Correlations in direct two-proton knockout and details of the reaction mechanism

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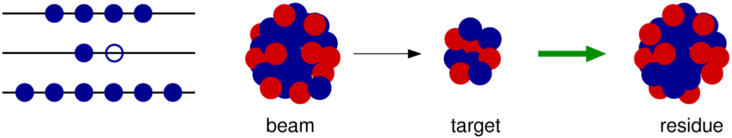
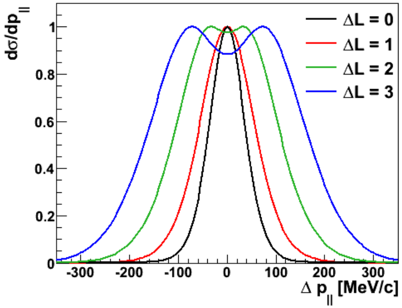
Intermediate energy knockout reactions

- fast ($\approx$ 100 MeV/u) beam interacts with light target (typically ^{9}Be or ^{12}C)
- peripheral collision removes one nucleon
- target and removed nucleon usually not detected



- momentum conservation: measure momentum of residue $\longrightarrow \Delta L$
- measure cross section $\longrightarrow$ spectroscopic factors

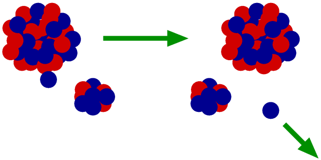
$$\sigma_{\text{exp}}(J^{\pi}) = S \cdot \sigma_{\text{sp}}(nlj)$$



The knockout reaction mechanism

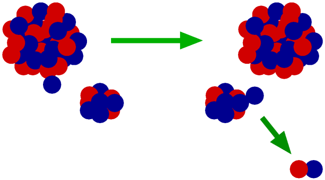
two processes contribute to the knockout reaction

- diffractive or elastic breakup



- dissociation through two-body interaction with target (elastic)
- forward direction with beam velocity
- target remains in the ground state

- stripping or inelastic breakup

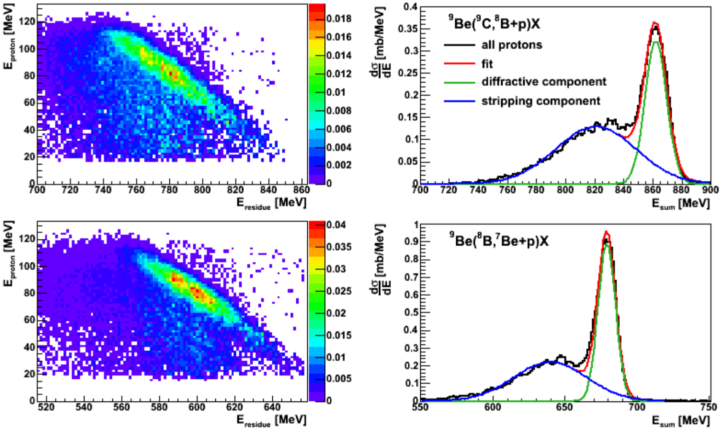


- removed nucleon reacts with target
- excites the target
- loses energy or picks up nucleons from the target

- stripping typically dominant
- calculate both processes $\longrightarrow$ incoherent sum compared to experiment

Previous experiments

- detection of light particles in coincidence with heavy residue
- deuterons, tritons etc. $\rightarrow$ stripping
- protons both elastic and inelastic interaction with the target

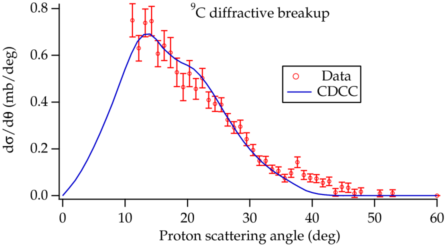


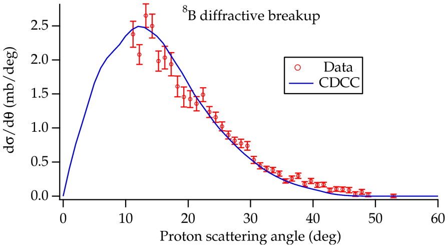
D. Bazin et al., Phys. Rev. Lett. **102** (2009) 232501

