

Investigating nucleon-nucleon correlations through QFS reactions

Ryo Taniuchi, Luke Rose, Matt Whitehead, Wei Zhang,
Marina Petri, and Stefanos Paschalis

*University of York for the s467 and s091 experiments
of the R³B collaboration*



Science and
Technology
Facilities Council

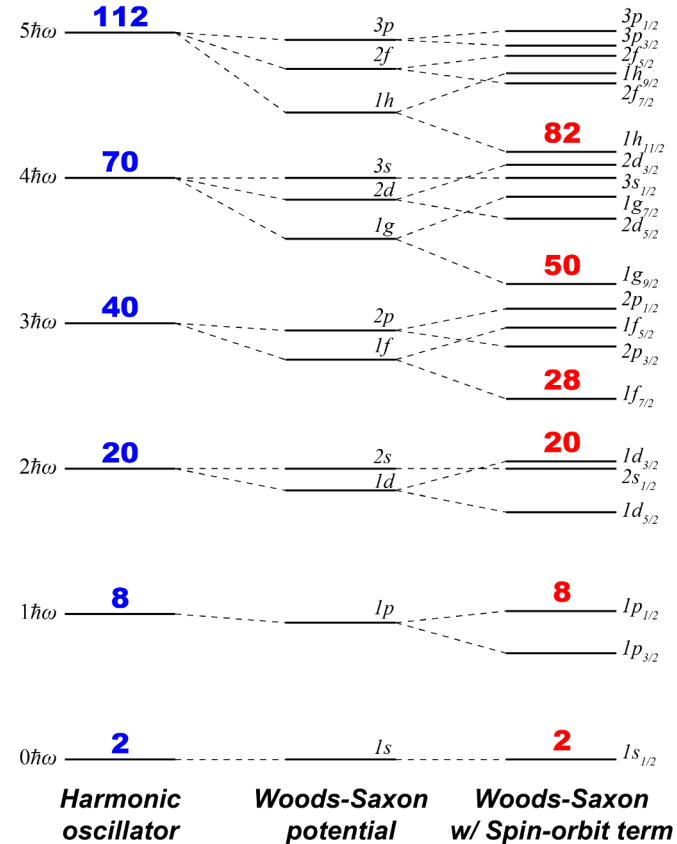


The results presented here are based on the experiment s467 and s091, which was performed at the target station FRS-HTC at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0.

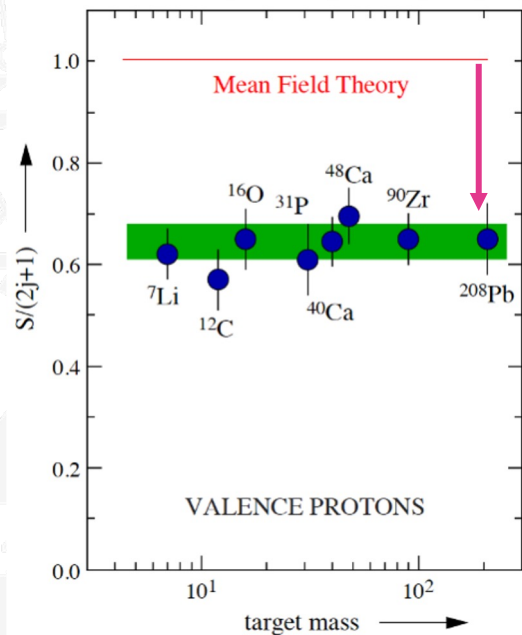
Single particle states in a mean-field potential

- Successful description of nuclear structure in a mean-field potential
- Shell gaps at 28, 50, 82... are induced by spin-orbit splittings
- Reproduces many properties of nuclei as spins and magnetic moments

➤ To what extent does the model describes the nuclear properties?



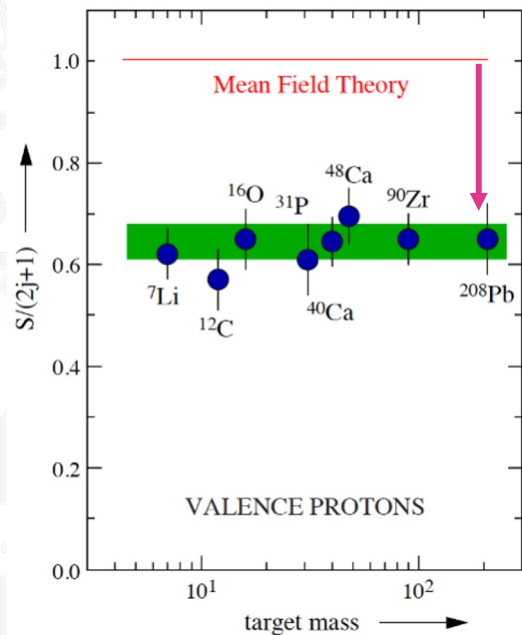
(e,e'p) experiments on stable nuclei



(e,e'p) at NIKHEF facility.

