KNOCKOUT REACTIONS: A TOOL FOR SPECTROSCOPY OF EXOTIC NUCLEI

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Nuclear Physics Conundrum

- *Using nuclear reaction to study nuclear structure*

Observable: cross section

Structure model: spectroscopic factor

Reaction model: single-particle cross section

$$\sigma^{if} = \sum_{|J_f - J_i| \leq j \leq J_f + J_i} S_j^{if} \sigma_{sp}$$

- *One observable, two models*
- *Extract valuable structure information*
- ***Need accurate reaction model!***

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Outline

- *Knockout reactions under the microscope*
  - *Precision test of reaction model using exclusive experiment*
  - *Validate the concepts used in the theory*
  - *Case for using this type of reaction as spectroscopy tool*

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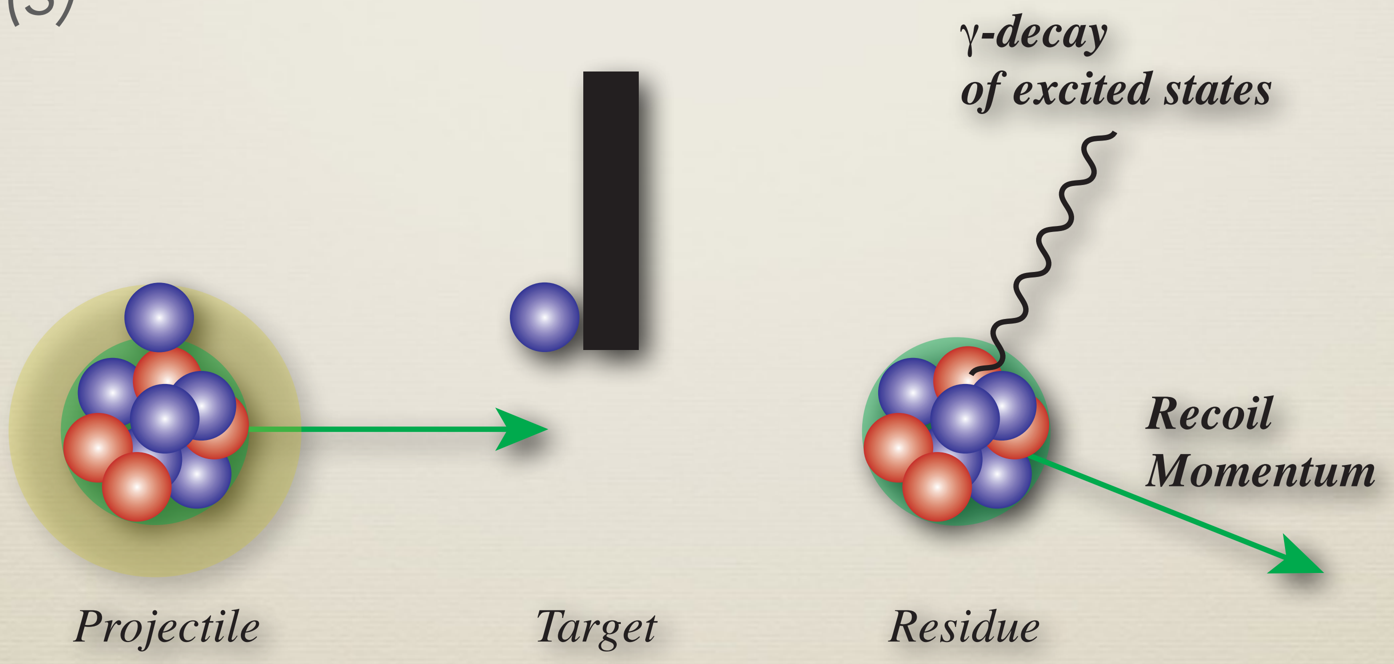
- *Knockout reactions under the microscope*
  - *Precision test of reaction model using exclusive experiment*
  - *Validate the concepts used in the theory*
  - *Case for using this type of reaction as spectroscopy tool*
- *Nuclear structure under the microscope*
  - *Test ab-initio nuclear structure models on p-shell nuclei*
  - *Emergence of nuclear structure models from first principles*
  - *Knockout reactions offer unique tool to probe these models*

Knockout reactions

- *Sudden removal of one or two nucleons from a projectile via nuclear interaction with a light target*
    - *Direct (one-step) peripheral reaction*
    - *High energy: sudden approximation + eikonal model*
    - *Recoil momentum of residue equivalent to that of removed nucleon(s)*



P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. **53**, 219 (2003)

Experimental Assets

- *High luminosity for inverse kinematics*
  - *Inclusive measurement: thick targets*
  - *Fast beams: focusing of projectile residues in small solid angle*
  - *High efficiency γ-ray array: CsI(Na) or γ-tracking Ge*
  - *Measurements possible down to ~ 1 projectile/second*
  - ***Very well suited to rare isotope beams produced via projectile fragmentation***
- *High physics output*
  - *Single-particle components of projectile wave function*
  - *Level scheme of residual nucleus (hole states)*

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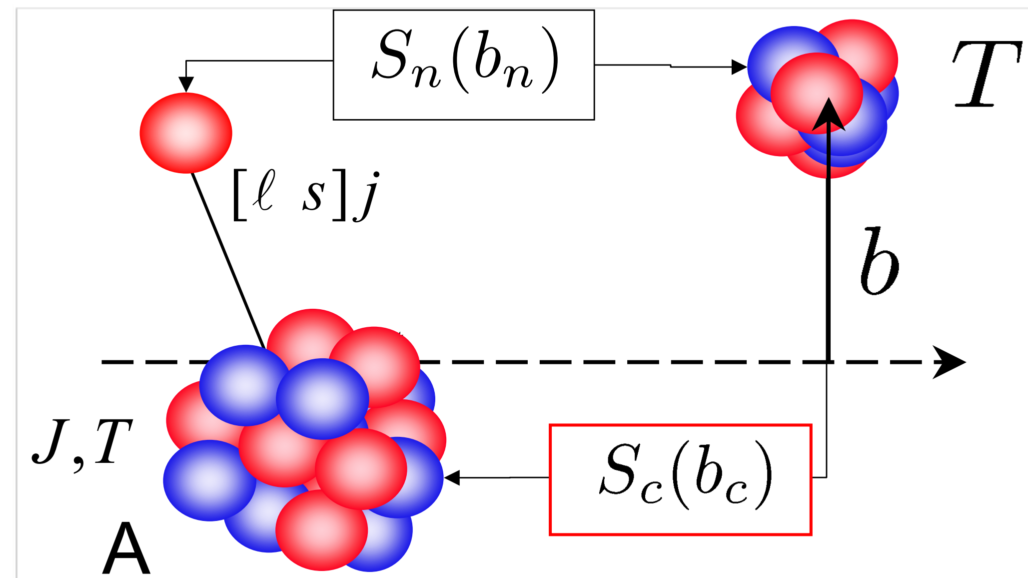
Theoretical Assets

- *Simple Glauber-type eikonal reaction model*
  - *Stripping: inelastic breakup*
  - *Diffraction: elastic breakup*
  - *Cross section independent of removed nucleon binding*



- **Does this model reflects reality?**

$$\sigma_{sp} = \sigma_{str} + \sigma_{dif} + \sigma_C$$

$$\sigma_{str} = \frac{1}{2j+1}\int d\vec{b} \sum_m \langle \psi_{jm} | (1 - |S_n|^2) |S_c|^2 | \psi_{jm} \rangle$$

$$\sigma_{dif} = \frac{1}{2j+1}\int d\vec{b} \left[\sum_m \langle \psi_{jm} | |1 - S_n S_c|^2 | \psi_{jm} \rangle - \sum_{m,m'} |\langle \psi_{jm'} | (1 - S_n S_c) | \psi_{jm} \rangle|^2\right]$$

