^{6}He Transfer and Breakup Reactions Near The Coulomb Barrier

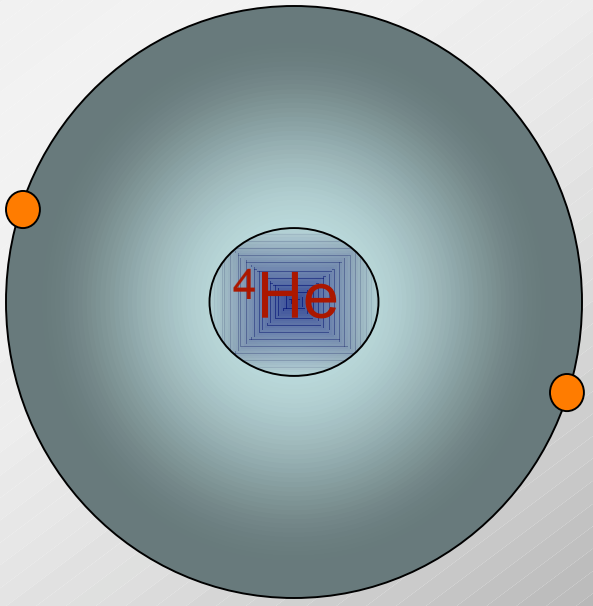
(A Status Report)

^{6}He: A Halo Nucleus

- ^{4}He (α) core with two weakly-bound neutrons that form the outer halo.

  (B.E. = 0.973 MeV)

- "Borromean" nucleus -- all two-body subsystems are unbound.

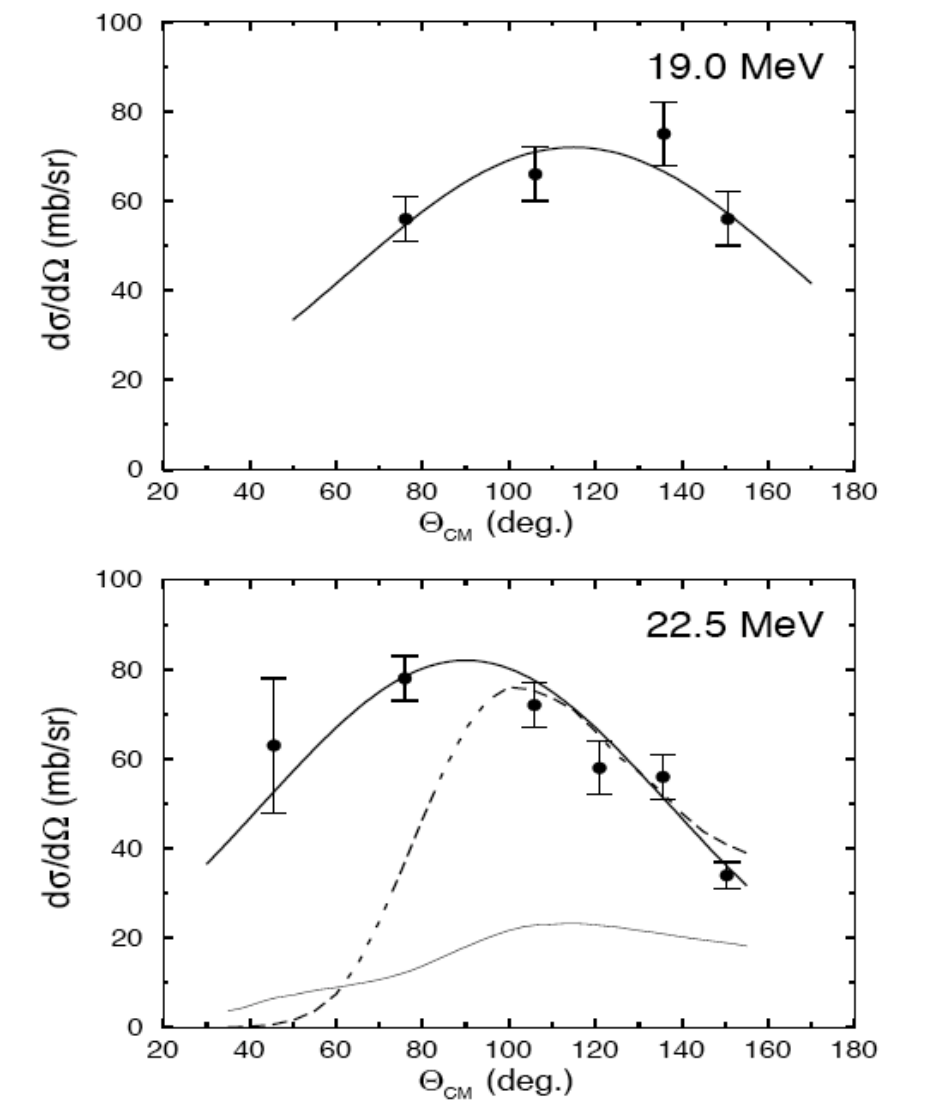


- "Helicopter" vs Cluster States

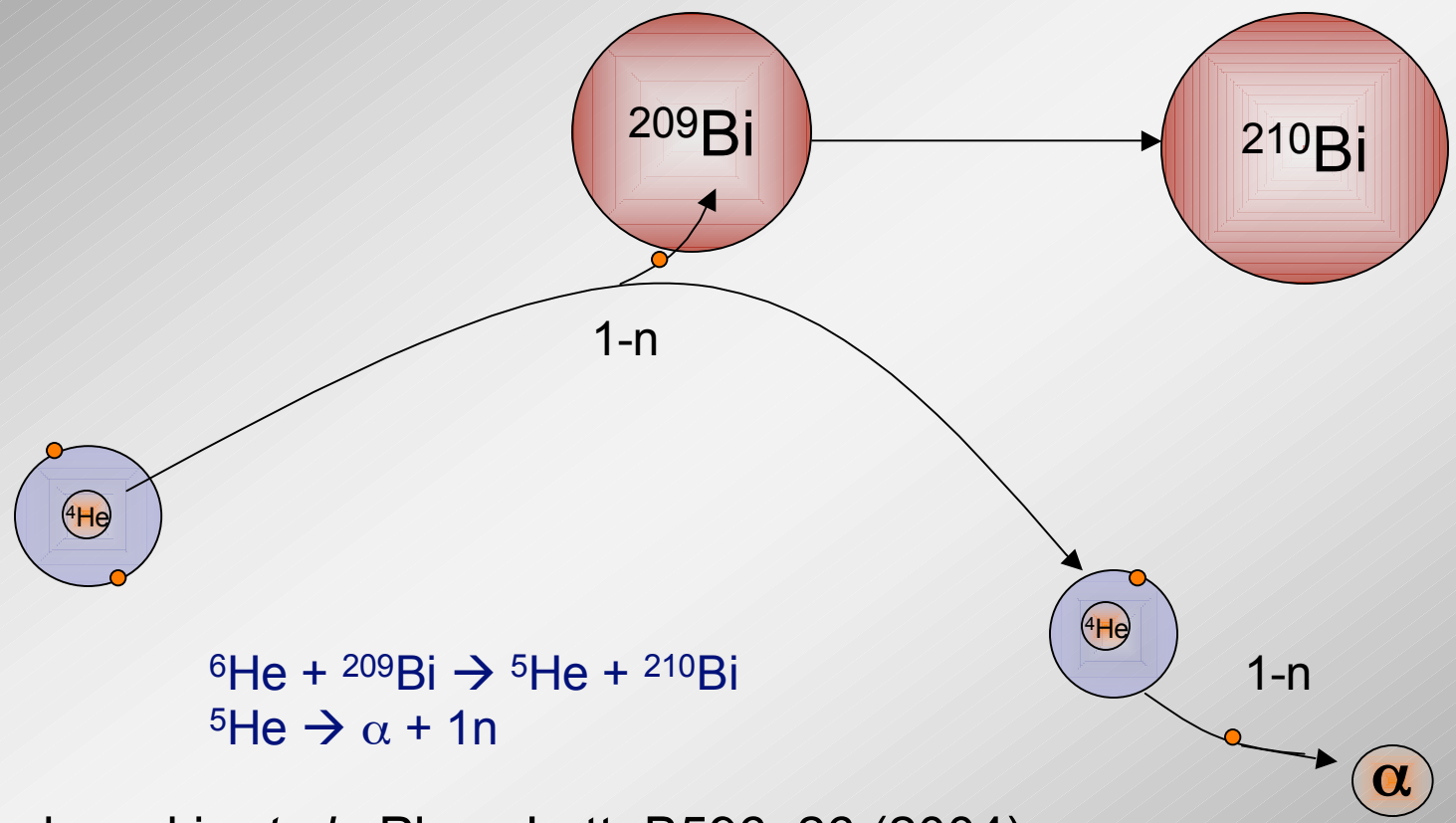
$^{209}Bi + ^{6}He$ => High α Yield

- Aguilera, et al. [PRL 84, 5058 (2000)]: exceptionally large α-particle yield---775±30 mb at E_{cm}=22.5 MeV and 645±45 mb at E_{cm}=19.0 MeV (the Coulomb barrier is at ~20 MeV).

- Average Q-value is about -2 MeV.



