- **Neutron Transfer and Projectile Breakup for ^{6}He + ^{209}Bi Near the Coulomb Barrier.**

a) Background: Fusion and transfer/breakup cross sections.

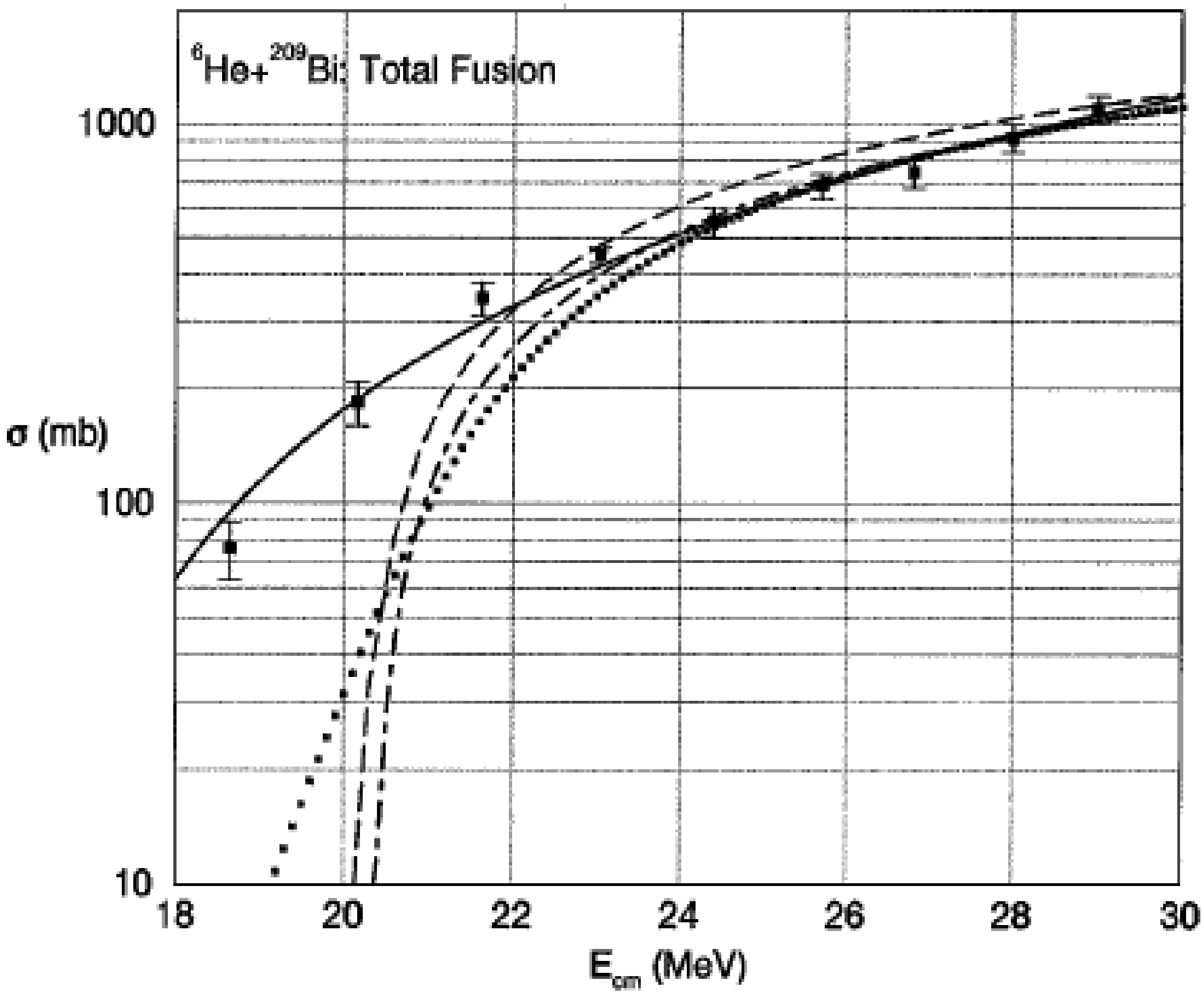
b) Neutron/α–particle coincidences with discrete detectors
...**^{5}He**.

c) Neutron/α–particle coincidences with a “neutron wall”
...**2n transfer and sequential breakup**.

d) Results and conclusions.

PRL **81**, 4580 (1998)

Sub-barrier fusion for ^{6}He+^{209}Bi anomalously large.



Effective Barrier Lowered by 5 MeV (25%)! (Coupling to Neutron Transfer Channels?)

PRL **84**, 5058 (2000)

Enormous transfer yield!

(About 0.8b at this energy).