- energy conservation: $E_\mathrm{p} + E_\mathrm{r} = E_\mathrm{beam}$
- diffraction: sharp peak in summed energy

Previous experiments

proton angular distribution from diffraction events





comparison with continuum discretized coupled channels (CDCC) calculations

Proj.	σ_{inc} [mb]	σ_{diff} [mb]	$\%_{diff}$	σ^{th}_{inc} [mb]	σ^{th}_{diff} [mb]	$\%^{th}_{diff}$	R_S
^{9}C	56(3)	13.8(6)	25(2)	62.9	15.0	26.8	0.84(5)
^{8}B	127(5)	49(2)	38(3)	144.3	47.1	37.1	0.88(4)

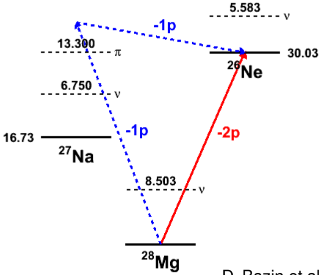
observed stripping and diffraction contributions are in very good agreement with eikonal model

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

Two-nucleon knockout spectroscopy

Two-proton knockout reactions from neutron-rich nuclei

- give access to even more exotic nuclei
- are direct reactions



D. Bazin et al., Phys. Rev. Lett. **91** 012501

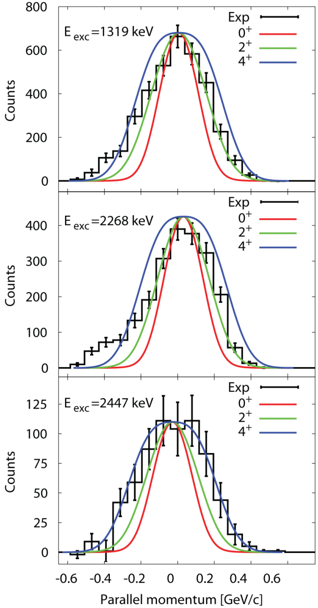
- can be used to determine angular momenta

E. C. Simpson et al., Phys. Rev. Lett. **102** 132502

- however, more complicated reaction mechanism

→ the cross section has three components:

$$\sigma = \sigma_{\text{dif}^2} + \sigma_{\text{str-dif}} + \sigma_{\text{str}^2}$$

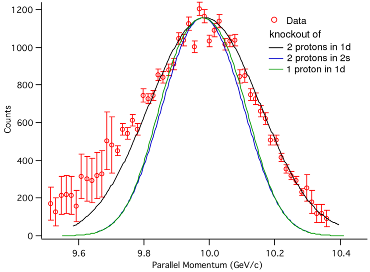


D. Santiago-Gonzalez et al., Phys. Rev. C **83** 061305(R)

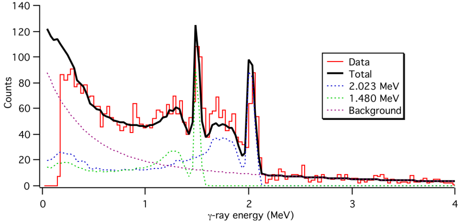
The experiment

two-proton knockout from a neutron-rich beam $^{9}Be(^{28}Mg, ^{26}Ne+X)Y$

- simple structure, proton *sd* and semi-magic $N = 16$ nuclei
- intense ^{28}Mg beam available at NSCL
- cross sections known from previous ^{26}Ne–γ coincidence experiment