W.H. Dickhoff and C. Barbieri,
PPNP **52**, 377-496 (2004); L. Lapikas,
Nucl. Phys. A **553**, 297c (1993).

(e,e'p) experiments on stable nuclei



How can we describe the reduction?

Lower probability of nucleons to be found as independent particles in a mean-field

✓ **Existence of NN-correlations**

(e,e'p) at NIKHEF facility.

W.H. Dickhoff and C. Barbieri,
PPNP **52**, 377-496 (2004); L. Lapikas,
Nucl. Phys. A **553**, 297c (1993).

The NN correlation in nuclear medium

The importance of the high-momentum components caused by NN correlations has been pointed out already in 1955.

np-pairs in Short-Range Correlation (SRC) would appear at **high-momentum** tail

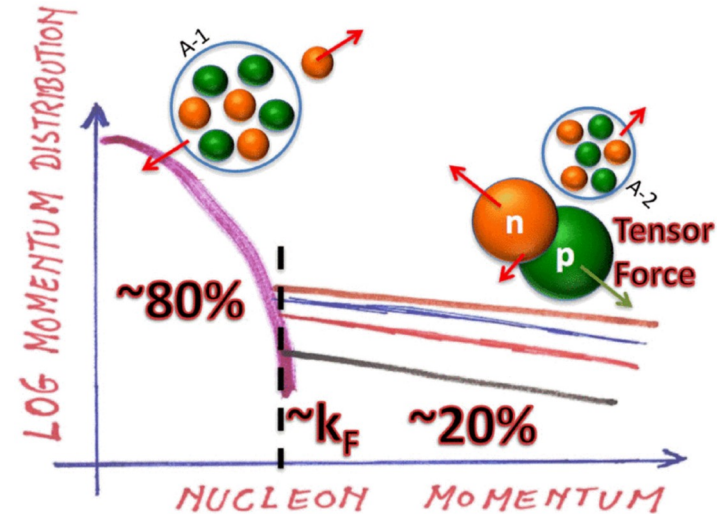
PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

High-Energy Reactions and the Evidence for Correlations in the Nuclear Ground-State Wave Function*

K. A. BRUECKNER, R. J. EDEN,[†] AND N. C. FRANCIS
Indiana University, Bloomington, Indiana
(Received January 13, 1955)

V. CONCLUSIONS

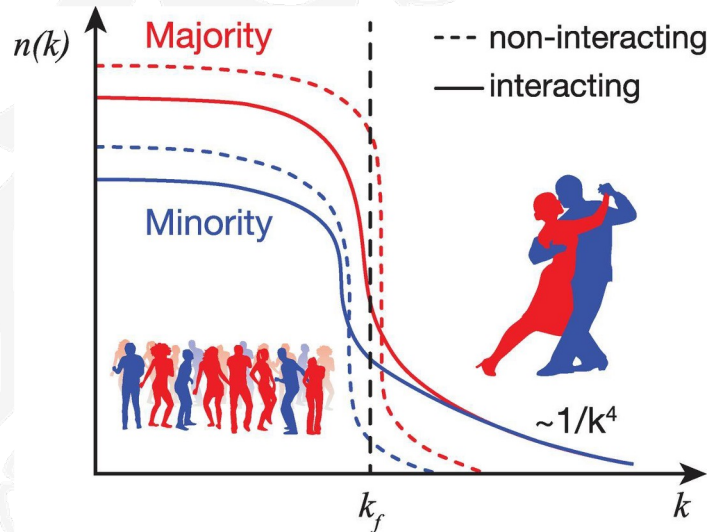
We have analyzed evidence derived from a variety of high-energy experiments which has bearing on the problem of nuclear structure. This evidence is particularly significant since it is for these (or similar) processes that the possible departure of the nuclear ground-state wave function from an independent-particle wave function is most apparent. The result predicted uniformly by the group of quite diverse experiments which we have examined is that the nuclear ground-state wave function must have a very marked admixture of high-momentum components and hence must depart quite appreciably from an independent-particle-model wave function. Consequently it follows that the usual assumptions of the shell-model theory of the nucleus, that the particles move independently in a uniform potential, cannot be other than very approximately correct.