Q_{gs} (2n) = +8.76 MeV

Q_{gs} (1n) = +2.74 MeV

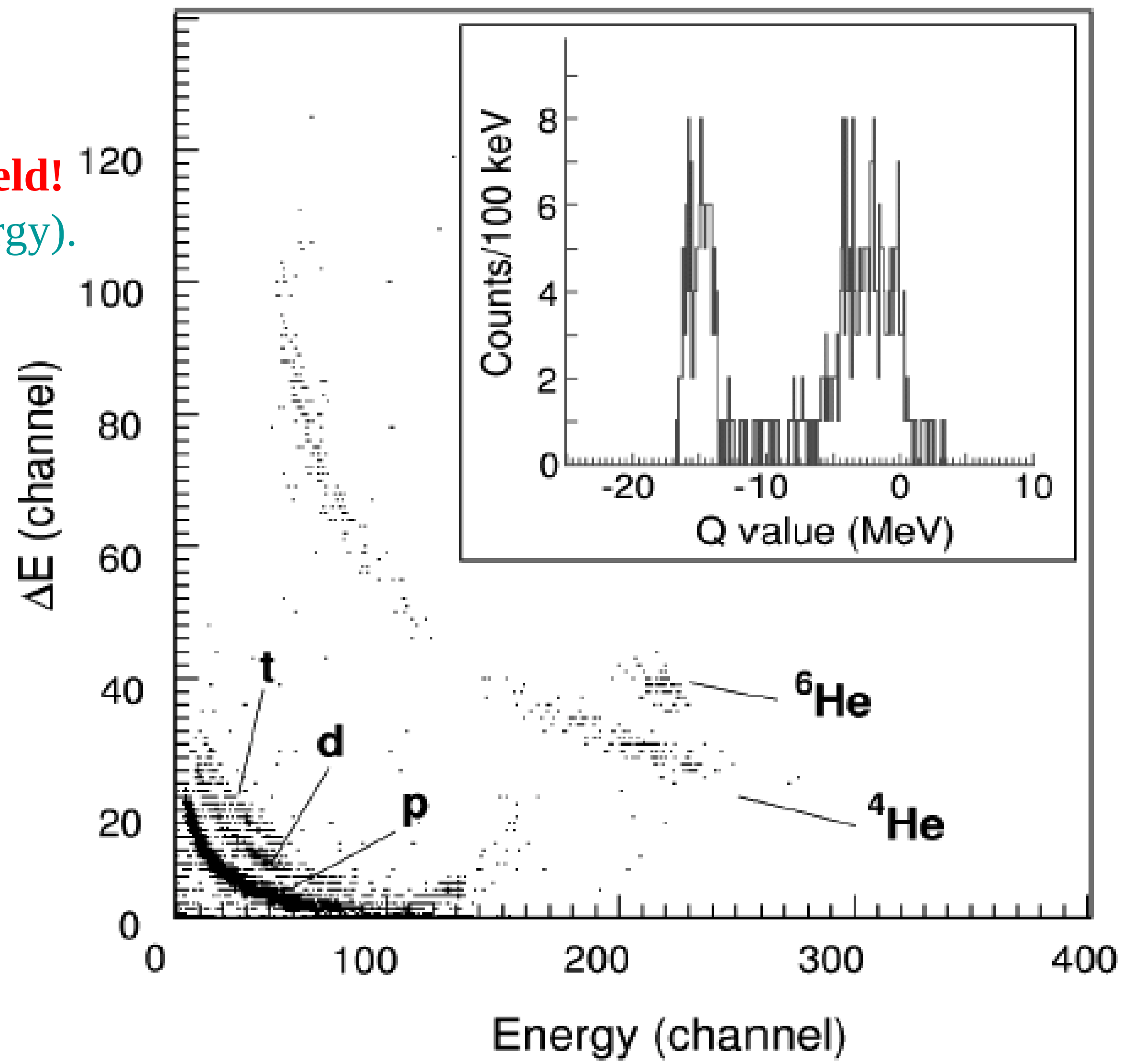


FIG. 1. A ΔE vs E_{total} spectrum taken at $\Theta_{\mathrm{lab}} = 135°$, at a laboratory ^{6}He energy of 22.5 MeV. A Q-value spectrum for the ^{4}He group is shown in the inset.

Angular distribution peaks at the "grazing" angle, indicating a direct process.

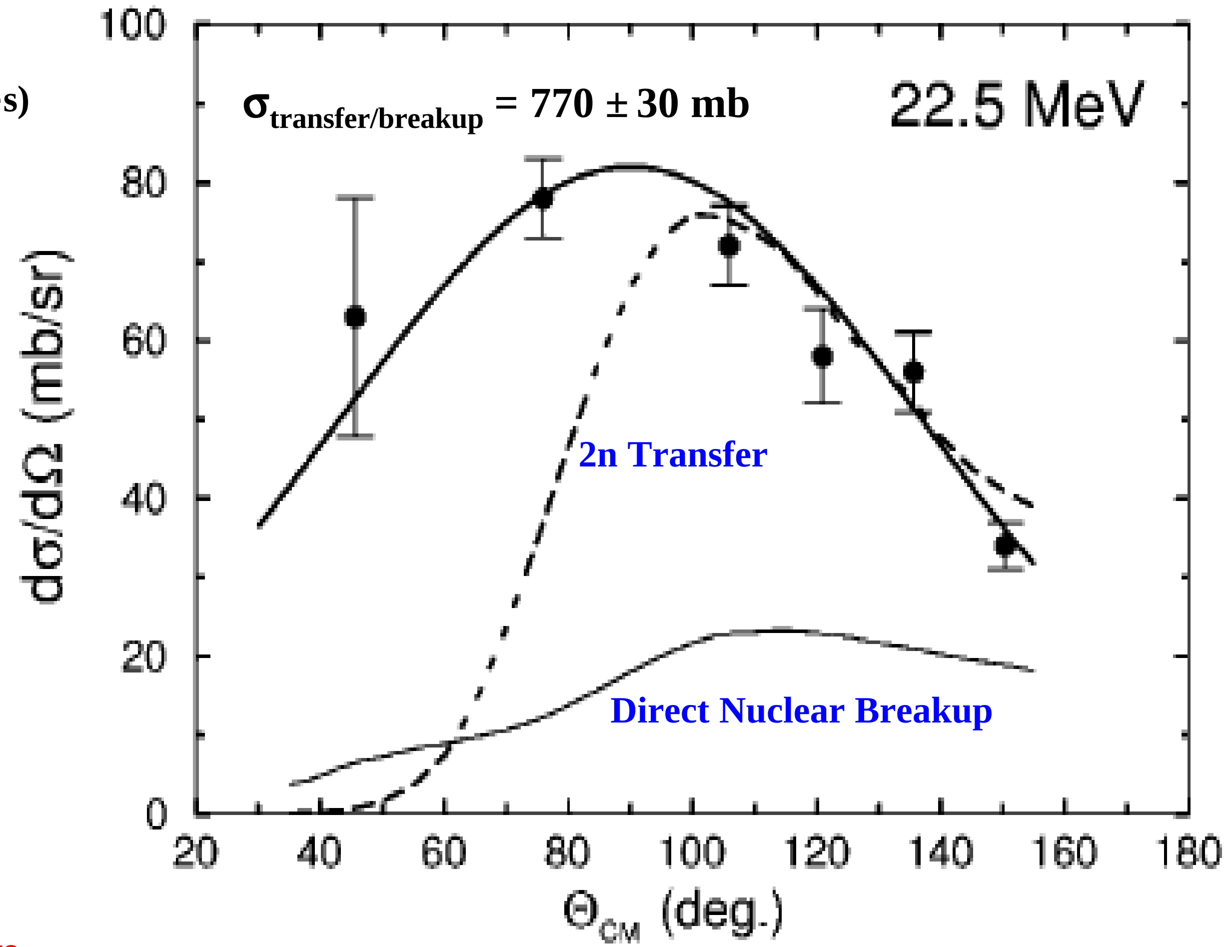
Calculations:

Schematic CCBA approach (Filomena Nunes)

Transfer to unbound 0^+ state; single-particle width;excitation energy corresponding to the peak of the α–particle energy distribution.

Coulomb breakup neglected (difficult to make it converge).

Coupling to the fusion channel gives a large sub-barrier enhancement.