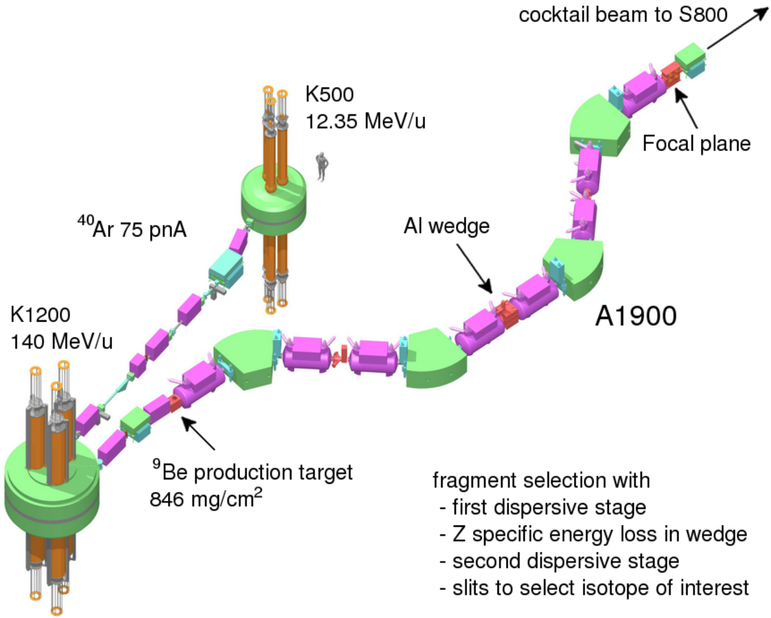
$\sigma^{\text{inc}} = 1.50(10)$ mb



D. Bazin et al., Phys. Rev. Lett. **91** 012501

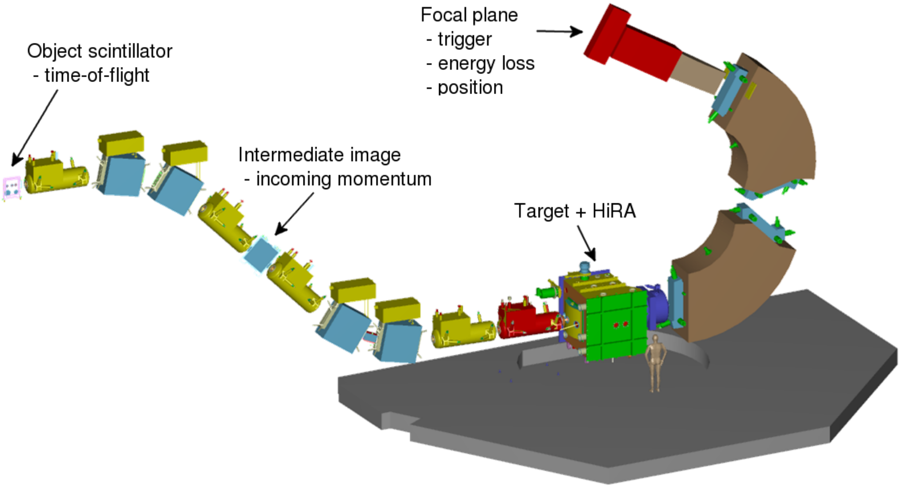
- now: first study of the reaction mechanism
- $\longrightarrow$ need to measure protons in coincidence with residue nucleus
- prediction $\sigma_{\text{dif}^2} = 90\ \mu$b

The coupled cyclotron facility at NSCL



fragment selection with
- first dispersive stage
- Z specific energy loss in wedge
- second dispersive stage
- slits to select isotope of interest

The S800 spectrograph



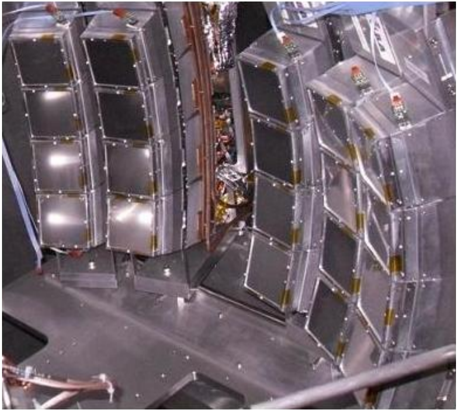
- particle identification by time-of-flight and energy loss
- position measurement in the focal plane
- momentum and position at target position by ray-tracing

