Quasi-free scattering in inverse kinematics with high-energy radioactive beams

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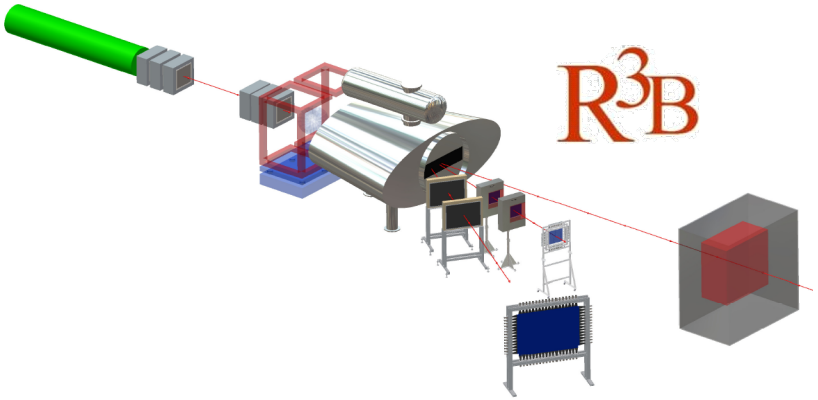
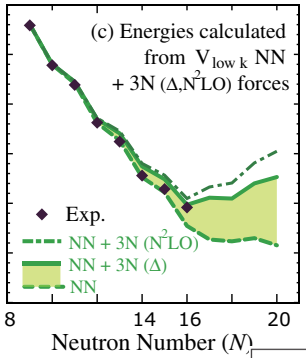
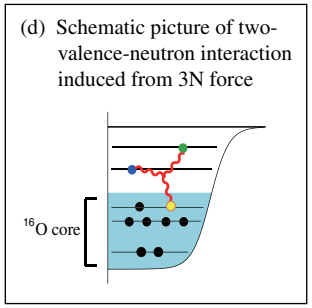
Quasi-free knockout reactions
(p,2p), (p,pn), (p,2p,n), (p,pd), (p,pα), (p,2p)fission, …

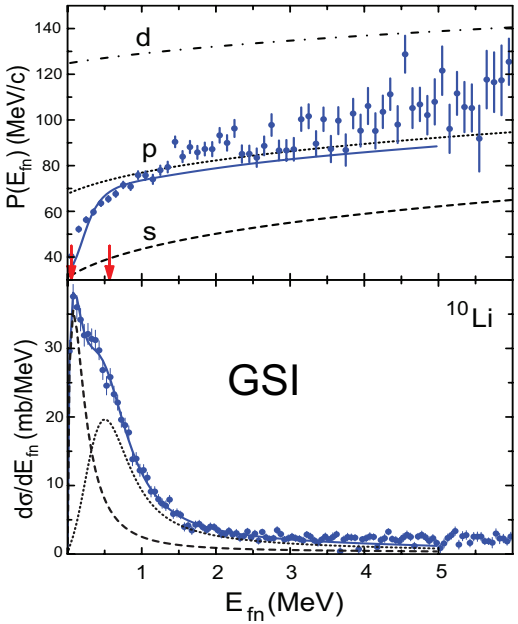
- Evolution of shell structure
- States beyond the neutron drip-line
- Nucleon-nucleon correlations
  (short-range tensor correlations)
- Cluster structure
- Fission barriers

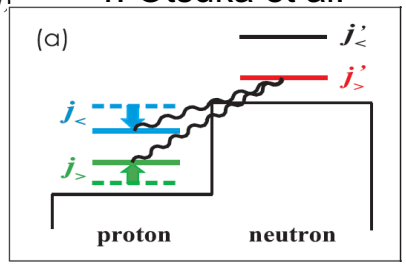


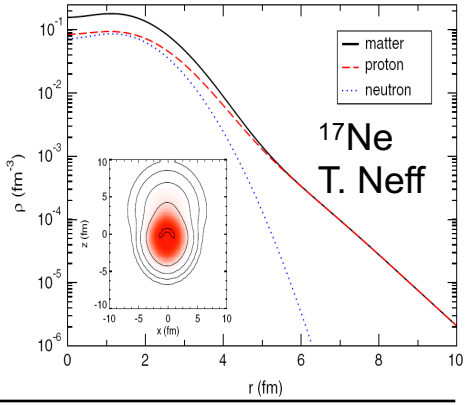




T. Otsuka et al.







Reminder: single-particle structure and correlations (e,e'p) and (p,2p) knockout reactions for stable nuclei

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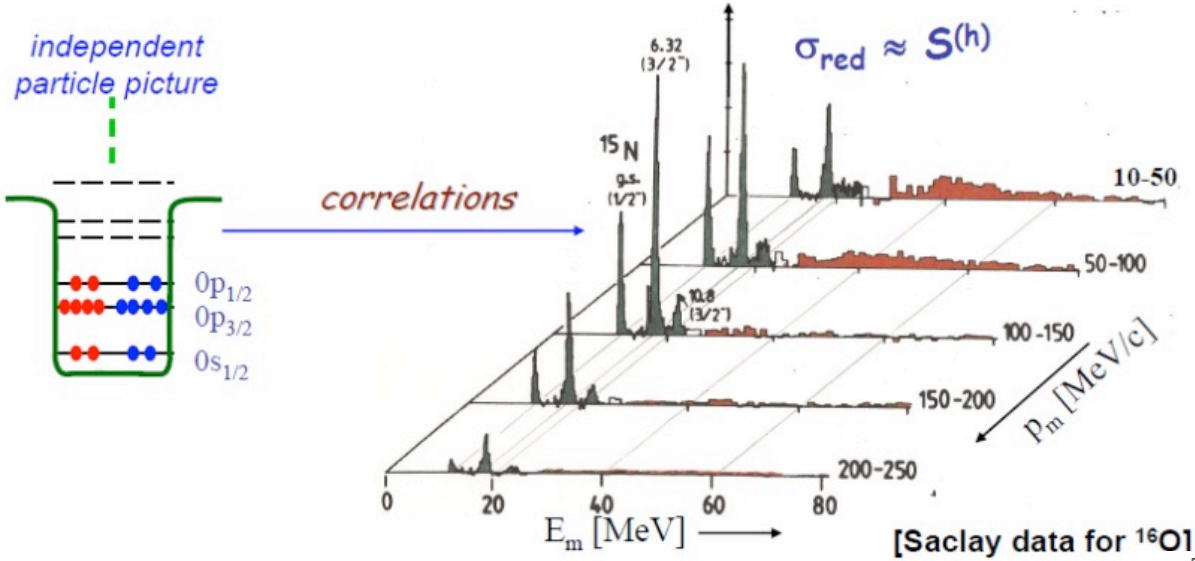
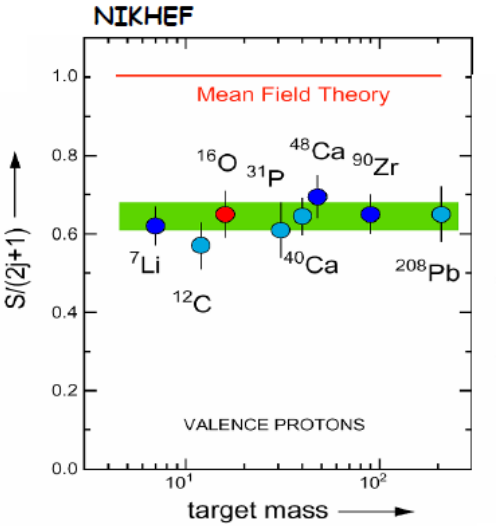