Case #1: 1-n Transfer



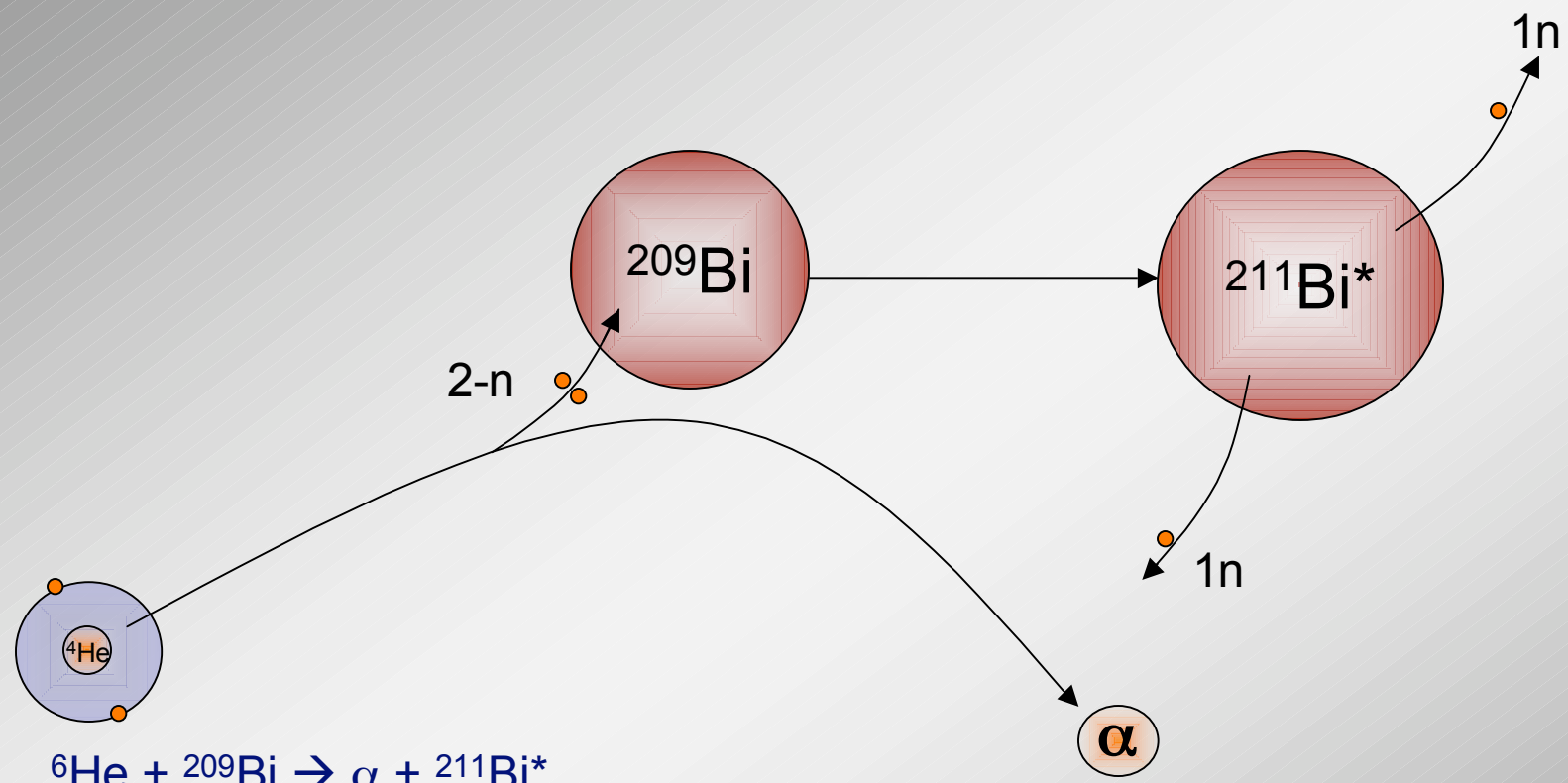
$^{6}He + ^{209}Bi \rightarrow ^{5}He + ^{210}Bi$

$^{5}He \rightarrow \alpha + 1n$

Bychowski, *et al*., Phys. Lett. B596, 26 (2004).

20% of α yield (155±25 mb) at 22.5 MeV.

Case #2: 2-n Transfer



$^{6}He + ^{209}Bi \rightarrow \alpha + ^{211}Bi^*$

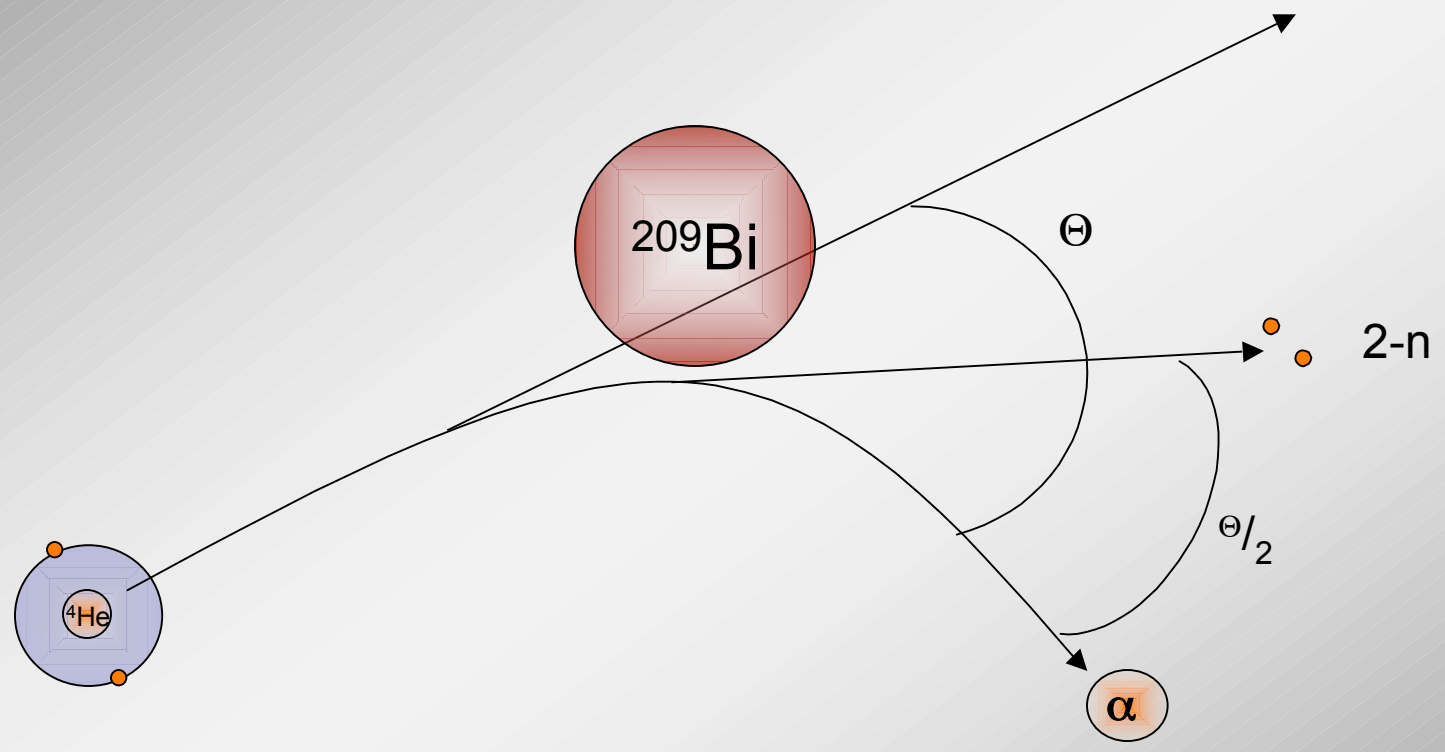
(Q_{gs} = +8.8 MeV => <u>only</u> neutron-unbound ^{211}Bi states are populated).

$^{211}Bi^* \rightarrow ^{209,210}Bi + 1.47n$

DeYoung, *et al*., PRC 71, 051601(R) (2005).

53% of α yield (410±122 mb) at 22.5 MeV.