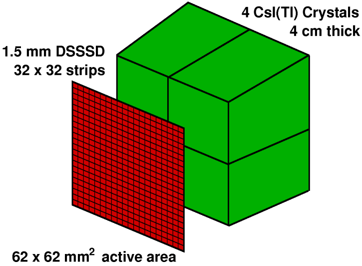
D. Bazin et al., NIMA **204** 629

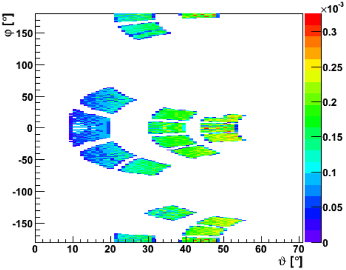
The High Resolution Array HiRA

charge particle detector array based on $\Delta E - E$ measurement

- up to 20 telescopes
- many possible configurations
- angular coverage $\vartheta = 9 - 54^{\circ}$







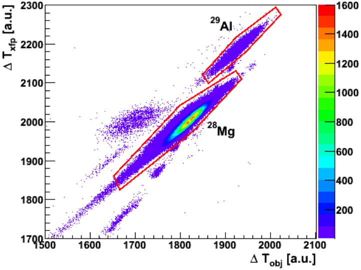
M.S. Wallace et al, NIMA **583** 302

The ^{9}Be(^{28}Mg,^{26}Ne)X reaction

- two-proton knockout from ^{28}Mg
- need to identify all reaction partners
- measure their energies and momenta
- $\sigma^{\mathrm{inc}} = 1.475(18)$ mb
- previous measurement: $\sigma^{\mathrm{inc}} = 1.50(10)$ mb

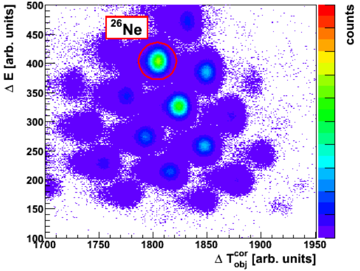
D. Bazin et al., Phys. Rev. Lett. **91** 012501

incoming beam, time-of-flight $\longrightarrow$ velocity

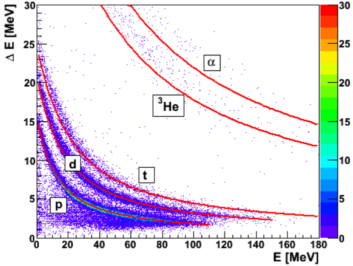


S800 spectrograph

reaction residue, energy loss and TOF

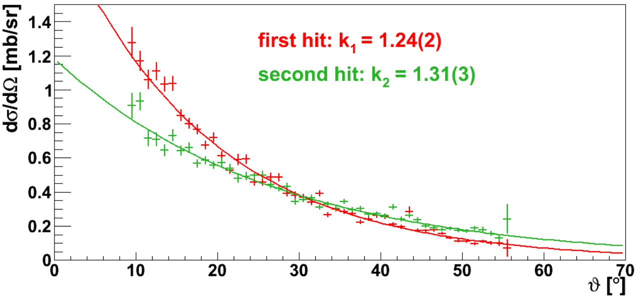


light charged particles in HiRA



The $^{9}Be(^{28}Mg,^{26}Ne)X$ reaction

- cross section for triple coincidences $\sigma_{obs}^{tot} = 0.88(2)$ mb
- this has to be corrected for the acceptance of HiRA
  $\sigma_{extr} = k_1 \cdot k_2 \cdot \sigma_{obs}$



- $\sigma_{extr}^{tot} = 1.43(5)$ mb
- in agreement with the inclusive cross section $\sigma^{inc} = 1.475(18)$ mb
- for every knockout event two light charged particles in the exit channel