[Saclay data for ^{16}O]



Nucl. Phys. A553 (1993) 297c

Deviation from the independent-particle picture:

Correlations: Configuration mixing,

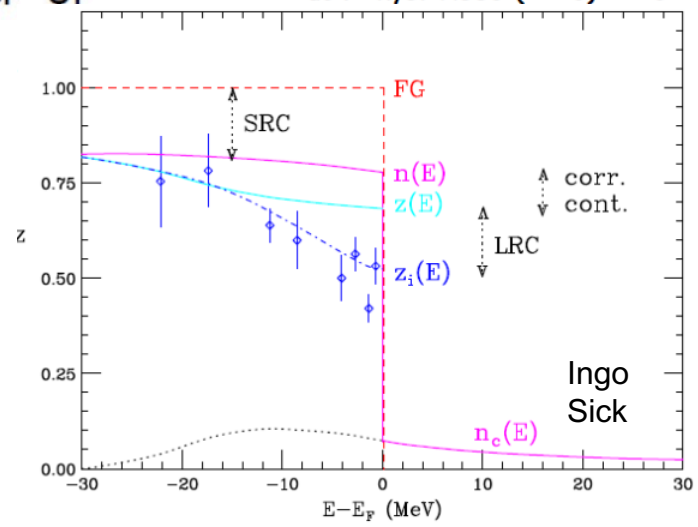
Coupling to collective phonons

Short-range and tensor correlations

→ high momenta

→ fragmentation / reduction of single-particle strength

(occupations, spectroscopic factors)



One-nucleon removal cross sections
'Quenching' for deeply-bound valence nucleons in neutron-proton asymmetric nuclei ?

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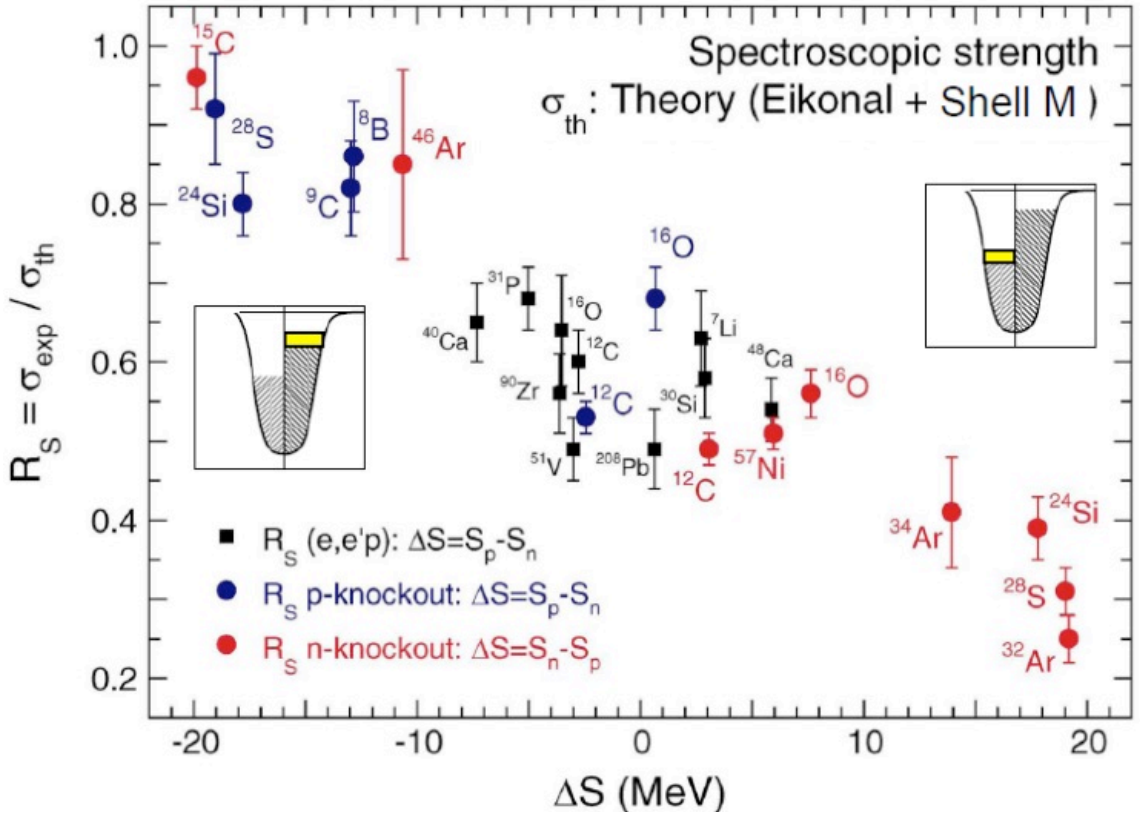
weakly bound nucleons

strongly bound nucleons



?

Origin unclear

?

Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)

Experimental setup: LAND/R3B@GSI

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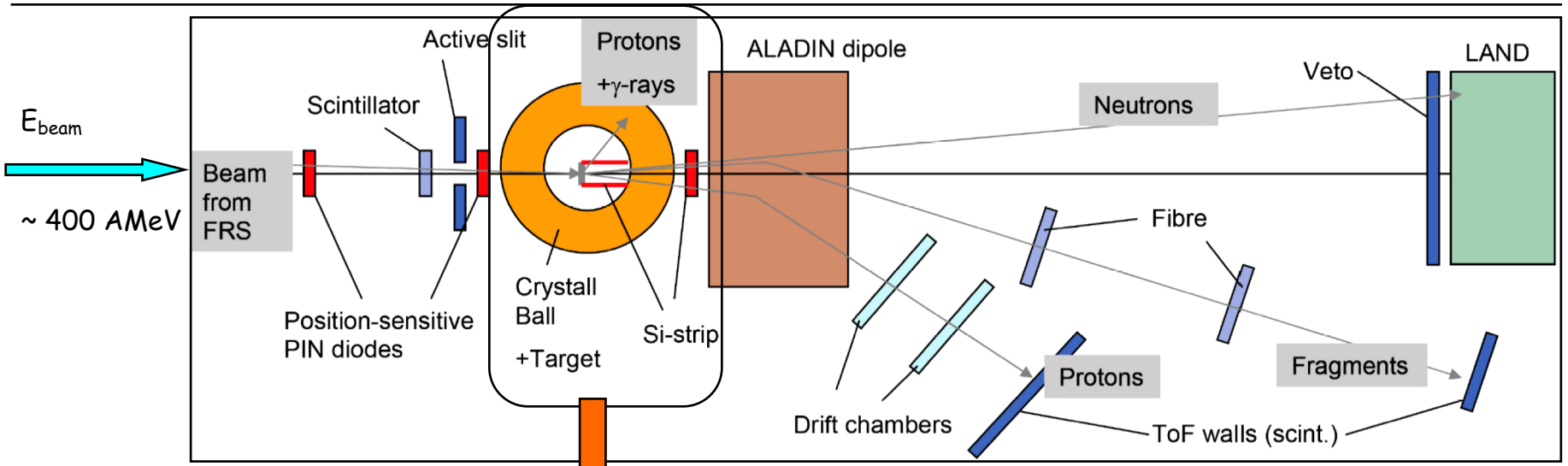

