k_F, \quad k_1 \approx k_2 \]

$k_F \approx 250$ MeV/c
SRC and single nucleons in nuclei

In nuclei the momentum distribution of nucleons can be divided into two distinct regions

$k < k_F$

Mean field region

$k > k_F$

Correlated / high momentum region

Single nucleons

SRC pairs

A. Schmidt et al., Nature 578, 540 (2020)
For high-momentum study the obstacle is FSI

$$^3\text{He}(e, e'p)$$
Nuclear Transparency

\[ A(e, e'p) \]

Glauber calculation

\[ T = \frac{\sigma_A}{Z \cdot \sigma_p} \]


Electron induced knockout reaction

Nucleon-knockout experiments in inverse kinematics

Accessing nuclear ground-state distributions

Electron beam

Scattered Electron

Change e\textsuperscript{-} to p beam

Inverse Kinematics

Flip the kinematics
$A(e, e' p)$
Large FSI

$A(p, 2p)$

Problem

Let's have one less bump

Solution?

Let's add two more protons
Young double slit experiment

Use a detected (post selected) heavy fragment as a "which-path marker" for no ISI / FSI
Demanding a surviving A-1 or A-2 system selects the transparent part of the reaction with no multiple scattering.
FSI suppression

Nucleon-knockout experiments in inverse kinematics

Inverse Kinematics
$p\ p \rightarrow pp$ elastic scattering near $90^0$ c.m

$$\frac{d\sigma}{dt} \propto s^{-10}$$

QE $pp$ scattering have a very strong preference for reacting with high-momentum nuclear protons (lower $s$).
Inverse kinematics

Independent-particle shell model works well only for nuclei close to $\beta$ stability

Nuclear structure changes dramatically with neutron-proton asymmetry

→ known magic numbers disappear

Study of unstable very asymmetric nuclei

Inverse kinematics with radioactive nuclear beams
Going Inverse: Towards Radioactive Beams

Detecting heavy fragment selects unperturbed knockout single proton removal events.
High-Energy Ion Beam @ JINR Nuclotron
Experiment at Nuclotron, JINR (Russia)

$^{12}$C Beam at 48 GeV/c
Uwr is a member of the BM@N collaboration

Antoni Ciszewski,
Armen Sedrakian,
David Blaschke,
Students and Postdocs.
Our Pilot-Experiment (JINR Dubna 2018)

- well known system: $^{12}$C
- high momentum: 4 GeV/c/u
- (p,2p) ~90° c.m. scattering
- inverse kinematics

→ extract missing- and recoil- momentum distributions for QE scattering
→ identify SRC signal in inverse kinematics
Experiment at BM@N / JINR

$^{12}\text{C}(p,2p)X$

Two-Arm Spectrometer

- RPC: Resistive Plate Chamber
- GEM: Gas Electron Multiplier
- BC: Beam Counters
- DCH: Drift Chambers

48 GeV/c $^{12}$C Ions

- GEM - gas electron multiplier
- MWPC - Multi Wire Proportional Chambers
- RPC - multi-gap resistive plate chamber
- BC – beam counters
- DCH - drift chambers
Outgoing Particle ID

$P/Z \sim$ Bending in Magnet

Reconstructed Momentum for $^{12}\text{C}$ and empty-target

$\sigma(P)/P = 1.5\%$

BM@N Preliminary

Patsyuk, Kahlbow et al.
Nature Physics (2021)

$Z_{\text{eff}} = \sqrt{\sum Z^2}$
Single Proton Knockout: Inclusive $^{12}\text{C}(p,2p)$

contaminated by:
Inelastic scattering (IE) and ISI / FSI

Patsyuk, Kahlbow et al.
Nature Physics (2021)
Single Proton Knockout: Exclusive $^{12}$C(p,2p)$^{11}$B

Fragment tagging suppresses initial/final state interactions

(p,2p)\textsuperscript{11}B: Inelastic Vs. Quasi elastic

\[ M^2_{\text{miss}} [\text{GeV}^2/c^4] \]

Counts

Patsyuk, Kahlbow et al.
Nature Physics (2021)

\[ ^{12}\text{C}(p,2p)^{11}\text{B} \] Quasielastic
(p,2p)_{^{11}\text{B}}: \text{Inelastic Vs. Quasi elastic}
Summary: single-nucleon knockout:

Can selects QE channel and strongly suppresses ISI / FSI by fragment tagging.

"Ground-state properties of exotic nuclei can be extracted quantitatively by the use of fully exclusive (p,pN) knockout reactions in inverse kinematics at the high-energy radioactive beam facilities."
Short-Range Nucleon Correlations (SRC)
How do we study SRC?

