Mechanisms in knockout reactions

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Motivation

- *Knockout reactions have become a common tool to study the structure of nuclei far from stability*
- *Determination of spectroscopic factors relies on reaction theory to calculate single-particle cross sections*
- *It is essential to test the validity and accuracy of the reaction theory*

Knockout reactions on fast beams

- *Removal of one or two nucleons via nuclear interaction with a low-Z target (typically ^{9}Be or ^{12}C)*
  - *Direct (one-step) reaction*
  - *Measure probability of finding A-1 or A-2 residual nucleus in a given state*
  - *Composition of initial nucleus wave function*
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- *High sensitivity well adapted to radioactive beams*
  - *Residual nucleus forward focused because of inverse kinematics*
  - *Final state of residual nucleus identified via γ-ray detection*
  - *Thick targets give high luminosity*

Determination of spectroscopic factors

- *Theoretical cross section between initial and final states directly related to spectroscopic factors*

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

- *Experimental determination of cross sections*
  - *Angular momentum of removed nucleon(s) deduced from parallel momentum distribution of residual nucleus*
  - *Final state of residual nucleus deduced from its γ-decay in flight*
  - *Spectroscopic factors can be determined from the experimental cross sections and the calculated single-particle cross sections*

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

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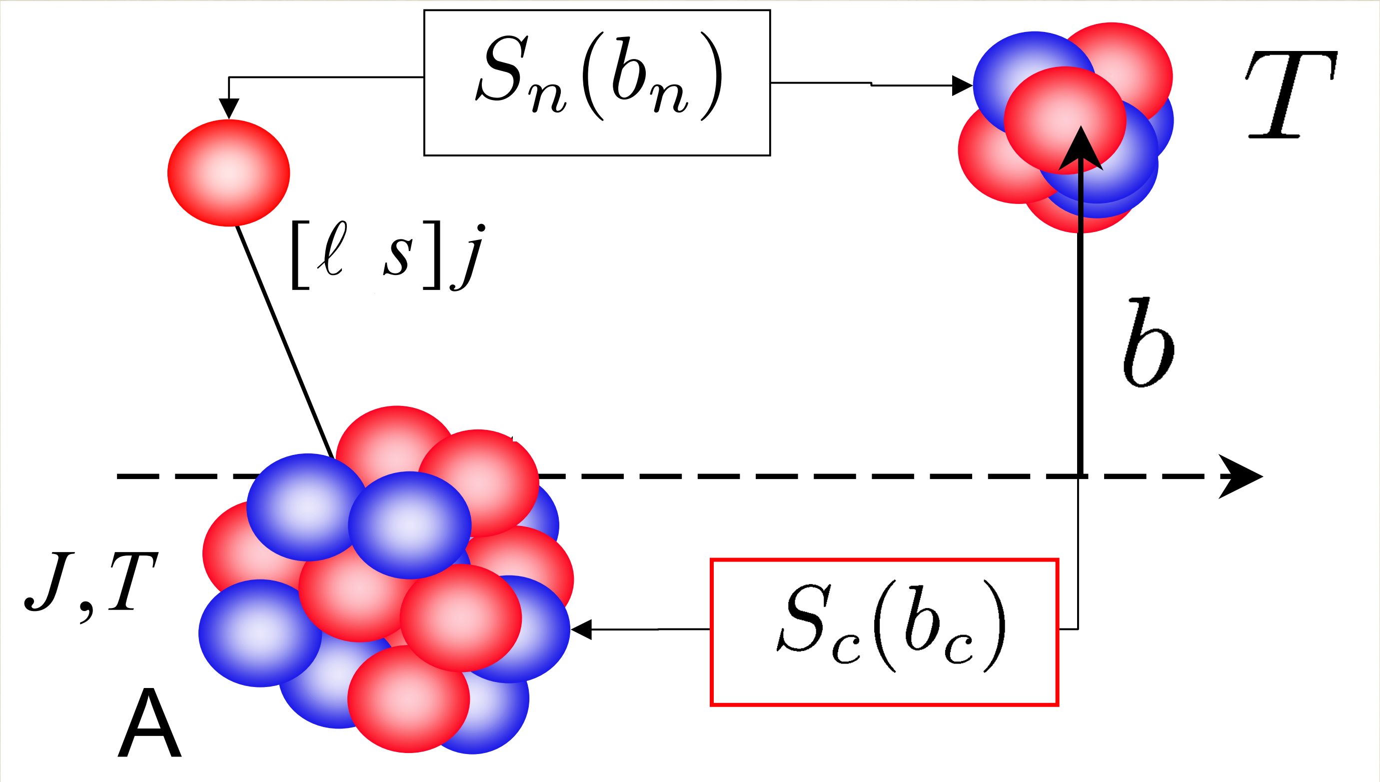
- *Inelastic breakup also called Stripping:*
  - *the removed nucleon(s) interact inelastically with the target*
  - *the target is excited or broken up*
  - *the removed nucleon(s) can escape with much lower velocity and/or as different particle*

Single-particle cross sections

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

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

- *Eikonal theory*
  - *S_n and S_c S-matrices for the scattering of the nucleon and the core (residual nucleus) respectively*
  - *Calculated using Glauber theory, HF densities and effective NN interaction*



J. A. Tostevin, Nucl. Phys. A682, 320c (2001)

Proposed experiment

- *Experiment aimed to measure stripping and diffraction parts of the cross section separately*
  - *Detect removed nucleon with maximum solid angle to differentiate diffraction*
  - *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_p (MeV)	σ_{str} (mb)	σ_{diff} (mb)	S_{SM}	σ_{tot} (mb)	$\%_{diff/str}$
^{9}C ($3/2^-$)	^{8}B (2^+)	1.300	46.0	15.7	0.94	58	25.4
^{8}B (2^+)	^{7}Be ($3/2^-$)	0.137	61.5	30.5	1.036	111.8	32.7
^{8}B (2^+)	^{7}Be ($1/2^-$)	0.566	52.7	22.5	0.22		

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- *Angles and energies of both residual nucleus and proton measured: full kinematics*

