Experimental Results on QFS in inverse kinematics

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R³B collaboration

Leyla Atar, Matthias Holl, Alina Movsesyan, Valerii Panin: Thanks for the slides!

Motivation

QFS in inverse kinematics as a tool to:

- perform spectroscopic studies of exotic nuclei
- populate systems beyond the neutron/proton driplines
- Study clustering in nuclei
- probe correlations (short range)
Knockout reactions: a tool to probe nuclei far from stability

Knockout reactions on light nuclear targets have helped to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion, halo nuclei…

Interaction cross section $\rightarrow$ Interaction radii

$$\sigma_{\text{reac}} = \pi \left( R_p + R_T \right)^2$$

$$R_X = r_0 A_X^{1/3}$$

Knockout reactions: a spectroscopic tool to study shell evolution far from stability

Knockout reactions on light nuclear targets have helped to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion, halo nuclei…

Spectrometer $\rightarrow$ momentum distributions and Mass ID
$\gamma$-ray detector $\rightarrow$ select final state

Momentum distributions $\rightarrow$ orb. ang. mom.
Partial cross sections $\rightarrow$ spectr. factors
Knockout reactions: a spectroscopic tool to study shell evolution far from stability

Knockout reactions on light nuclear targets have helped to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion, halo nuclei…

Quenching of spectroscopic factors
Complementary spectroscopic tools

**Knockout reactions** on light nuclear targets

Strong absorption $\rightarrow$ surface localized
Complementary spectroscopic tools

Knockout reactions on light nuclear targets
Strong absorption $\rightarrow$ surface localized

QFS reactions (p, 2p), (p, pn), (p, pα) etc.
on a proton target in inverse kinematics
Weaker absorption $\rightarrow$ probing inner shells
- Evolution of shell structure
- Nucleon-Nucleon correlations
  (short-range, tensor, ...)
- Cluster structure
- States beyond the neutron dripline

few hundred MeV/nucleon to minimize rescattering of outgoing nucleons
Quasi-free scattering

QFS reactions
Spectrometer → momentum distributions and Mass ID
γ-ray detector → select final state
Target recoil detector → detect scattered nucleons
Quasi-free scattering

QFS reactions
Spectrometer $\rightarrow$ momentum distributions and Mass ID
$\gamma$-ray detector $\rightarrow$ select final state
Target recoil detector $\rightarrow$ detect scattered nucleons

Scattered nucleons $\rightarrow$ complete and redundant kinematical measurement
Quasi-free scattering

QFS reactions
Spectrometer $\rightarrow$ momentum distributions and Mass ID
$\gamma$-ray detector $\rightarrow$ select final state
Target recoil detector $\rightarrow$ detect scattered nucleons

Scattered nucleons $\rightarrow$ complete and redundant kinematical measurement

$p, 2p$ in normal kinematics
Quasi-free scattering

QFS reactions
Spectrometer → momentum distributions and Mass ID
γ-ray detector → select final state
Target recoil detector → detect scattered nucleons

Scattered nucleons → complete and redundant kinematical measurement

\[ ^{16}\text{O} (p,2p) \text{ in normal kinematics} \]
G. Jacob et al.,
RMP 1966 38 121
PLB 45 (1973) 181
Quasi-free scattering

QFS reactions
Spectrometer $\rightarrow$ momentum distributions and Mass ID
$\gamma$-ray detector $\rightarrow$ select final state
Target recoil detector $\rightarrow$ detect scattered nucleons

Scattered nucleons $\rightarrow$ complete and redundant kinematical measurement

Minimizing FSI at larger momentum transfer

$^{16}\text{O} (e,e'p)$
Saclay data
QFS calculations by C. A. Bertulani

T. Aumann, C. A. Bertulani, J. Ryckebusch
PRC 88, 064610 (2013)

Removal probability:
proton target compared to C target

Momentum width dependence on separation energy

Cross section dependence on separation energy
Experimental setup for QFS

hundreds of MeV/nucleon incoming beam
Experimental setup – SAMURAI @ RIBF

SAMURAI: Kinematically complete measurements by detecting multiple particles

- Superconducting Magnet
  - 3T with 2m dia. pole
  - (designed resolution 1/700)
  - 80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

Invariant Mass Measurement
Missing Mass Measurement
A very schematic layout discussed in the breakout session, evolved from an earlier preliminary design and considerations of various existing/planned other systems.