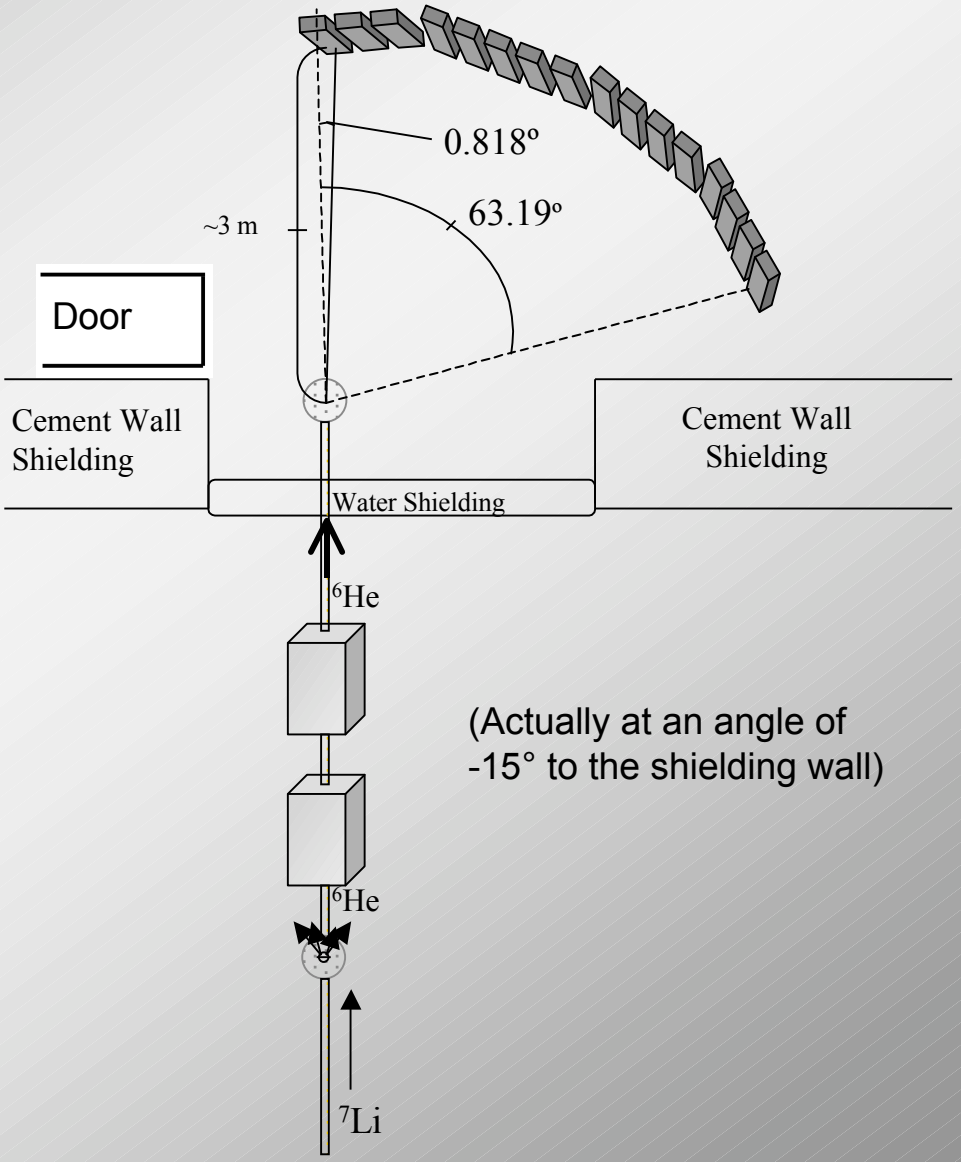
Case #3: Projectile Breakup



$^{6}He + ^{209}Bi \rightarrow ^{209}Bi + \alpha + 2n$

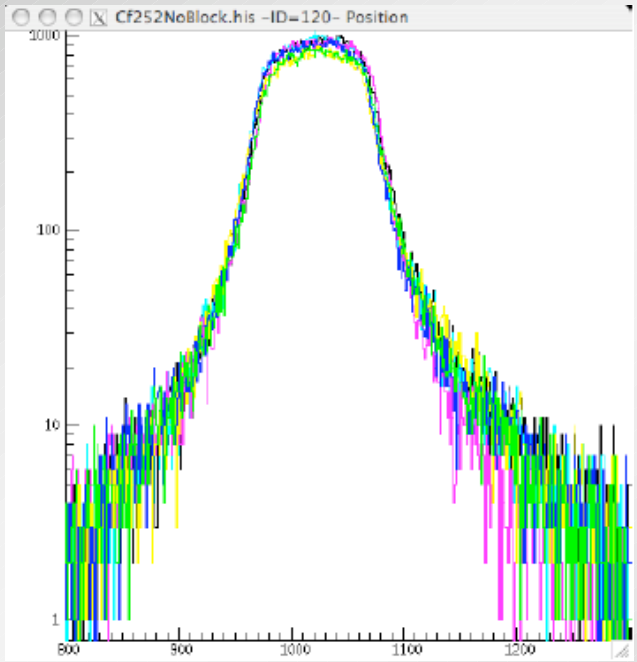
Experimental Setup

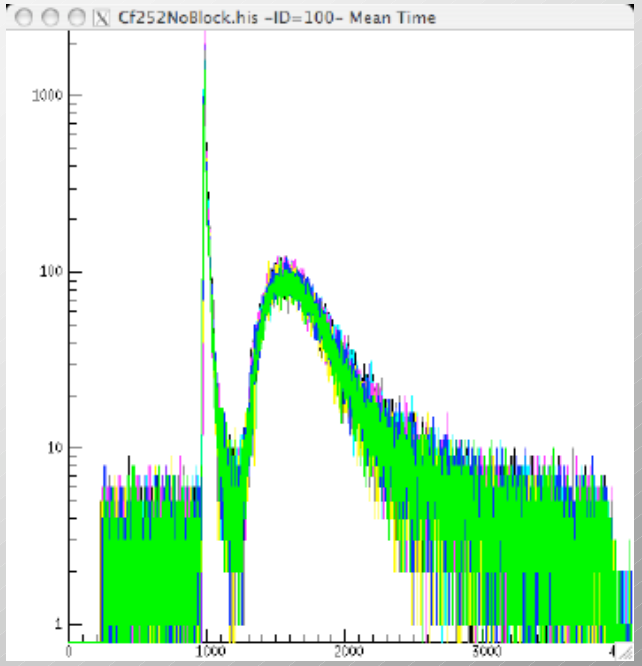
- Primary ^{7}Li beam
- Primary ^{9}Be target gives ^{6}He.
- Focused with *TwinSol* 6T Superconducting Solenoids.
- Secondary ^{209}Bi target gives reaction of interest
- α-particles detected at 60°.
- "Second generation" neutron wall (16 elements).



- Sixteen elements, each 152 cm by 15.2 cm by 5 cm plastic scintillator. Position sensitive.

Results with ^{252}Cf source =>



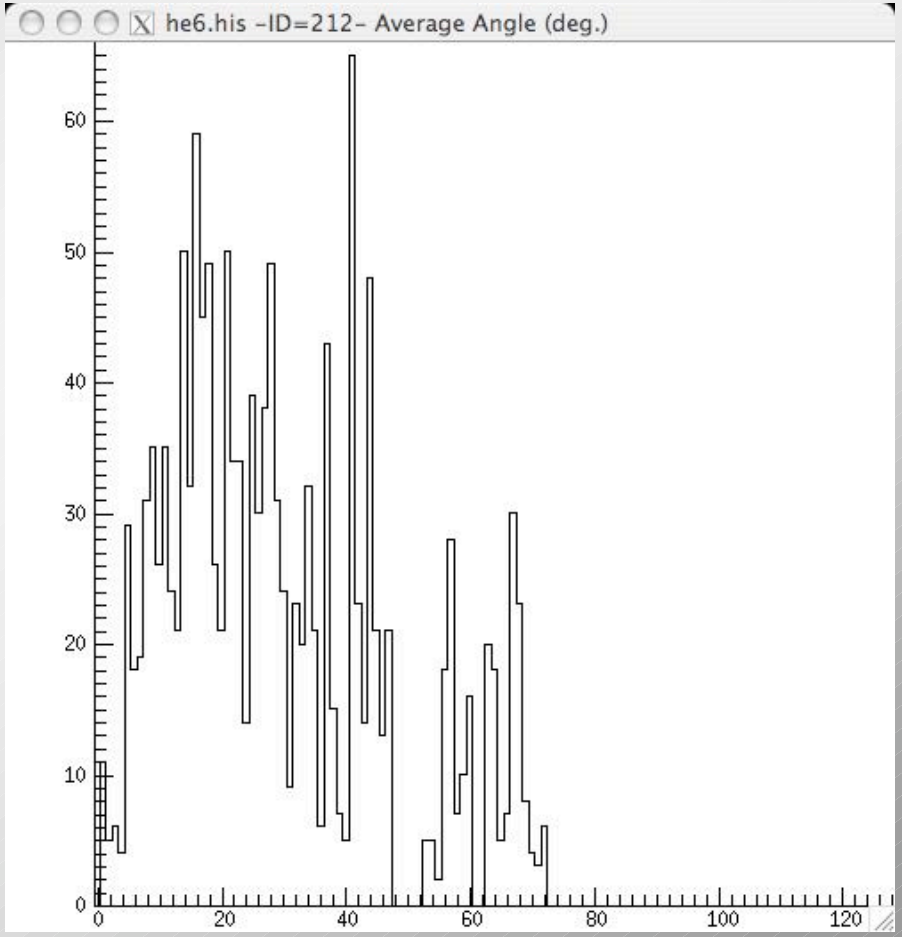


- Neutrons identified by time of flight.

Neutron Angular Distribution

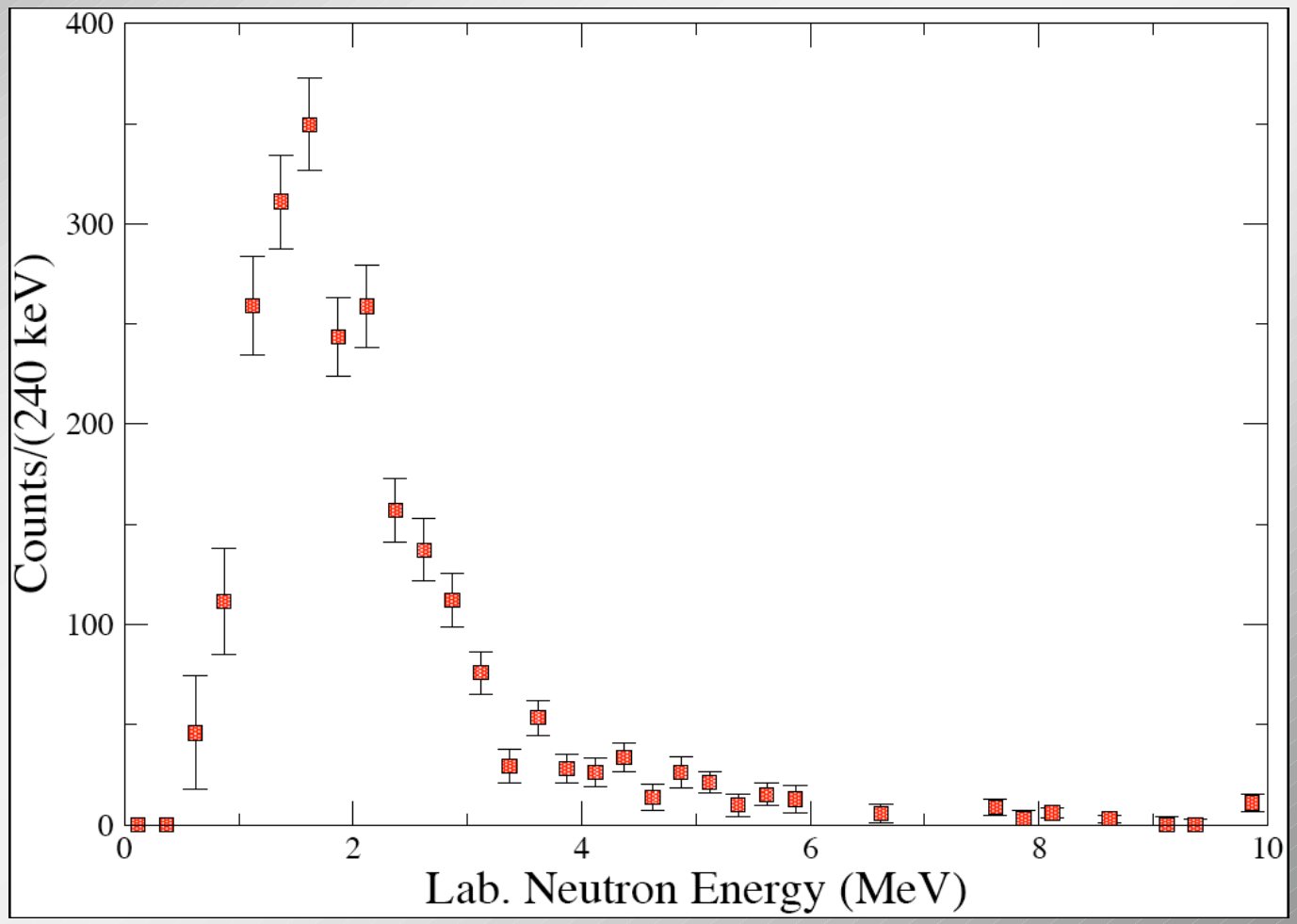
- With α-detector at 60º, peak in α-n coincidences from breakup expected at ~30º.

- Peak at ~60° comes from ^{5}He (1n transfer).