S800 Spectrograph

Focal plane detectors

Particle identification

Scattering angle and energy of residual nucleus

Incoming ^{9}C cocktail beam

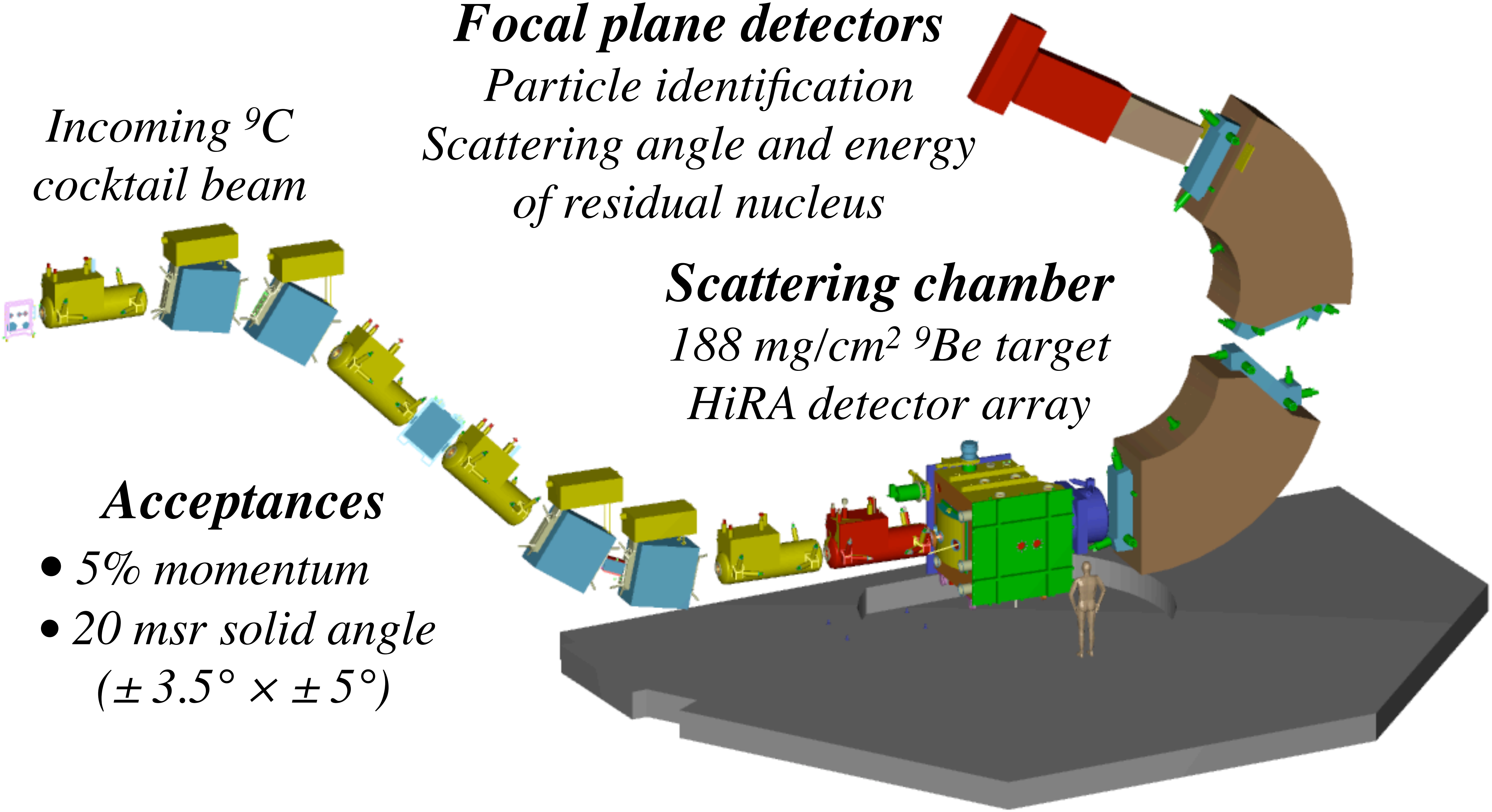
Scattering chamber

188 mg/cm^2 ^{9}Be target

HiRA detector array

Acceptances

- *5% momentum*
- *20 msr solid angle ($\pm 3.5° \times \pm 5°$)*

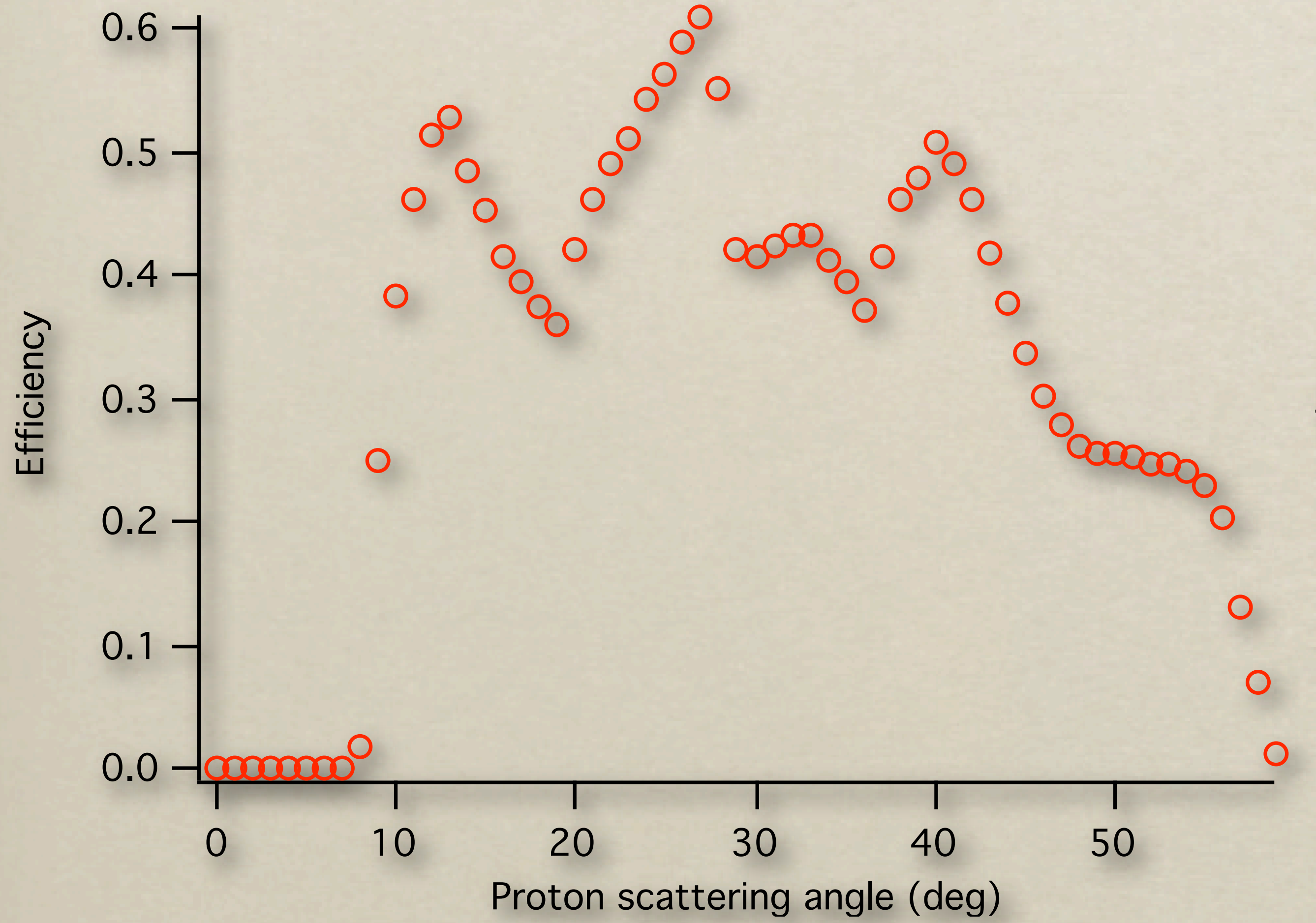


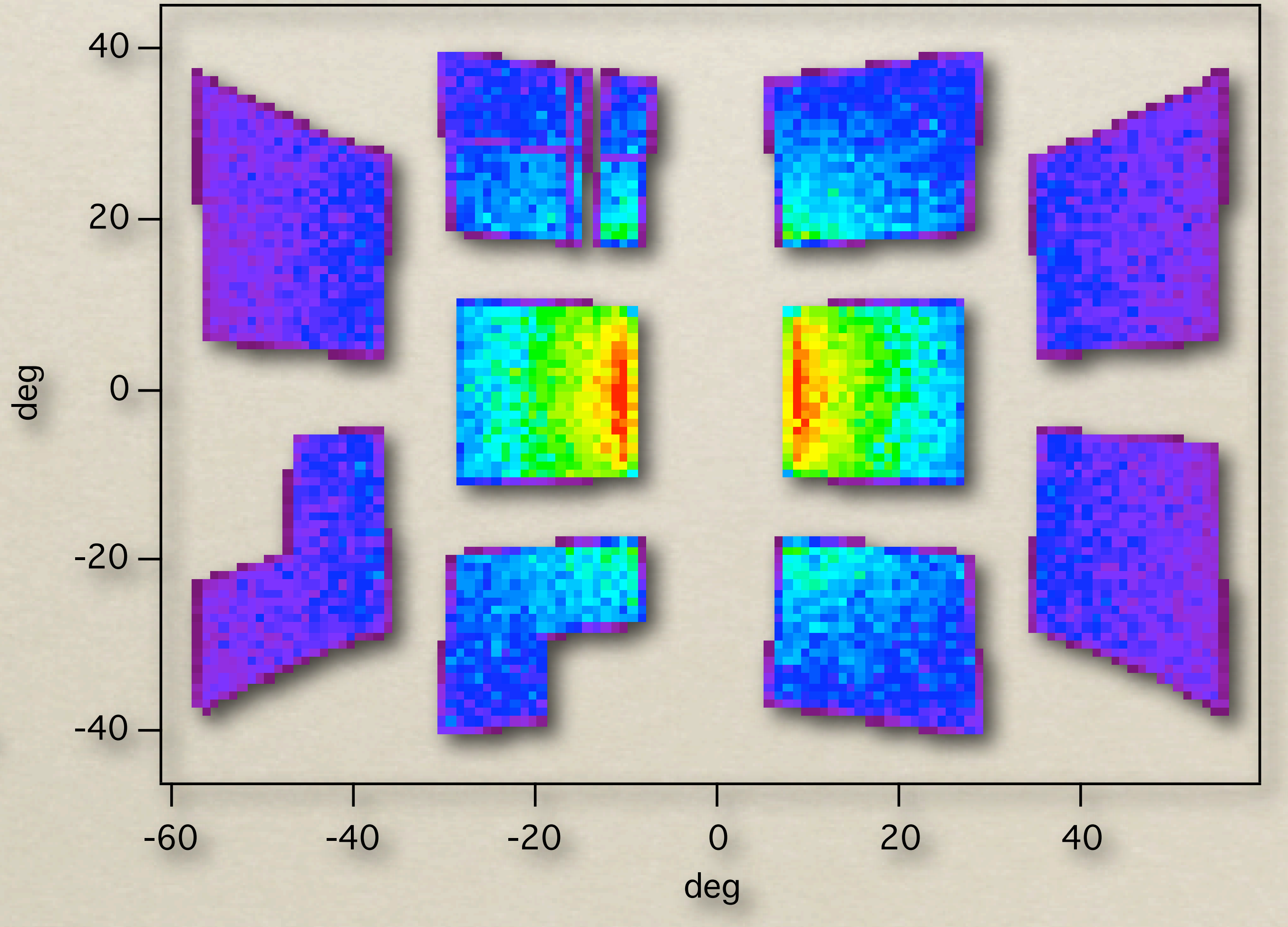
HiRA detector array

- *10 telescopes covering scattering angles between 10° and 60°*
- *Each telescope composed of 32×32 DSSD Silicon detectors, followed by 4 CsI crystals*
- *Digital electronics located inside the scattering chamber*