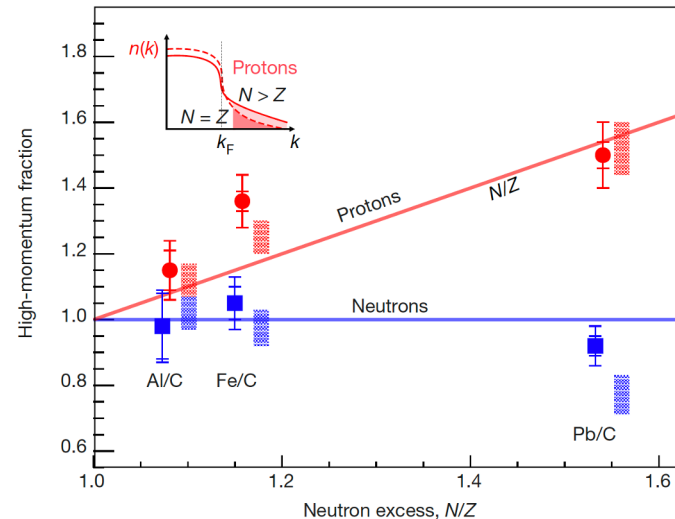
O. Hen, et al., Rev. Mod. Phys. **89**, 045002 (2017).

SRC in asymmetric matter

- Various (e,e'N) reactions on **stable isotopes** with CLAS at J-Lab
- The more asymmetric system, the less single-particle states due to SRC

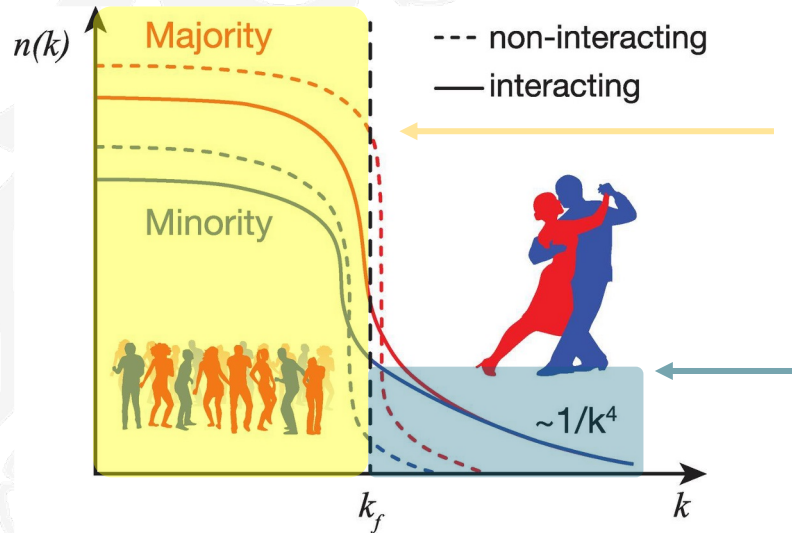


O. Hen, et al., Science **346**, 614-617 (2014).



M. Duer, et al., Nature **560**, 617-621 (2018).

Systematic studies along isotopic chains



O. Hen, et al., Science **346**, 614-617 (2014).

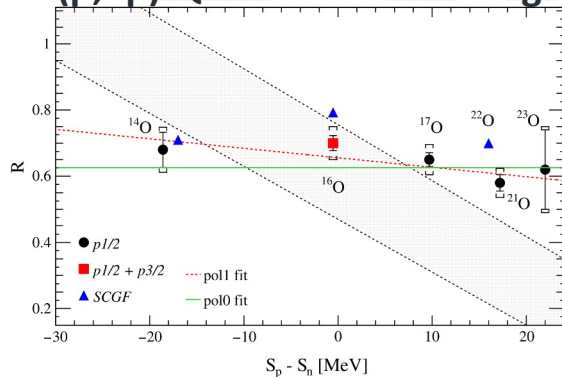
- Quantitative approach towards **asymmetric systems** is a key.
 - Employment of **inverse kinematics** to access asymmetric systems
1. Depletion in single-particle strength
→ through $(p,2p)$, (p,pn) reactions
 2. Enhancement of pn -pairs (quasi-deuterons) at high-mom
→ through (p,pd) reactions

