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Proton-induced quasifree scattering reactions studied in inverse kinematics with the LAND-R$_3$B experiment at GSI/FAIR

University of Surrey, June 12, 2012
The Future International Facility FAIR at GSI: Beams of Ions and Antiprotons
Primary Beams
- \(10^{12}/s\) \(^{238}\text{U}^{28+}\) @ 1.5-2 AGeV; factor 100 -1000 over present in intensity
- \(2(4)\times10^{13}/s\) 30 GeV protons
- \(10^{10}/s\) \(^{238}\text{U}^{73+}\) up to 25 (-35) AGeV

Secondary Beams
- Broad range of radioactive beams up to 1.5 - 2 AGeV; up to factor 10 000 in intensity over present
On-going and future research programme at GSI and FAIR

- How do nucleon-nucleon correlations evolve in isospin-asymmetric nuclei and nuclear matter?
- Hadronic quasifree scattering reactions in inverse kinematics with RIBs at high energy using the ALADIN/LAND setup at GSI
- Future prospects at FAIR with the new $R^3$B experiment
Beyond the Nuclear Mean-Field

**Nucleon-Nucleon correlations:**
- Short-range (SRC)
- Tensor
- Long-range (LRC)

Modification of NN correlations as a function of density, temperature, isospin asymmetry determine the nature of many-body systems:
- Finite nuclei, nuclear structure
- Extended nuclear matter, EOS
- Compact astrophysical object e.g. neutron stars

Very challenging theoretically to incorporate correlations in the nuclear many-body system starting from bare NN interactions
- Experimental studies crucially needed
Correlations in (Near-) Symmetric Nuclei

Electron induced proton knockout reactions: [A,Z] (e,e’p) [A-1,Z-1]

Reduction in spectroscopic strength relative to mean-field prediction
Only 60-70% of the protons participate in independent-particle motion in valence states

Low occupancy caused by correlated pairs of nucleons within the nucleus, i.e. effect of long-range, tensor and short-range correlations
Short-Range and Tensor Correlations in Symmetric Nuclei

From high-momentum transfer nucleon knockout reactions \((e,e'p)\), \((e,e'pN)\) and \((p,2pN)\) and \((e,e')\) data on stable nuclei (JLab, BNL, NIKHEF, Mainz …)


np pairs dominate SRC – 20 times more likely than pp pairs

- Direct consequence of NN tensor force
- Implications for description of n stars?

2N momentum distributions calculated for g.s. of light nuclei using realistic Hamiltonian with 2- and 3-body potentials (AV18/UIX)

- Much larger for np pairs than pp pairs for relative momentum \(\sim 300-600\) MeV/c
- Universal character originating from tensor components in realistic NN potential
Short-Range and Tensor Correlations in Symmetric Nuclei

- **80 ± 5%** single particles moving in average potential
- **60-70%** independent single particle in a shell-model potential
- **10-20%** shell model long-range interactions
- **20 ± 5%** two-nucleon short-range and tensor correlations

Correlations induced by tensor force strongly influence the structure of np pairs, which are predominantly in deuteron-like states (T=0, S=1), while ineffective for pp pairs, which are mostly in T=1, S=0 quasi-bound states.

New experiments to explore 2N and 3N SRCs planned at Jlab: 
(e,e’) in $^3\text{He}/^3\text{H}$ and $^{48}\text{Ca}/^{40}\text{Ca}$ 
(e,e’pN) on $^4\text{He}$ 
Isospin dependence?

Isospin Dependence of Mean Field and Residual Interactions

How do short-range, tensor and long-range NN correlations evolve in nuclei and nuclear matter as a function of isospin and density?

Shell structure predicted to change in exotic nuclei (particularly in neutron rich nuclei)
Weak binding, impact of the particle continuum, collective skin modes and clustering in the skin...