Proton detection angular coverage

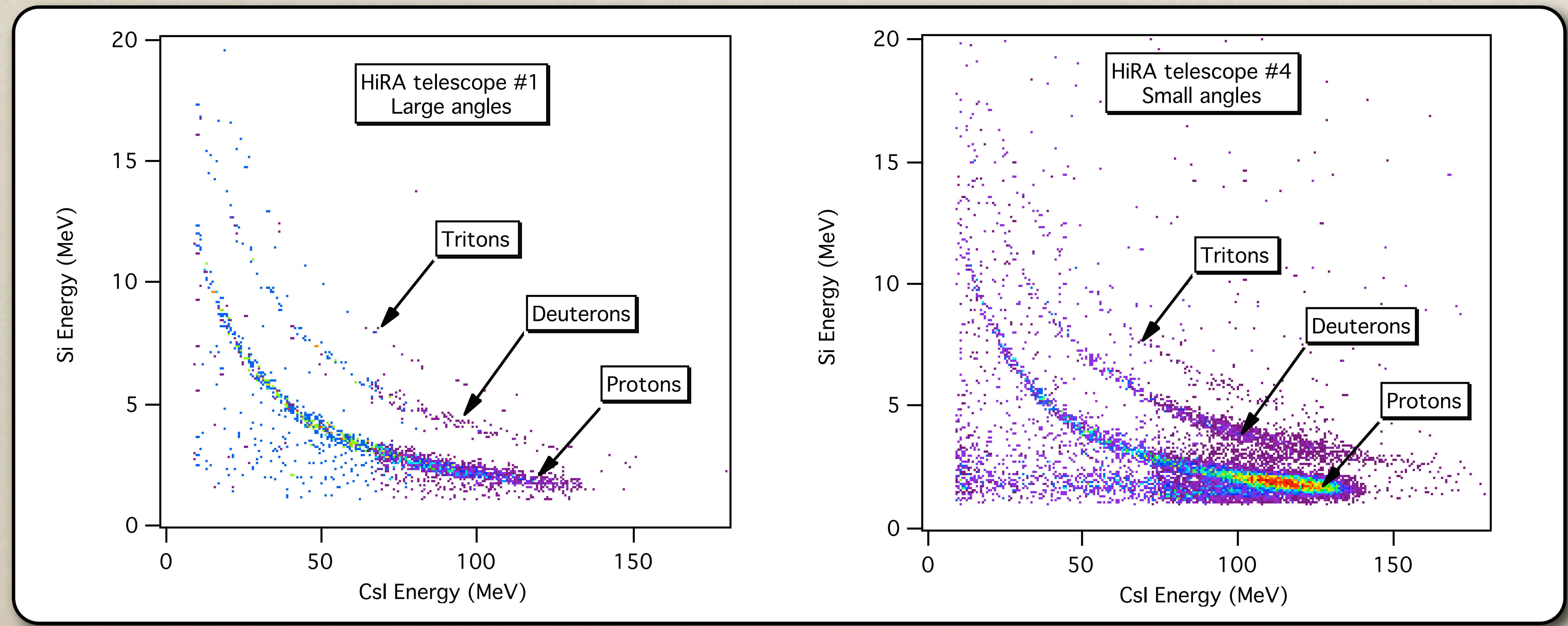
- *Efficiency determined from Monte-Carlo simulation using a lookup table to take missing or bad channels into account*





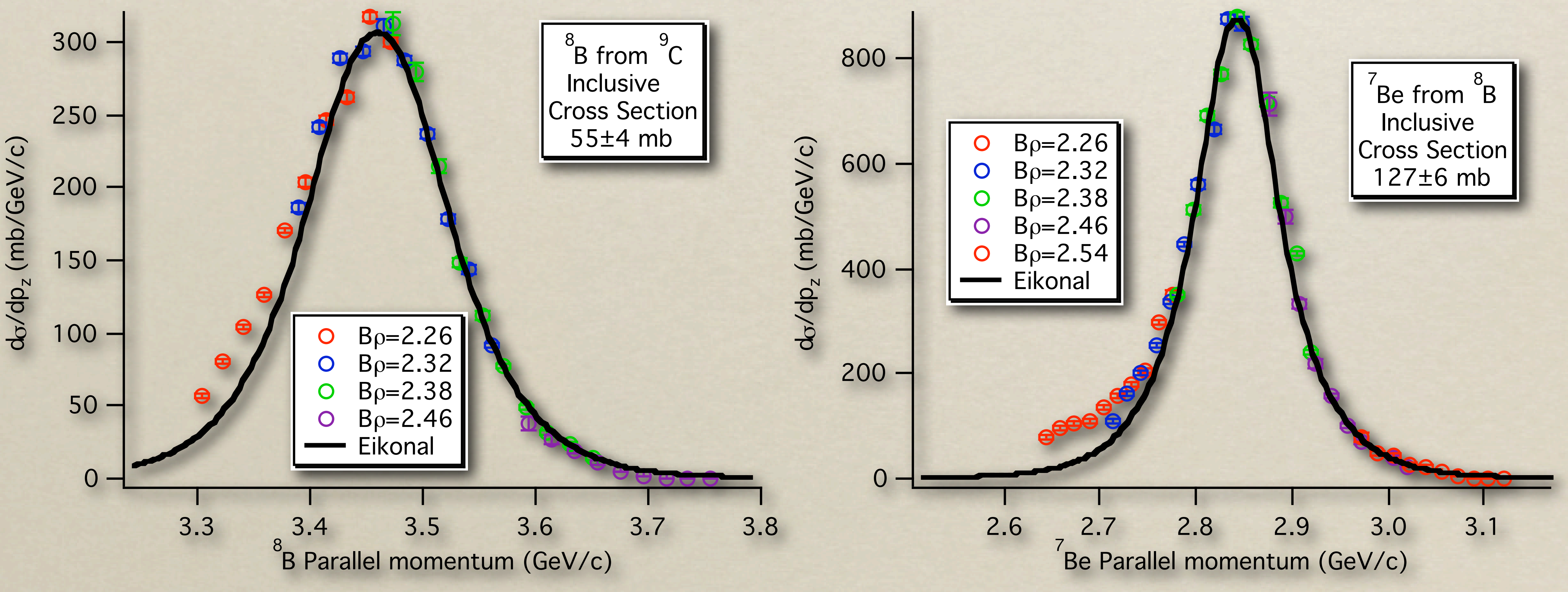
Particle identification in HiRA

- *Events in coincidence with a ^{8}B residual nucleus observed in the S800 focal plane*
- *Standard E-ΔE plot*