J. A. Tostevin, Nucl. Phys. A **682**, 320c (2001)

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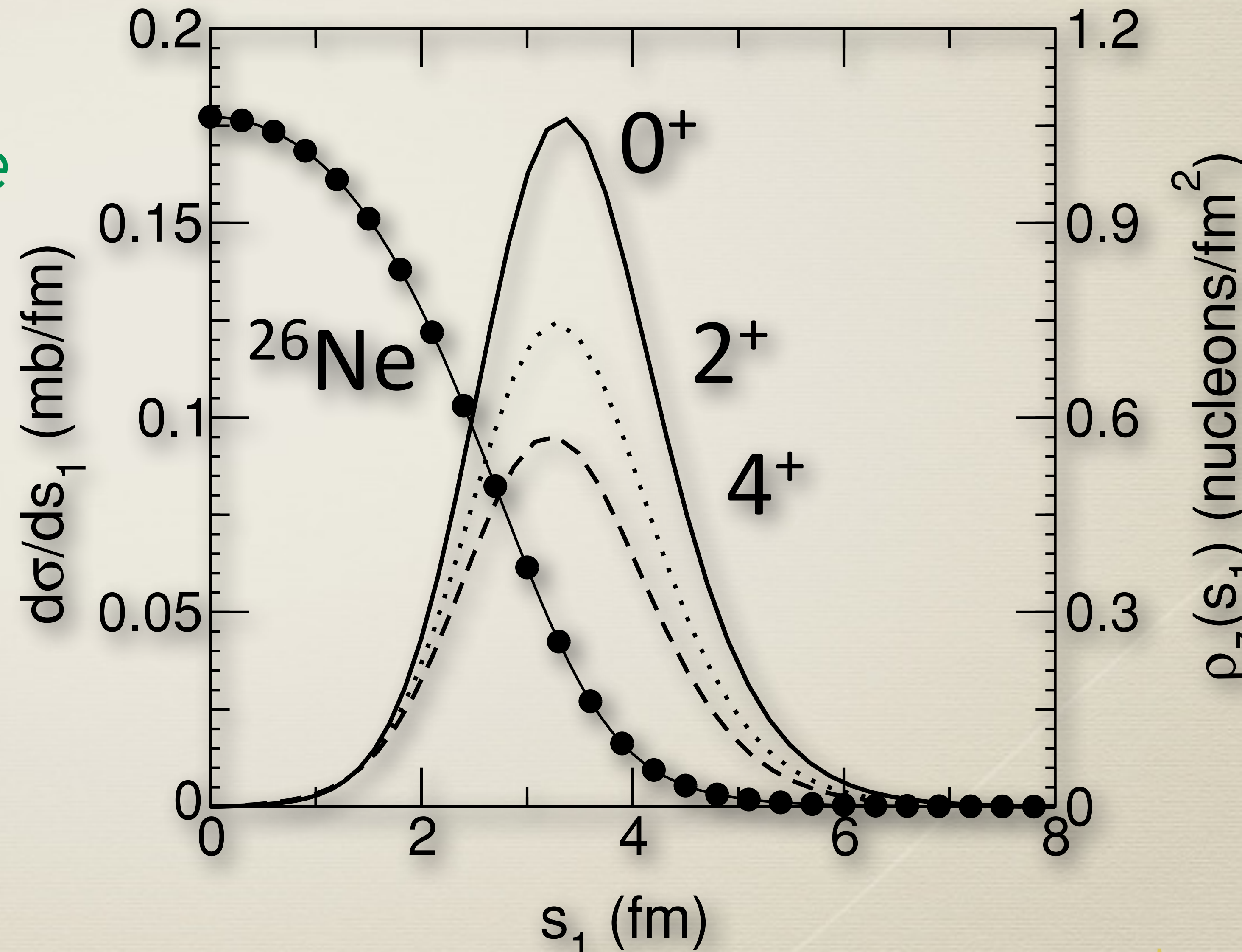
Surface localization of reaction

- *Part of the WF probed by the knockout mechanism*
  - *Case shown: 2p knockout from ^{28}Mg on ^{9}Be target*
- *Spectroscopic sensitivity near surface and non-asymptotic*
- *Eikonal model uses descriptions of size and surface behavior of single-particle orbitals*



E. C. Simpson *et al.*, Phys. Rev. C **79**, 064621 (2009)

Exclusive experiment

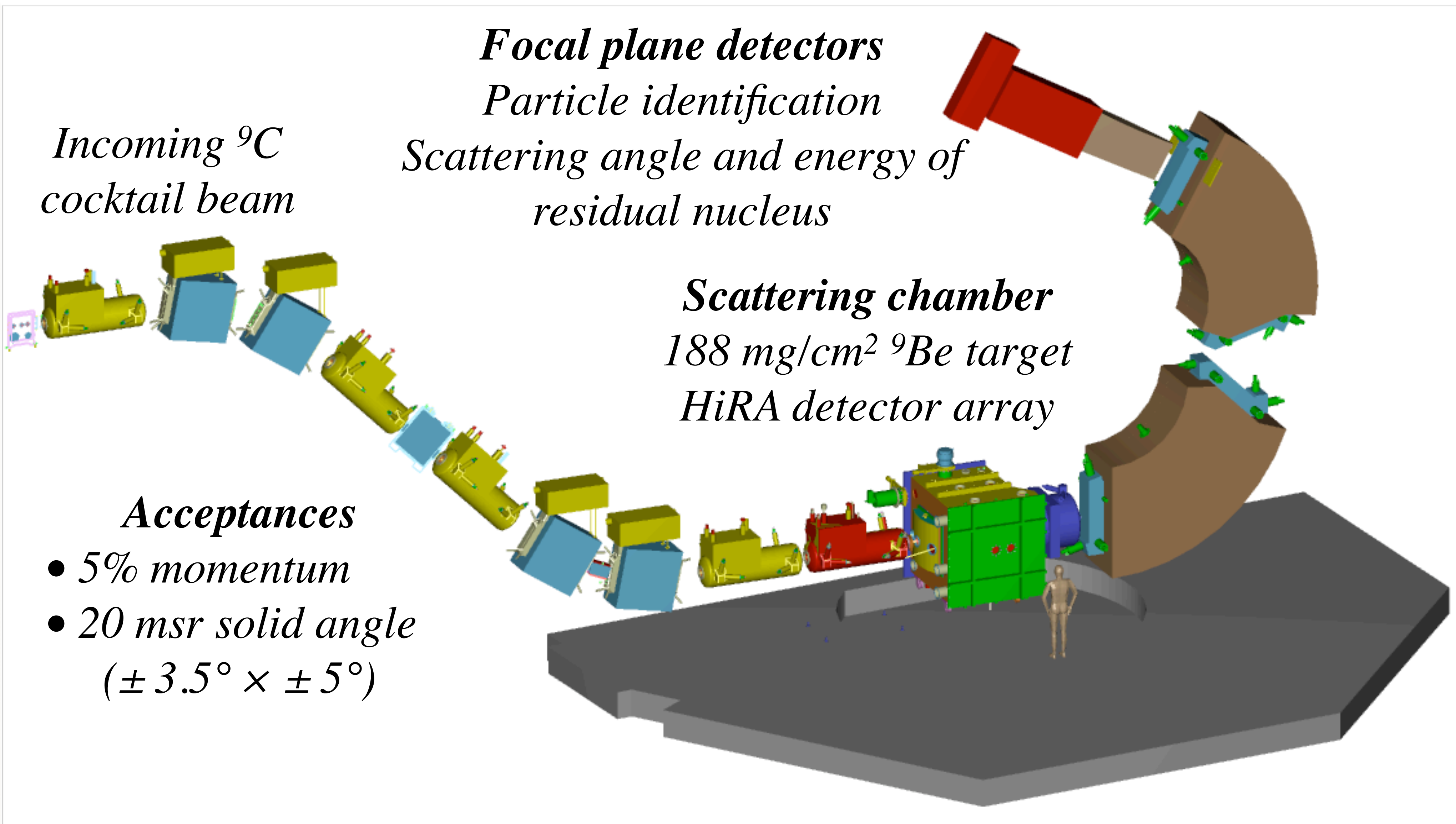
- *Experiment aimed to measure stripping and diffraction parts of the cross section separately*
    - *Detect removed nucleon with maximum solid angle*
    - *One-proton knockout: easier to detect proton than neutron*
    - *Choose two cases with different binding energies and only one or two final states*

Initial state	*Final state*	*S*	*σ*	*σ*	*σ*	*S*	*%*
9	8	1.296	44.57	15.27	1.1	0.94	26.8
8	7	0.137	64.42	31.65	7.7	1.036	37.1
8	7	0.566	57.34	24.44	3.4	0.22	