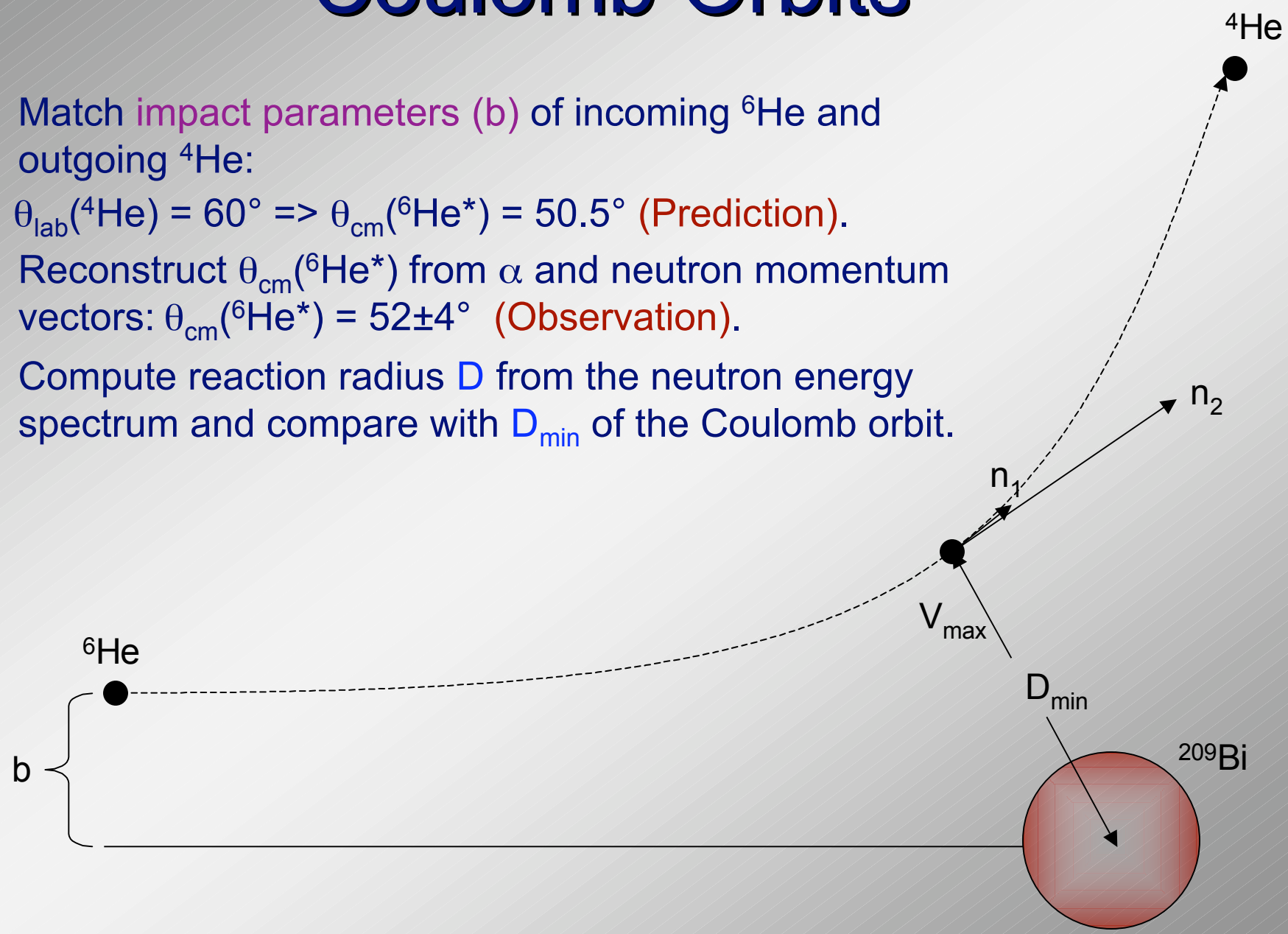
Neutron Energies

- Corrected for neutron detection efficiency and "evaporated" neutrons.
- "Consistent" with neutrons from projectile breakup.
- A few neutrons of energy beyond the "maximum" value of 3.75 MeV.



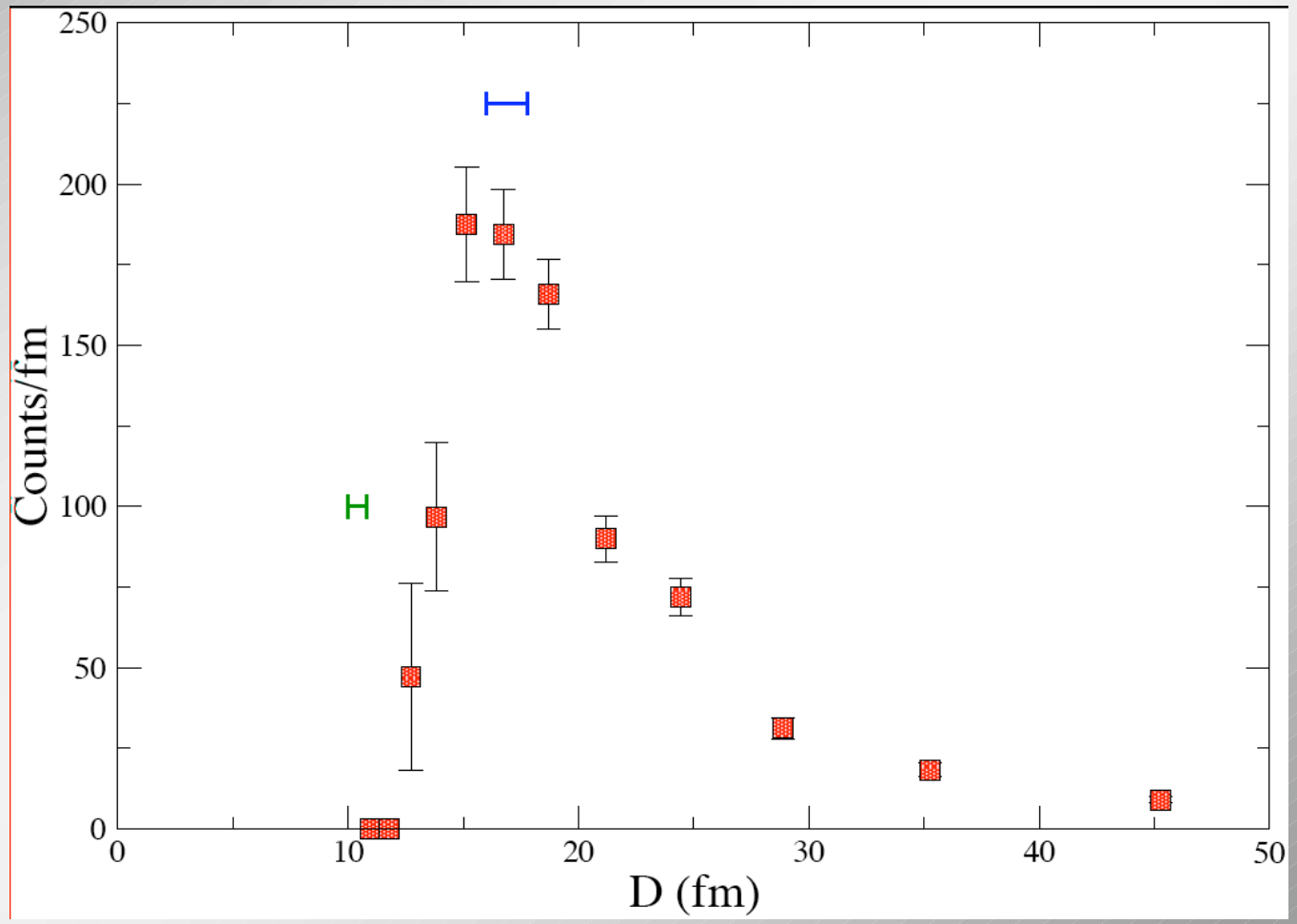
Coulomb Orbits

- Match impact parameters (b) of incoming ^{6}He and outgoing ^{4}He:
  $\theta_{lab}(^4He) = 60° \Rightarrow \theta_{cm}(^6He^*) = 50.5°$ (Prediction).
- Reconstruct $\theta_{cm}(^6He^*)$ from α and neutron momentum vectors: $\theta_{cm}(^6He^*) = 52 \pm 4°$ (Observation).
- Compute reaction radius D from the neutron energy spectrum and compare with D_{min} of the Coulomb orbit.



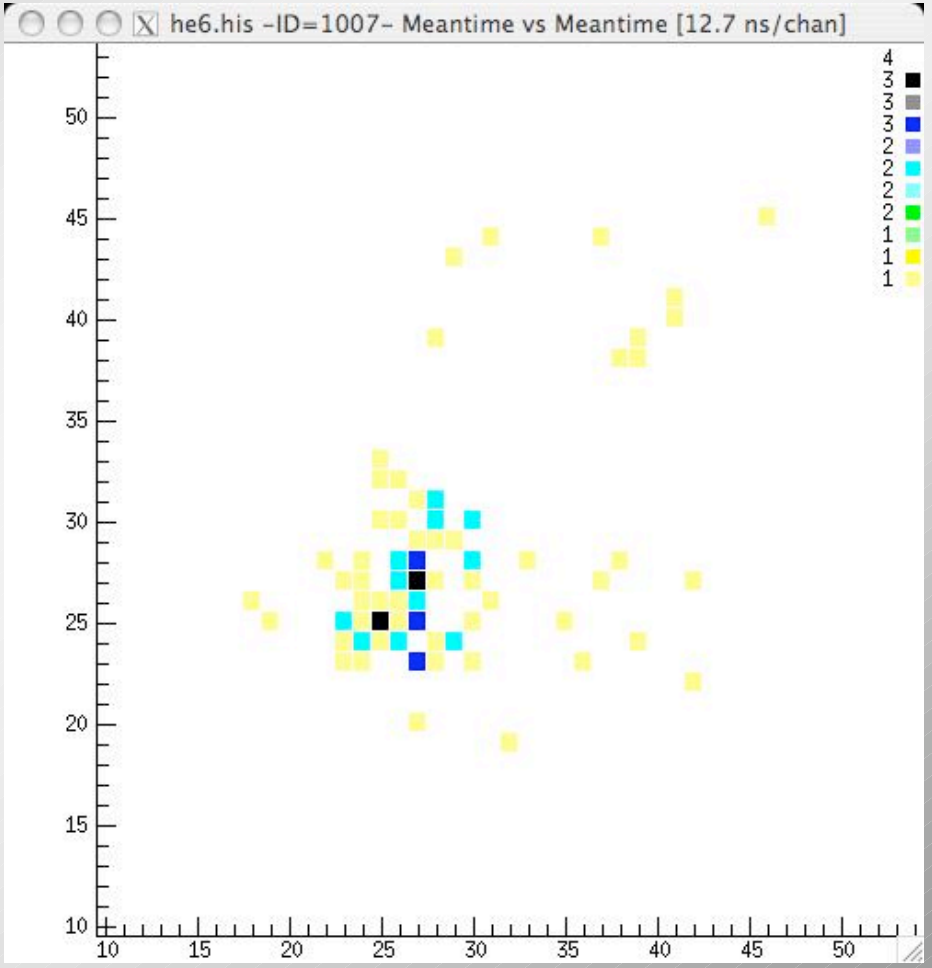
Reaction Distance

- Red data points computed from the neutron energy distribution.
- Blue "error bar" is the distance of closest approach D_{min} on the Rutherford orbit, computed from the reconstructed $^{6}He^{*}$ scattering angle (52±4°).
- Green "error bar" is the fusion radius [see PRL 81, 4580 (1998)].