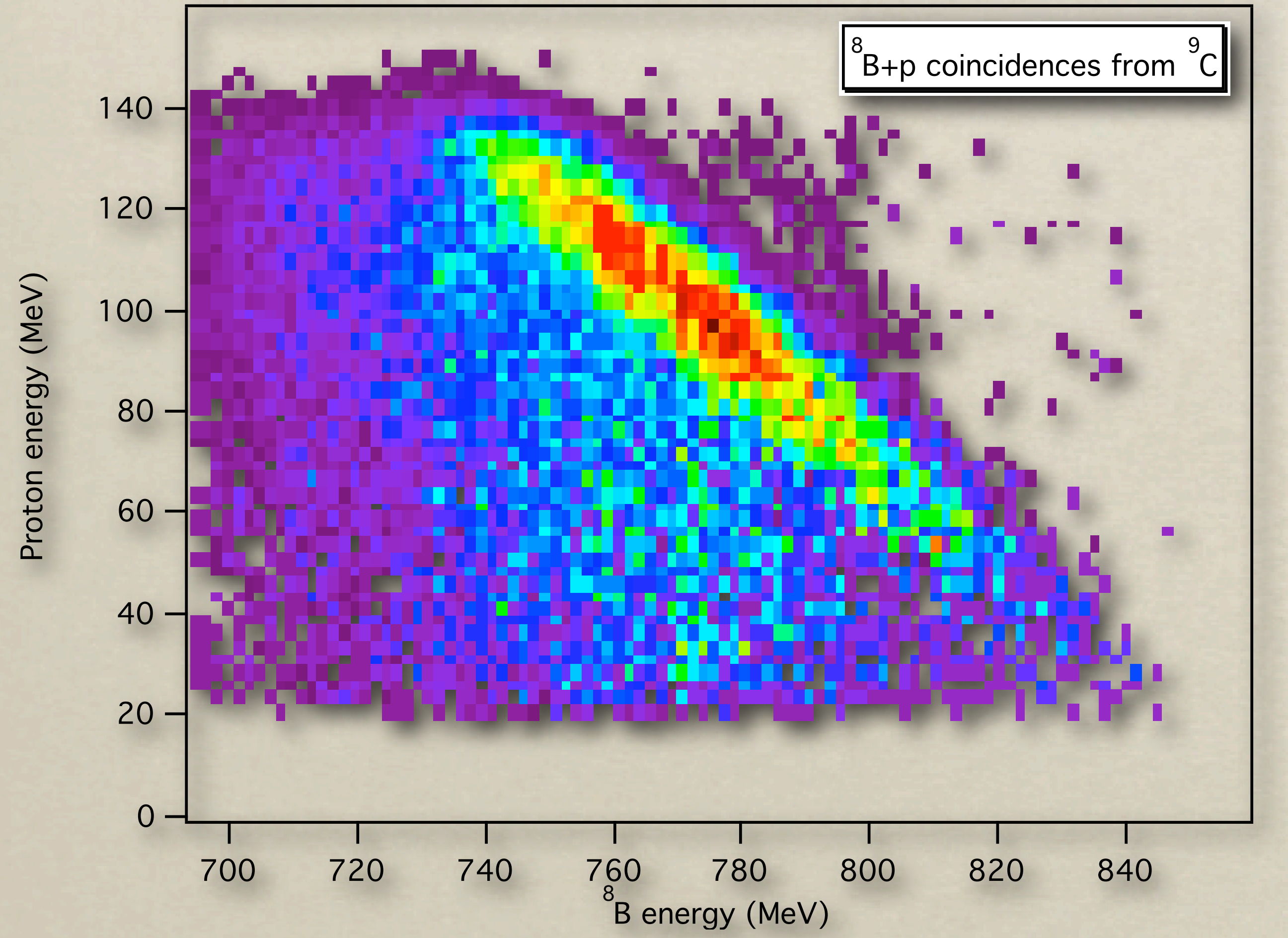
Residual nucleus momentum distributions

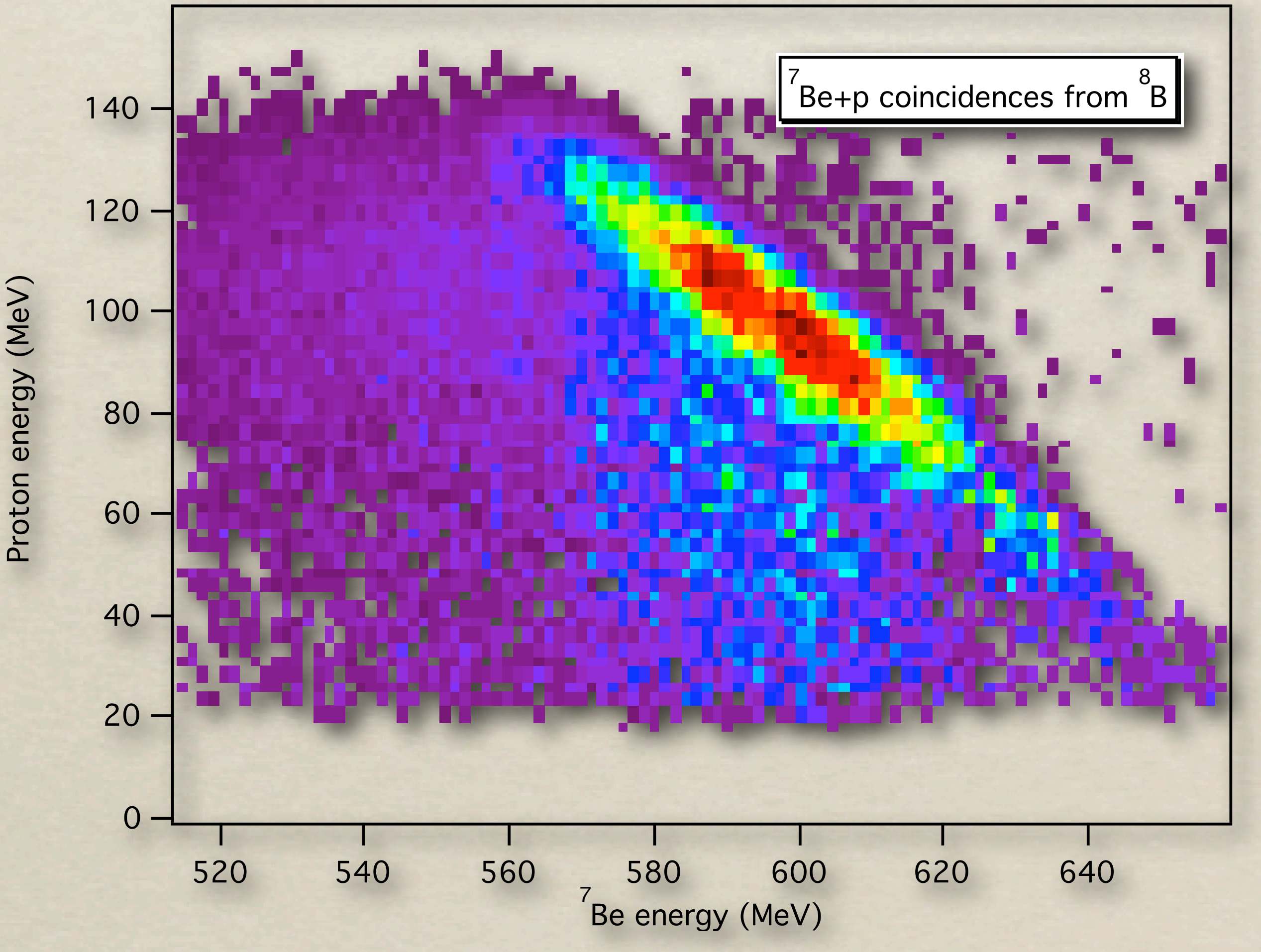
- *Inclusive distributions compared to eikonal calculation*
  - *Several settings necessary to cover whole distribution*
  - *Eikonal calculation reproduces data very well except for low momentum tail*