Systematic study on depletions of (p,2p) and (p,pn) cross sections

Luke Rose (PhD student) and RT

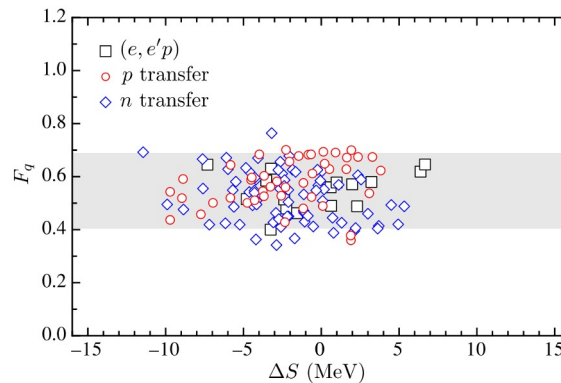
- Evaluate the degree of absence from ordinal shells
- **QFS and transfer**: Weak isospin dependency
- **QFS**: Ability for inverse-kinematics to access wider isospin regions

(p,2p) Quasi-free scatterings



L. Atar et al., PRL **120**, 052501 (2018)

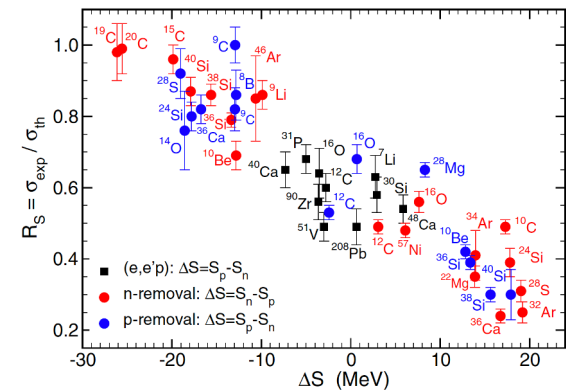
Transfer reactions



B. P. Kay et al., PRL **111**, 042502 (2013)

Reaction with composite target \rightarrow FSIs