Reaction mechanism

^{26}Ne + p + p triple coincidences

- all three processes contribute
  how to disentangle?
- for diffraction we expect
  $M_{\text{miss}} = M(^{9}\text{Be}) = 8.395$ GeV/c^2
- for reactions involving stripping
  $M_{\text{miss}} > M(^{9}\text{Be})$

for each event calculate the missing mass M_{miss}:

$$
\begin{aligned}
M^2_{\text{miss}} &= \left(\sum P_{\text{in}} - \sum P_{\text{out}}\right)^2 \\
&= \left(\sum E_{\text{in}} - \sum E_{\text{out}}\right)^2 - \left(\sum \vec{p}_{\text{in}} - \sum \vec{p}_{\text{out}}\right)^2
\end{aligned}
$$

- free two component fit (two Gaussians) gives peak at 8.399(3) GeV/c^2
- width in agreement with resolutions

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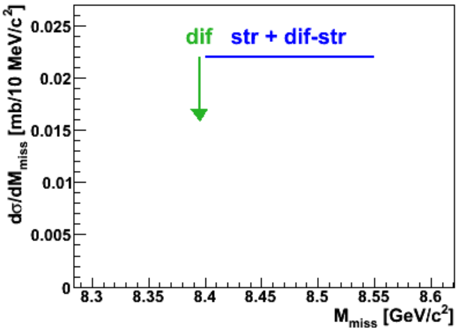

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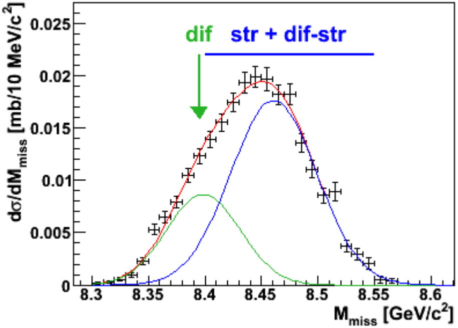

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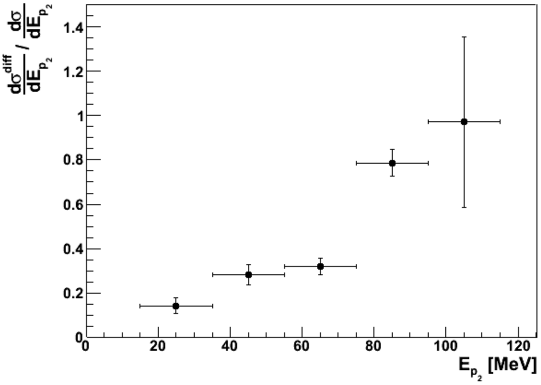
Reaction mechanism

- diffraction cross section: $\sigma_{\text{obs}}^{\text{diff}} = 0.07(2)$ mb



- relative diffraction yield as a function of proton energy
- E_{p_2}: smaller of the two proton energies
- almost only diffraction if both protons have large energies

Reaction mechanism

- diffraction cross section: $\sigma_{\text{obs}}^{\text{diff}} = 0.07(2)$ mb
- how to determine diffraction-stripping and stripping?
- events where one particle is a proton, the other one not a proton so a deuteron, triton, etc.
- additional neutrons can only come from the target $\sigma_{\text{diff-str}}/\sigma_{\text{str}} = 0.7(2)$
- both detected particles are not protons $\longrightarrow$ this can only be stripping

	diff	diff-str	str	tot.
σ_{extr} [mb]	0.11(3)	0.44(23)	0.87(23)	1.43(5)
fraction [%]	8(2)	31(16)	61(16)	
$\sigma_{\text{theo}} \cdot R_S(2N)$ [mb]	0.09	0.55	0.83	1.475
$\text{fraction}_{\text{theo}}$ [%]	6.3	37.4	56.3	

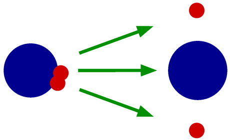
- good agreement for relative contributions of the reaction processes