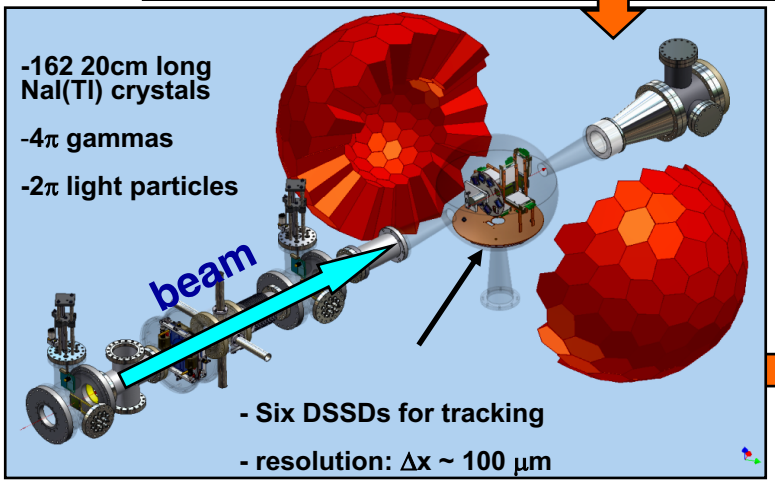

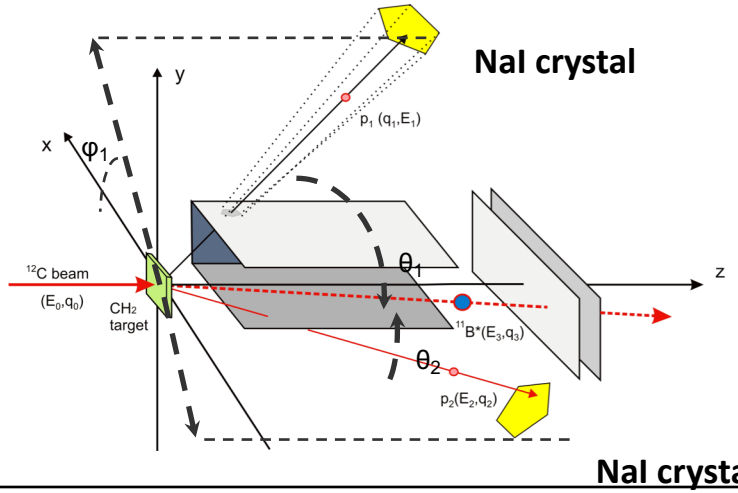

^{12}C beam at 400 MeV/u: ^{12}C(p,2p)^{11}B*

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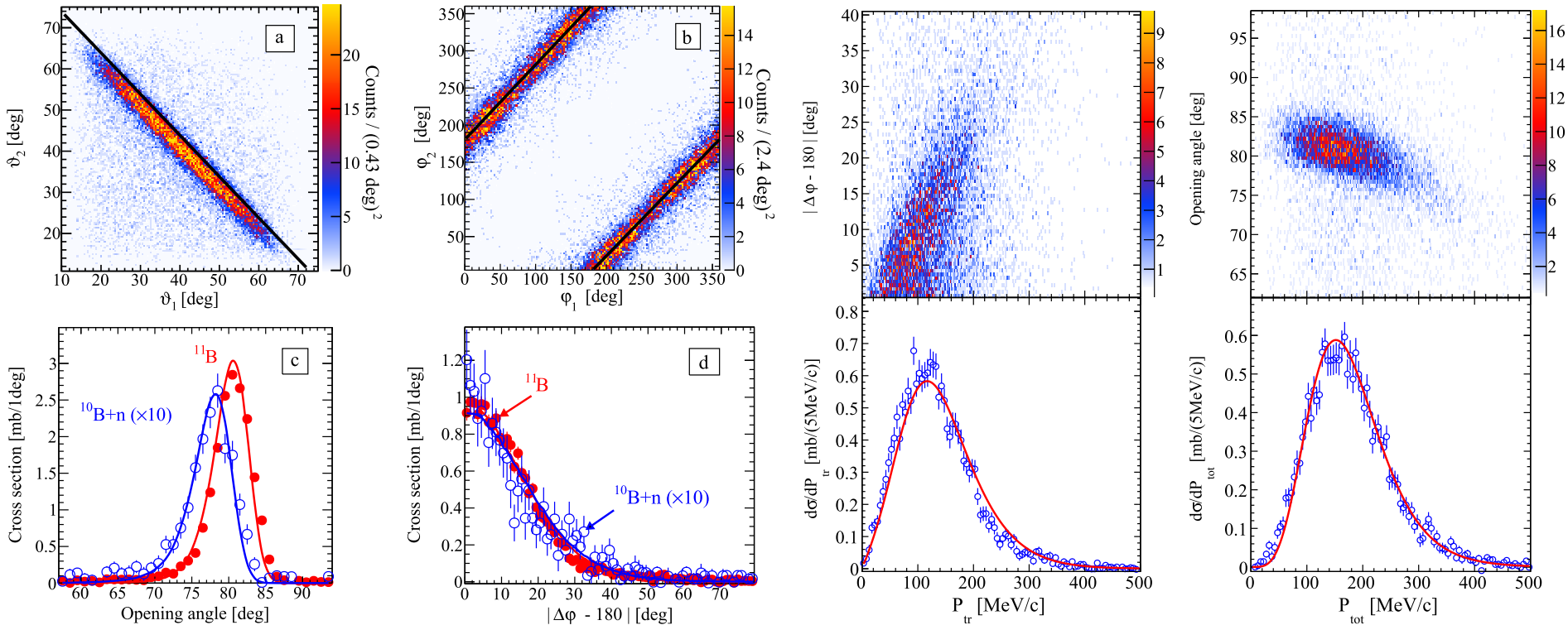
Angular correlations and (fragment) momentum distributions