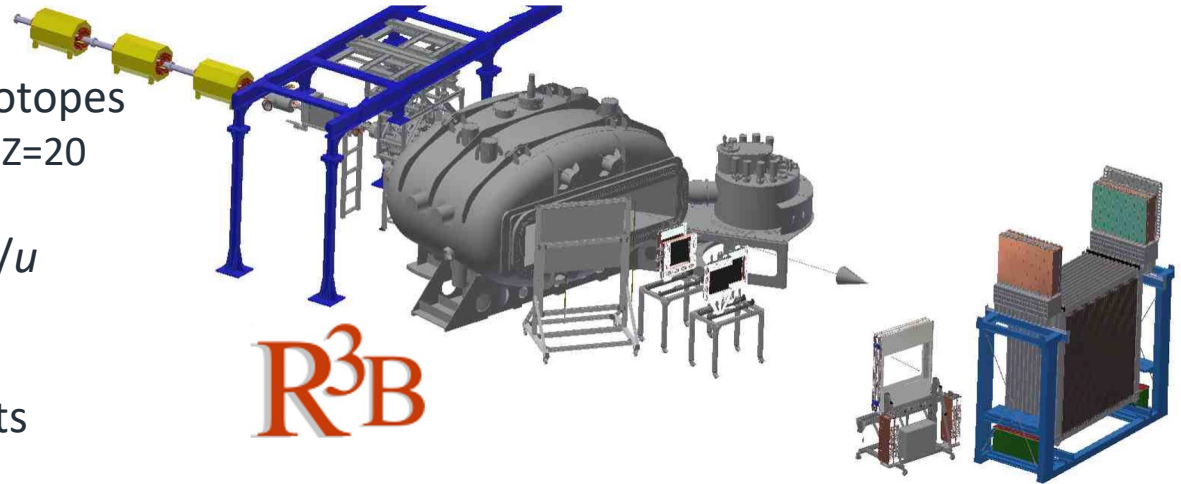
Knockout reactions



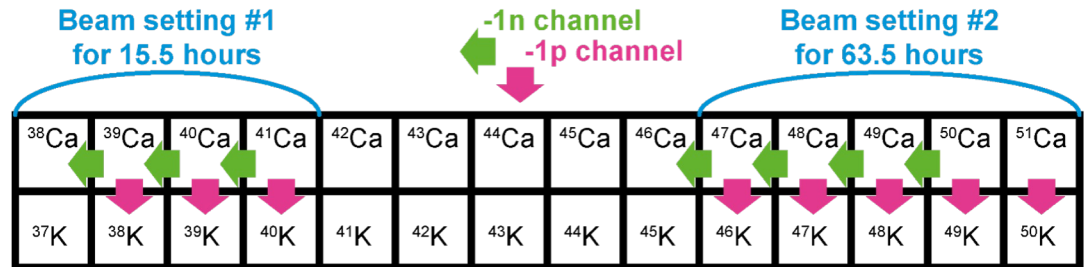
J. A. Tostevin and A. Gade, PRC **90**, 057602 (2014)

The R³B setup at GSI/FAIR

- Study along Calcium isotopes
 - Proton shell closed: Z=20
- Fast beam at 500 MeV/u
 - Minimise FSIs
- Reaction at solid targets
 - Carbon: 2.0 g/cm²
 - CH₂: 2.3 g/cm²
 - $\sigma_p = (\sigma_{CH_2} - \sigma_C) / 2$
- Large acceptance for the fragments
 - Less syst. uncertainties

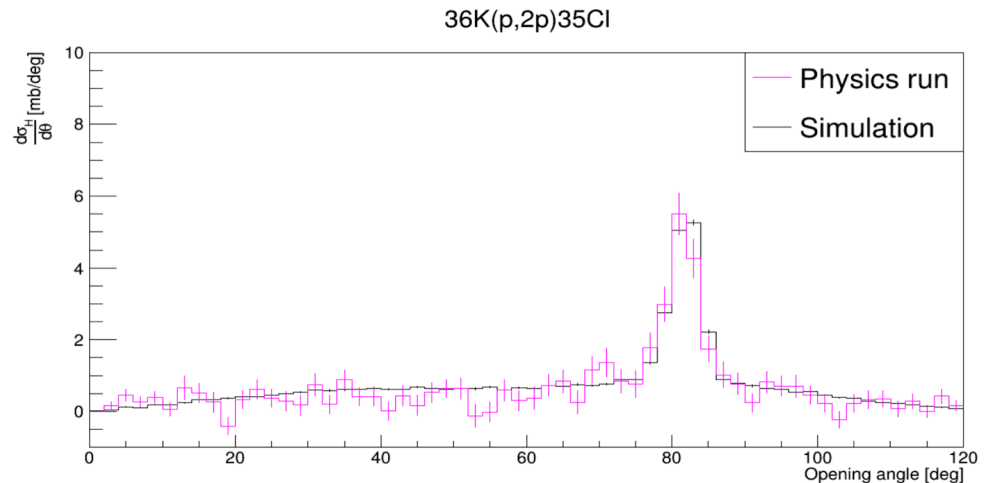
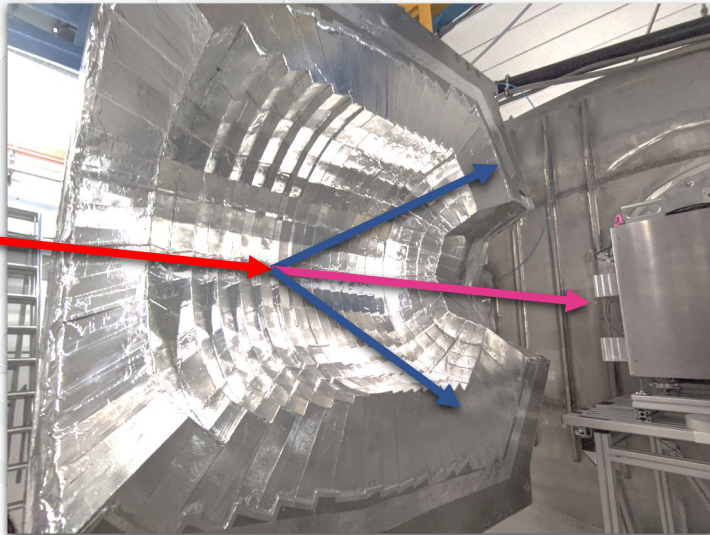