Mean-field modifications
- surface composed of diffuse neutron matter
- derivative of mean field potential weaker and spin-orbit interaction reduced

Residual interaction modifications
- partly occupied orbits
- $V_{\sigma\tau}$ monopole interaction: coupling of proton-neutron spin-orbit partners
- deformed intruder configurations

Diagram showing levels for $N=4$ and $N=5$ with various orbit labels and their corresponding quantum numbers.
New Magic Number at N=16

$V_{\sigma\tau}$ monopole interaction: coupling of proton-neutron spin-orbit partners

Examples of experimental evidence:
- Two-neutron separation energies
- In-beam fragmentation gamma spectroscopy
- Interaction cross-sections and longitudinal momentum distributions (direct reactions)

Present in stable nuclei but missing in n-rich nuclei where the spin-orbit partner state of the valence neutrons are not occupied by protons

Correlations in Asymmetric Nuclei

Are NN correlations modified in isospin-asymmetric nuclei and nuclear matter?

Spectroscopic factors for valence nucleons in asymmetric nuclei extracted from nucleon-removal reactions on light nuclear targets and transfer reactions performed with radioactive ion beams.

Strong dependence on isospin asymmetry:
- $R_S$ close to 1 for loosely-bound valence n in n-rich nuclei (expected in low-density nuclear matter)
- Suppression of single-particle strength for strongly-bound n in n-poor nuclei

Not yet understood
Correlations in Asymmetric Nuclei

Isospin dependence of SRC in infinite nuclear matter studied using SCGF method and realistic NN interactions

Ab-initio calculations:
Self-Consistent Green’s Function (SCGF) method using realistic chiral N3LO force + G-matrix for effects of SRC

- Significant change of depletion in momentum distributions with isospin asymmetry
- Asymmetry dependence of spectroscopic factors similar (but smaller) than observed experimentally – on-going theoretical effort, effect may increase with improved interactions

\[ \alpha = \frac{\rho_n - \rho_p}{\rho} \]
Experimental Probes

- Proton and electron induced quasifree scattering (QFS) e.g. \((e,e'p), (p,2p), (p,pn)\)... 

Most direct experimental probes to investigate single-particle properties of nuclei and the role of nucleon-nucleon correlations

- Construct spectral functions for bound nucleons (probability that a nucleon as a certain energy and momentum within the nucleus)

Integrated strength => spectroscopic factors, occupation probabilities

To probe SRC (short distance scales) => high energy and momentum => **Need high energy beams**

Both valence and deeply-bound nucleons can be removed ⇒ different densities probed ⇒ disentangle LRC and SRC

High-energy, high-intensity radioactive ion beams at GSI (and in future at FAIR) opportunity to perform such studies with isospin asymmetric nuclei
**The R³B Experiment at FAIR**

Universal setup for kinematical complete measurements of high-energy reactions

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**R³B**
- Reactions with Relativistic Radioactive Beams

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**Experiments**
- elastic scattering
- knockout and quasi-free scattering
- electromagnetic excitation
- charge-exchange reactions
- fission
- spallation
- fragmentation

**Physics goals**
- radii, matter distribution
- single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
- single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, B(E2)
- Gamov-Teller strength, spin-dipole resonance, neutron skins shell structure, dynamical properties
- reaction mechanism, applications (waste transmutation, ...)
- γ-ray spectroscopy, isospin-dependence in multifragmentation
The $R^3B$ Experiment at FAIR

Universal setup for kinematical complete measurements of high-energy reactions

$R^3B$
Reactions with Relativistic Radioactive Beams

- identification and beam "cooling" (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- exclusive measurement of the final state:
  - identification and momentum analysis of fragments
    (large acceptance mode: $\Delta p/p \sim 10^{-3}$, high-resolution mode: $\Delta p/p \sim 10^{-4}$)
    - coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- applicable to a wide class of reactions
The R³B Experiment at FAIR

Universal setup for kinematical complete measurements of high-energy reactions

Proton-induced low- and high-momentum transfer quasifree scattering reactions, e.g. (p,2p) and (p,pn), in inverse kinematics using relativistic radioactive ion beams at GSI/FAIR (0.5-2 AGeV)

- Measurements of spectral functions of both valence and deeply-bound nucleons in isospin asymmetric nuclei
- Comparison to modern many-body theories of nuclei and nuclear matter using realistic nucleon-nucleon interactions
- Future measurements of polarization observables foreseen.
Recent QFS Experiment in Normal Kinematics:
$^{12}\text{C}(p,2p)^{11}\text{B}$