D. Bazin *et al.*, Phys. Rev. Lett. **102**, 232501 (2009)

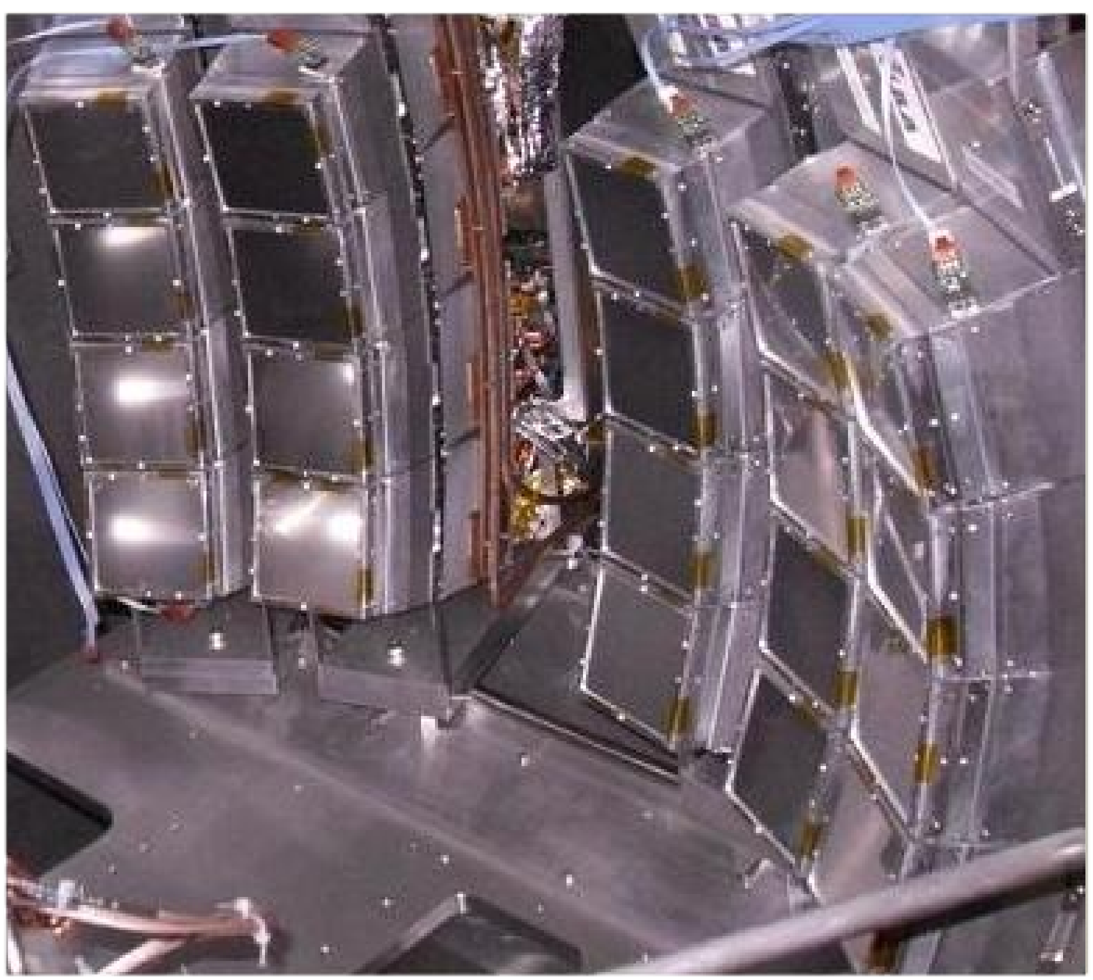
Experimental Setup

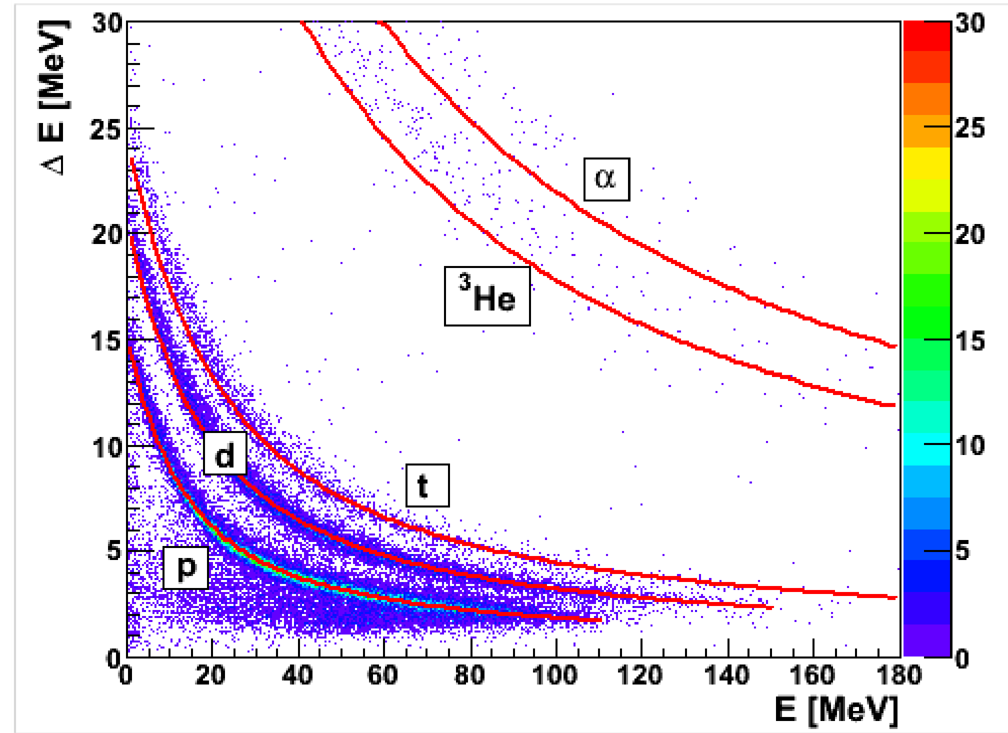
- *S800 spectrograph to measure projectile residue*
- *HiRA telescope array to measure knocked out proton*

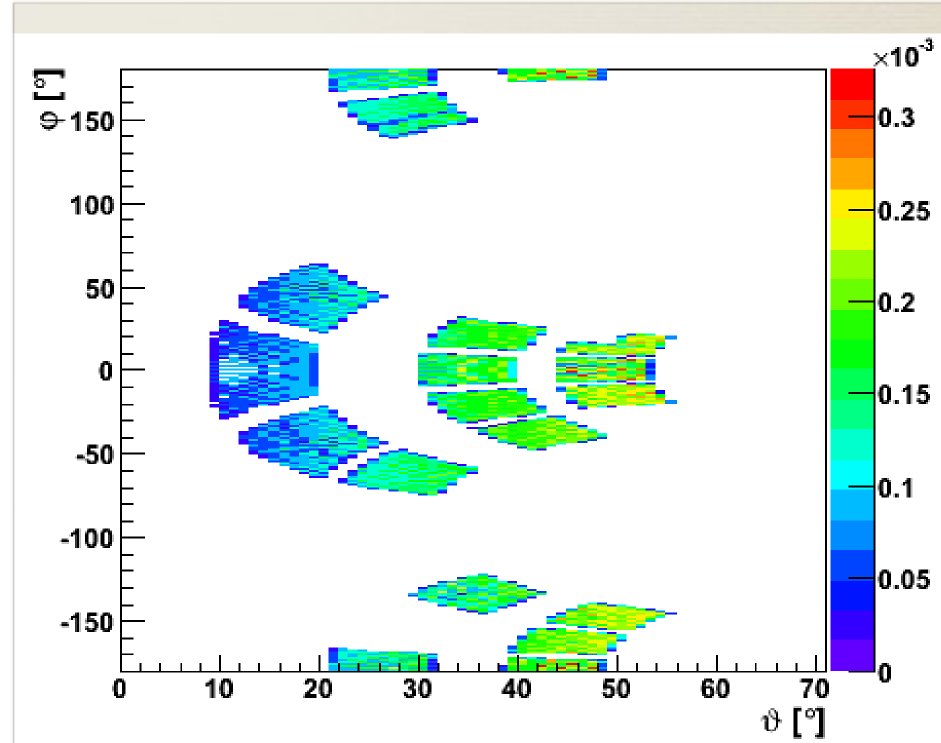


High Resolution Array HiRA

- *Up to 20 telescopes*
- *Angular coverage 9° to 54°*
- *Energy, identification of p,d,t…*