R³B



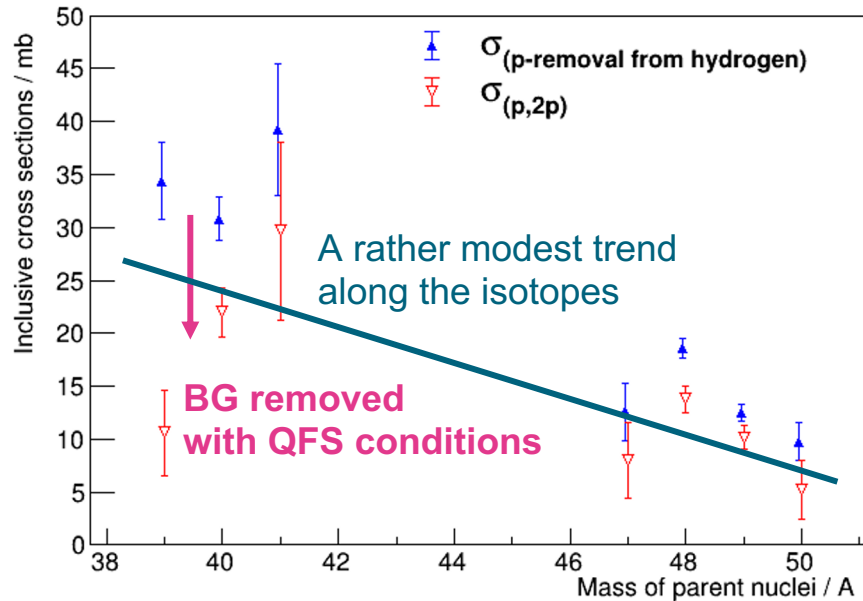
CALIFA: Recoil proton detections

- A highly-segmented CsI(Tl) based scintillator array
- Two protons after the (p,2p) reaction are detected as “**high-energy hits**”
- The **opening angle** between two protons → QFS condition



(p,2p) cross sections along Ca chain

Inclusive cross sections for -1p channel



Detailed calculations are ongoing with theorists.

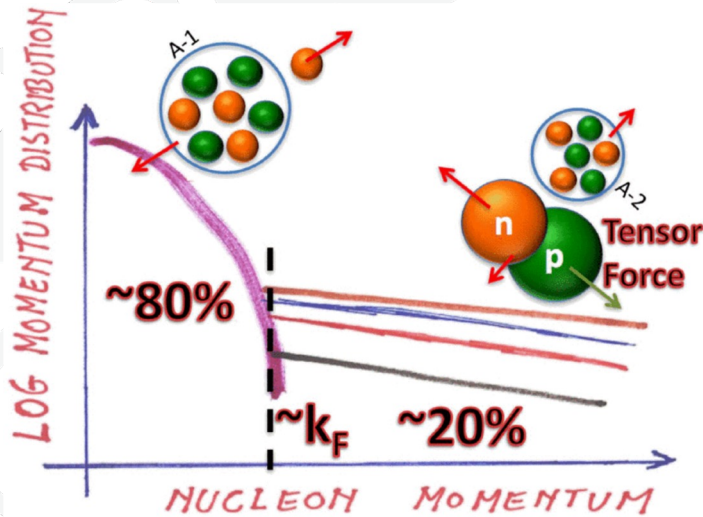
Reaction: Carlos Bertulani

Structure: Carlo Barbieri

Investigations of enhanced quasi-deuterons via (p, pd) reactions

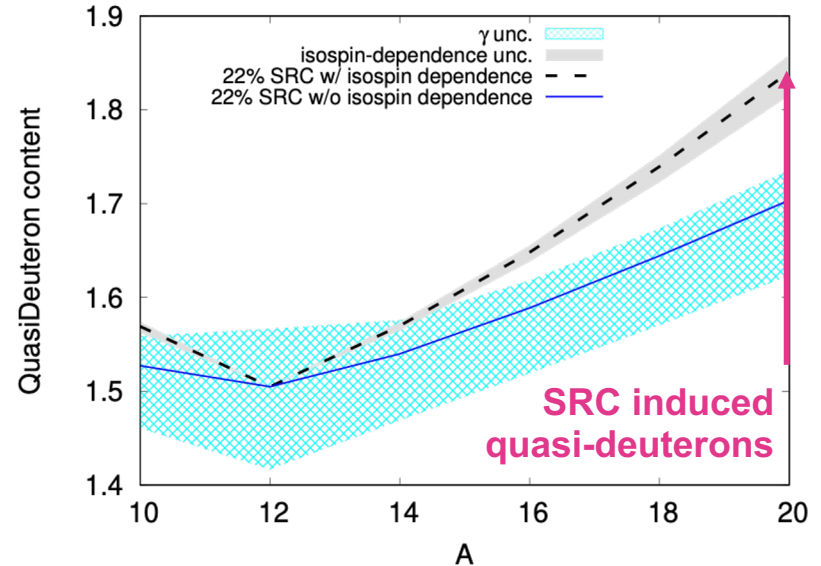
More quasi-deuteron in asymmetric systems due to the correlated pn-pairs originating from SRC