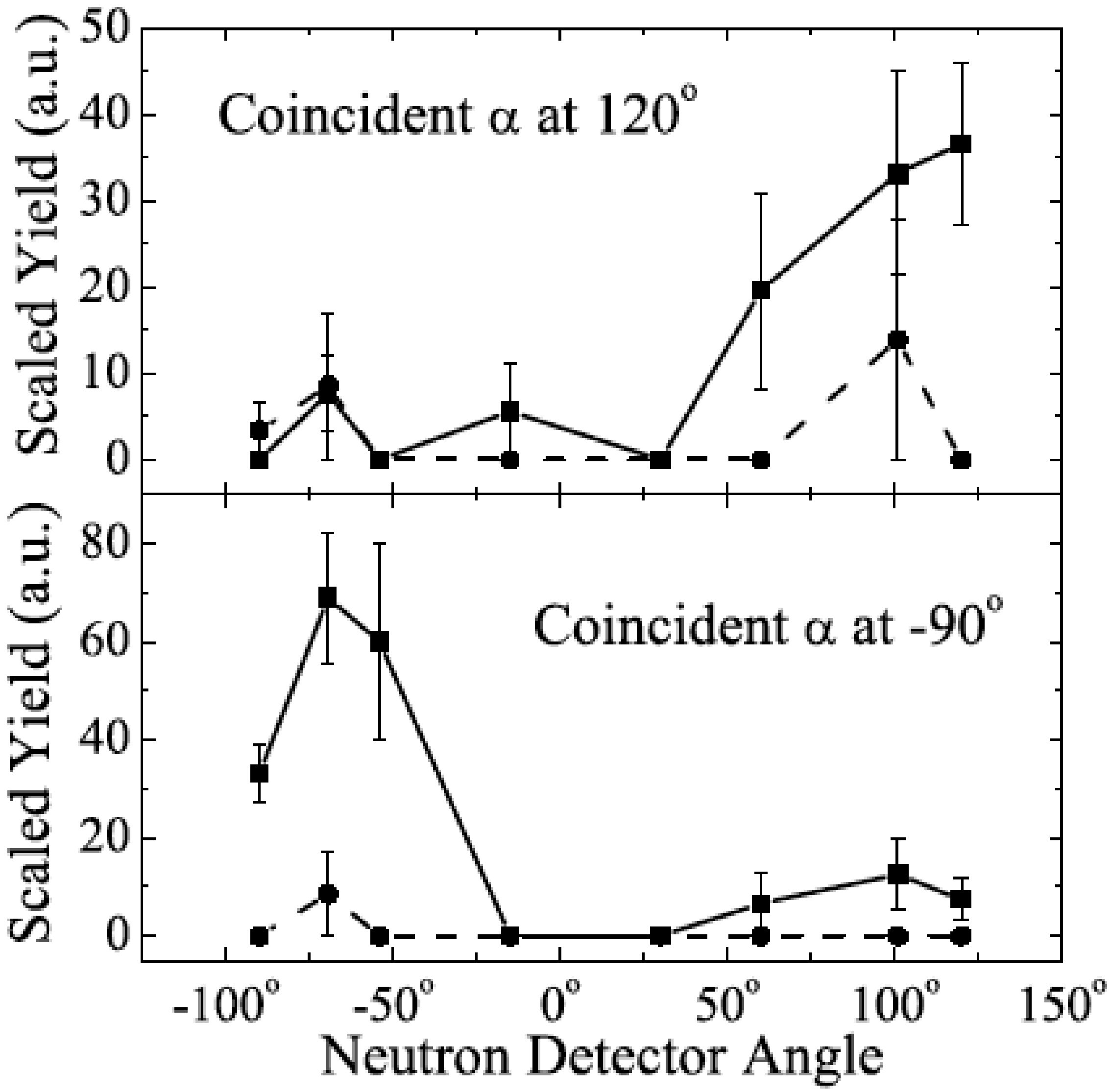
Question:

What exactly is the relative importance of 1n transfer, 2n transfer, and direct breakup?

Discrete Neutron Detectors at Selected Angles.

Experimental Details:

^{6}He beam energy = 23 MeV.
NE213: 12.5cm dia. x 5cm thick.
Approx. 1.5 MeV neutron threshold.
Efficiency = 30% above threshold.
Squares: ^{209}Bi target.
Circles: Mylar backing.



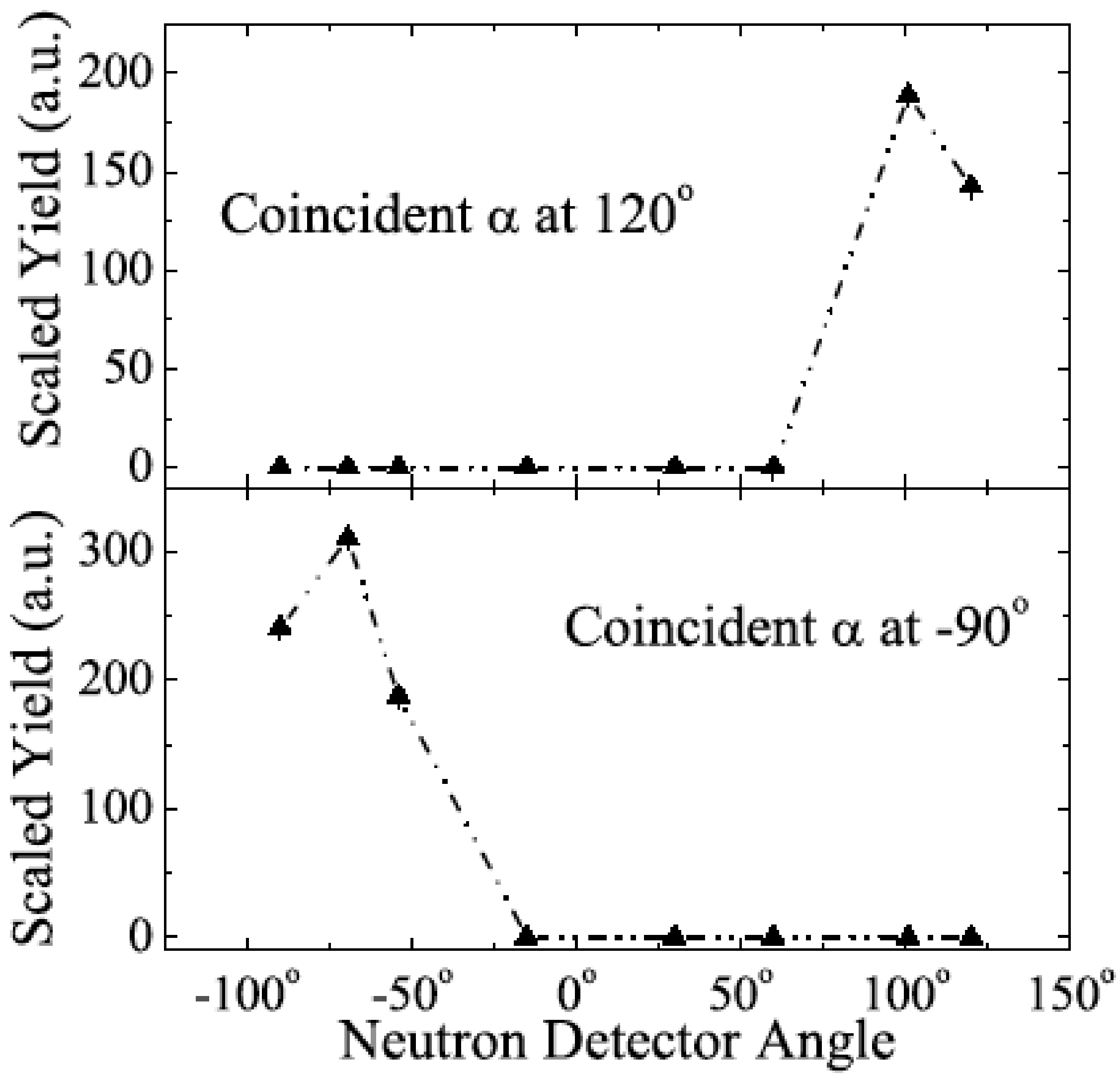
Monte-Carlo Simulation---1n Transfer.