V. Panin et al., Phys. Lett. B 753 (2016) 204

$^{12}C(p,2p)^{11}B^* \rightarrow (^{10}B + n), (^{10}Be + p), (^{7}Li + ^{4}He), \ldots$

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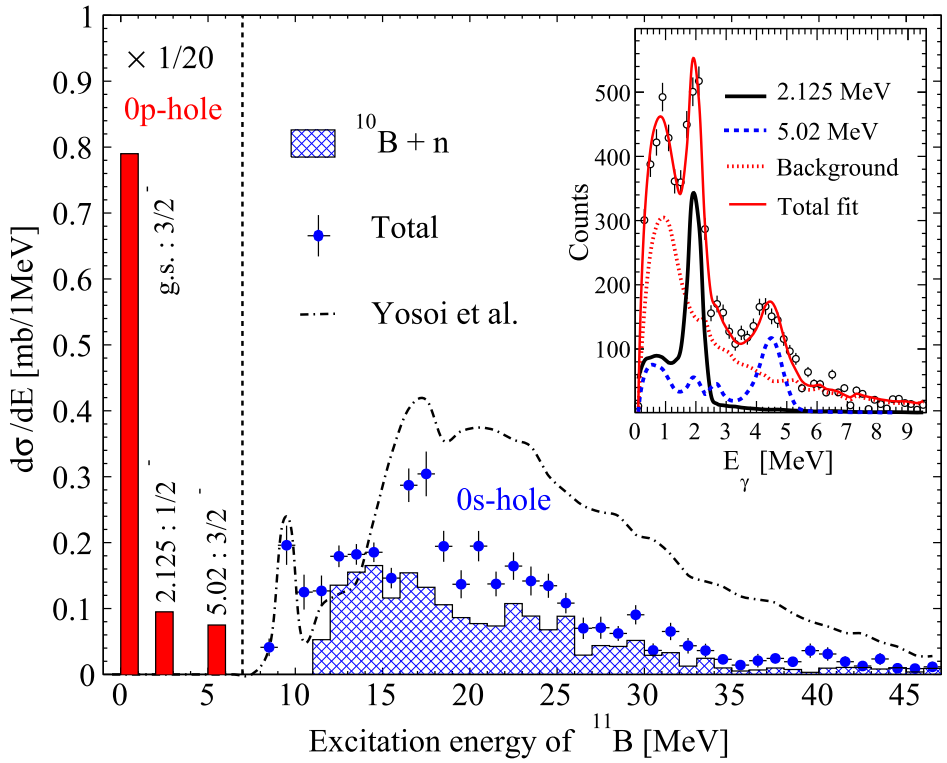

Excitation-energy distribution (hole states)

Bound states:
γ spectroscopy

Unbound states:
invariant mass

$$M_{inv}^2 = \mathbf{P}^2 = E_{tot}^2 - \vec{P}_{tot}^2 = \left(\sum_j^N E_j\right)^2 - \left(\sum_j^N \vec{p}_j\right)^2,$$

$$E^* = \sqrt{\sum_j^N m_j^2 + \sum_{j\neq k}^N \gamma_j \gamma_k m_j m_k (1 - \beta_j \beta_k cos\vartheta_{jk})} - M_0.$$

V. Panin et al., Phys. Lett. B 753 (2016) 204

Reduction factors from $^{A}O(p,2p)^{A-1}N$ (bound states)

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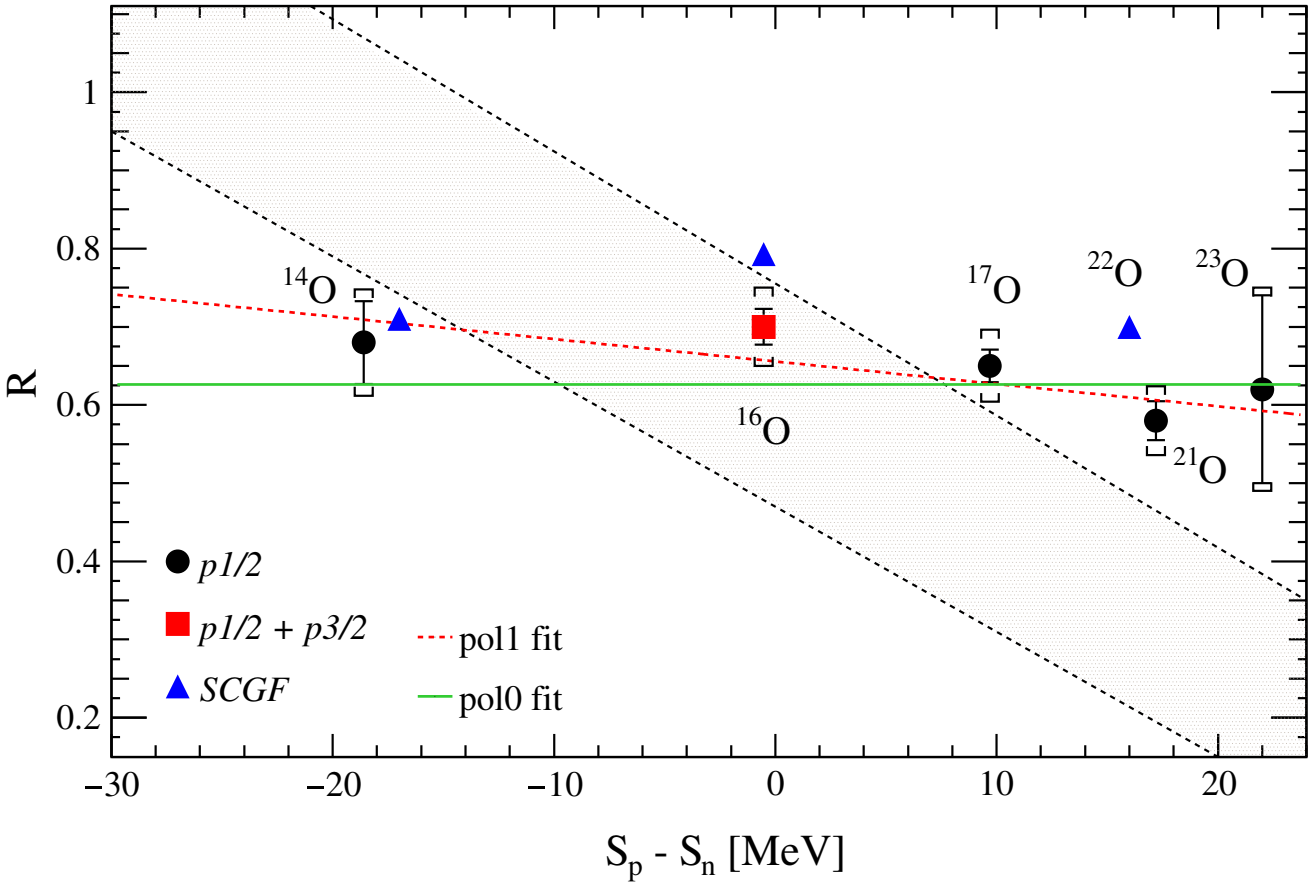

Ab initio theory (prediction !):
Carlo Barbieri
Self-consistent Green's function with NNLO-sat:
Good radii and particle-hole gaps

No strong asymmetry dependence observed in (p,2p) !!!