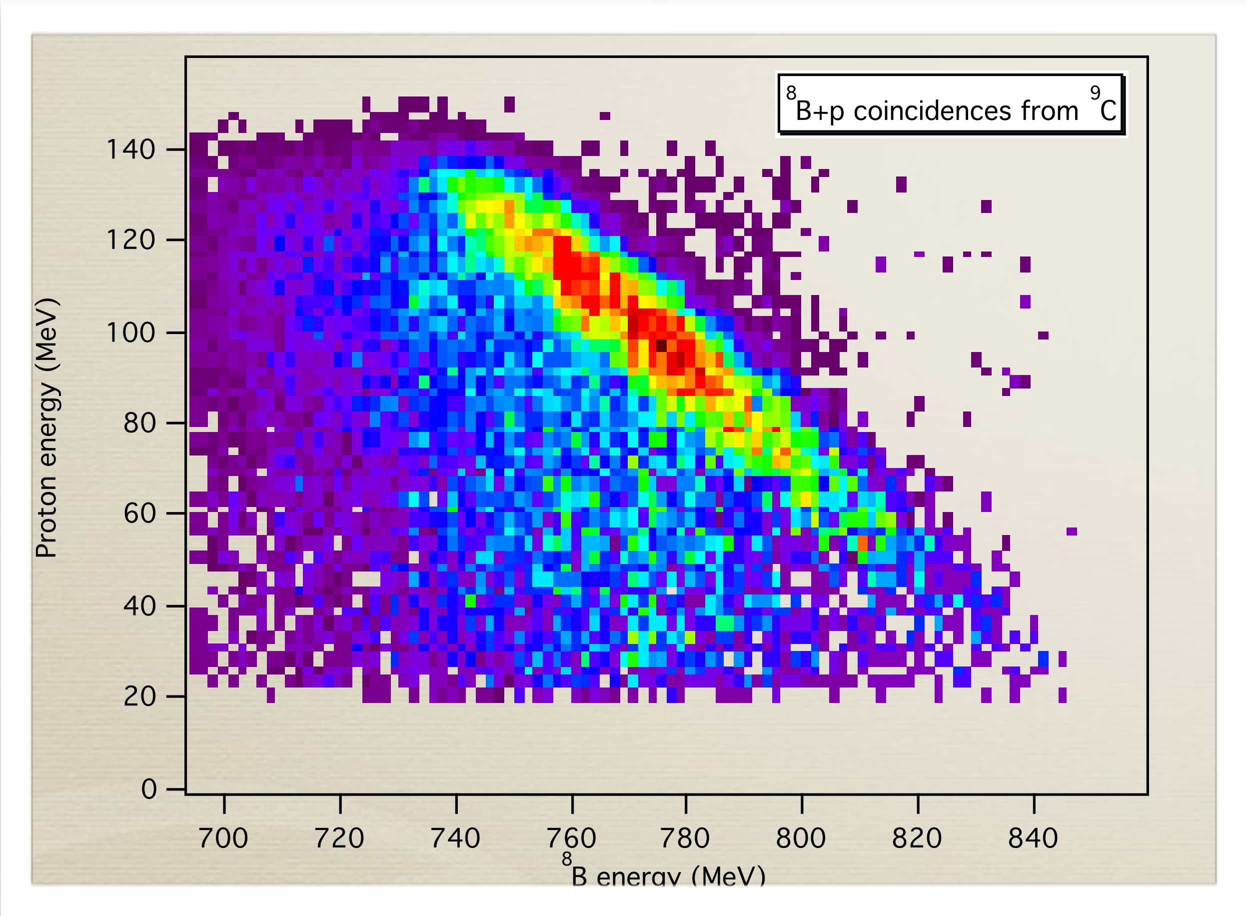


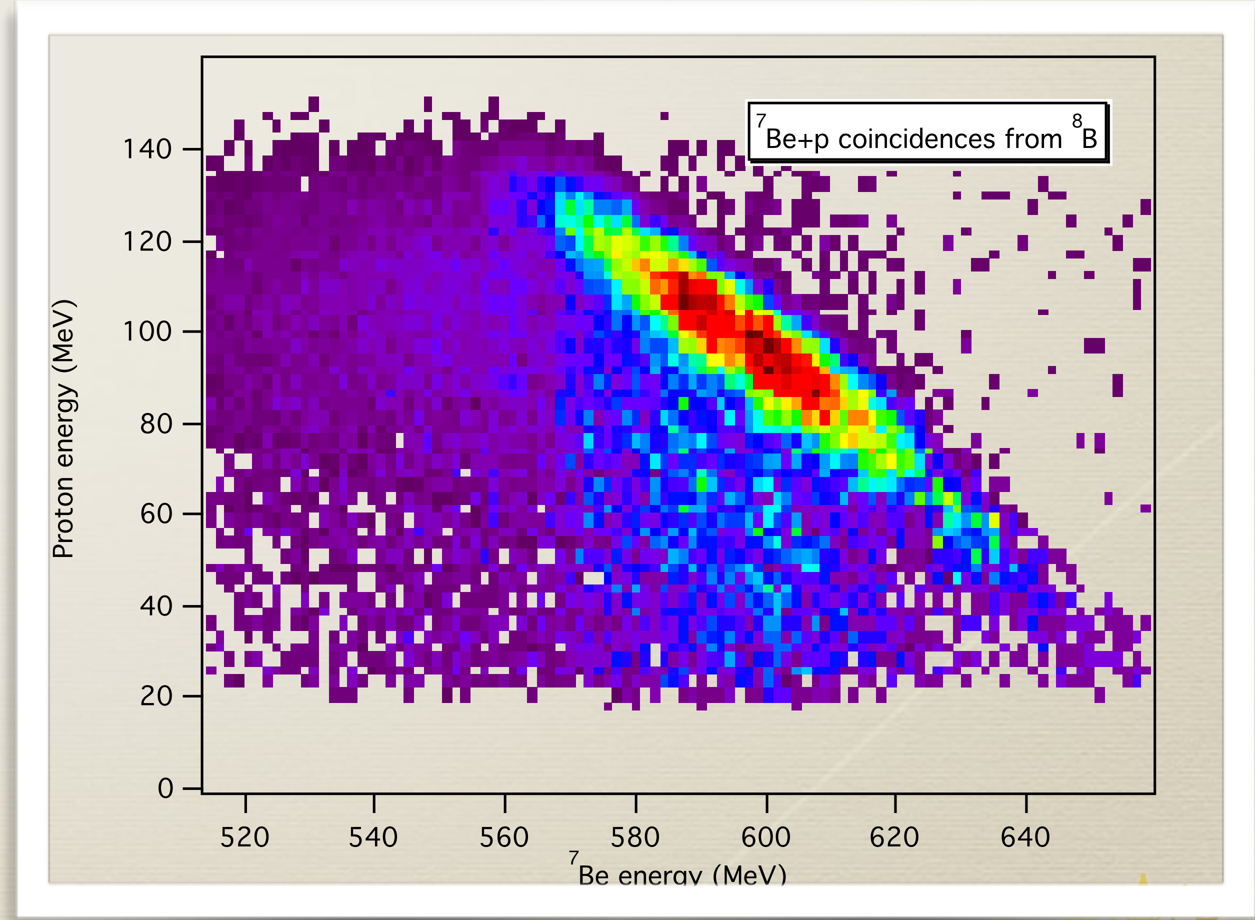




Proton coincidences

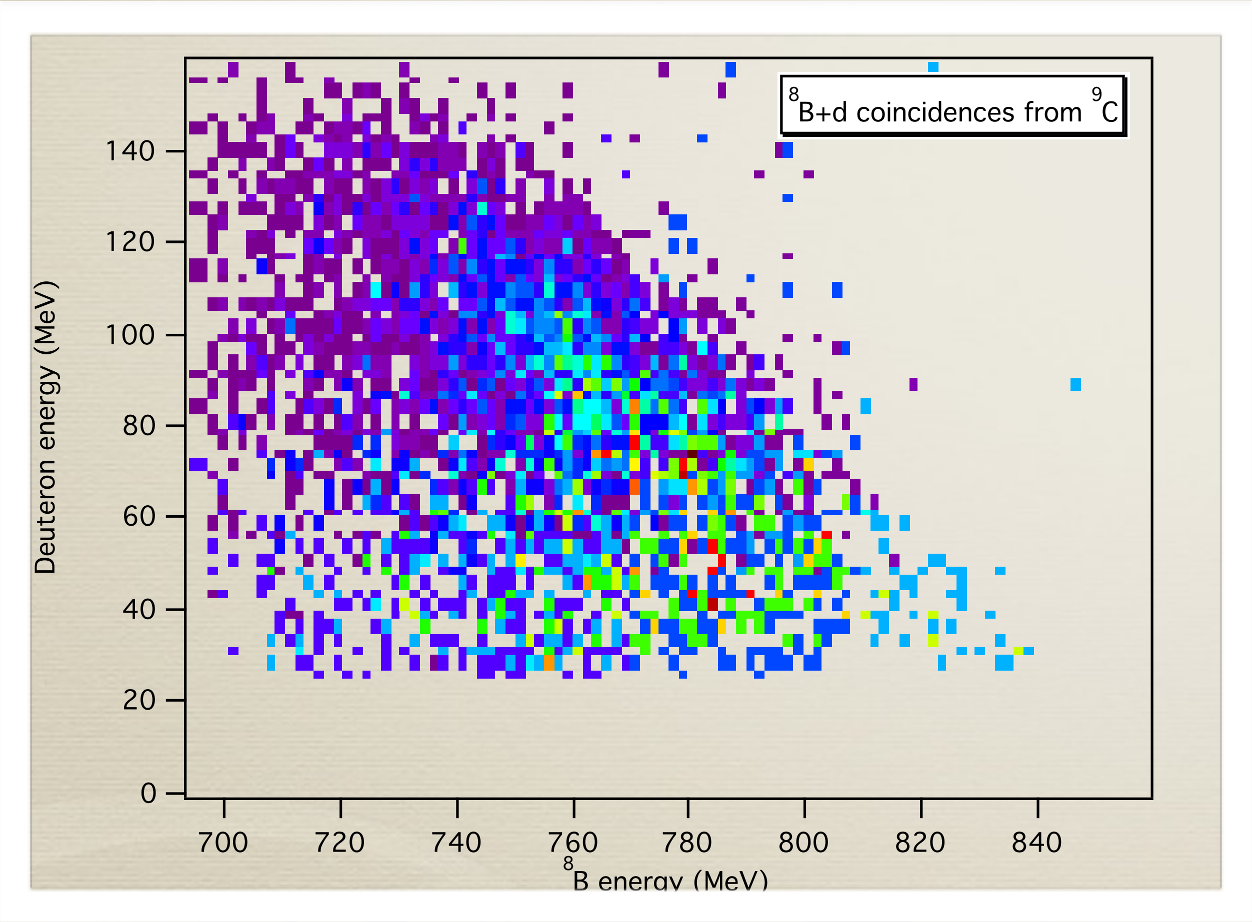
- *Evidence for elastic breakup reaction mechanism*
  - *Diagonal "band" corresponds to elastic process where energy is conserved*
  - *For other events proton interacts inelastically with target*