Simulation Details:

^{5}He energy-per-nucleon and angular distribution derived from the measured α–particle data.

Isotropic breakup with a decay energy of 890 keV.

Entire α–particle yield assumed to result from this process.



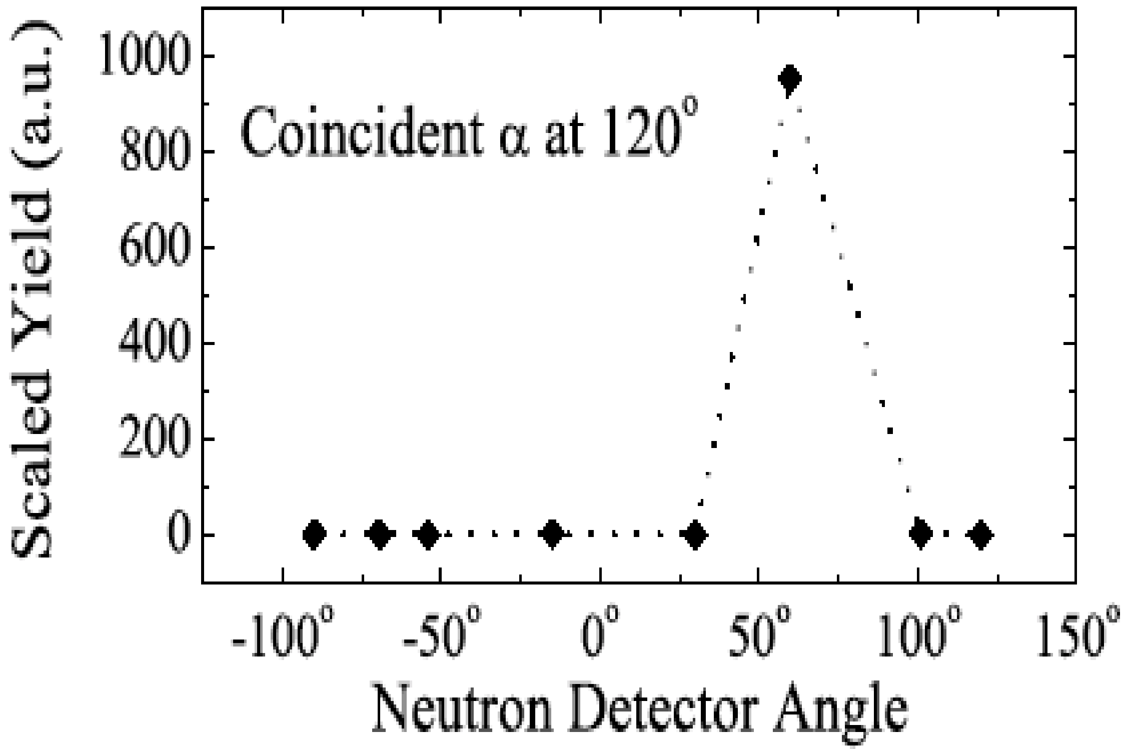
Monte-Carlo Simulation---Direct Breakup.

Simulation Details:

Breakup into α+2n at the distance of closest approach.

Neutron angle = 1/2 of the final α–particle angle.

Entire α–particle yield results from this process.



Comparison of Experiment and Simulation.

Normalizations:

Circles: 1n transfer multiplied by 0.225 at -90° and 0.175 at 120°.