Multiplicity = 2 Neutron Events

- Small data set --- poor statistics (~70 events).
- Only ~25% of the "expected" yield.
- But---events seem to be "clean".
  - Small contamination from electronic crosstalk.
  - ^{252}Cf calibration showed that neutron scattering crosstalk is very small (~0.5%).



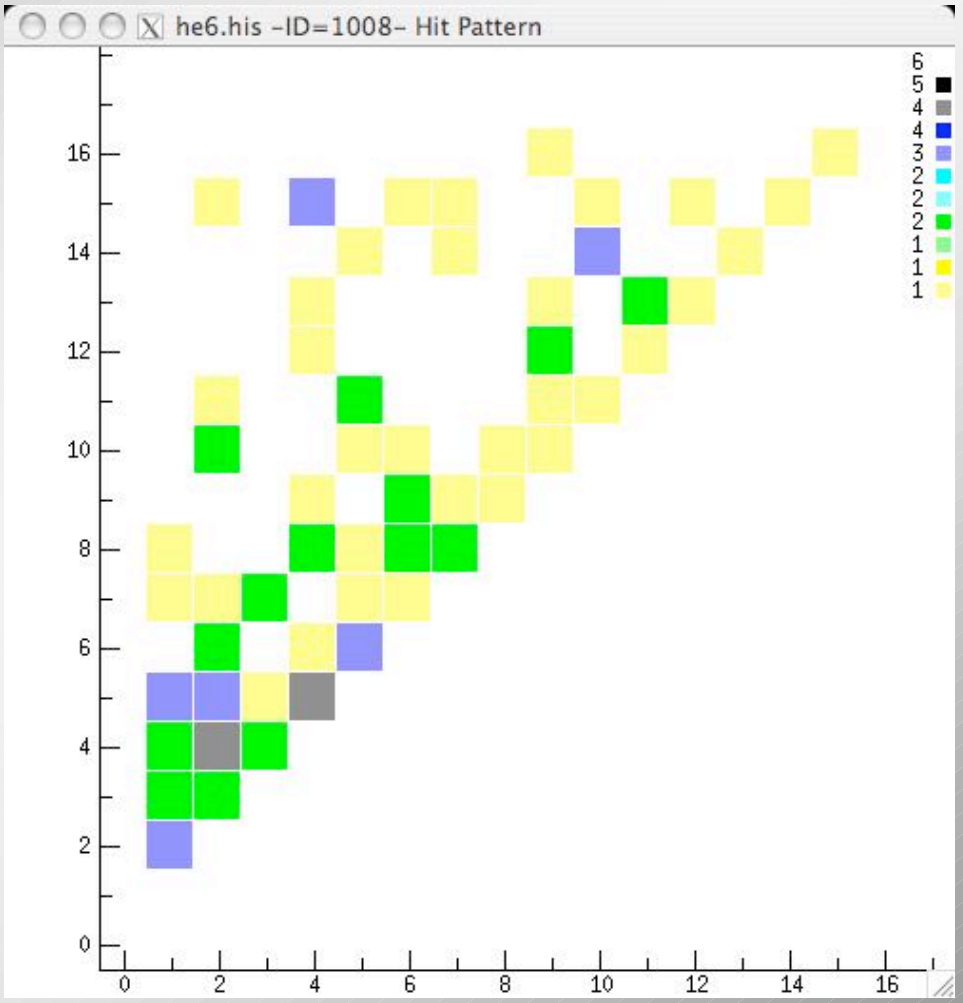
Meantime(1) vs Meantime(2)
Neutrons only

Hit Pattern

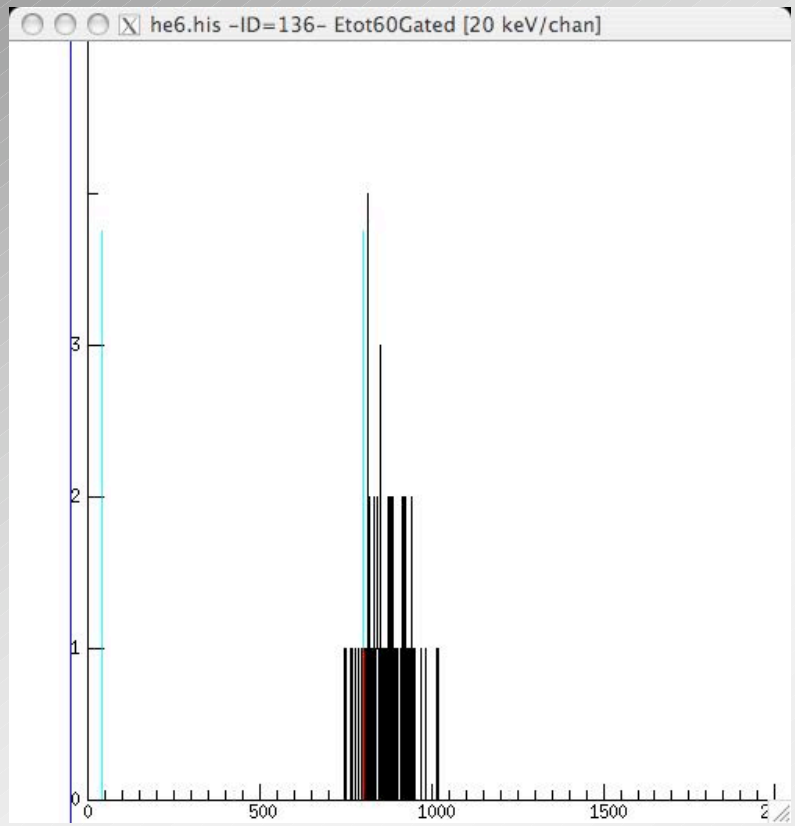
- Detector numbers of “first and “second” hits (converted to an upper triangular matrix since we don’t actually know which neutron came first). The lowest-number detectors are at the smallest angles.

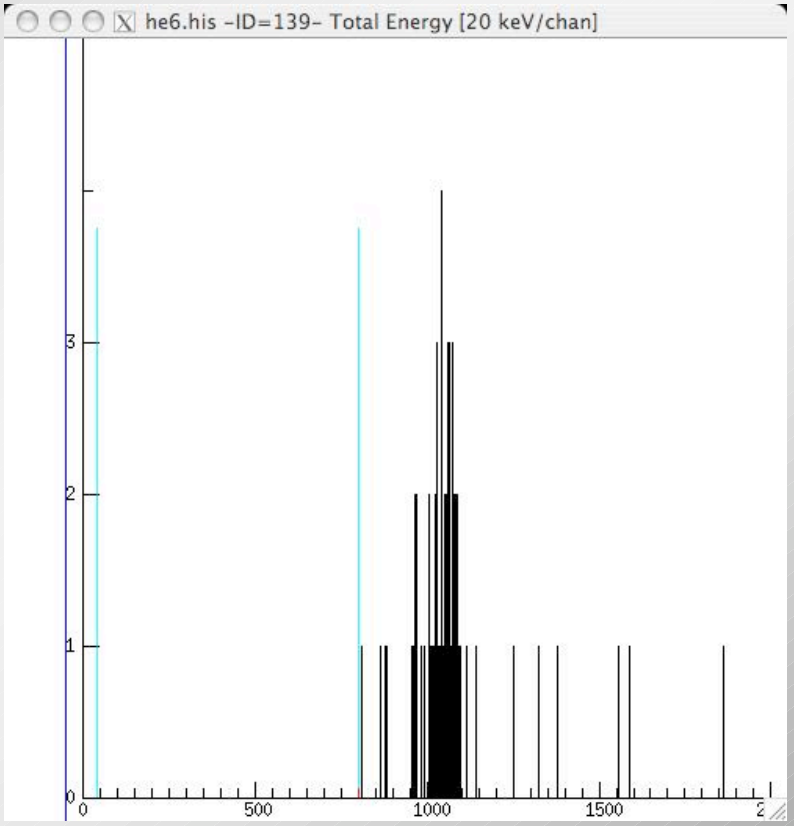
- Most events at small angles!

- This means we will have to put neutron detectors on the other side of the beam.



Energetics





Energy in the Si detector:
~17.5 MeV

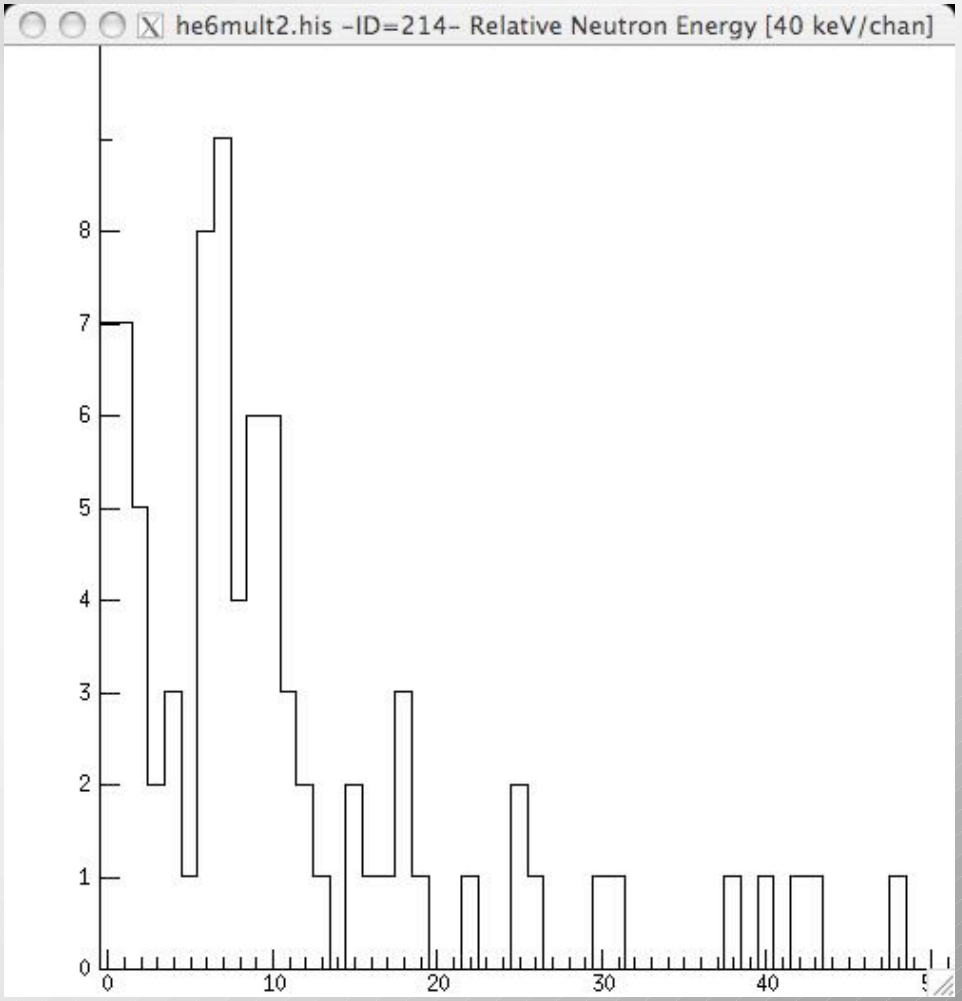
Total Energy:
~21 MeV

Total Energy = E_{beam} - E_{recoil} - $Q_{breakup}$ = 22.5 MeV - 0.63 MeV - 0.97 MeV