Exclusive hard scattering in selected kinematics (almost entirely electron scattering)
The high momentum tail in nuclei is dominated by SRC pairs. Most of the SRC pairs (90%) are np only, 5% pp and 5% nn.
Nucleons has Isophobia (np – dominance at 300-600 MeV/c)

\[ V_{NN}(r) = V_c(r) + V_T(r)S_{12} \]

\[ S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2 \]

Ciofi and Alvioli PRL 100, 162503 (2008).
Summary of SRC results

In nuclei the momentum distribution of nucleons can be divided into two distinct regions

\[ k < k_F \]
Mean field region
Single nucleons

\[ k > k_F \]
Correlated / high momentum region
SRC pairs

Universality

np-SRC dominance (tensor force)

A. Schmidt et al., Nature (in print)
Description of hard scattering off SRC

\[ e^{-} \rightarrow (\tilde{q}, \omega) \rightarrow (\tilde{p}_{i}, \epsilon_{i}) \rightarrow N \rightarrow (\tilde{p}_{N} = \tilde{p}_{i} + \tilde{q}, \sqrt{\rho_{N}^{2} + m_{N}^{2}}) \]

\[ \rho_{\text{recoil}} = \sqrt{\rho_{\text{recoil}}^{2} + m_{N}^{2}} \]

\[ (\tilde{p}_{CM}, m_{A} - \epsilon_{A-2}) \rightarrow \text{SRC} \rightarrow A-2 \rightarrow (\tilde{p}_{CM}, E_{A-2} = \sqrt{\rho_{CM}^{2} + (m_{A-2} + E*)^{2}}) \]

\[ n_{p}(k) \xrightarrow{k \to \infty} C_{pn}^{d} |\varphi_{pn}^{d}(k)|^{2} + C_{pn}^{0} |\varphi_{pn}^{0}(k)|^{2} + 2C_{pp}^{0} |\varphi_{pp}^{0}(k)|^{2} \]

Generalized Nuclear Contact Formalism  
Experiment at BM@N / JINR

$^{12}\text{C}(p,2pn)^{10}\text{B}$ np SRC removal

$^{12}\text{C}(p,2pp)^{10}\text{Be}$ pp SRC removal


($Z_{\text{eff}} = \sqrt{\sum Z^2}$)
Selection of SRCs
Guided by the Simulation in Generalized Contact Formalism

**Selection Cuts:**

- inclusive \((p,2p) + {}^{10}\text{B or } {}^{10}\text{Be}\)
- \(p_{\text{miss}} > 350 \text{ MeV/c}\)
- \(-110 < E_{\text{miss}} < 240 \text{ MeV}\)
- In-plane opening angle > 63°
- \(M_{\text{miss}} > 420 \text{ MeV}^2/c^4\)
np-SRC Dominance

26 $^{10}$B events
3 $^{10}$Be events
$\rightarrow np$ pair dominance

Possible contamination:

1. $^{11}$B + FSI nucleon knockout?
   Result in $^{10}$B $\sim^{10}$Be due to similar np / pp cross section.

2. QE mean-field events with excited $^{11}$B?
   Estimated maximal contribution of 5 ($^{10}$B) and 2 ($^{10}$Be) events.

SRC Pair: Angular Correlation

Counts

$\cos(p_{\text{miss}}^\perp, p_n^\perp)$

Patsyuk, Kahlbow et al.
Nature Physics (2021)
Pair c.m. Motion (Fragment Momentum)


Cohen PRL (2018)
SRC pairs: No Correlation between $P_{\text{rel}}$ and $P_{\text{cm}}$

As expected from a scale separation between c.m. and large relative momentum
Summary of the new JINR Results

First observation of ISI/FSI suppression and single-step nucleon knockout selection using fragment detection.

First observation of SRCs with bound residual A-2 system:

Direct measurement of pair c.m. motion

Check factorization!

Reaching for the (neutron) stars

A new campaign to study SRC in unstable asymmetric nuclei

ERC Synergy proposal: Piasetzky (TAU), Aumann (TUD) Hen (MIT)
SRC studies with Hadrons

JINR • HADES • HESR • R3B •
Exploring nuclei under extreme conditions

**Neutron stars**

\[ \frac{N}{Z} = 95\%/5\% = 20 \]
\[ \rho_0 = (2 - 5) \rho_0 \]

**Radioactive beams**

\[ \frac{N}{Z} < 2.5 \]

**SRC in nuclei**

\[ \rho_0 = (2 - 5) \rho_0 \]

**Asymmetry**

\[ Z < 82 \]
\[ \frac{N}{Z} < 1.5 \]
\[ \rho_0 = 0.16 \text{ N/fm}^3 \]
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