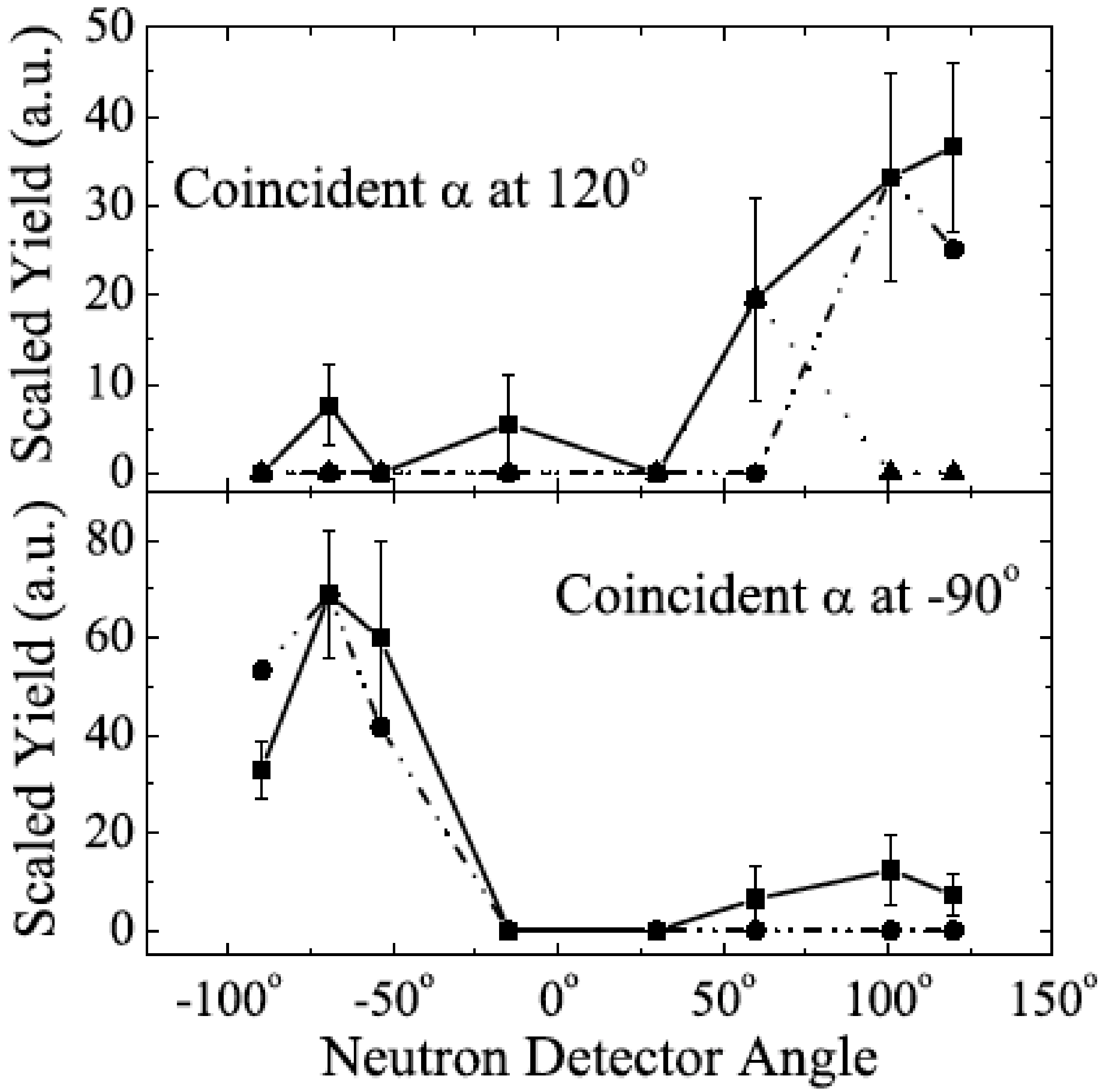
Triangles: direct breakup x 0.02.

Conclusions:

1n transfer (^{6}He,^{5}He) accounts for 20±2% of the total direct α–particle yield.

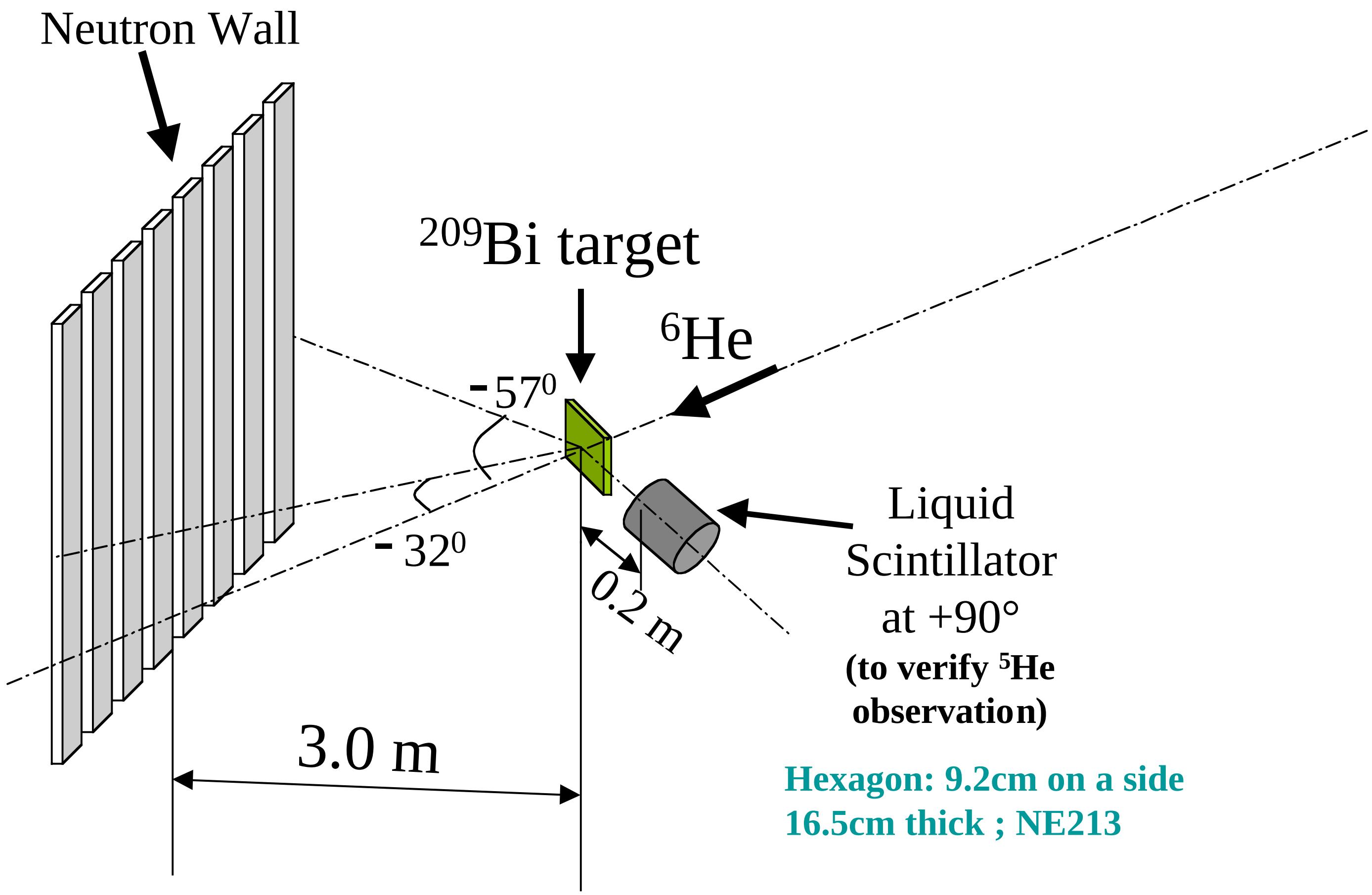
Direct breakup small??? (The neutron energy is below threshold for most events).

Room for an isotropic component from 2n transfer followed by neutron evaporation. A "small" yield of ~10 units would account for about 60% of the direct α–particle yield.