L. Atar et al. (R3B collaboration), PRL 120 (2018) 052501

Nuclear Structure
^{17}Ne: one-nucleon removal + (p,2p) knockout

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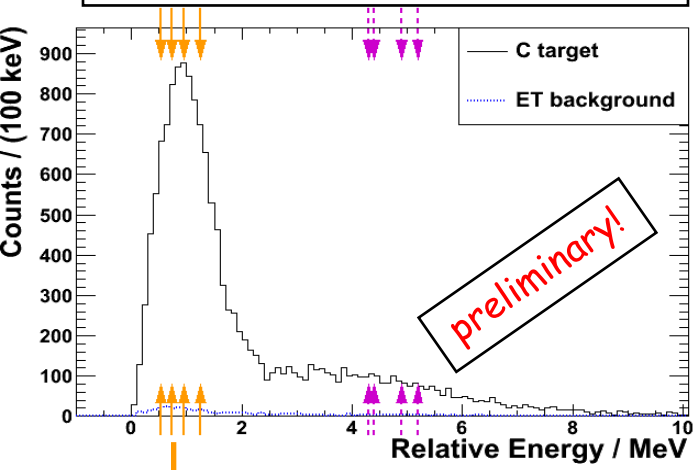
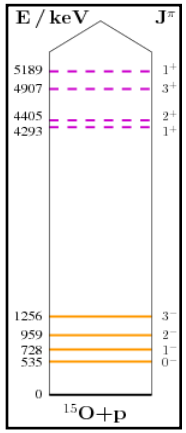
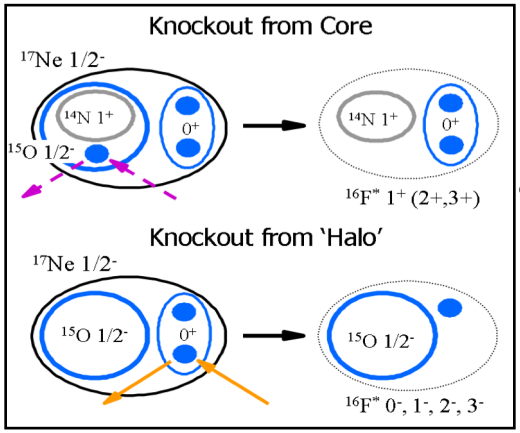
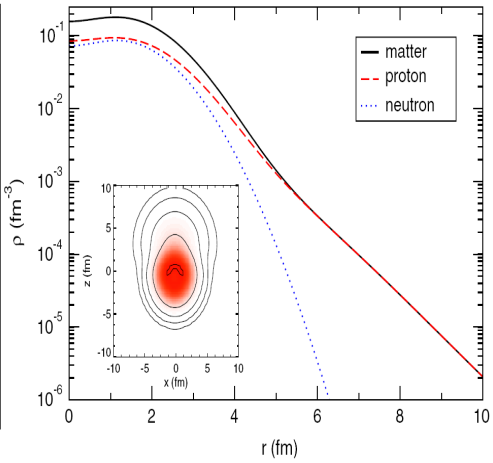
^{16}F (=^{15}O+p) relative energy









Exclusive selection of knockout from 'halo'-states for the first time possible!

→

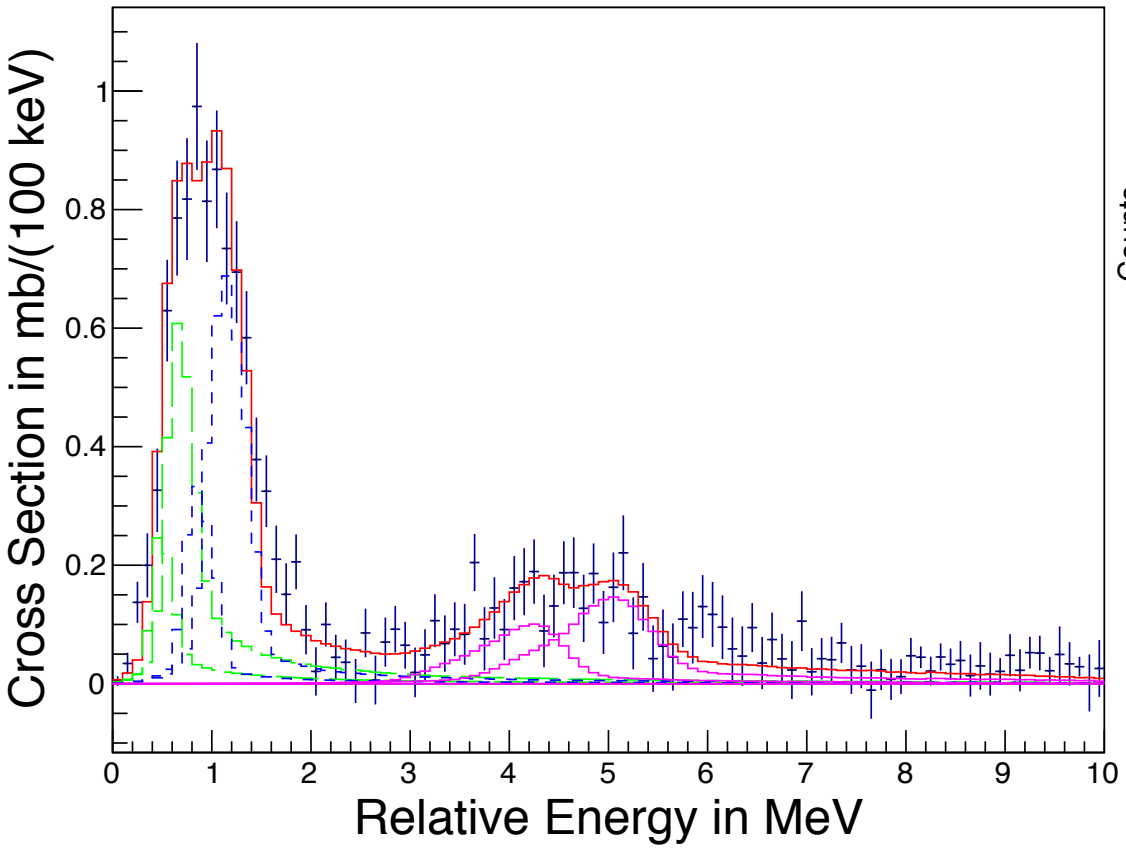
First exclusive measurement of knockout of valence (halo) protons