= 20.9 MeV

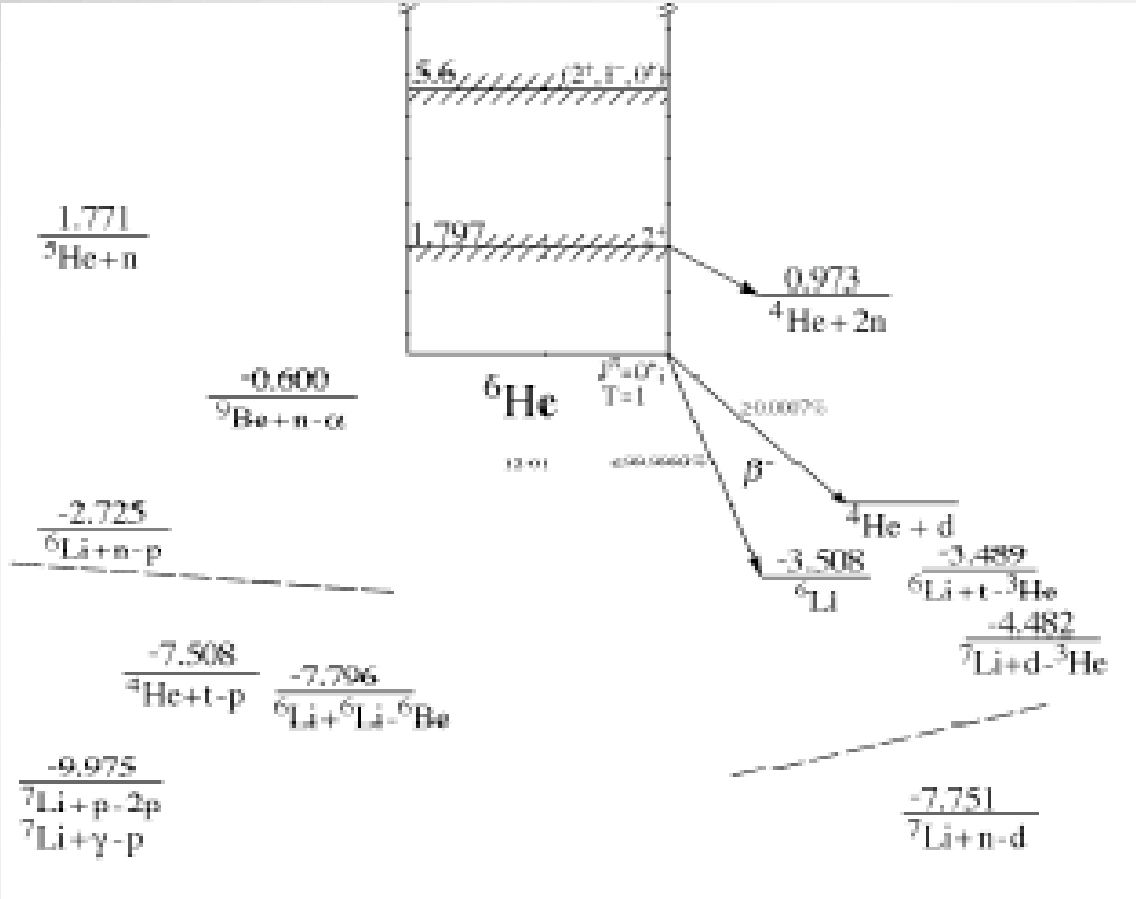
Relative Energy

- Relative energy between the two neutrons.
  - Two (or three?) groups.
  - Group at zero relative energy: direct breakup to the $^{4}He+2n$ channel.
  - Group at ~300 keV: resonant breakup through the 2^{+} excited state of ^{6}He.
  - Third group: (~600 keV) ???



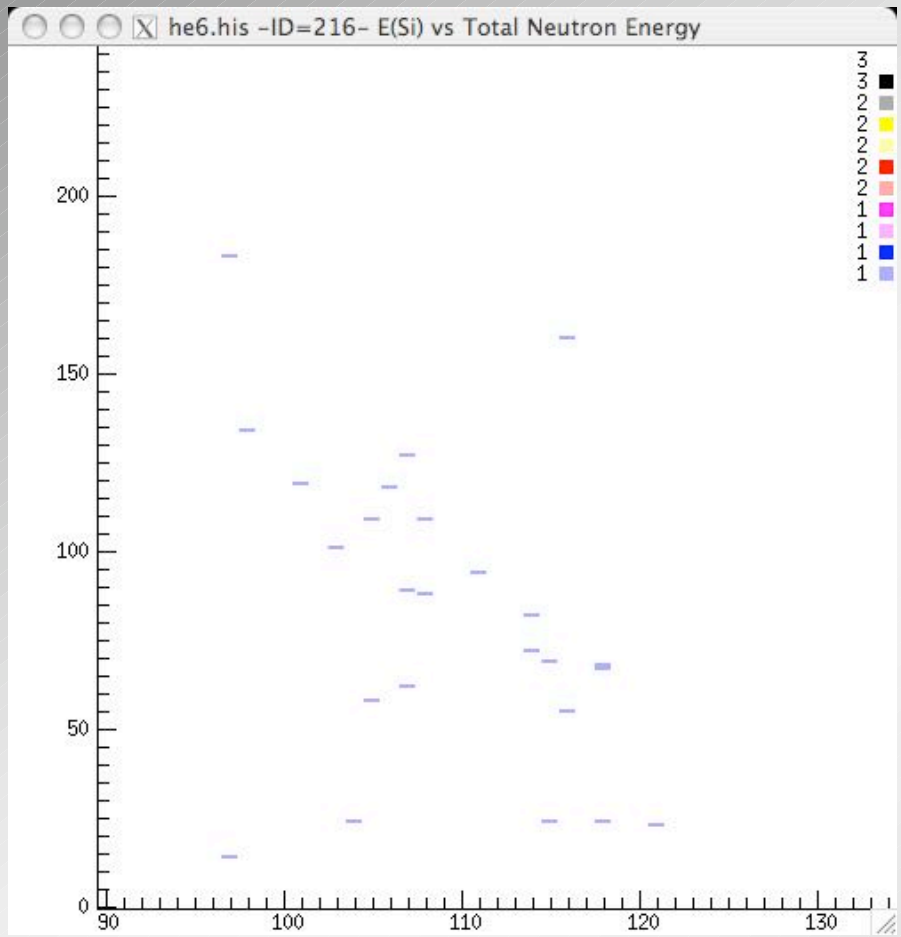
^{6}He Levels

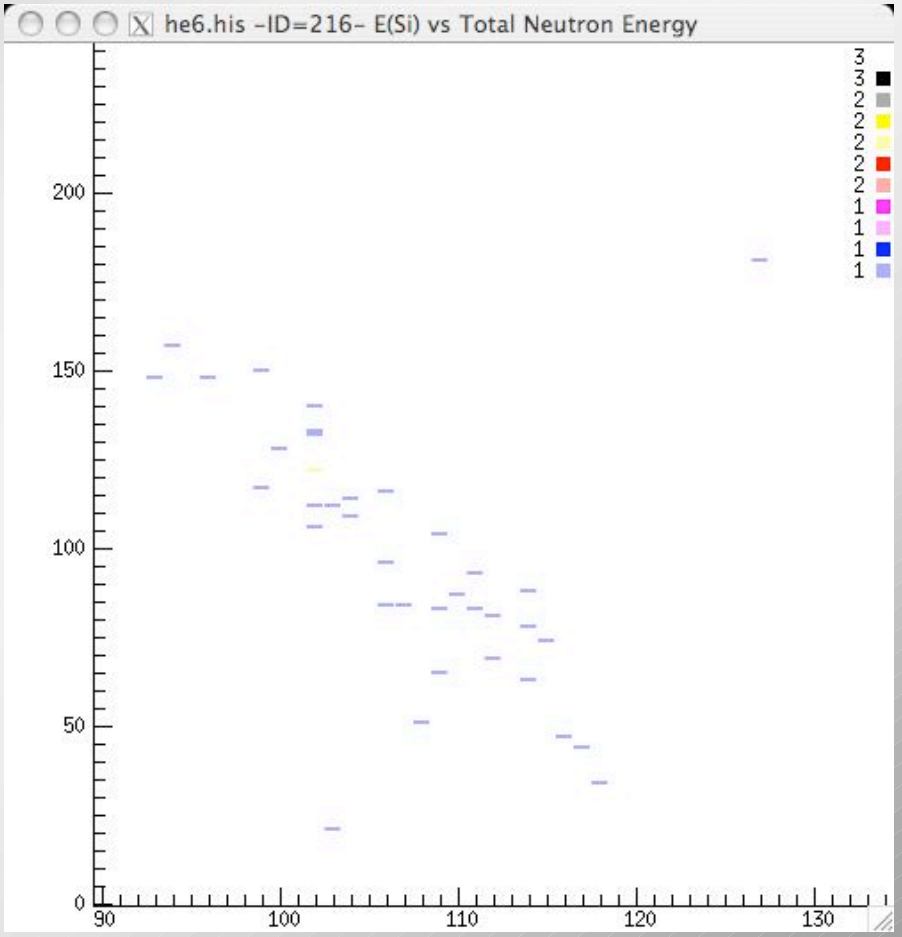
- Assumption: Excitation energy is shared according to the mass of the particles. Thus, the two neutrons get 1/3 of the excitation energy.



E_{rel} = (1.797 MeV - 0.973 MeV)/3 = 0.275 MeV.