K. Wimmer et al., subm.

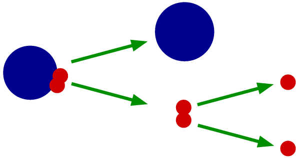
two-proton knockout: a valuable tool to study exotic nuclei

Correlations: possible processes

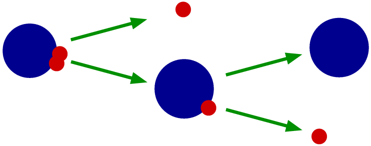
- 3-body decay



- correlated proton pair (di-proton mode)



- two step process through ^{27}Na (excluded by separation energy)

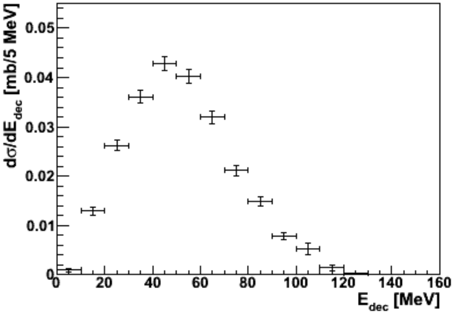


Relative energy

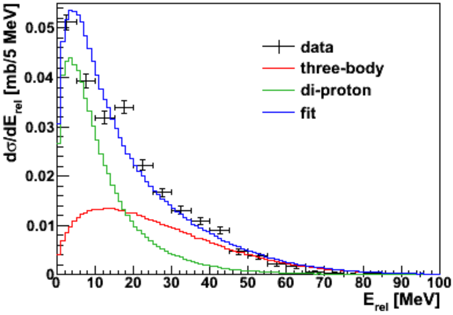
Three-particle phase space simulations:

- using the decay energy as input
- including all experimental resolutions and acceptance limitations

$$E_{\mathrm{dec}} = \sqrt{(\sum P_{\mathrm{i}})^2} - \sum m_{\mathrm{i}}$$



two-proton relative energy:



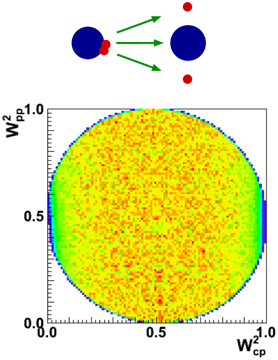
- correlated proton pair breakup fraction: 0.56(14)

Dalitz plots

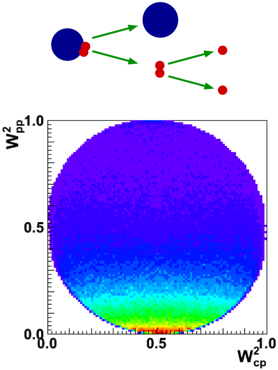
- normalized invariant mass

$$W_{ij}^2 = \frac{M_{ij}^2 - (m_i + m_j)^2}{(E_{\mathrm{dec}} + m_i + m_j)^2 - (m_i + m_j)^2}$$

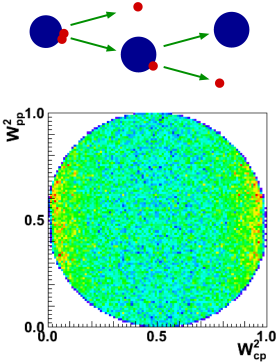
F. M. Marqués et al., Phys. Rev. C **64** (2001) 061301