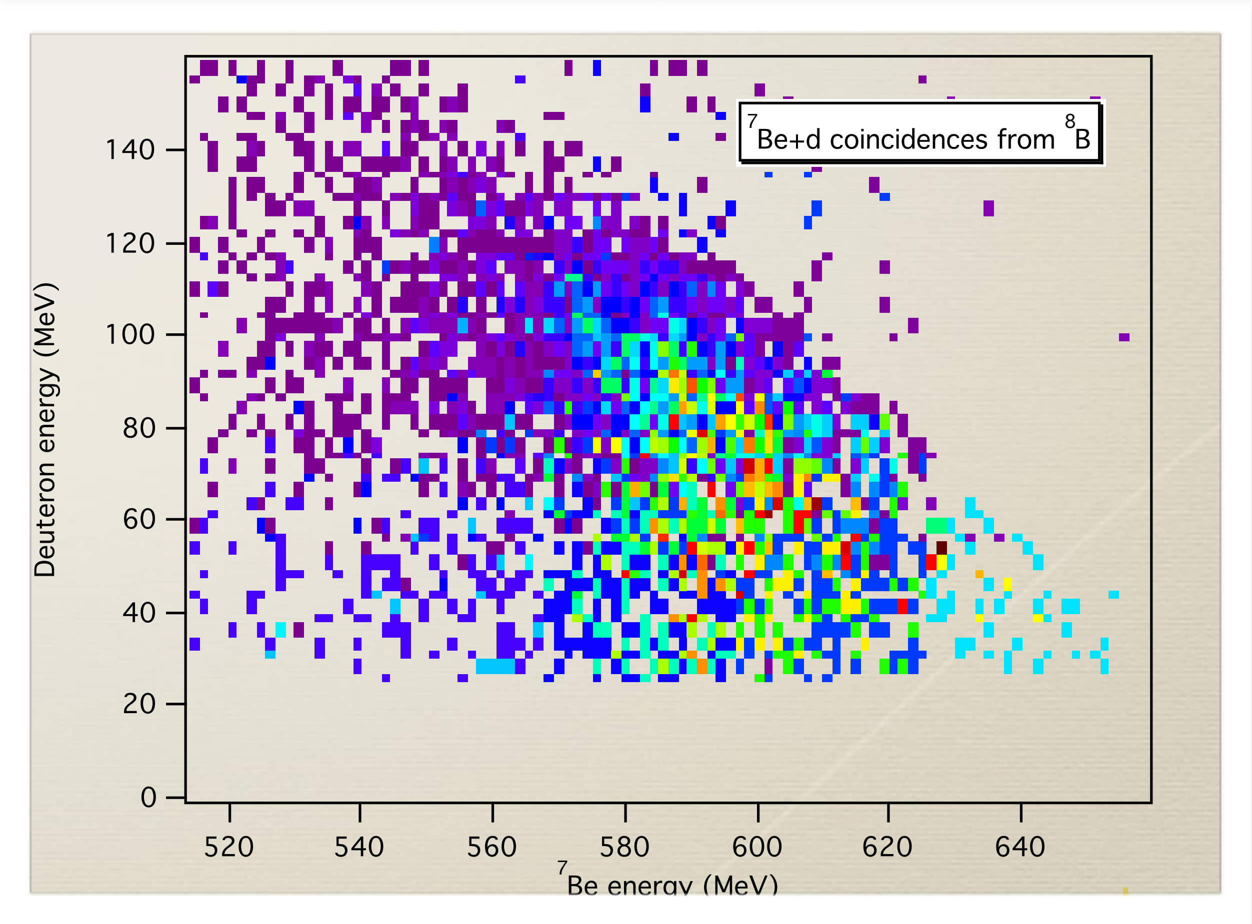




Deuteron coincidences

- *Must come from stripping events*
  - *Additional neutron in deuteron comes from (p,d) on ^{9}Be target*
  - *Diagonal "band" previously observed in proton coincidences has disappeared*





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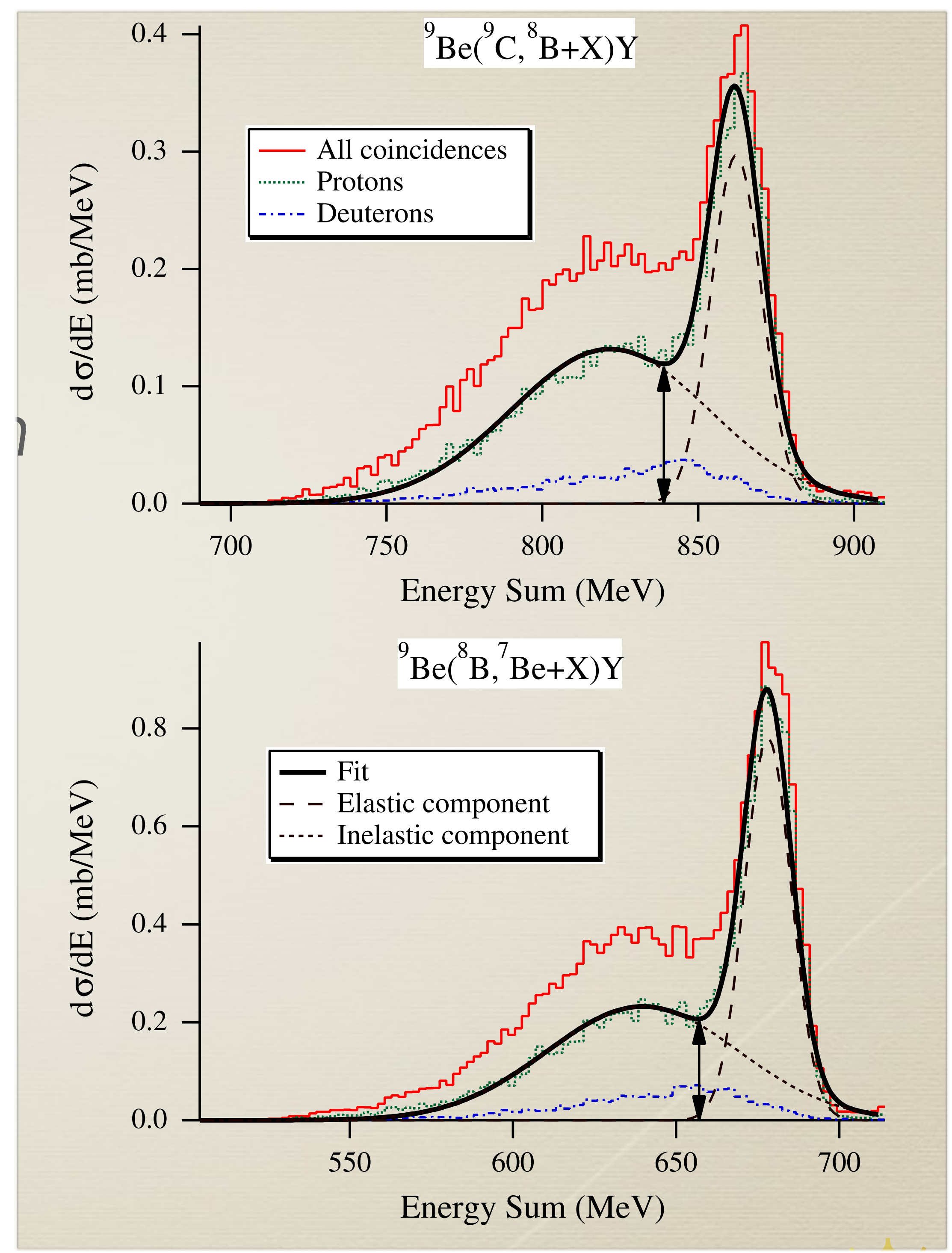
Energy sum spectra