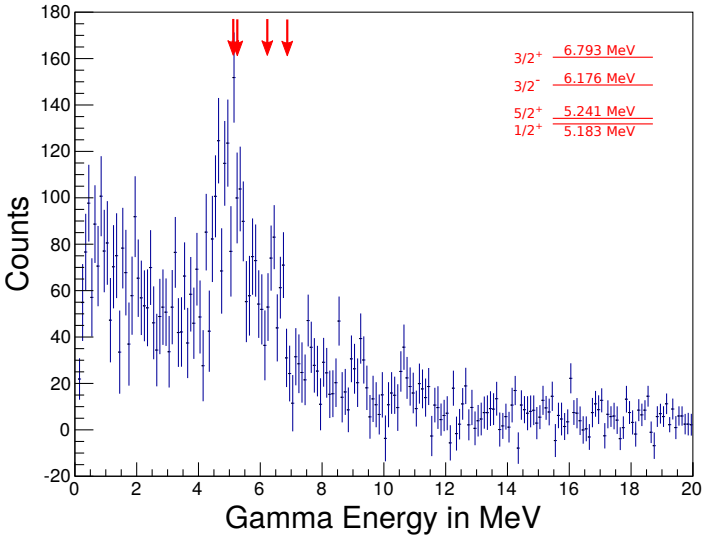
→ s^2/d^2 configuration mixing

(previous inclusive data not conclusive)

Felix Wamers, PhD thesis, TU Darmstadt; (p,2p): Christopher Lehr, Master Thesis, TUDa 2017

^{17}Ne (p,2p): ^{16}F energy spectrum



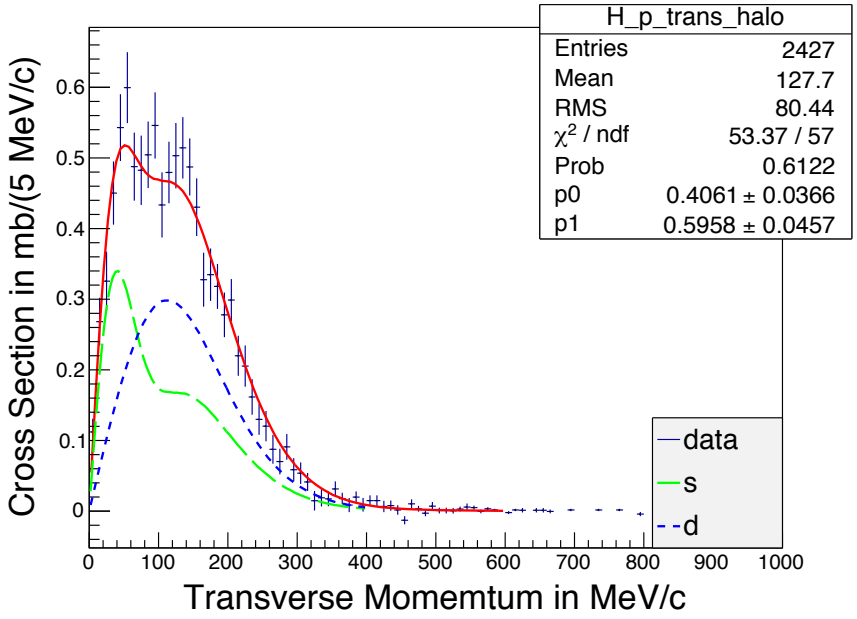


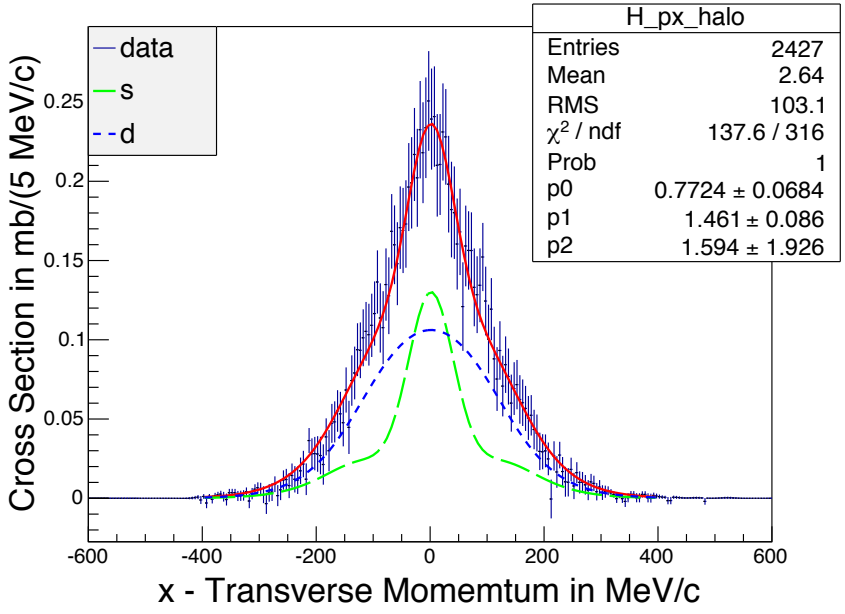
Contribution with excited ^{15}O core subtracted
Large fraction of cross section from non-halo proton knockout:
Previous interpretation of inclusive cross sections has to be revisited !!!

s^2/d^2 cross section ratio: 41(4)/59

Christopher Lehr, Master Thesis (TU Darmstadt), publication in prep.

^{17}Ne (p,2p): Momentum distributions





Transverse momentum distribution for ^{15}F low-lying s and d states
(Halo contribution only)
Perfect description by Eikonal-based reaction theory (T.A., C. Bertulani, J. Ryckebusch)

s^2/d^2 cross section ratio: 42(4)/58
s^2/d^2 configuration ratio: 34(3)/66

Christopher Lehr, Master Thesis (TU Darmstadt 2017), to be published

Short-range correlations

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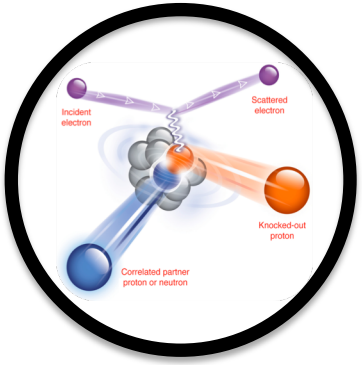
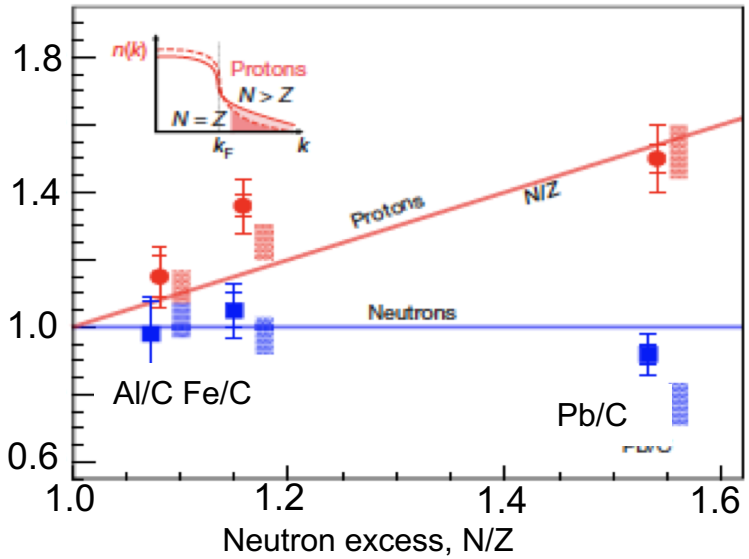
JLAB