High-resolution measurement of the out-going protons at RCNP, Osaka

\[ E_p = 392 \text{ MeV} \]

Two spectrometer measurement

Energy resolution (FWHM) \( \approx 450 \text{ keV} \)

Study of deep-hole states \( (s_{1/2}) \)


\[ ^{12}\text{C}(p,2p)^{11}\text{B}^* \]

\[ E_p = 392 \text{ MeV} \]
Quasifree Scattering in Inverse Kinematics

High energy heavy ion beams, \( E = 100-1000 \text{ A.MeV} \)
- simplify reaction mechanism: impulse approximation
- minimise final state interactions: spectator nucleons

Could measure **momentum distribution** \( k_{A-1} \) in two ways:
- directly
- **indirectly** by measuring \( k_1 \) and \( k_2 \) as in normal kinematics

In inverse kinematics, \( k_{A-1} \) is related to momentum of knocked-out nucleon \( k_3 \) by:

\[
k_3 = \frac{A - 1}{A} k_A - k_{A-1}
\]

Hence, by only measuring \( k_{A-1} \) we can obtain:
- l-value from momentum distribution of core nucleus
- energy of core states can be obtained with \( \gamma \)-rays
The ALADIN/LAND Set-up at GSI

Charged fragments

tracking → $B_\rho \sim A/Q\beta\gamma$

CH$_2$, C and Pb targets

Target-recoil detector

Protons

gammas

ToF, $\Delta E$

ALADIN

large-acceptance dipole

Neutrons

ToF, x, y, z

~12 m

Excitation energy $E^*$ from kinematically complete measurement of all outgoing particles:

$$E^* = \left( \sqrt{\sum_i m_i^2} + \sum_{i\neq j} m_i m_j \gamma_i \gamma_j \left(1 - \beta_i \beta_j \cos \theta_{ij}\right) - m_{proj}\right) c^2 + E_{\gamma}$$
The ALADIN/LAND Set-up at GSI

Target position
Z=0, X=0

12C beam
400 A.MeV

Large Dipole Magnet

Drift chambers

ToF-wall

Neutrons

Fragment arm

Proton arm
Target-Recoil Detector for QFS Experiments

Detectors around the reaction target:

- **New**: Crystal Ball for γ-rays and protons
  - 4π gamma detector (~1980 - ...)
  - 162 NaI(Tl) crystals of 20 cm length
  - Measure energy of recoil protons with additional low-gain readout of the forward 64 crystals (~ 2π)

**Crystal Ball 4π NaI γ-detector:**
- spectrometry of protons

**DSSDs: fragment & proton ID & tracking**

**New**: DSSDs for proton and fragment tracking
- 4 ‘box’ μ–strip detectors for proton tracking
- polar angle coverage ≈ 15° ≤ θ ≤ 80°
- resolution: Δx ~ 100 μm; ΔE ~ 50 keV
- range: 100 keV < E < 14 MeV
- 2 in-beam μ–strip detectors for tracking & ID of fragments and protons
Angular Correlations of Two Protons from \((p,2p)\) QFS Reaction

Selecting \(^{12}\text{C}(p,2p)X\) channels:
2 signals in box DSSDs and 2 NaI clusters with similar angle in Crystal Ball
Angular Correlations of Two Protons from $^{17}\text{Ne}(p,2p)$ QFS Reaction

Selection of QFS (p,2p) events: Very clear characteristic angular correlations

$\varphi_1$ vs $\varphi_2$ distribution

$\theta_1$ vs $\theta_2$ distribution

Looking along beam:
Correlation in $\varphi$: $\Delta\varphi = 180^\circ$

Looking from side:
Anti-correl. in $\theta$: Opening angle $\approx 80^\circ$

F. Wamers, GSI
Angular Correlations of Two Protons from $^{12}\text{C}(p,2p)$ QFS Reaction

Background from carbon

(p,2p) reactions on hydrogen component of CH$_2$

Nearly constant angle between two scattered protons

Quasi-free scattering kinematics

“Back-to-back” scattering
Coplanar reactions

V. Panin, TU Darmstadt
J. Taylor, Univ. Liverpool
$^{12}\text{C}(p,2p)^{11}\text{B}$ in Inverse Kinematics

PhD Theses of J. Taylor (Univ. Liverpool, 2011) and V. Panin (T.U. Darmstadt, 2012)