The HRS will be a medium-resolution, large acceptance spectrometer, with ample opportunity to install auxiliary detection systems for n, γ and charged-particle detection to perform detailed (invariant-mass) spectroscopy.

Slide from: M. Thoennessen
Experimental setup – $R^3B$ @ GSI/FAIR
Target recoil detection setup

2005

2007 - 2010
Target recoil detection setup

These setups provided good coverage but not good total energy measurement
Target recoil detection setup

2005

2007 - 2010

Future setup

CALIFA
Rich physics cases in available (p,2p and p,pn) QFS data sets obtained with R³B @ GSI

- \(^{12}\text{C}\) isotope: benchmark case
- \(\text{C isotopic chain : } Z = 6; \ N = 3 – 14\)
- \(\text{O isotopic chain : } Z = 8; \ N = 8 – 15\)
- \(\text{Ni isotopic chain : } Z = 28; \ N = 28 – 30, 39 – 44\)
Rich physics cases in available (p, 2p and p, pn)
QFS data sets obtained with R³B @ GSI

\(^{12}\text{C isotope: benchmark case} \)
\(\text{C isotopic chain:} \)
- known up to the drip lines
- accessible to ab-initio theories

…..

\(\text{O isotopic chain:} \)
- “unexpected” end of drip line

…..

\(\text{Ni isotopic chain:} \)
- How magic is \(^{68}\text{Ni}\)? – N=40 sub-shell closure
- Close to the “New” island of inversion (\(^{64}\text{Cr}, \text{ }^{66}\text{Fe}\))
- Shell evolution towards \(^{78}\text{Ni}\)

…..
Rich physics cases in available (p,2p and p,pn) QFS data sets obtained with R³B @ GSI

large range of separation energies and more sensitive to deeply bound states $\rightarrow$ independent and consistent measurement of reduction factors

\[ \begin{array}{c}
\text{12C} \\
\text{16O} \\
\text{57Ni}
\end{array} \]

\[ \begin{array}{c}
\text{1s}_{1/2} \\
1\text{p}_{3/2} \\
2
\end{array} \]

\[ \begin{array}{c}
\text{1s}_{1/2} \\
1\text{p}_{3/2} \\
2
\end{array} \]

\[ \begin{array}{c}
\text{l}_{g_{9/2}} \\
2\text{p}_{1/2} \\
28
\end{array} \]

\[ \begin{array}{c}
\text{l}_{p_{1/2}} \\
\text{l}_{p_{3/2}} \\
2
\end{array} \]

\[ \begin{array}{c}
\text{l}_{p_{1/2}} \\
\text{l}_{p_{3/2}} \\
\text{l}_{s_{1/2}}
\end{array} \]
$^{12}\text{C}(p,2p)$: QFS in inverse kinematics: a Benchmark experiment

Strong angular correlations of the two protons

Analysis by V. Panin
$^{12}\text{C}(p,2p)$: QFS in inverse kinematics: a Benchmark experiment

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Kinematics are particularly important!

Analysis by V. Panin

reaction theory by C.A. Bertulani
$^{12}\text{C}(p,2p)$: QFS in inverse kinematics: a Benchmark experiment

Kinematics are particularly important!