- *Sharp peak corresponds to elastic breakup*
- *Double gaussian fit to determine elastic cross section*
- *Deduce elastic breakup distributions by subtraction*
- ***Very good agreement!***

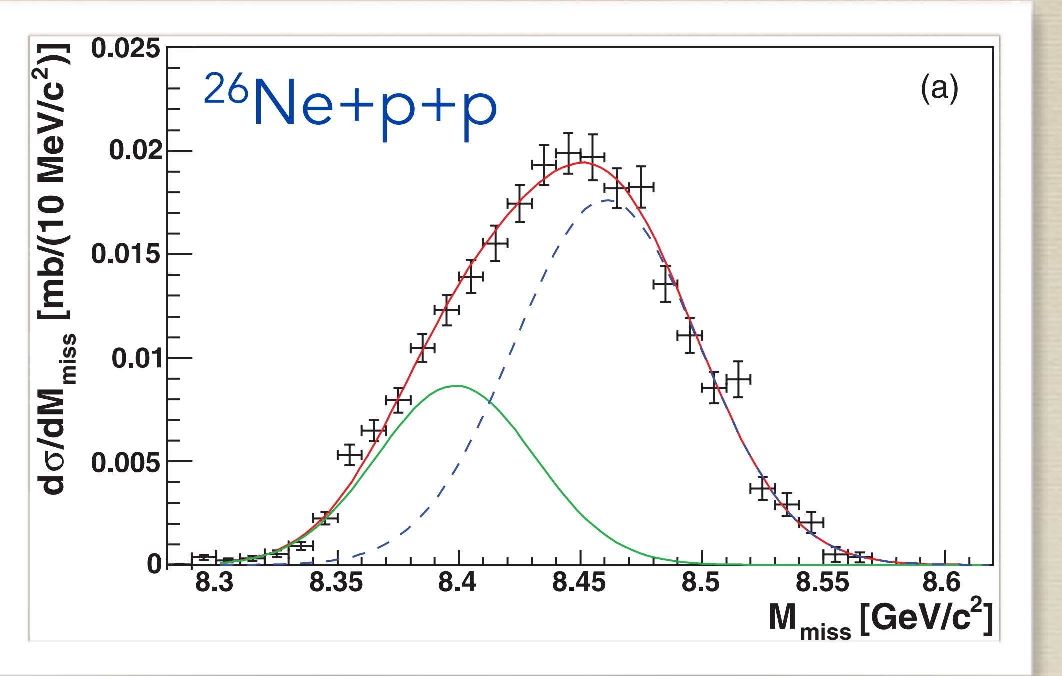
Proj.	% (model)	% (exp.)
9	26.8	25(2)
8	37.1	38(3)

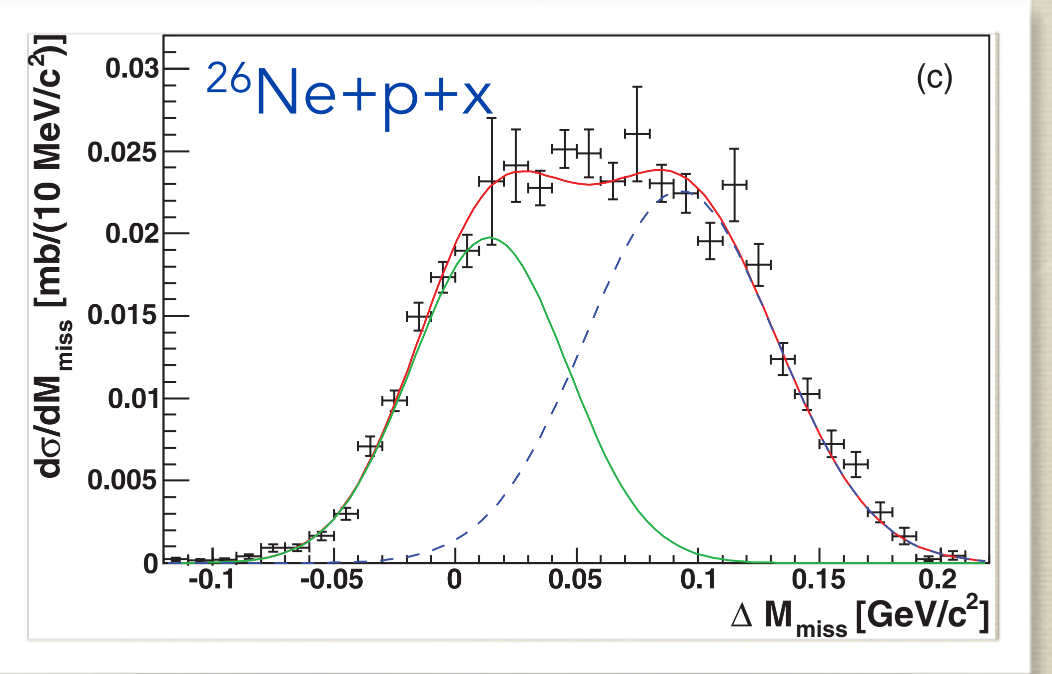


D. Bazin *et al.*, Phys. Rev. Lett. **102**, 232501 (2009)

Two-proton knockout exclusive experiment

- *Performed with the same setup on ^{28}Mg-2p → ^{26}Ne*
  - *26Ne + p + p triple coincidences missing mass → σ_{dd}*
  - *26Ne + p + x triple coincidences missing mass → σ_{sd}/σ_{ss}*





	diff	diff-str	str	tot
σ_{obs} (mb)	0.07(2)	0.27(14)	0.54(14)	0.88(2)
σ_{extr} (mb)	0.11(3)	0.44(23)	0.87(23)	1.43(5)
fraction (%)	8(2)	31(16)	61(16)	
σ^{inc} (mb)				1.475(18)
σ_{theo} incl. (mb)	0.19	1.13	1.70	3.02
$\sigma_{theo} R_S$(2N) (mb)	0.09	0.55	0.83	1.475
fraction$_{theo}$ (%)	6.3	37.4	56.3	

K. Wimmer *et al.*, Phys. Rev. C **85**, 051603(R) (2012)

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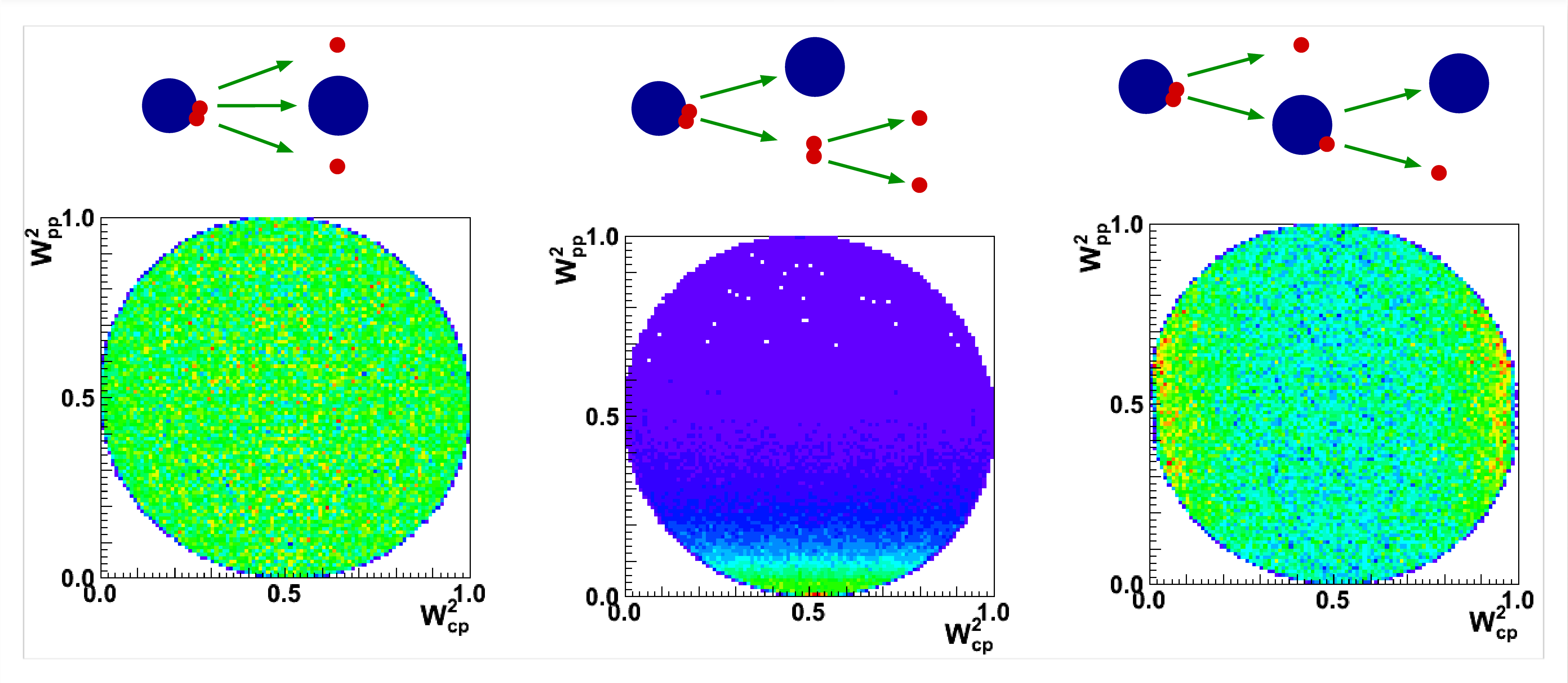
Two-proton correlations