Proton - residual nucleus coincidences

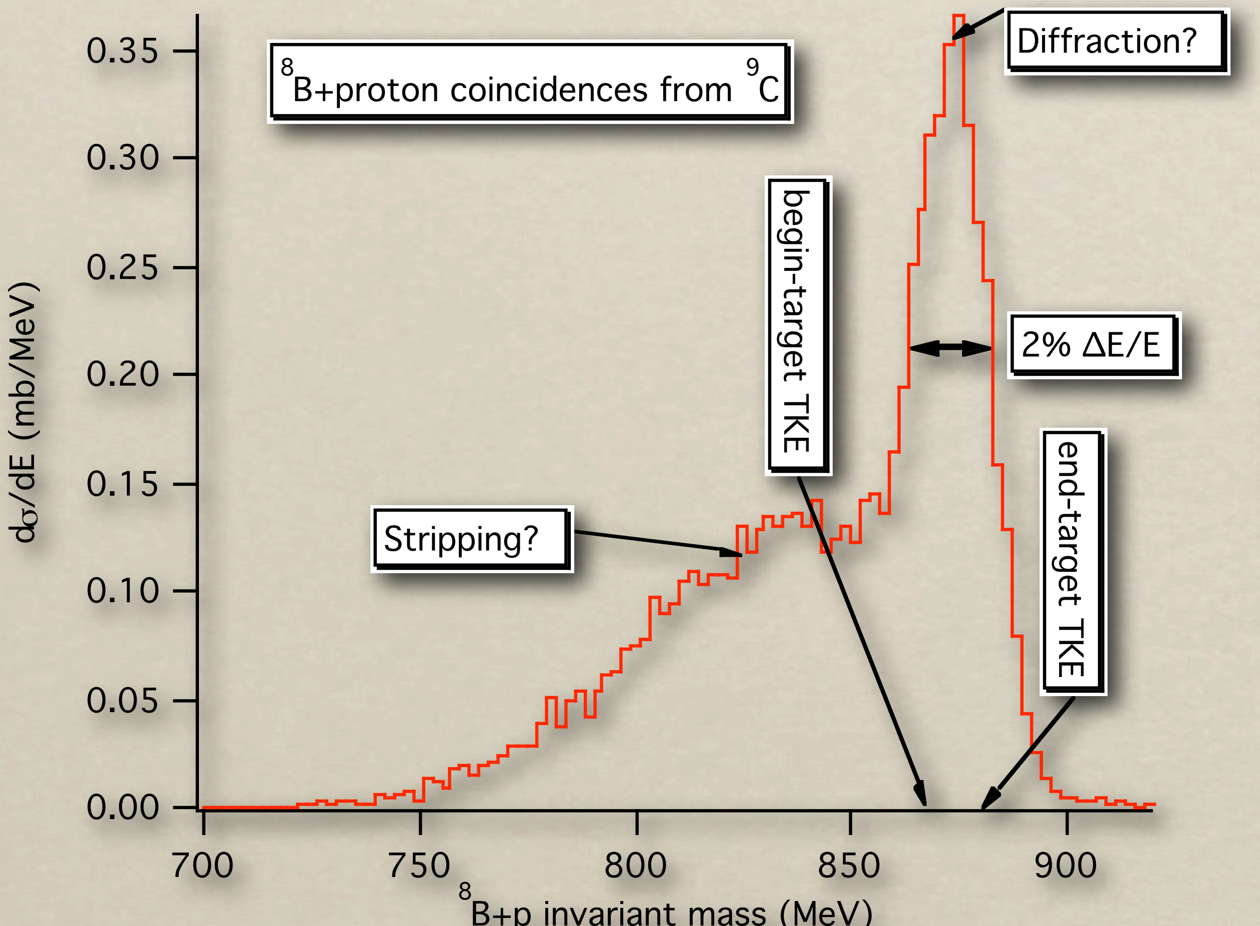
- *Evidence for elastic breakup reaction mechanism*
  - *Diagonal "band" corresponds to elastic process where energy is conserved*
  - *For other events proton interacts inelastically with target*

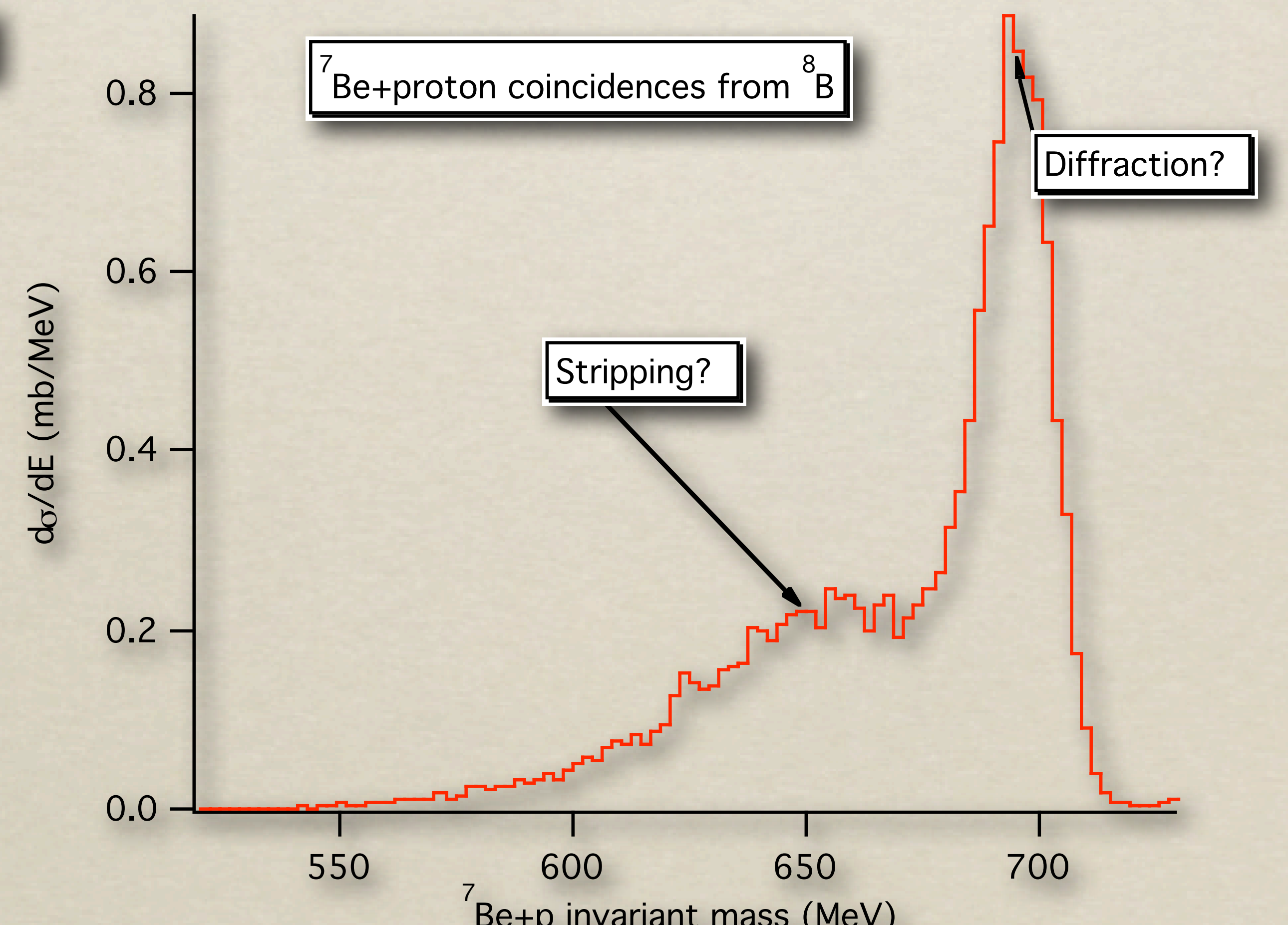




Energy sum spectra

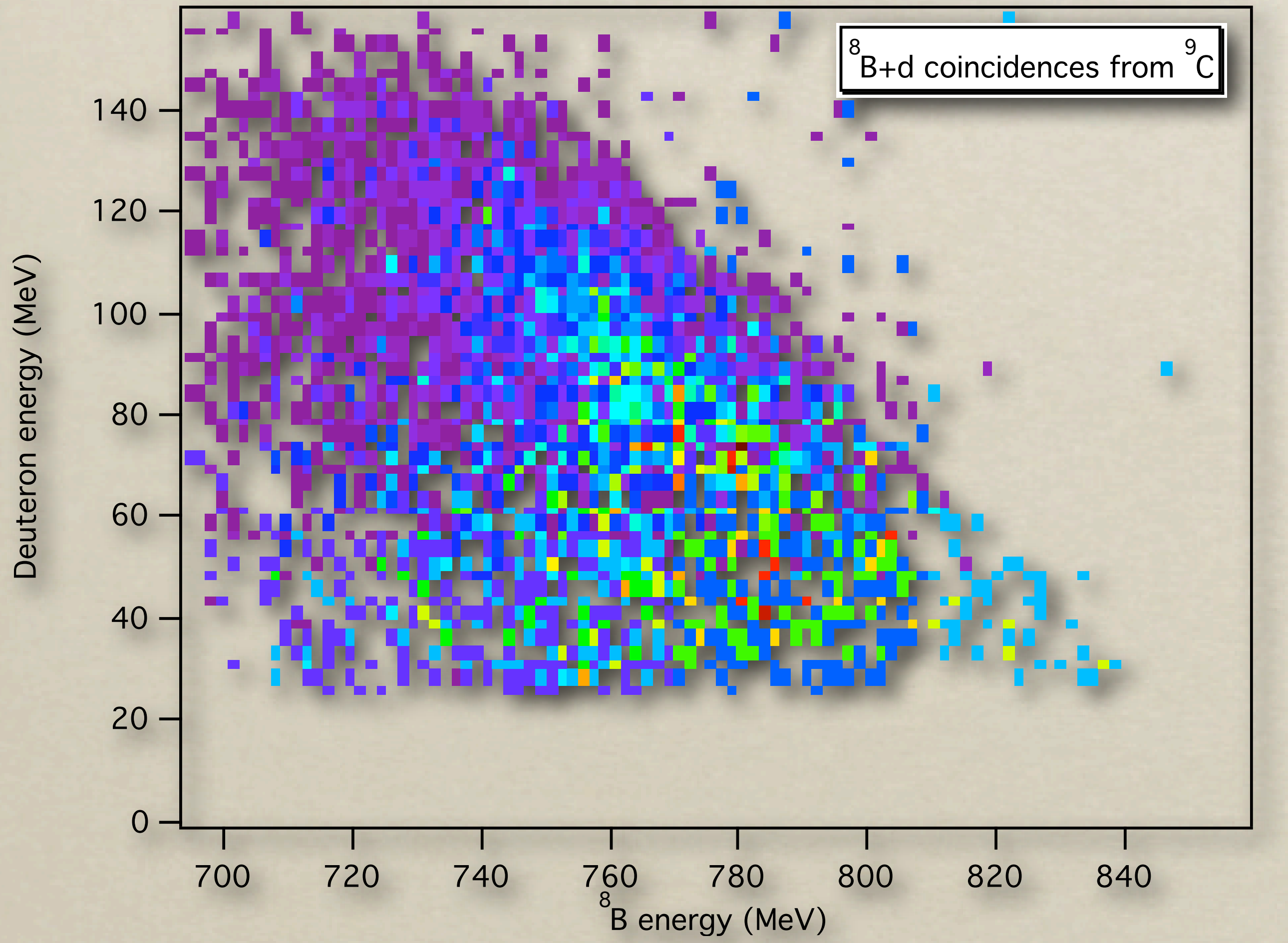
- *Hint of experimental distinction between diffraction and stripping reaction mechanisms*
- *Width of sharp peak due to target thickness and momentum width of incoming radioactive beam (1% ΔP/P)*