- Benchmark the QFS experimental technique in inverse kinematics for future experiments with RIBs at GSI/FAIR - First exclusive measurements of p-induced QFS reactions
- Provide useful information for the design of the new R3B target-recoil detector

Fragment identification in coincidence with two high-energy hits in the Crystal Ball (CH$_2$ target)

PID of outgoing fragments

PID in Target-Recoil Detector DSSDs
Momentum of $^{11}$B fragment is directly related to the momentum of the knocked-out proton:

$$k_3 = \frac{A-1}{A} k_A - k_{A-1}$$

Can be measured in DSSDs behind the CH$_2$ target if $^{11}$B is bound (i.e. knock-out from outer p-shell).
To measure the internal proton momentum when $^{11}$B is unbound (i.e. knock-out from inner s-shell) requires energy and angular measurements of QFS protons.

Total momentum of a proton:

$$Q_k = \frac{1}{c} \sqrt{E_k \left(E_k + 2m_p c^2\right)}$$

Transverse component of the internal momentum

$$P_{x,y} = Q_k \times \sin \theta_k \sin (\varphi_k - \varphi_i)$$

Momentum Distributions of $^{11}$B Fragments (s-shell knock-out)

$$P_{x,y} = Q_k \times \sin \theta_k \sin (\varphi_k - \varphi_i)$$

Kinematical simulation

Experiment (p-shell knockout)

First measurement of this kind!

$\leftarrow$ Internal momentum distribution of protons occupying s-shell.

(Width 25% increased compared to p-shell).

No theoretical calculations to compare with at present
## Integrated Cross-Sections (mb)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>CH$_2$</th>
<th>Carbon</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C($p$, $2p$)$X$</td>
<td>81.5 ± 4.0</td>
<td>20.5 ± 1.9</td>
<td>30.5 ± 2.3</td>
</tr>
<tr>
<td>$^{12}$C($p$, $2p$)$^{11}$B</td>
<td>47.3 ± 3.3</td>
<td>11.1 ± 1.5</td>
<td>18.1 ± 2.0</td>
</tr>
<tr>
<td>p-removal</td>
<td>82.7 ± 7.7</td>
<td>45.9 ± 4.4</td>
<td>18.4 ± 2.7</td>
</tr>
<tr>
<td>pn-removal</td>
<td>48.1 ± 5.3</td>
<td>30.7 ± 2.3</td>
<td>8.7 ± 1.7</td>
</tr>
<tr>
<td>Inel. breakup to $^{11}$B</td>
<td>2.64 ± 0.97</td>
<td>0.96 ± 0.65</td>
<td>0.84 ± 0.59</td>
</tr>
</tbody>
</table>

- **12.4 ± 3 mb (45%)** to unbound $^{11}$B (knockout from s-shell)
- **16 ± 4 mb** integral ($p$,2$p$) c.s. for p-shell knockout
  *Nuclear Physics* 18 (1960) 46---64.
γ-ray Energy Spectrum in Crystal Ball

Doppler-corrected γ-ray energy spectrum in coincidence with $^{12}$C(p,2p)$^{11}$B reaction + Detector response from GEANT4/R3BROOT simulation.
Relative populations of the 3 p-hole states in $^{11}$B compared to relative spectroscopic factors from (e,e’p), (p,2p) in normal kinematics and at lower energy, and (d,$^3$He) transfer reactions.