Neutron Wall Experiment

Si Telescopes:
+90° and -60°
(not shown)



Hexagon: 9.2cm on a side
16.5cm thick ; NE213

Experimental Details

Neutron Wall:

Eight **NE102 plastic scintillator** bars
152cm x 15.2cm x 5.1cm

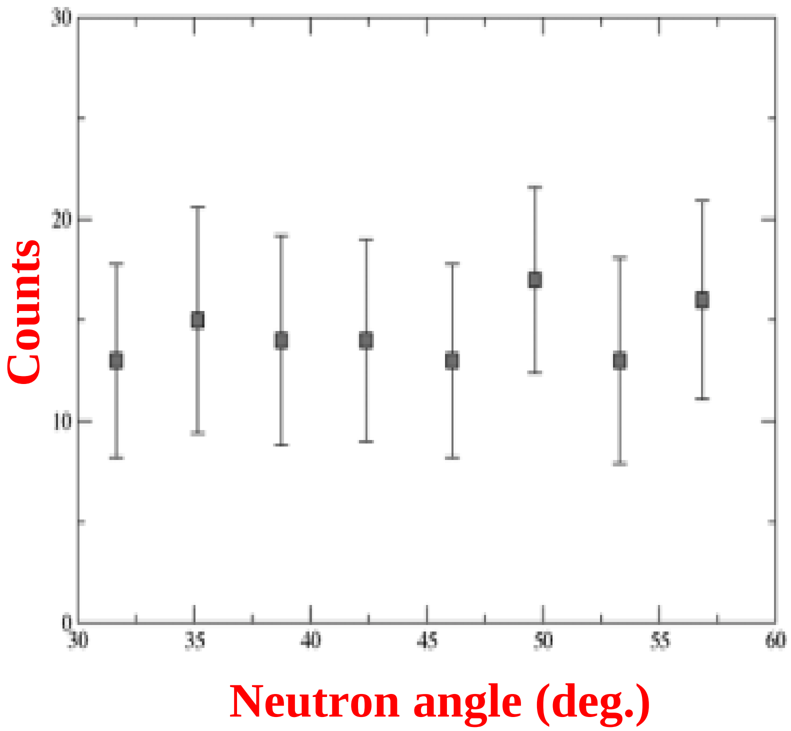
Fast Phototubes: Amperex XP2020
Time resolution approx. 1 ns

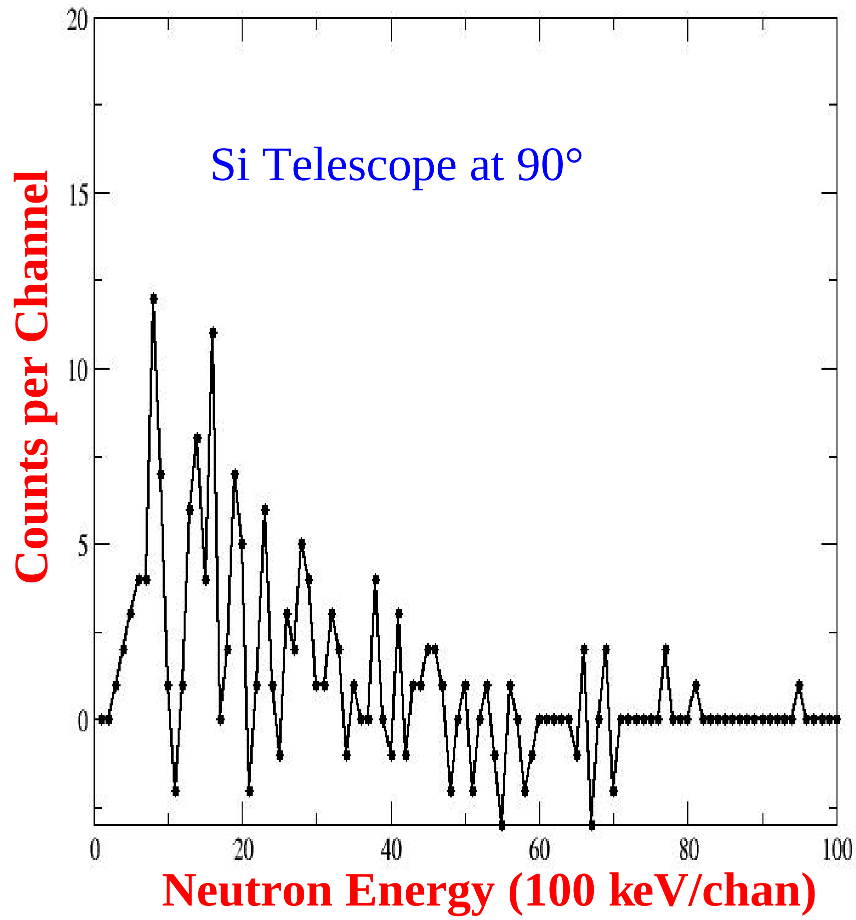
Position sensitive: timing between two phototubes on each bar. Resolution about 15cm.

Performance: threshold below 1 MeV neutron energy; efficiency ~40% above threshold.

“Evaporation” Neutrons

$^{6}He + ^{209}Bi \rightarrow ^{4}He + ^{211}Bi$
$^{211}Bi \rightarrow ^{210}Bi + n$ or $^{209}Bi + 2n$
Neutron multiplicity = 1.75