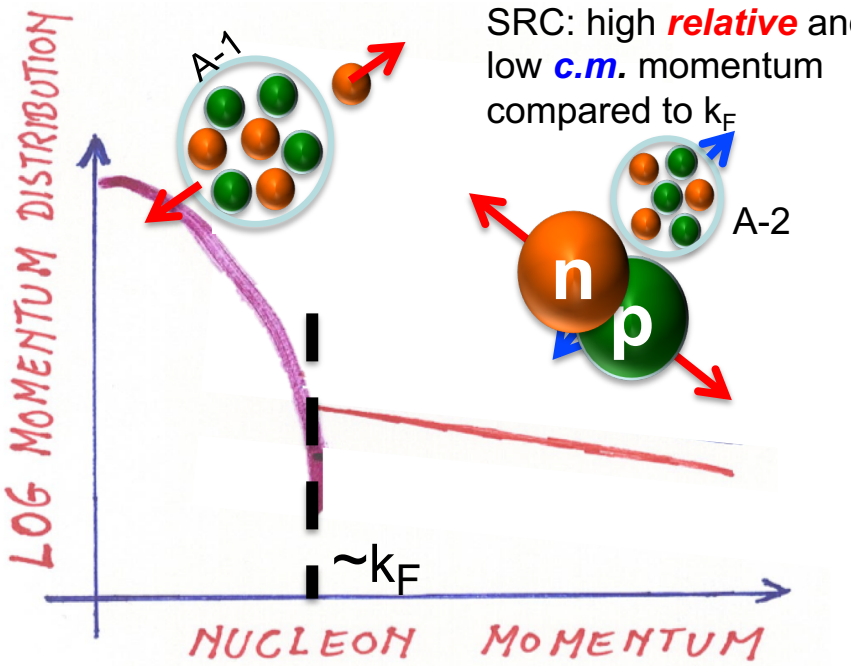
Nature 578, 540 (2020)

Nature 566, 354 (2019)

Nature 560, 617 (2018)







SRC: high ***relative*** and low ***c.m.*** momentum compared to k_F

Proposed Experiment at R^{3}B

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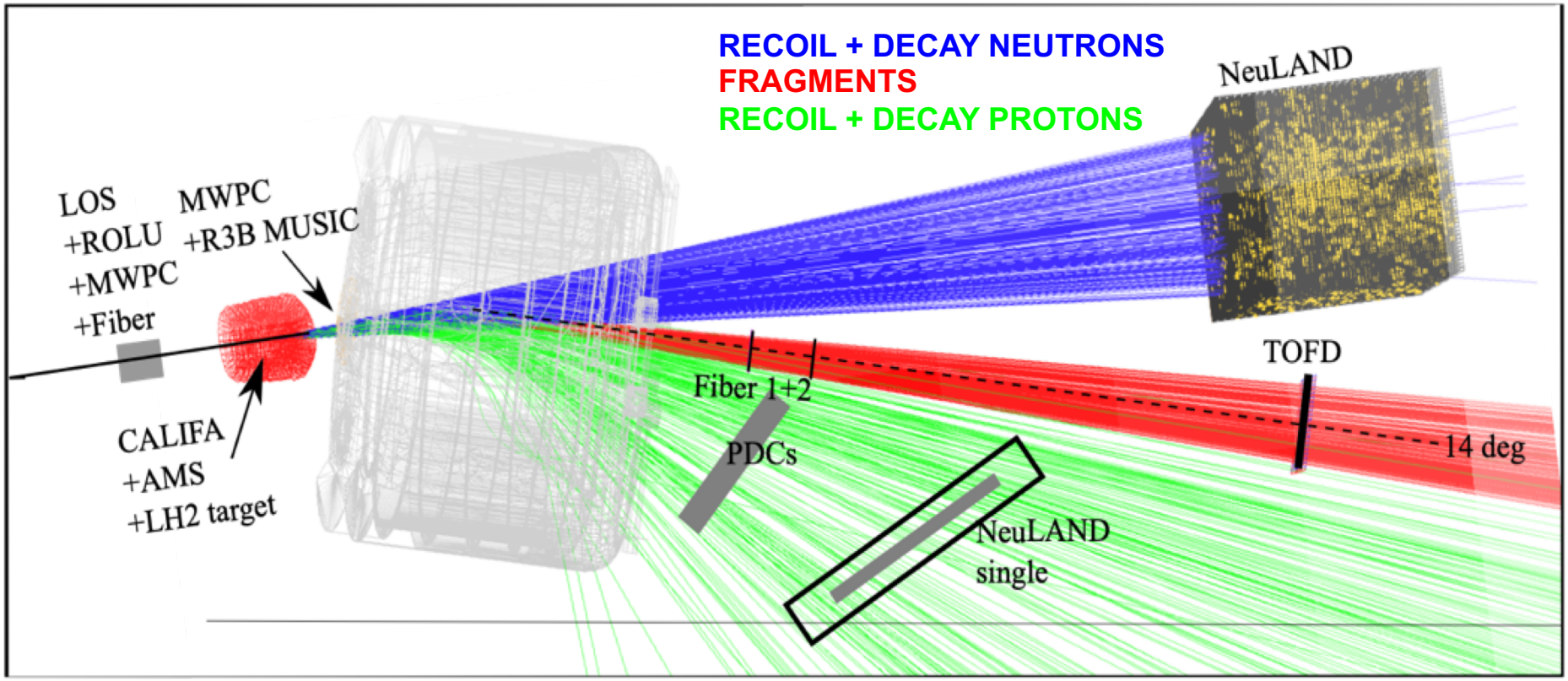
- **^{12}C(p,2pN)^{10}B/Be** fully exclusive measurement
- Spectroscopy of the heavy fragment