Matt Whitehead (PhD student),
Wei Zhang, and RT



O. Hen, et al., Rev. Mod. Phys. **89**, 045002 (2017).

Enhancement of quasi-deuterons with SRC



Calculation by M. Petri, S. Paschalis and A.O. Macchiavelli (2024).

The deuteron KO (p,pd) experiment

- **A successful experiment completed** in February 2024.
- (p,pd) reactions identified with kinematic complete measurement.

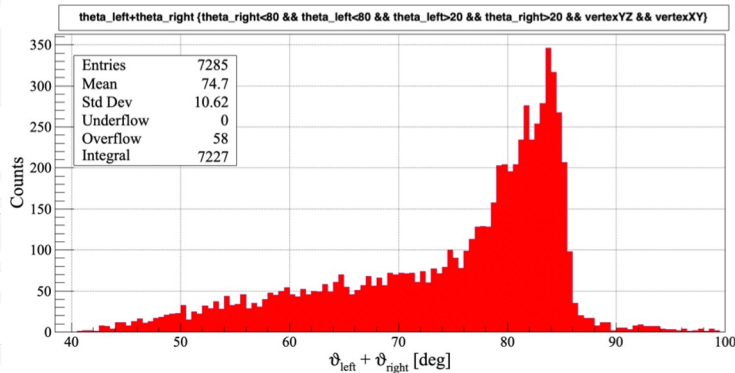
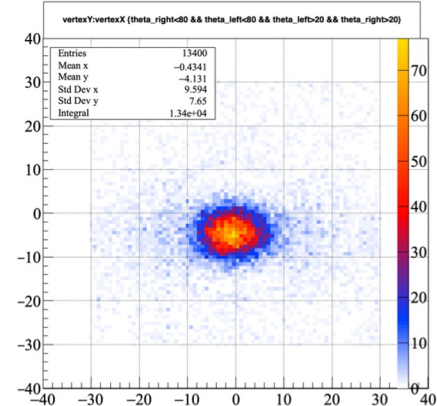
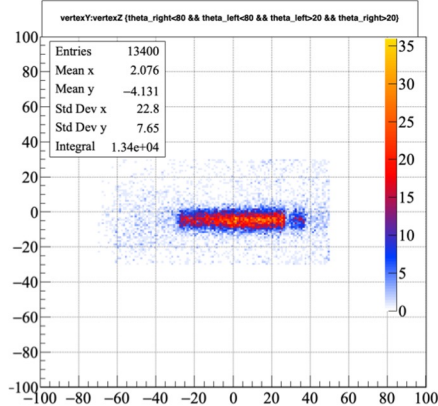
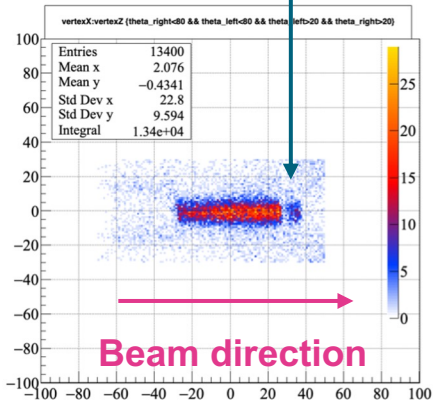
Key device: Si tracking detectors

- ✓ Track the recoil particles
 - Optimised for (p,pd) channels
- ✓ Missing mass spectroscopy
- ✓ ΔE -E for particle identifications



Vertex reconstructions (online)