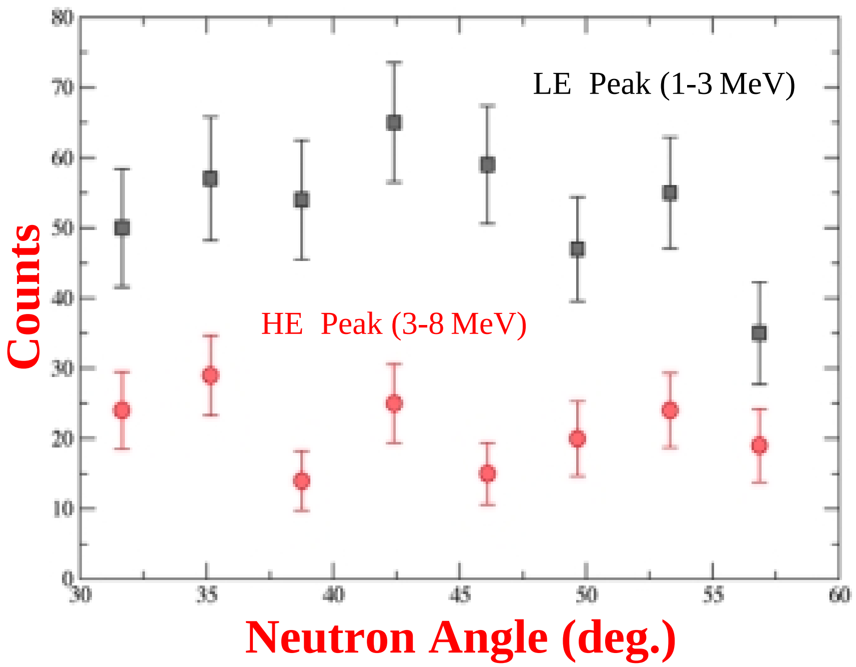


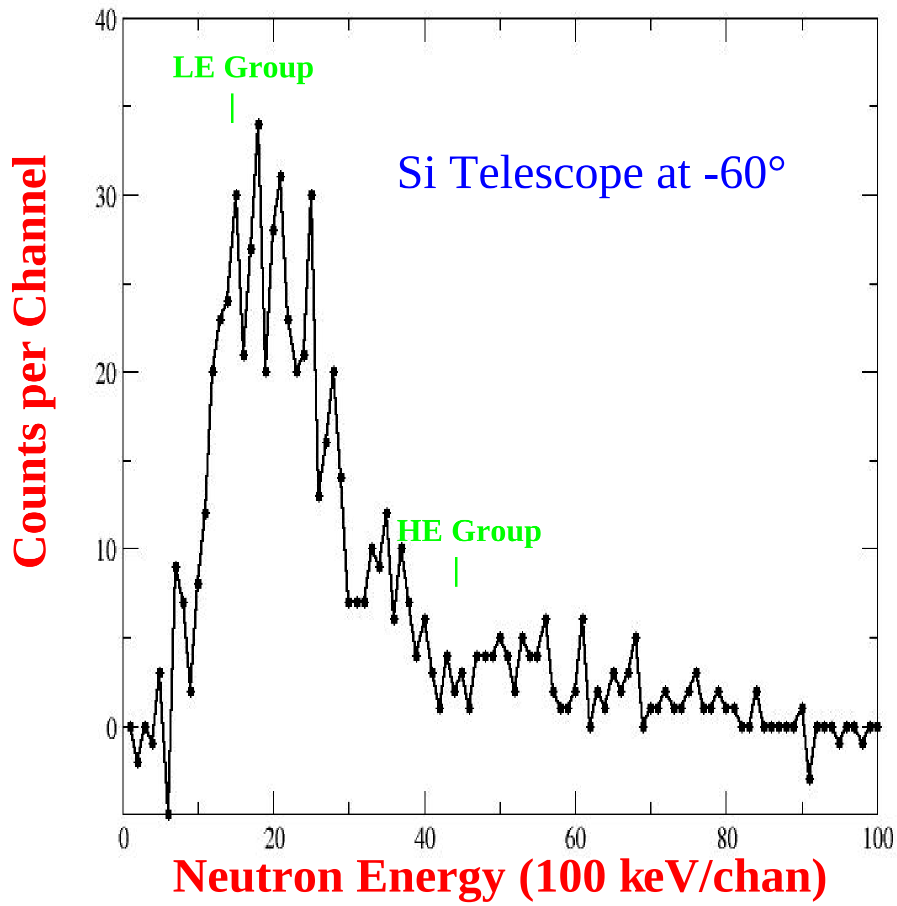


The “evaporation” neutrons account for **60±7%** of the total α–particle yield.

“Sequential Breakup” Neutrons

$^{6}He + ^{209}Bi$ --> $^{5}He + ^{209}Bi + n$
$^{5}He + ^{209}Bi$ --> $^{4}He + ^{209}Bi + n$





The LE (HE) peak accounts for approx. **24% (8%)** of the **60°** α–particle yield.

Preliminary Conclusions

1. The integrated cross section for the $^{209}Bi(^{6}He,^{5}He)$ single-neutron transfer reaction at E_{cm} = 22 MeV (~10% above the nominal barrier) is **155±15 mb**. This is about **50% of the total fusion cross section** at that energy. The reaction proceeds to low-lying states in ^{211}Bi.

- The integrated cross section for the $^{209}Bi(^{6}He,^{4}He)$ two-neutron transfer reaction at this energy is **455±60** mb. This is about **3x the single-neutron transfer yield and 1.5x the fusion yield**. The reaction proceeds to high-lying neutron-unbound levels of ^{211}Bi that decay by evaporating neutrons.

- The observed dominance of 2n vs. 1n transfer channels is unusual. It may occurs because **2n transfer populates neutron-unbound levels in ^{211}Bi** with extended wavefunctions that overlap well with the weakly-bound neutrons in ^{6}He, while **1n transfer proceeds to low-lying bound states of ^{210}Bi**. It would be interesting to see if CCBA calculations could confirm this observation.

4. The direct 3-body breakup of ^{6}He could not be observed in this experiment due to the low energy of the corresponding neutrons. However, the spectrum of neutrons in coincidence with α–particles at 60° (~0.6x the grazing angle) gives **evidence for a significant "sequential breakup" yield**: $^{6}He \rightarrow n+{}^{5}He \rightarrow 2n+{}^{4}He$.

II. Structure of ^{7}He

- Background: Proposed low-excitation-energy spin-orbit partner of the ground state of ^{7}He.

b) Population of **analog states** of ^{7}He via the ^{6}He (p,n) reaction.

c) Experimental details: the “parallel mode” of *TwinSol* operation and the neutron wall.

d) Results and conclusions.

Evidence for a New Low-Lying Resonance State in ^{7}He

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Low-lying resonance states in ^{7}He(^{6}He + n), formed after fragmentation reactions of a 227 MeV/nucleon ^{8}He beam on a carbon target, have been studied. Coincidences between ^{6}He nuclei and neutrons, corresponding to the one-neutron knockout channel in ^{8}He, were selected. The relative energy spectrum in the ^{6}He + n system shows a structure, which is interpreted as the ^{7}He ($I^\pi = 3/2^-$) ground state, unbound with 0.43(2) MeV relative to the ^{6}He + n system and a width of $\Gamma = 0.15(8)$ MeV overlapping with an excited ($I^\pi = 1/2^-$) state observed at 1.0(1) MeV with a width of $\Gamma = 0.75(8)$ MeV.

Phys. Rev. Lett. **88**, 102501 (2002)

Spin-Orbit Partner at 0.6 MeV (typically 2-3 MeV for 'normal' nuclei).