- *How are the two protons removed from the projectile?*

Normalized invariant mass: $$W_{ij}^2 = \frac{M_{ij}^2-(m_i+m_j)^2}{(E_{obs}+m_i+m_j)^2-(m_i+m_j)^2}$$

3-body mode | pair removal | two-step process

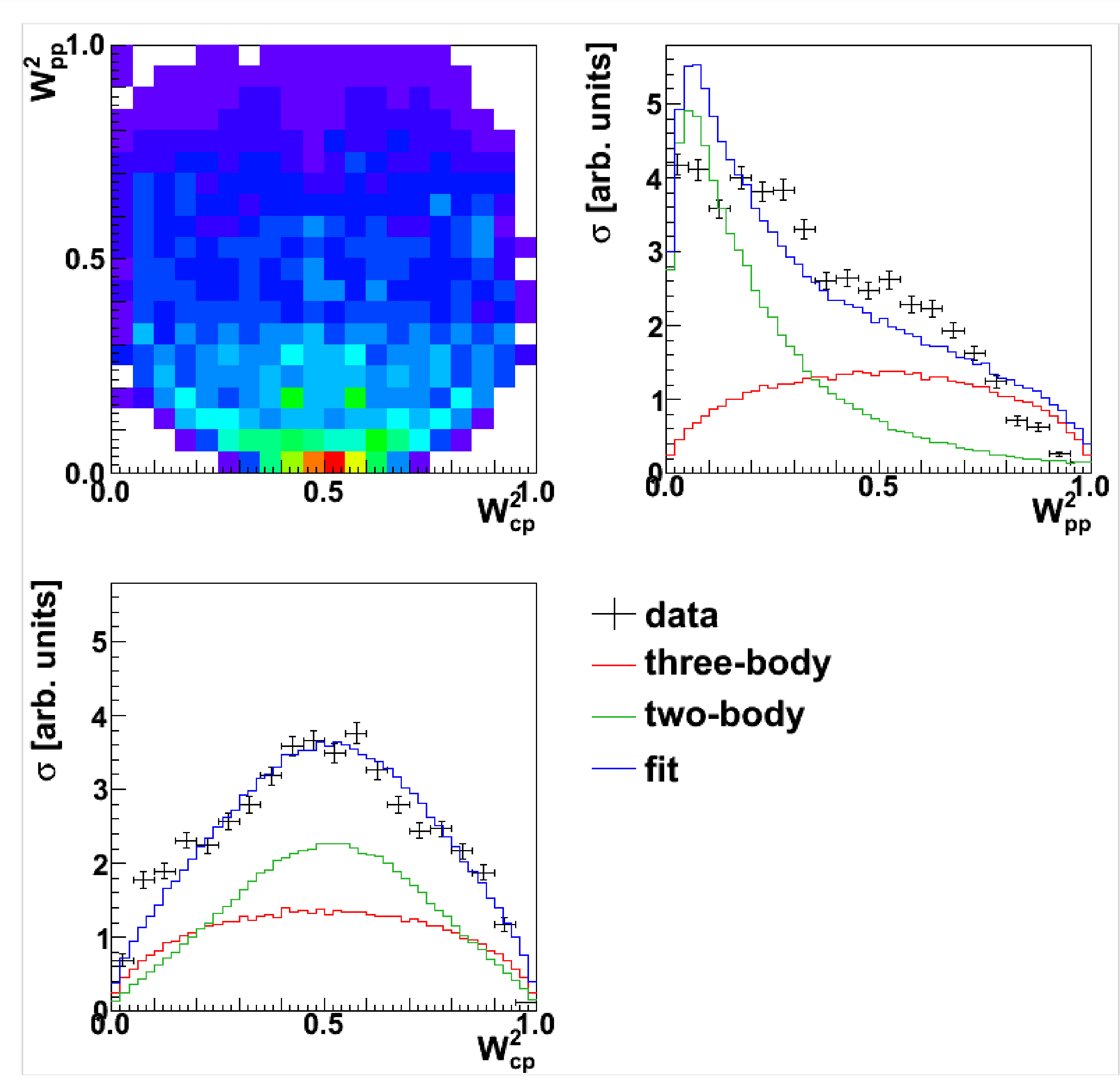


Dalitz plots: W_{pp} (proton-proton) versus W_{cp} (core-proton)

Spatially-correlated pair removal

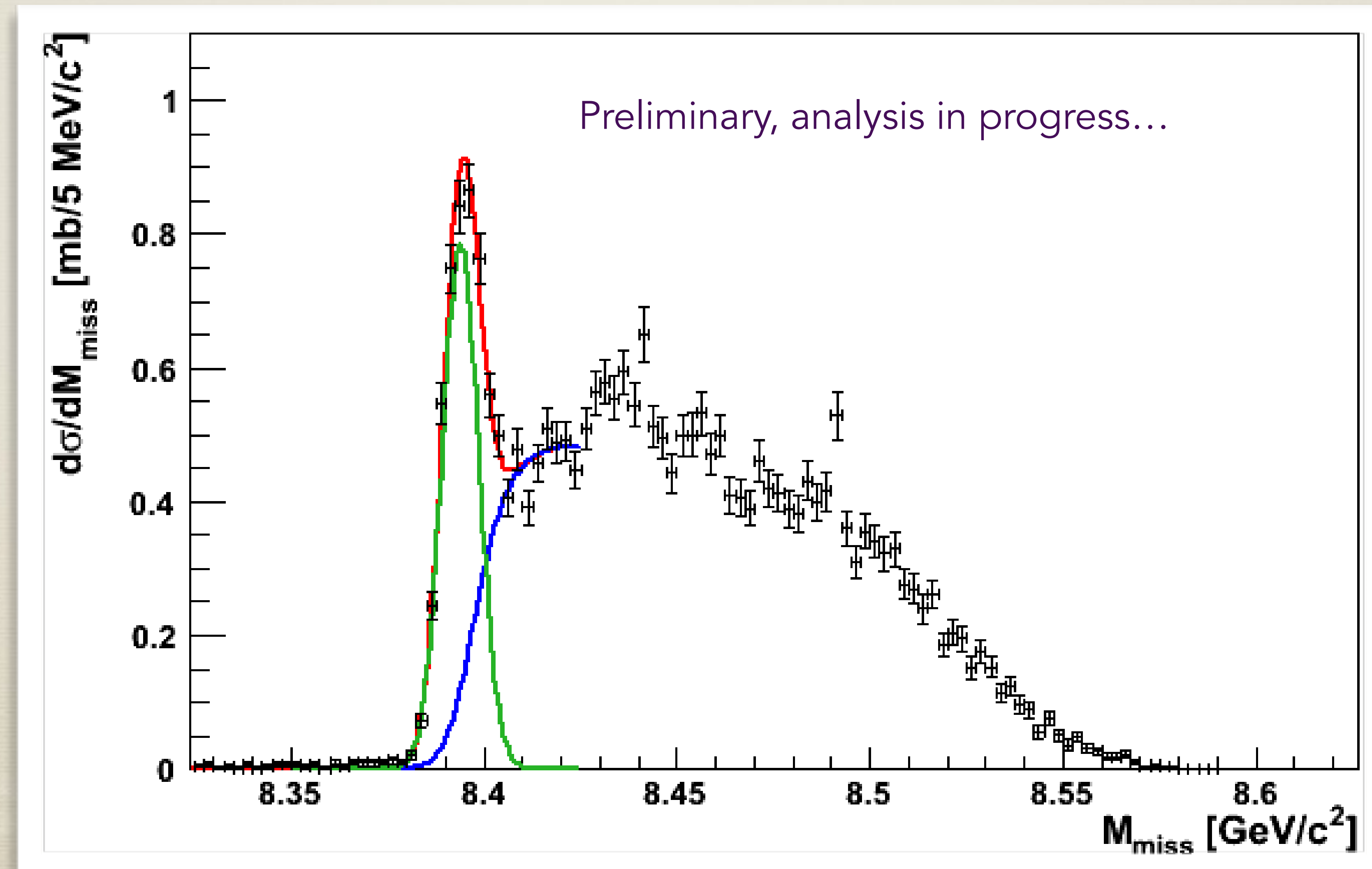
- *Two-step process excluded energetically*
- *Fit of experimental Dalitz plot give fraction of two-body 0.56(12)*
- *Significant surface localization and spatial proximity of the two protons*