Analysis by V. Panin

reaction theory by C.A. Bertulani
$^{12}\text{C}(p,2p)^{11}\text{B}$

Spectroscopy of 0p-hole residual states in $^{11}\text{B}$ from $^{12}\text{C}(p,2p)^{11}\text{B}$ reaction

via Doppler-corrected $\gamma$-spectrum in coincidence with outgoing (bound) $^{11}\text{B}$
$^{12}\text{C}(p, 2p)^{11}\text{B}^* \rightarrow (^{10}\text{B} + n), (^{10}\text{Be} + p), (^{7}\text{Li} + ^{4}\text{He}), ...$
$^{11}\text{C}(p,2p)^{10}\text{B}$

Analysis by M. Holl
Momentum distributions for $^A\text{O}(p,2p)^{A-1}\text{N}$ and $(p,pn)^{A-1}\text{O}$

Analysis by L. Atar, reaction theory by C. A. Bertulani
Momentum distributions for $^{16}$O(p,2p)$^{15}$N and (p,pn)$^{23}$O

Analysis by L. Atar, reaction theory by C. A. Bertulani

Sauvan et al., PRC (2004)
Gamma-ray spectra for $^{16}\text{O}(p,2p)^{15}\text{N}$ and $(p,pn)^{16}\text{O}$

Analysis by L. Atar
Inclusive (p,2p) and (p, pn) Ni

From what we have seen so far: theoretical calculations work better for light nuclei in terms of momentum width.

Analysis by A. Movsesyan
Inclusive \((p,2p)\) and \((p,pn)\) Ni
Quenching of spectroscopic factors from inclusive p,2p

A. Gade, et al., PRC 77, 044306 (2008)

Spectroscopic factors in $^{16}$O and nucleon asymmetry

C. Barbieri
Output of kinematical code for the $^{12}$C(p,pn) case (i.e. no absorption)

- $\frac{d\sigma}{d\Omega}$ (mb)
  - $\theta_{\text{c.m.}}$ (deg)
  - $\theta_{\text{Lab}}$ (deg)

Free p,pn input to the kinematical code

Counts

Entries: 100000
Mean: 67.07
RMS: 46.74

Entries: 100000
Mean: 38.06
RMS: 19.71

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Output of kinematical code for the $^{12}$C(p,pn) case (i.e. no absorption)

- Free p,pn input to the kinematical code

Output of kinematical code for the $^{12}$C(p,pn) case (i.e. no absorption)

- Counts
  - $\vartheta_{c.m.}$ (deg)
  - $\vartheta_{Lab}$ (deg)

- $d\sigma/d\Omega$ (mb)
Output of kinematical code for the $^{12}\text{C}(p,pn)$ case (i.e. no absorption)

Free $p,pn$ input to the kinematical code

Output of kinematical code for the $^{12}\text{C}(p,pn)$ case (i.e. no absorption)
Nuclei beyond the drip line @ R3B
"First observation of $^{15}$Ne ground and excited states"

$^{16}$Ne and daughter nuclei

$^{15}$Ne 3-body decay

$^{15}$Ne ground state unbound by $S_{2p} = 2.522(66)$ MeV

Short-Range Correlations (SRC)

- 60-70% of nucleons in nuclei are in single-particle mean-field orbitals
- The rest are in long- and short-range correlated pairs
  - Mainly SRC correlated pairs, and most of them are pn pairs

**Figure from O. Hen et al. “A proposal to Jefferson Lab PAC 38, Aug. 2011”**

SRC arises from the repulsive core of the NN interaction

> Responsible for the high momentum component of the nuclear wavefunction
Probes

Most of our knowledge about SRC has been obtained from electron scattering experiments on a fixed target at large momentum transfer, performed e.g. at JLab.

Radioactive beams $\rightarrow$ require electron-ion scattering in a storage ring (e.g. ELISe project at FAIR).

Instead, use hadronic probes (proton target) $\rightarrow$ study SRC in exotic nuclei.

Some References:
Probes

- SRC in inverse kinematics with a hydrogen target → access exotic nuclei.
- part of the QFS reactions for large momentum transfer
Summary

• Quasi-free scattering
  ➢ QFS is successfully applied in inverse kinematics
  ➢ Rich data sets covering a wide range of nuclei are under analysis
  ➢ Rich future physics program: shell structure, cluster structure, unbound nuclei, N-N correlations ….

• R3B Setup @ GSI/FAIR ideal for such investigations

• reaction theory by C. Bertulani provides a good understanding of the data
Thank you for your attention!