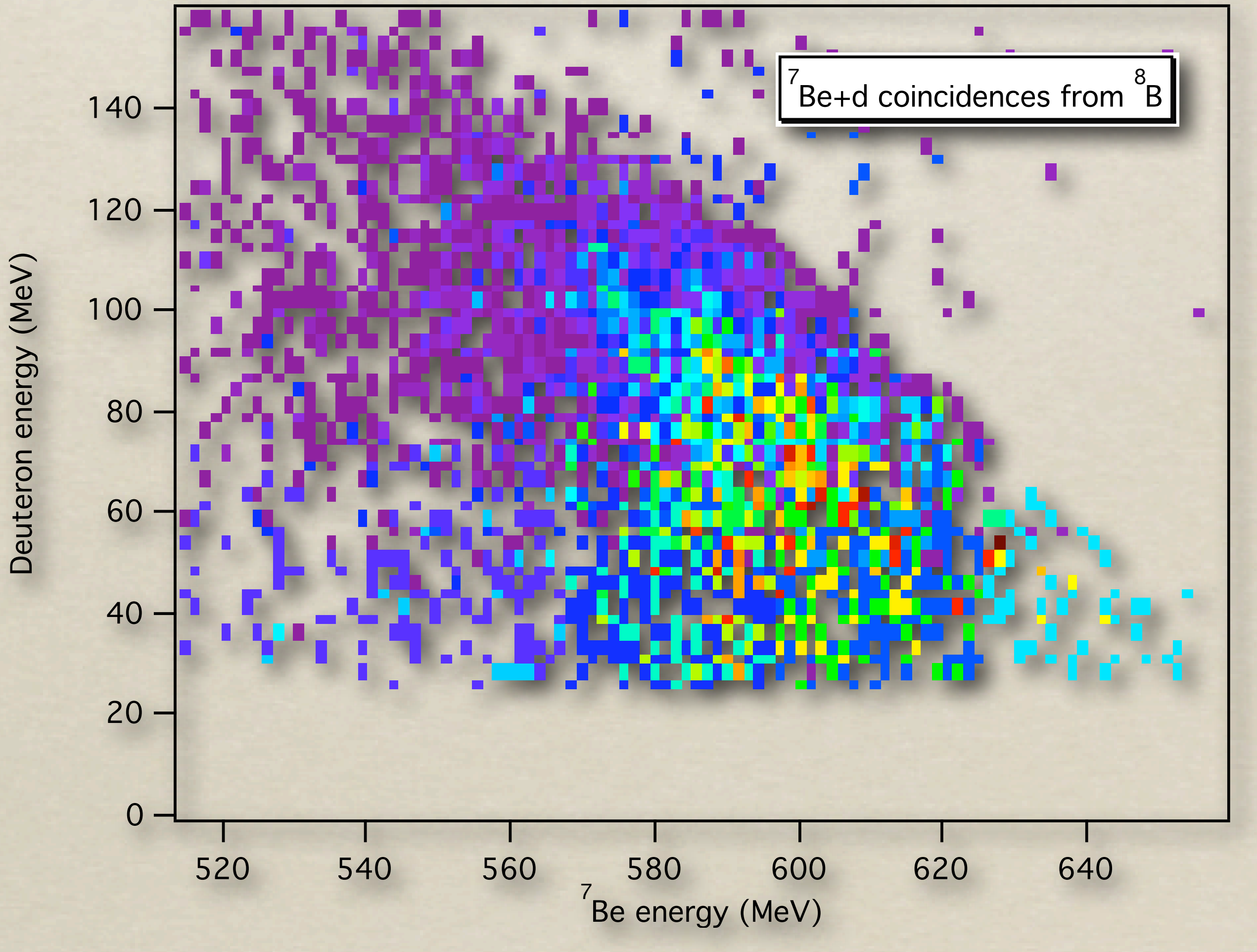




Deuteron - residual nucleus coincidences

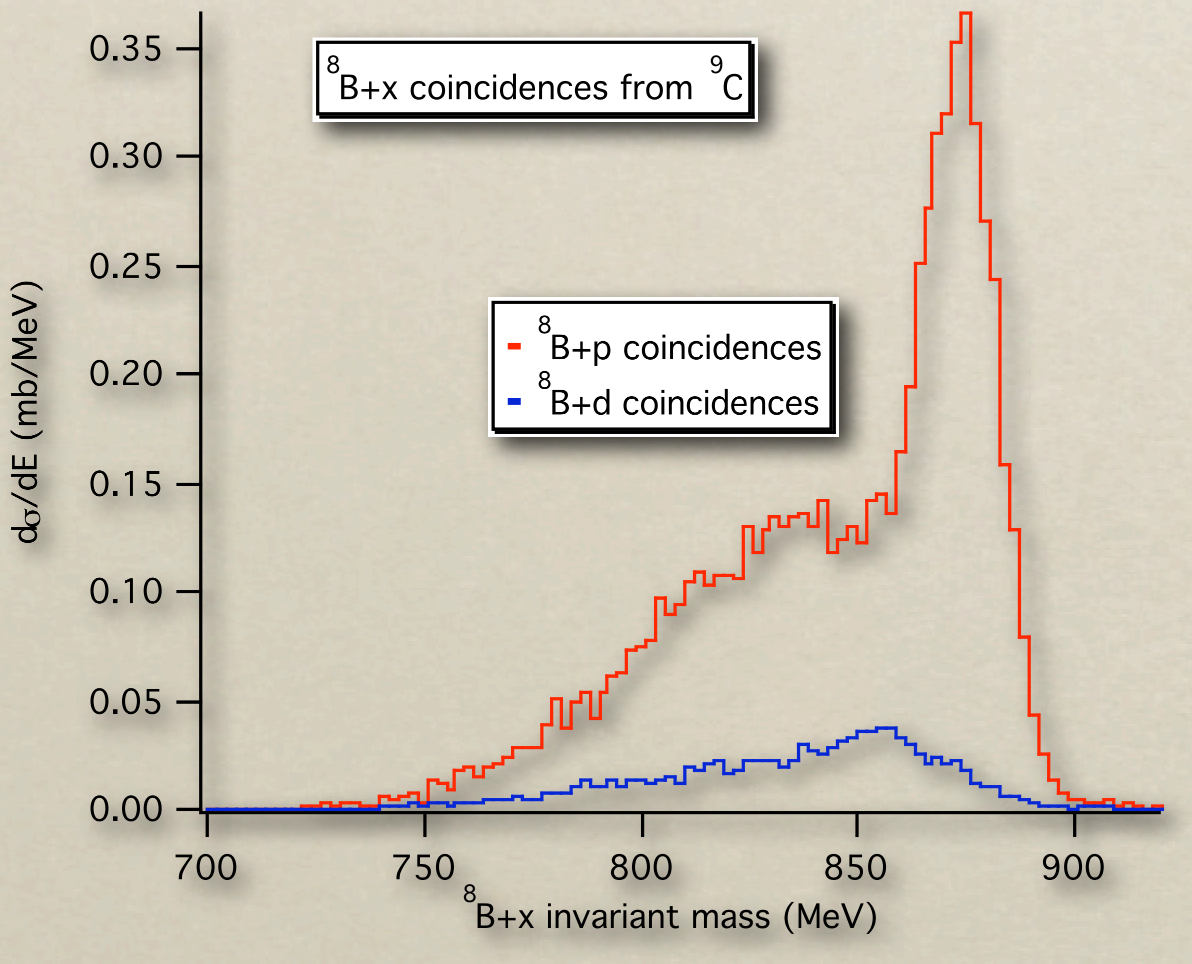
- *Must come from stripping events*
  - *Additional neutron in deuteron comes from (p,d) on ^{9}Be target*
  - *Diagonal "band" previously observed in proton coincidences has dissapeared*