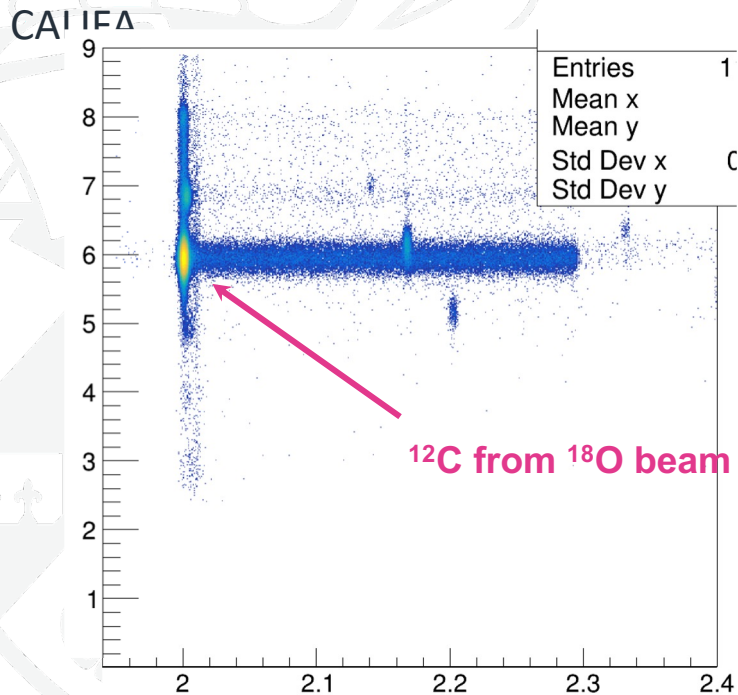
Heat insulator



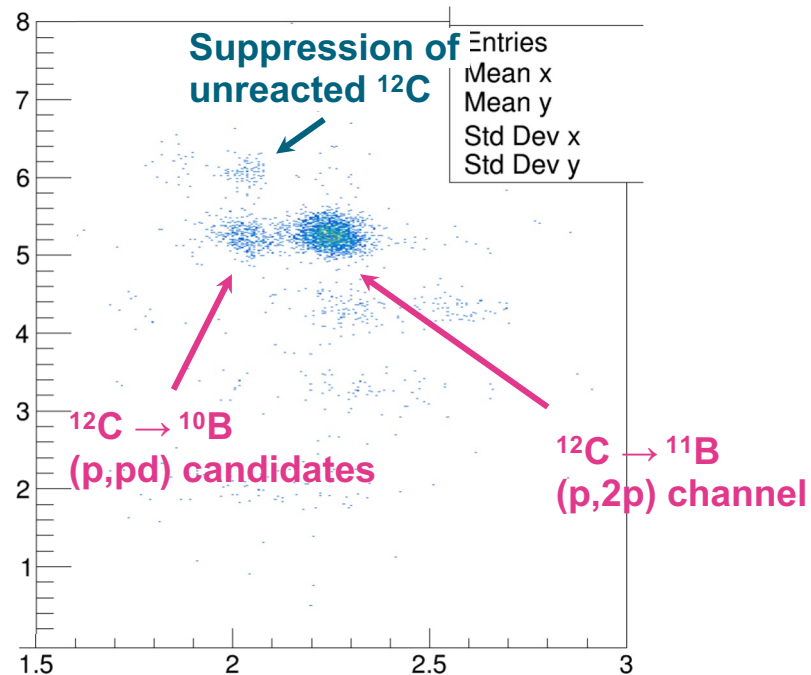
Opening angle with LH2 vertex cut

Fragment particle identifications

Left: PID of incoming beam for the ^{12}C setting



Right: Reaction trigger with



Summary and Outlook

- Two complementary experiments were conducted with the R³B setup at GSI/FAIR.
- (p,2p) cross sections along the calcium isotopes at 500 MeV/*u* were measured:
 - Recoil protons are used to tag QFS reactions
 - Cross sections along the isotopes indicated a weak dependency with isospins
- Kinematically complete (p,pd) experiment has just completed in February:
 - Cross sections along the carbon isotopes is expected to provide a direct insight of SRC-driven enhancement of quasi-deuterons in nuclei
 - Very preliminary analysis indicated good quality of the data and the statistics
 - **More exciting results to be shown in the next IOP.** Stay tuned!

Acknowledgement for the collaborations of **s467** and **s091** experiments of

R³B