- uniform filling

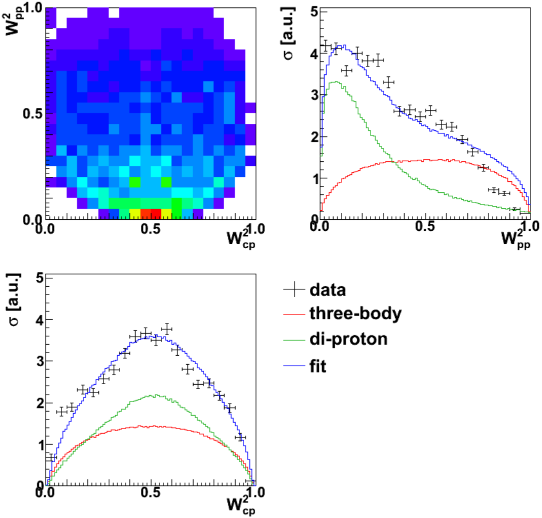


- small W_{pp} $\leftrightarrow$ small relative momentum



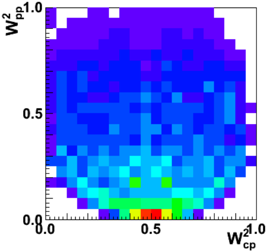
- vertical bands for ^{27}Na resonance

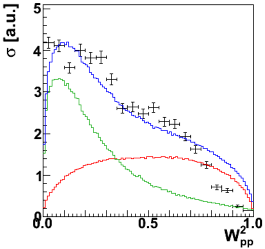
Dalitz plots



- fit with two components three-body and di-proton model
- results:
  0.56(7) for W_{pp} projection
  0.55(20) for W_{cp} projection
- in agreement with E_{rel}

Dalitz plots





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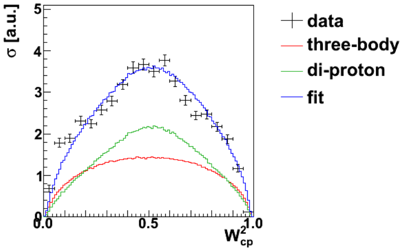
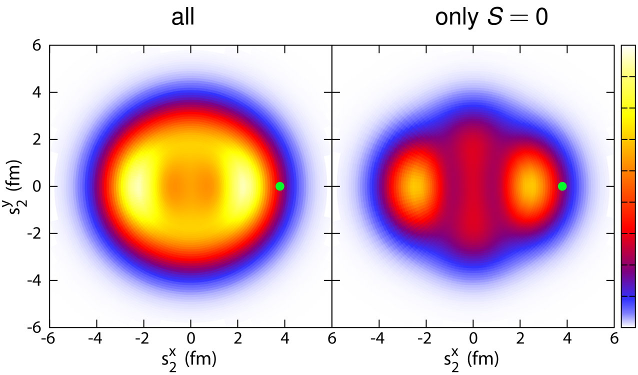


- no intermediate ^{27}Na found
- significant correlation of the two protons
- small relative momentum
- $\longrightarrow$ surface localization and spacial proximity

Correlations

- two-nucleon joint position probabilities in the impact parameter plane: $P(\mathbf{s}_1, \mathbf{s}_2)$ integrated over $z_{1,2}$ ($z =$ beam axis)
- proton 1 $\mathbf{s}_1$ at the surface
- $S = 0$ enhances spacial correlation

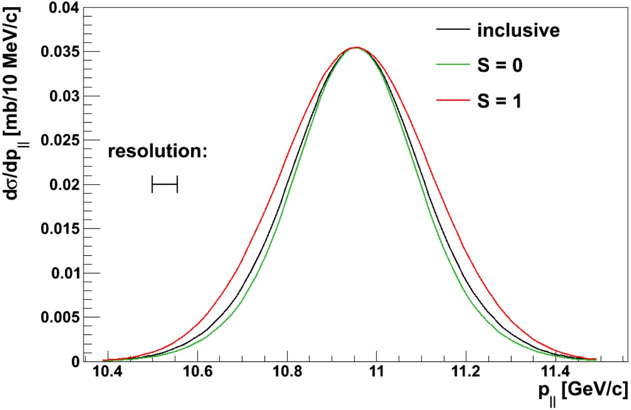


E. C. Simpson and J. A. Tostevin, pirv. comm.

- 64 % of the inclusive cross section $S = 0$
- 56(7) % correlated proton pair fraction measured

Correlations

$S = 0$ should have a more narrow momentum distribution:



J_f	$S = 0$ [%]
0^+	90
2_1^+	22
4^+	49
2_2^+	54
Incl.	64

we need final state exclusive measurements to confirm this

Summary

detailed study of the two-proton knockout reaction at NSCL

- first exclusive measurement of diffractive and stripping components for two-particle knockout
- fractional cross sections of the individual components in agreement with theory
  $\longrightarrow$ use for spectroscopy of exotic nuclei

observation of correlated proton pairs

- removal of a $S = 0$ pair
- correlations in the entrance channel
  $\longrightarrow$ final state exclusive measurements
  neutron-γ-residue coincidence experiment planned

Collaboration

D. Bazin, A. Gade, E.C. Simpson, J.A. Tostevin, T. Baugher, Z. Chajecki, D. Coupland, M.A. Famiano, T.K. Ghosh, G.F. Grinyer, R. Hodges, M.E. Howard, M. Kilburn, W.G. Lynch, B. Manning, K. Meierbachtol, P. Quarterman, A. Ratkiewicz, A. Sanetullaev, S.R. Stroberg, M.B. Tsang, D. Weisshaar, J. Winkelbauer, R. Winkler, and M. Youngs

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Department of Physics, University of Surrey
Department of Physics, Western Michigan University
Variable Energy Cyclotron Centre
Department of Physics and Astronomy, Rutgers University
Department of Chemistry, Michigan State University

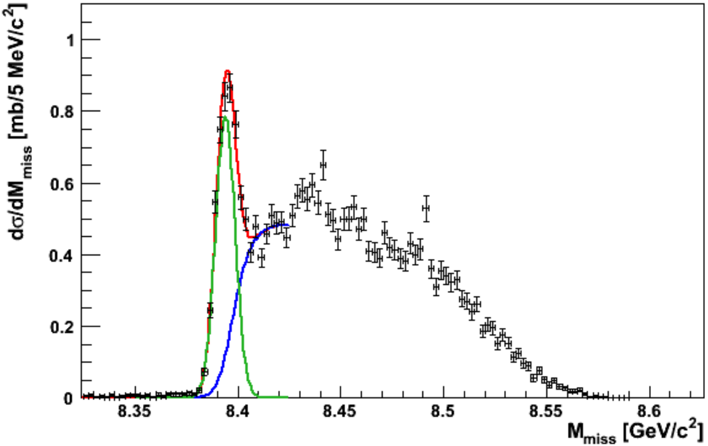
Funded by
NSF, DOE, and UK-STFC

Thank you for your attention

Backup

One-proton knockout

missing mass in high-resolution one-proton knockout:



- thin target
- high resolution mode
- this is not possible for the two-proton knockout

Two proton knockout

- no separation of reaction dynamics and structure anymore
- transition amplitudes for total angular momentum J coherent sum of many pair contributions
- three contributions to the cross section

$$\sigma = \sigma_{\text{str}^2} + \sigma_{\text{str-dif}} + \sigma_{\text{dif}^2}$$

- both stripped

$$\sigma_{\text{str}^2} = \frac{1}{2J_i+1} \sum_{M_i} \int \mathrm{d}\vec{b} \langle \psi_{J_i M_i} | |S_r|^2 (1 - |S_1|^2)(1 - |S_2|^2) | \psi_{J_i M_i} \rangle$$

- one diffracted, one stripped $\sigma_{\text{str-dif}} = \sigma_1^{\text{dif}} + \sigma_2^{\text{dif}}$

$$\sigma_1^{\text{dif}} = \frac{1}{2J_i+1} \sum_{M_i} \int \mathrm{d}\vec{b} \langle \psi_{J_i M_i} | |S_r|^2 |S_1|^2 (1 - |S_2|^2) | \psi_{J_i M_i} \rangle$$

- both diffracted, only estimate:

$$\sigma_{\text{dif}^2} = \left[\frac{\sigma_1^{\text{dif}}}{\sigma_{\text{str}^2}} \right]^2 \cdot \sigma_{\text{str}^2}$$

J. A. Tostevin and B. A. Brown, Phys. Rev. C **74** (2006) 064604