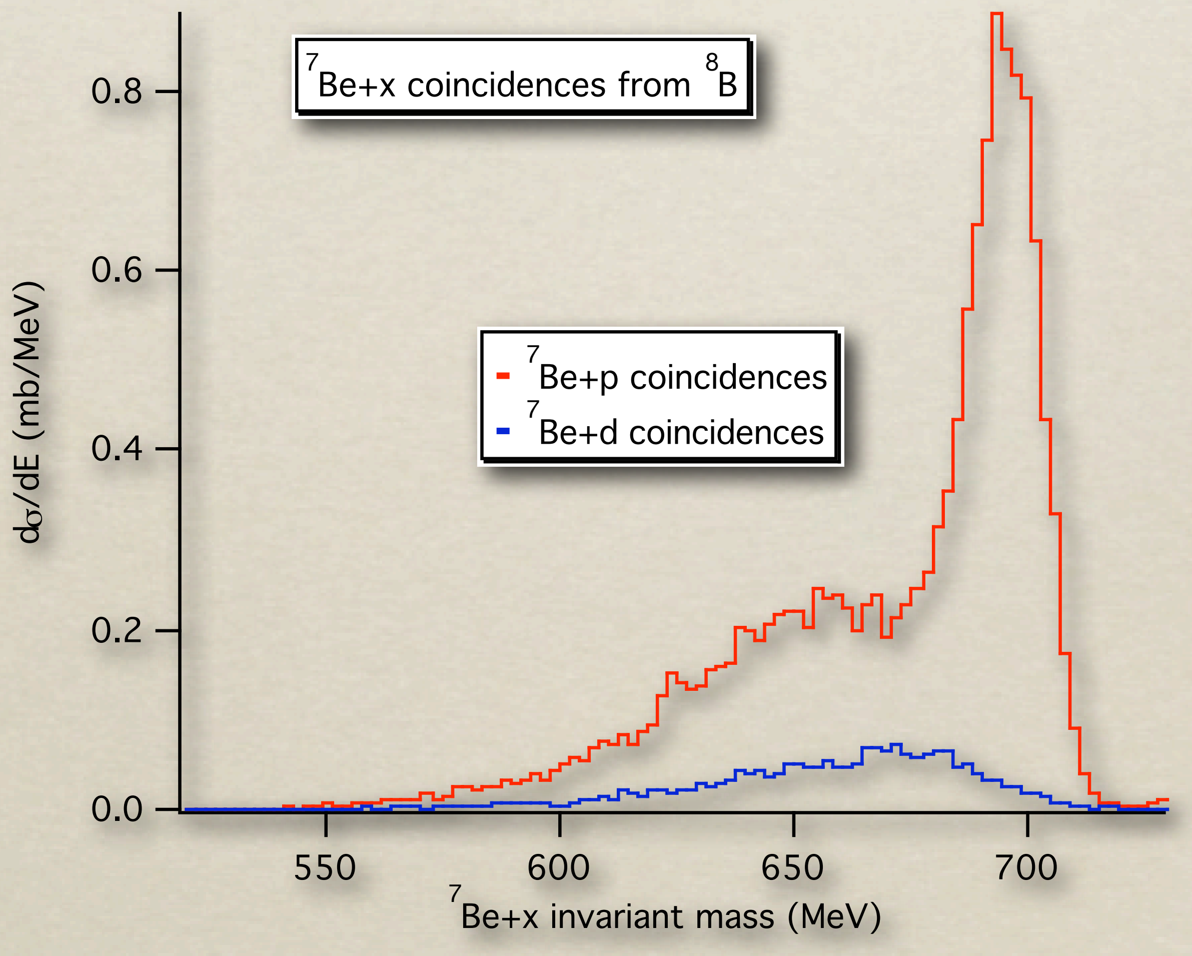




Energy sum spectra

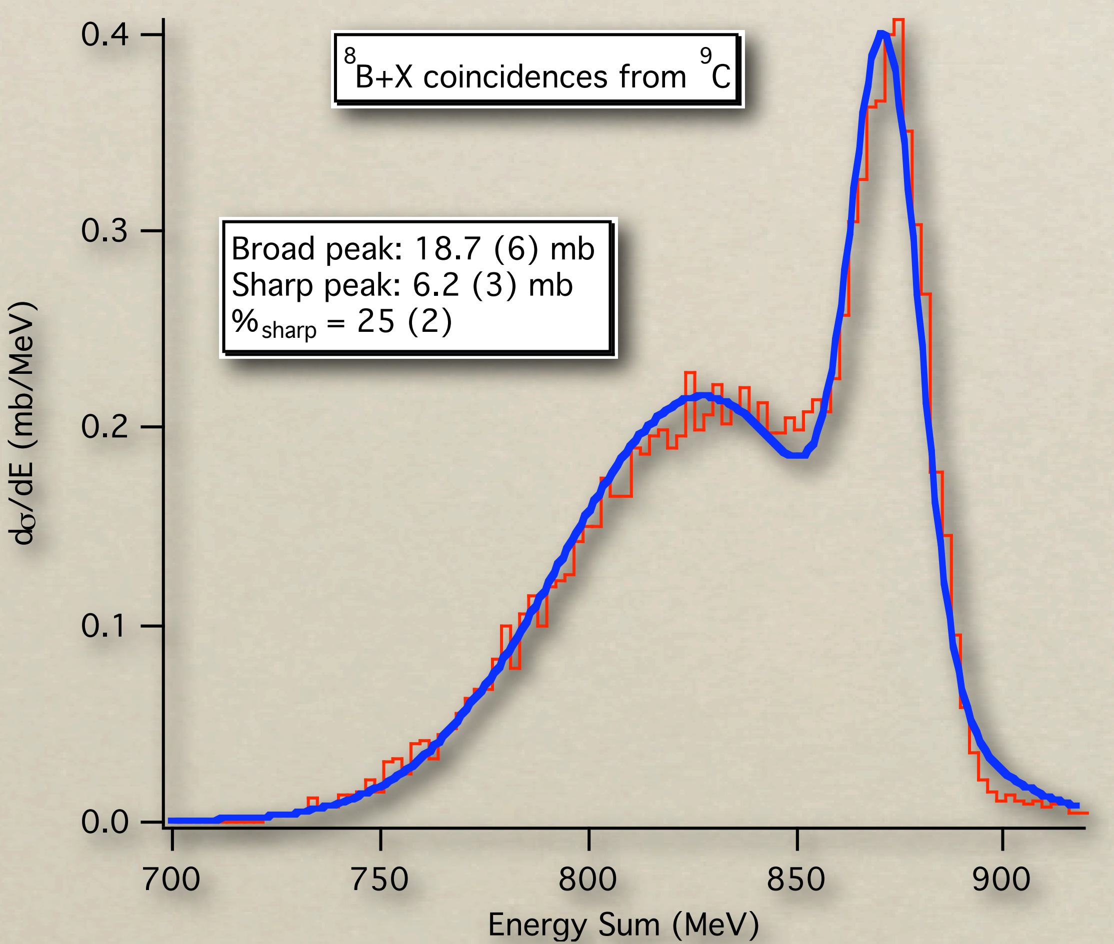
- *Sharp peak corresponding to diffraction reaction mechanism is absent in residual nucleus + deuteron coincidences*