Decays from $^{11}\text{B}$ bound states: γ-rays detected in the Crystal Ball

Total reconstructed cross-section for unbound states: $6.8 \pm 1$ mb (55%)

Invariant mass reconstruction in case of 2- and 3-body decays of $^{11}\text{B}$:

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j \cos \theta_{ij})} + E_\gamma - m_{proj}$$

Cross section, $d\sigma/dE$ [mb / 1MeV]
Excitation Energy Spectrum of $^{11}$B

Invariant mass reconstruction in case of 2- and 3-body decays of $^{11}$B

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j \cos \theta_{ij})} + E_\gamma - m_{proj}$$

Normal Kinematics

$^{11}$B(g.s.) $^{3/2^-}$

Counts

$450$ keV (FWHM)

$2.125$ $^{1/2^-}$

$5.02$ $^{3/2^-}$

$s$-shell knockout

Cross section, $d\sigma/dE$ [mb / 1MeV]

$^{11}$B + $\gamma$

$^{10}$Be + $p$

$^7$Li + $^4$He

$^{10}$B + $n$

$^9$Be + $^3$H

$^4$He + $^4$He + $^3$H

$^7$Be + $^3$H + $n$

Total unbound

Excitation energy, [MeV]
The $R^3B$ Si Tracker

$R^3B$
Reactions with
Relativistic
Radioactive
Beams

Note:
Si Tracker sits in CALIFA Calorimeter, which together form the Target-Recoil Detector

$R^3B$ reactions with relativistic radioactive beams

- Target
- Recoil detector ($p$, $n$, $\gamma$): Si tracker
- Large acceptance dipole
- Protons
- Neutrons
- Heavy fragments
- High Resolution measurement

To be built by April 2015 for the $R^3B$ experiment at FAIR

Fully funded NUSTAR/$R^3B$ grant ~ £5M
(Liverpool, Daresbury, Birmingham, Edinburgh, Surrey)
The R³B Si Tracker Design

Optimised for high-energy (0.5-2 AGeV) p-induced quasifree scattering reactions in inverse kinematics, e.g. (p,2p), (p,pn)...

Inner layer (green)
6 detector modules, each with 2 silicon wafers (100um).

Outer detectors (blue)
2 layers of 12 detector modules, each with 3 silicon wafers (300um).
Detectors manufactured from 6” (150mm) wafers by Micron Semiconductors (UK).

With 50 μm strips the effective pixel pitch is 176 μm x 26 μm (52 μm) with detector stereo angle of 17 degrees.

Readout electronics this end only
Blue = N side strips
Orange = P side strips

17deg stereo angle

Detectors will be wire bonded at their joints on both P and N sides to form one long detector assembly. To be done in the Liverpool Semiconductor Detector Centre.

First prototype expected in Liverpool by the end of this month.
Custom ASIC used as part of Si ladders and read out through μTCA format readout cards designed in-house.

Resolution 10keV - Threshold to be measured in situ - Dyn. range 40 keV to 50MeV - Counting Rate max 5kHz/channel.

STFC DL & RAL, Liverpool
High-energy RIBs at GSI, and at FAIR in the future, provide a unique (but very challenging!) opportunity to investigate how nucleon-nucleon correlations (SRC, Tensor, LRC) evolve in isospin-asymmetric nuclei and nuclear matter – and much more!

Proton-induced quasifree scattering reactions performed in inverse kinematics with high-energy RIBs are being pioneered using the ALADIN/LAND setup at GSI.

Interpretation of the analysis of $^{12}\text{C}(p,2p)$ - and $^{12}\text{C}(p,pn)$ - data awaits theoretical calculations (C. Bertulani).

Future prospects at FAIR with the new R$^3$B experiment, for which the UK is building the Si Tracker.
Collaborators

- **GSI Darmstadt**
- **University of Birmingham**
  N. Ashwood, M. Barr, M. Freer et al.
- **University of Edinburgh**
  T. Davinson, P. Woods et al.
- **University of Liverpool**
  M. Chartier, J. Taylor et al.
- **University of Surrey**
  W. Catford et al.
- **STFC Daresbury Laboratory**
  M. Labiche, R. Lemmon et al.

And the international R³B Collaboration
http://www.gsi.de/forschung/kp/kr/R3B_e.html

Special thanks to Jonathan Taylor (Liverpool), Valerii Panin and Felix Wamers (Darmstadt)