Anna Corsi
Or Hen



Nuclei beyond dripline

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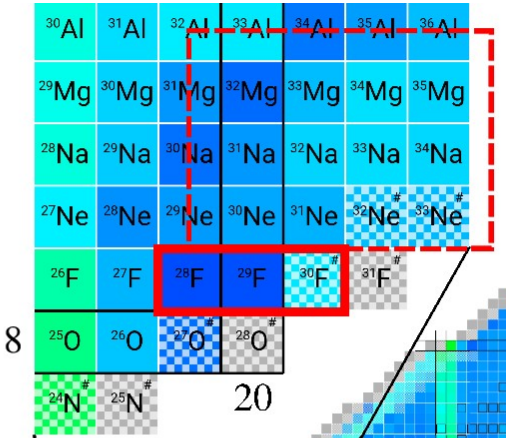
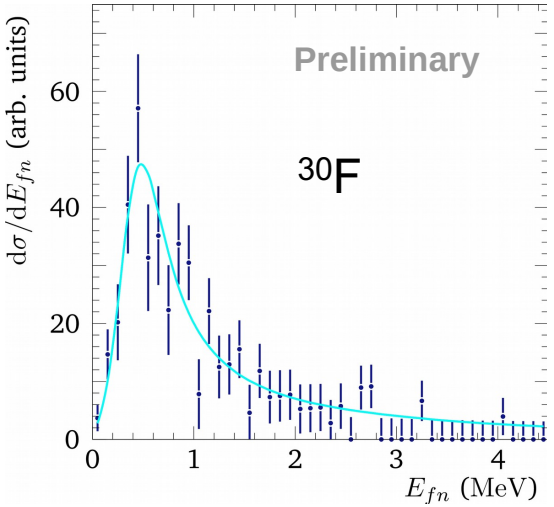
Examples

GSI: ^{17}Ne(p,pnn)^{15}Ne 2 p beyond drip (Wamers et al.)
^{27}F(p,2p)^{26}O 2 n beyond drip (Caesar et al.)

RIBF: ^{31}Ne(p,2p)^{30}F (Kahlbow et al., in prep.)
^{29}F(p,2p)^{28}O (Kondo et al., in prep.)
(SAMURAI + NeuLAND)

Neutron states: ^{8}He(p,pα)^{4}n → tetra neutron
^{6}He(p,pα)^{2}n → nn scattering length





Alpha Clusters at the surface of heavy nuclei

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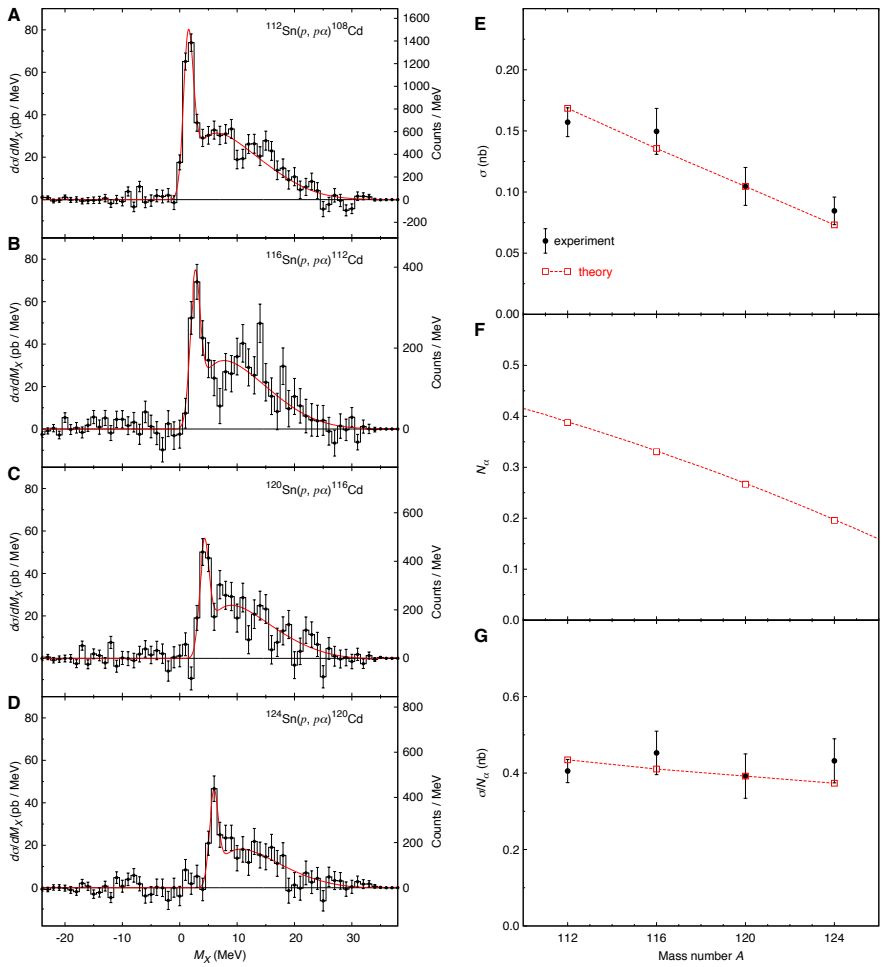

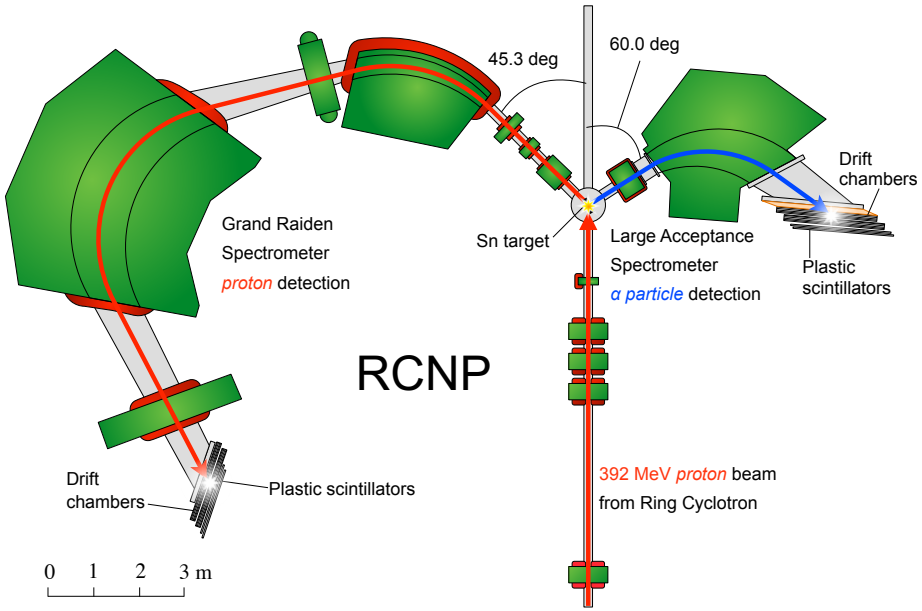

Junki Tanaka et al., submitted

→ at RIBF and R3B
(p,pα) for heavy α emitters