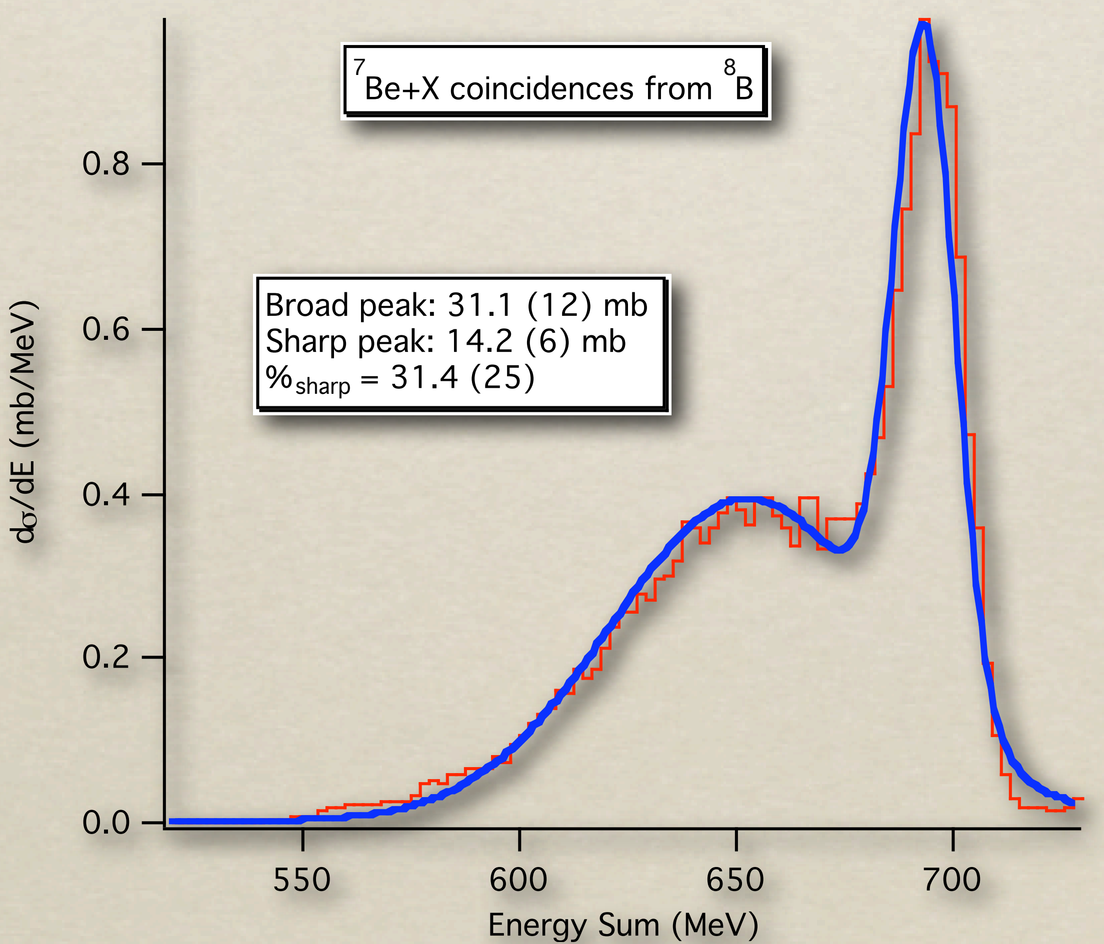




Contributions from each reaction mechanism

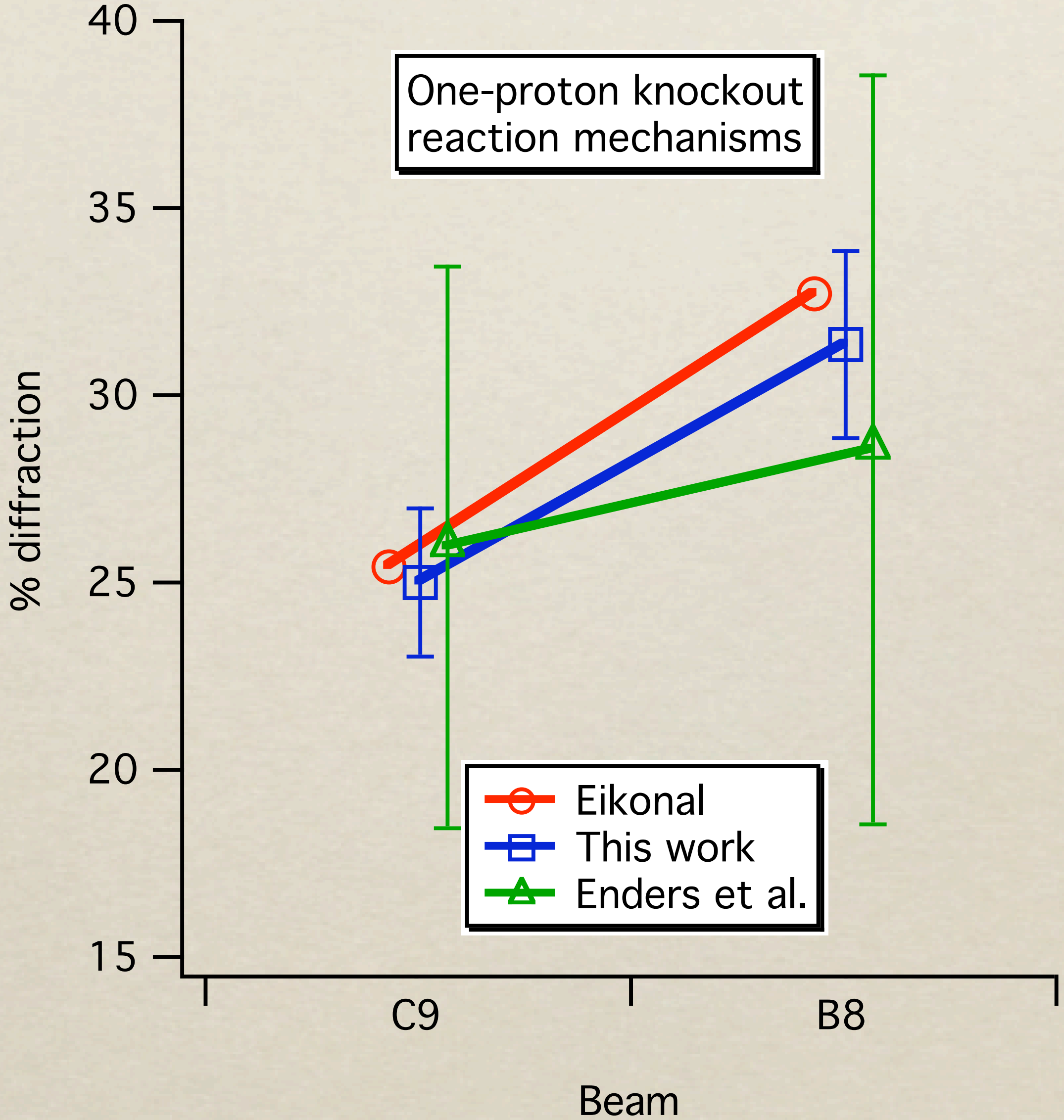
- *Take all particles in coincidence (not just protons)*
- *Assume sharp peak corresponds to diffraction*
- *Double Gaussian fit*





Comparison to eikonal theory

- *Eikonal prediction follows data both in trend and absolute value*
    - *Assumed angular distributions for stripping and diffraction are similar*
    - *Agrees with previous work by Enders et al., although error bars very large due to transmission method used*
- *Comparison with Continuum Discretized Coupled Channel (CDCC) calculations in progress*
    - *Study characteristics of diffraction reaction mechanism*



J. Enders et al., Phys. Rev. C 67, 064301 (2003)

Conclusions and prospects

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- *First full kinematics experiment on proton knockout*
  - *Experimental evidence for two separate reaction mechanisms, stripping and diffraction as assumed in the eikonal reaction theory*
  - *Observed proportion between diffraction and stripping very well reproduced by eikonal calculation*
  - *Interpretation of observed features require careful comparison with more refined theory such as CDCC calculations for diffraction*

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- *Next step: test of two-proton knockout reaction theory*
  - *Diffraction/Stripping combined channel can account for up to ~ 50% of cross section*
  - *Use same experimental setup : S800 + HiRA*
  - *Study well known case of two-proton knockout on ^{28}Mg to populate final states in ^{26}Ne for which branching ratios were already measured*

Credits

- *S800 team*
  - *D. Bazin, A. Gade, A. Obertelli, R. Terry, S. Mcdaniels*
- *HiRA group*
  - *B. Lynch, B. Tsang, M. Famiano, L. Sobotka, S. Hudan, V. Henzl, D. Henzlova, M. Wallace, A. Rogers, A. Sanetullaev, S. Lobastov, R. Krishnasamy, M. Kilburn, J. Clifford, J. Lee*