E_α vs E_{2n}



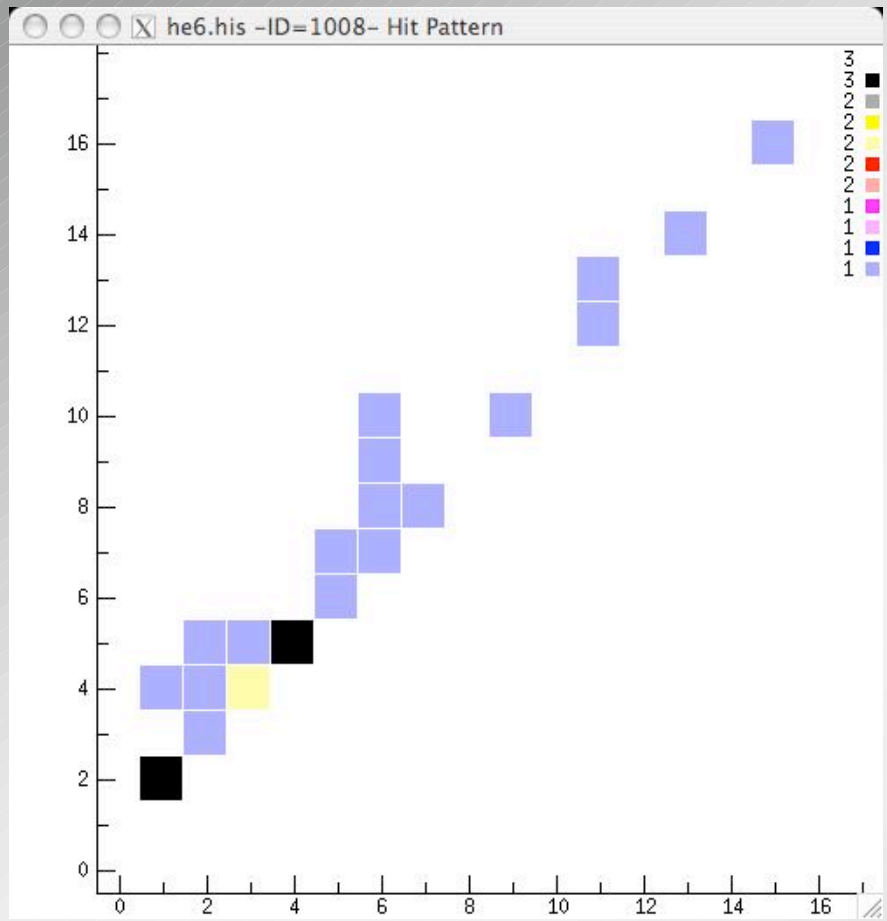


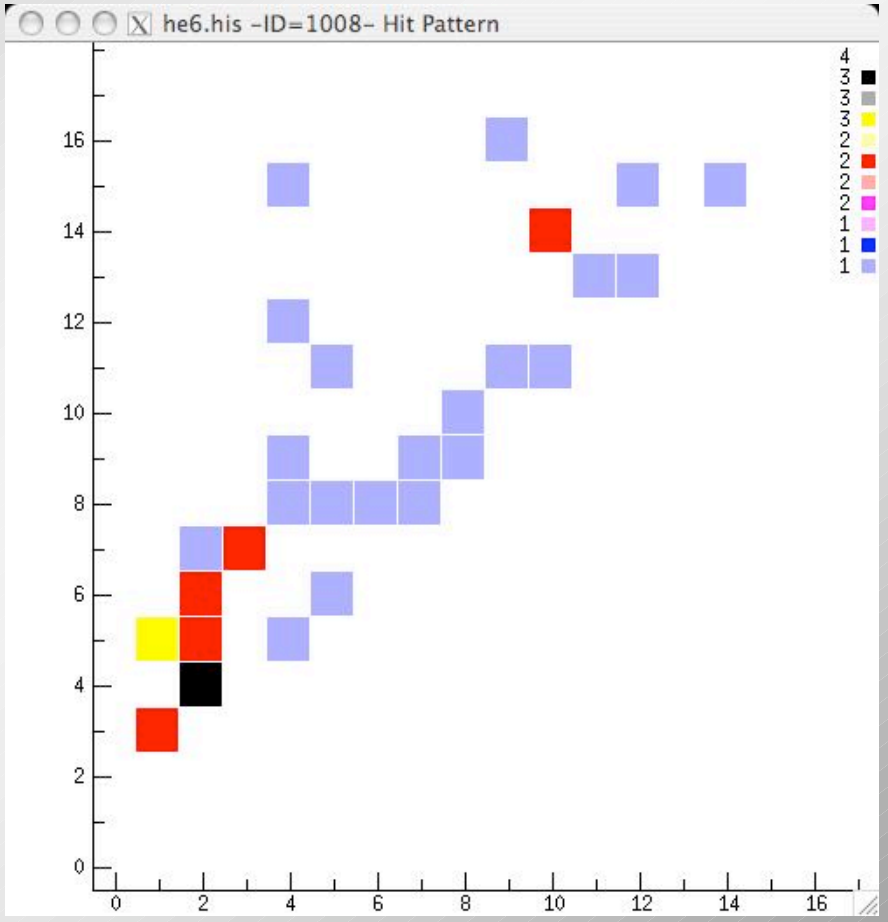
Direct breakup

"Resonant" breakup

Most events occur in well-defined "kinematic loci"

Hit Patterns



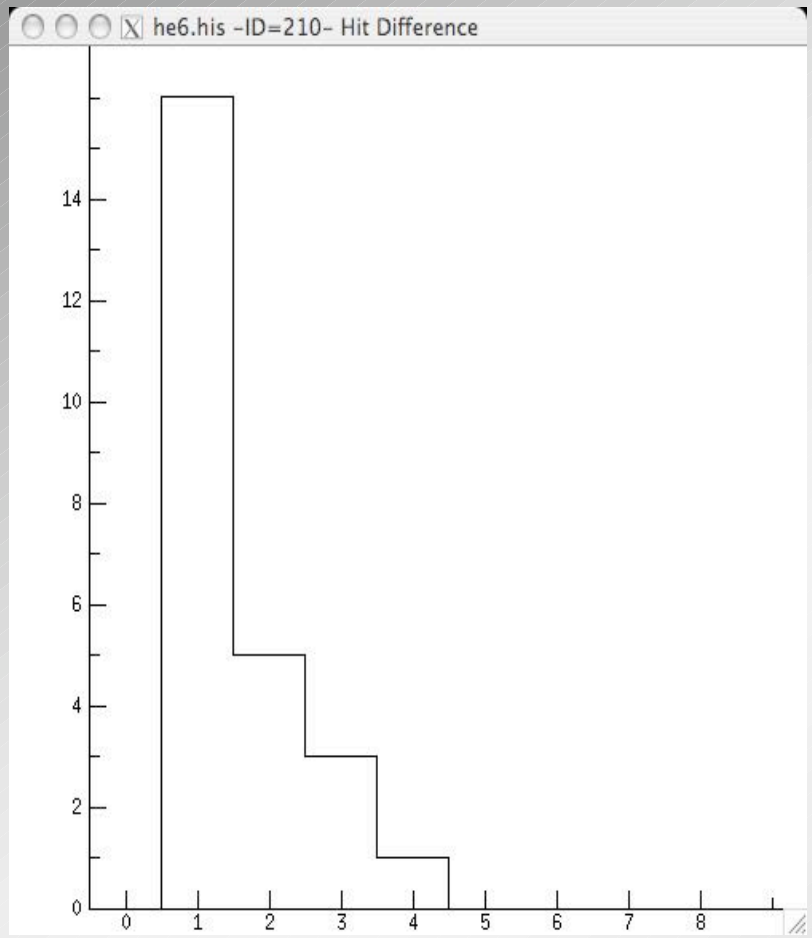


Direct breakup

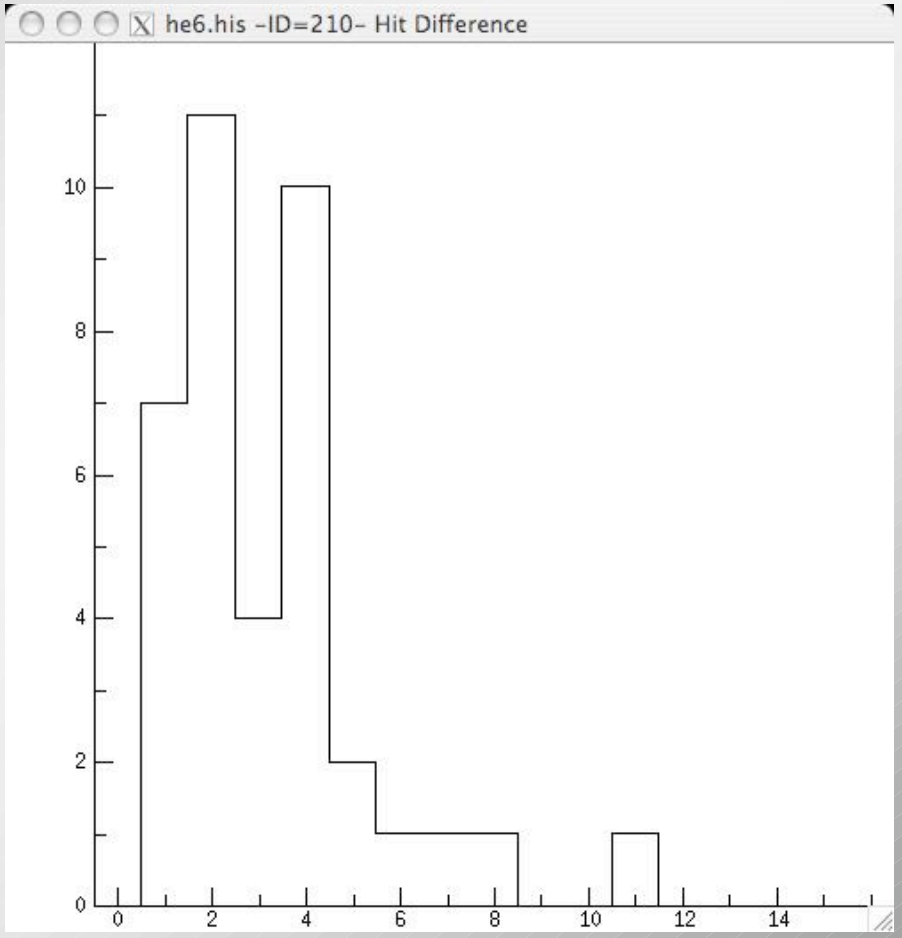
"Resonant" breakup

Events are weighted toward small angles for both processes.