K. Wimmer *et al.*, PRC **109**, 202505 (2012)



Diffraction of deeply-bound valence proton

- *One-proton knockout ^{28}Mg-1p → ^{27}Na in high resolution mode*
- *Proton binding energy 16.8 MeV*
- *Diffraction peak at missing mass of ^{9}Be target*



At the forefront of nuclear structure models

- *Beyond the shell model: ab initio models*
  - *Solve many-body problem using NN bare interactions*
  - *Variational and Green's function Monte Carlo (VMC)*
  - *No-core shell model (NCSM)*
  - *So far limited to p-shell nuclei with $5 \leq A \leq 16$*
- *Absolute cross sections from knockout reactions*
  - *Related to spectroscopic factors of overlapping states*
  - *Can reach rare isotopes and neutron orbitals*
  - *Can use densities and overlaps from ab initio models*

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Proposed experiment

- *Goals and challenges*
  - *Achieve 5% precision on cross section measurement*
  - *Light ions need large acceptances: corrections needed*

Proposed experiment

- Goals and challenges
  - Achieve 5% precision on cross section measurement
  - Light ions need large acceptances: corrections needed
- Chosen reactions: neutron knockout on ^{10}Be and ^{10}C
  - No bound excited states in ^{9}Be and ^{9}C: one final state only
  - Different neutron binding energies: 6.8 MeV and 21.3 MeV
  - Both VMC and NCSM densities and overlaps available
  - Consistent comparison by using these densities and overlaps in reaction model

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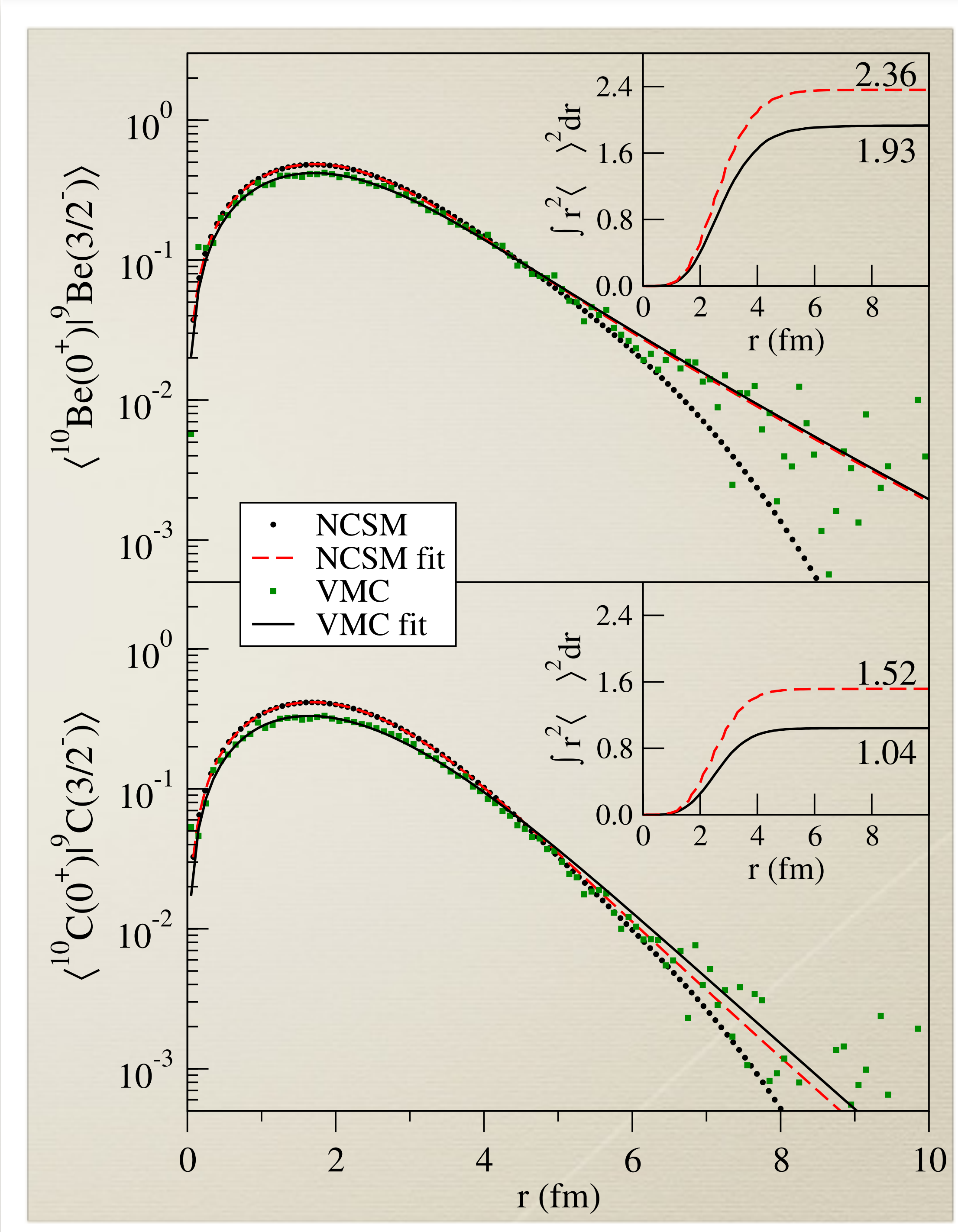
Single-particle cross sections

- *Densities and fit Wood-Saxon from overlaps*
  - *VMC (AV18 + UIX)*
  - *NCSM (CD-Bonn)*
- σ_{sp} very similar

$\langle ^{10}\mathrm{Be}\vert ^9\mathrm{Be}+n\rangle$	r (fm)	a (fm)	V_0 (MeV)	σ_{sp} (mb)
SM	1.25	0.70	60.4	36.8
NCSM	1.34(2)	0.57(2)	42.9	36.8(7)
VMC	1.25(3)	0.78(4)	48.0	37.7(7)
$\langle ^{10}\mathrm{C}\vert ^9\mathrm{C}+n\rangle$				
SM	1.06	0.70	91.1	24.8
NCSM	1.51(2)	0.79(2)	61.6	28.6(6)
VMC	1.38(4)	1.14(6)	70.9	29.5(6)



Results

- *Consistent approach of reaction model*
- *Experiment clearly differentiates between VMC and NCSM*
- *NCSM missing 3-body forces and continuum effects*
- *^{10}C discrepancy with VMC may be due to reaction model assumption (^{9}C spectator core when removing 21.3 MeV neutron)*

$\langle ^{10}\mathrm{Be} \vert ^{9}\mathrm{Be} + n \rangle$	S_F	σ_{th} (mb)	σ_{exp} (mb)
SM	2.62	96.6	
NCSM	2.36	86.9(16)	73(4)
VMC	1.93	72.8(13)	
$\langle ^{10}\mathrm{C} \vert ^{9}\mathrm{C} + n \rangle$			
SM	1.93	48.0	
NCSM	1.52	43.4(9)	23.2(10)
VMC	1.04	30.8(6)	

G. F. Grinyer *et al.*, Phys. Rev. Lett. **106**, 162502 (2011)

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Where we are headed

- *Limitations of reaction model for deeply bound cases*
  - *Core-spectator assumption breaking down?*
  - *How to improve reaction model to include core breakup?*
- *Extend comparison with ab initio calculations*
  - *Several other p-shell cases including excited final states*
  - *Mirror removal reactions with same SFs*
  - *Example: (^{10}Be, ^{9}Li) mirror of (^{10}C, ^{9}C)*
- *Next exclusive experiment looking at neutrons and gammas*

Main partners…

- *Alexandra Gade (NSCL/MSU)*
- *Jeff Tostevin / Ed Simpson (University of Surrey)*
- *Geoff Grinyer (GANIL)*
- *Kathrin Wimmer (Central Michigan University)*

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Thank you for your attention!

谢谢大家听我的演讲！

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