Hit Difference



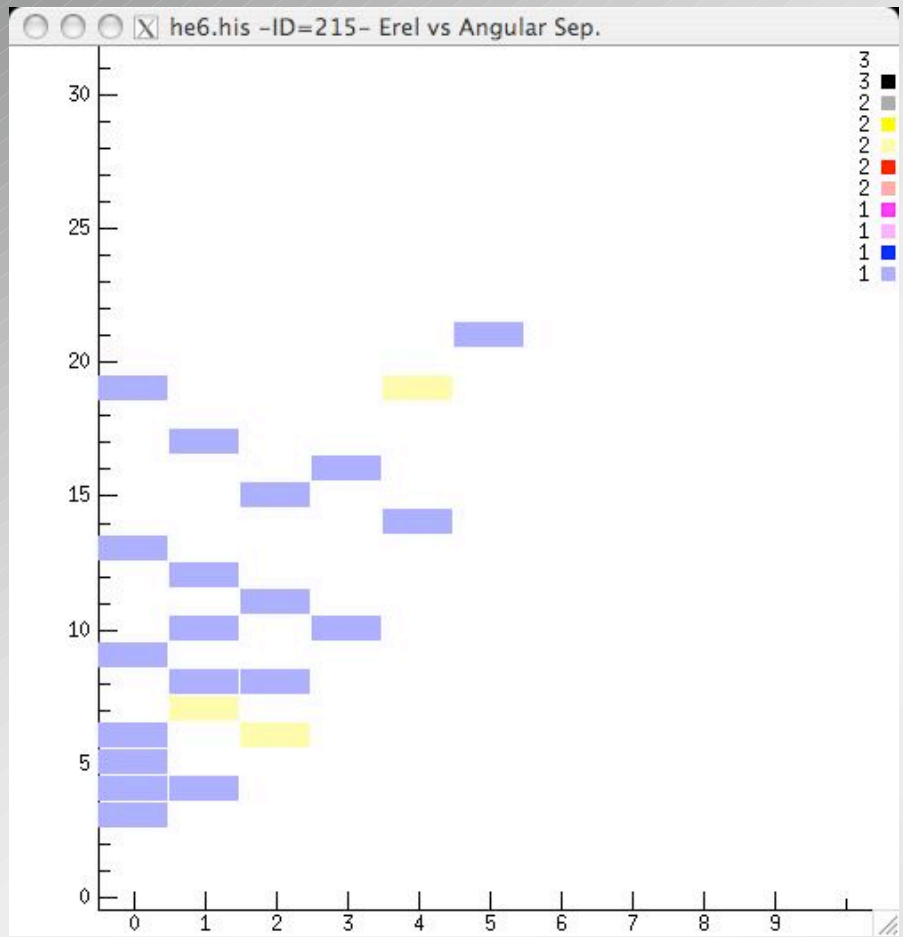
Direct breakup



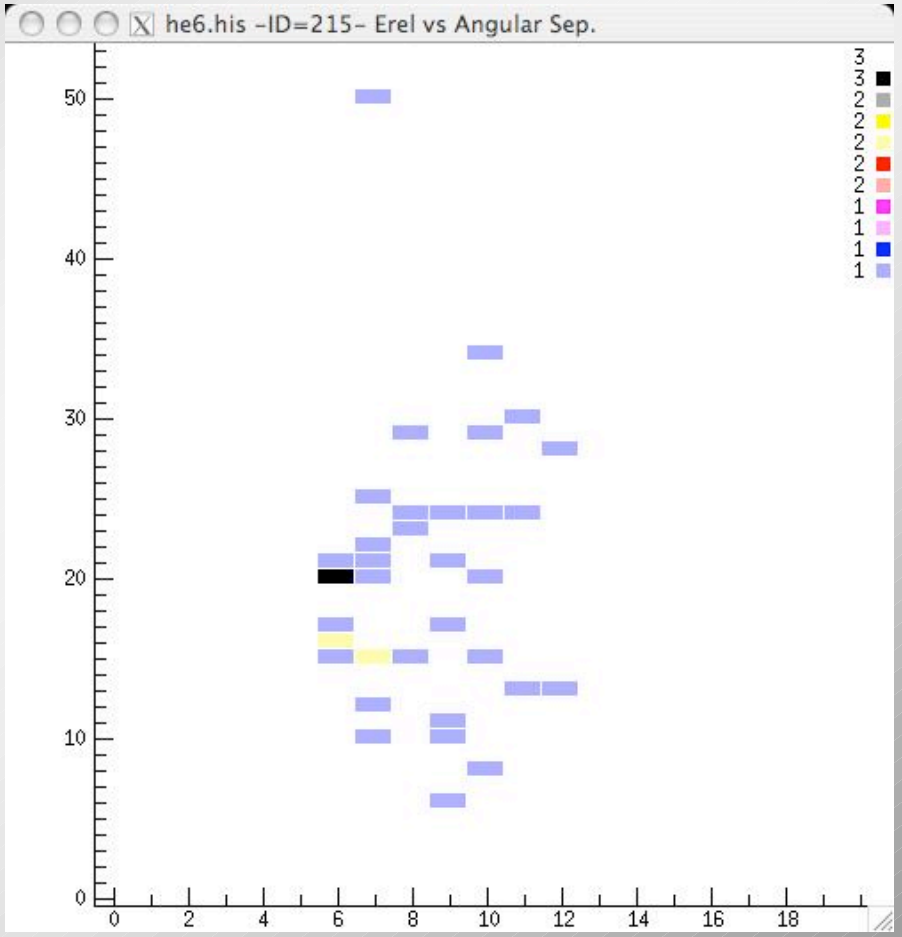
"Resonant" breakup

Direct-breakup neutrons are much more likely to end up in the <u>same</u> bar.

E_{rel} vs Angular Separation



Direct breakup



"Resonant" breakup

The two processes behave differently! Selection effect? Pauli repulsion????

Cross Sections (mb)

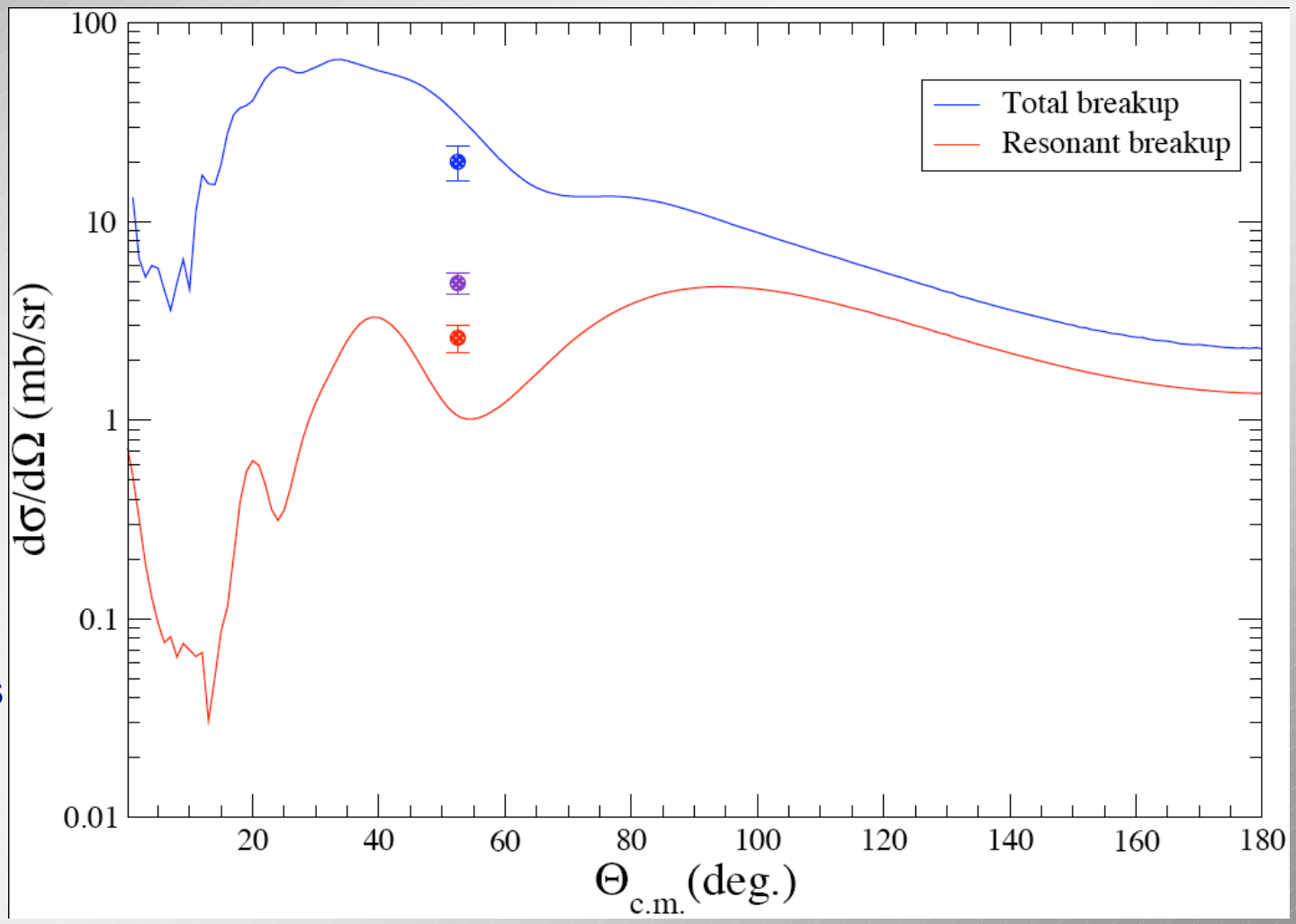
	Experiment	Theory[3]
$\sigma_{reaction}$	1170±150[1]	1182
σ_{fusion}	310±45[2]	333
σ_{1n}	155±25	
σ_{2n}	410±122	
$\sigma_{breakup}$	(210±128)[4]	218

[1] E.F. Aguilera, et al., PRL84, 5058 (2000).
[2] J.J. Kolata, et al., PRL81, 4580 (1998).
[3] K. Rusek, et al., PRC 72, 037603 (2005).
[4] From subtraction.

Theory: Continuum Discretized Coupled Channels (CDCC).
Di-neutron cluster model.
Dipole polarizibility renormalized by a factor of 0.5.

CDCC Calculation

- Blue data point is the total breakup cross section from the multiplicity = 1 neutron data.
- Red data point is the resonant breakup cross section from the multiplicity = 2 neutron data.
- Purple data point is the total breakup cross section from the multiplicity = 2 neutron data.



Future Goals

- Complete the analysis of this experiment.
  - Reconstruct all the relevant interaction parameters.
  - Evaluate the backgrounds.
  - Monte-Carlo to extract the breakup cross sections.
- Repeat the experiment.
  - Better statistics would be very helpful.
  - Neutron detectors on the other side of the beam essential.
  - Verify extrapolations from the Monte-Carlo simulation.
- Investigate breakup at larger impact parameter.
  - More breakup cross section. Less transfer.
  - Ratio of direct to “resonant” breakup should change.
  - Investigate Coulomb-nuclear interference.
- Theoretical input required.
  - Complete 4-body reaction calculations (CDCC).
  - Structure of ^{6}He (cluster vs “helicopter” modes).
  - “Pauli repulsion” in the direct breakup channel?

Acknowledgements

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