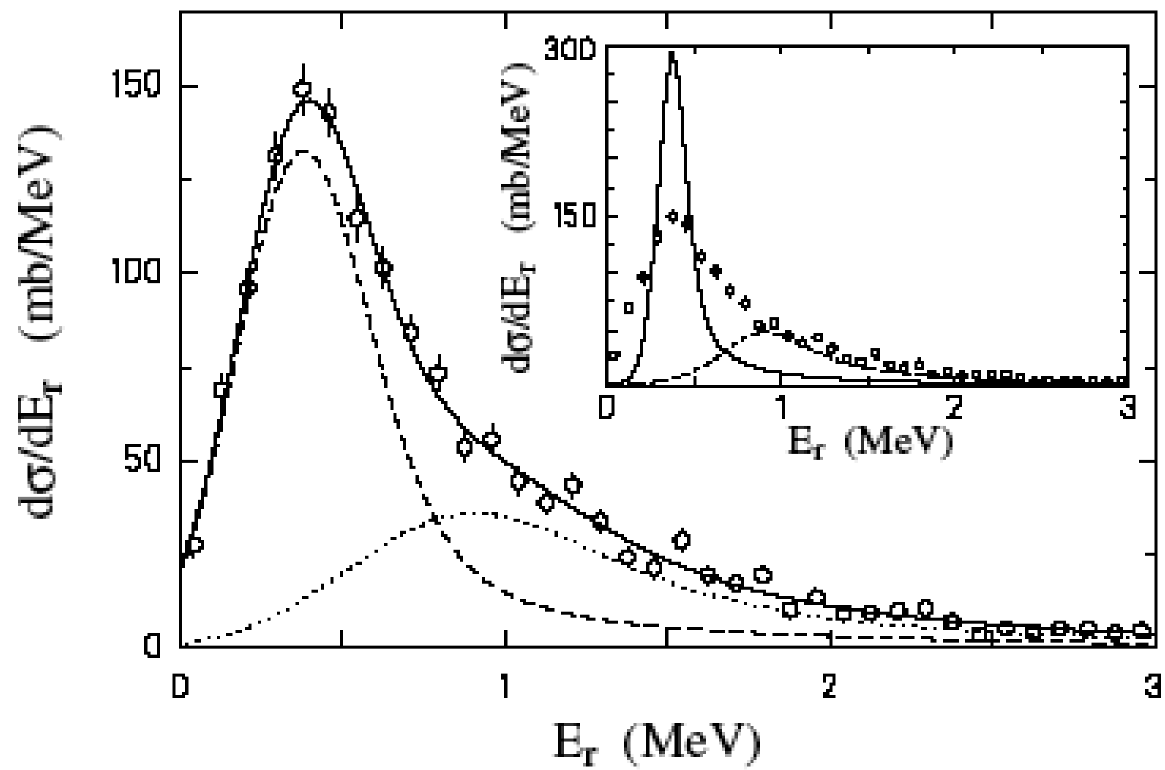
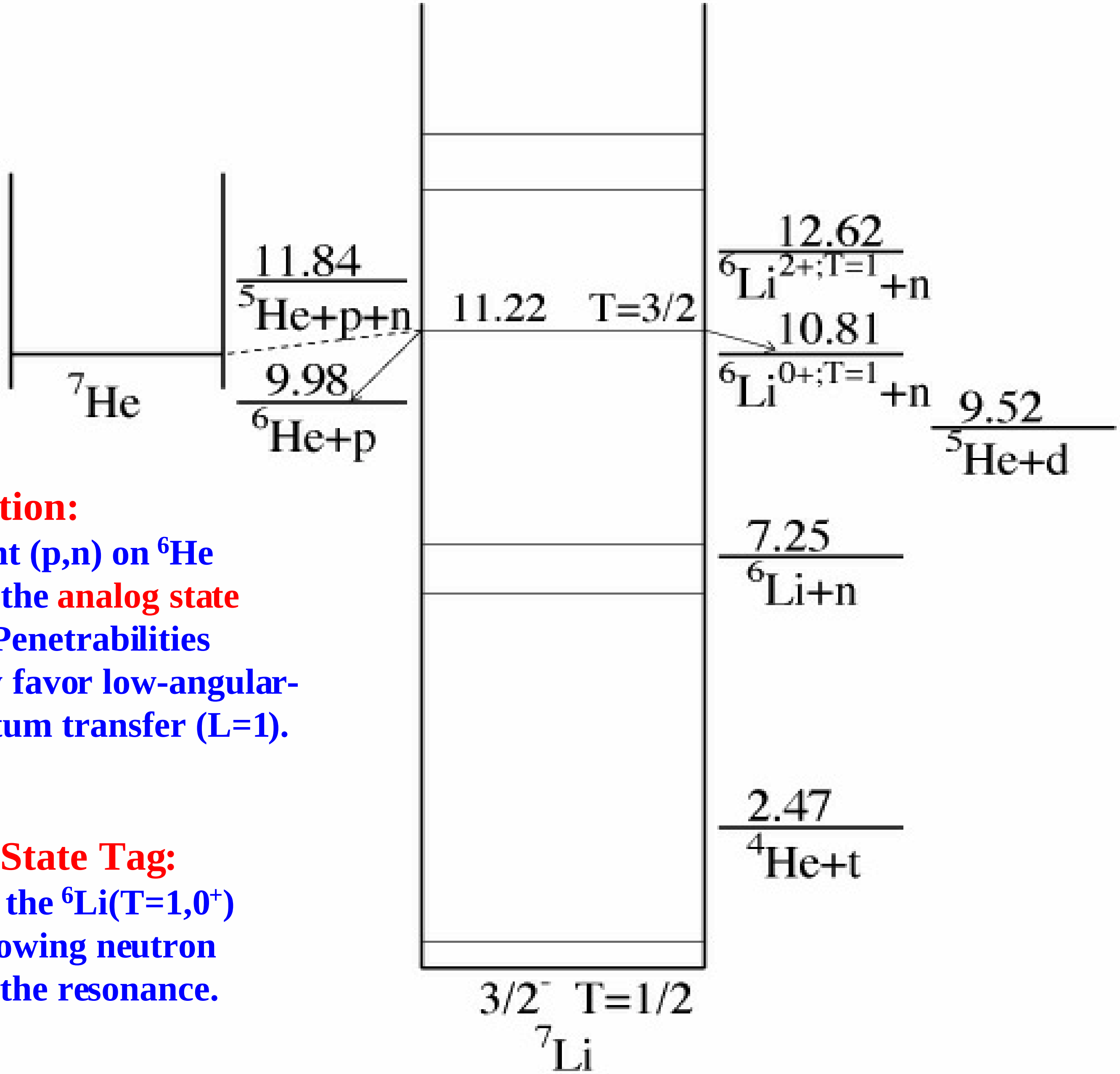


FIG. 2. Same data as in Fig. 1 with the assumption of contributions from two p-wave resonances. The solid line shows a fit to the experimental data using two Breit-Wigner shaped resonances keeping all six parameters free. The dashed line represents the contribution from the ^{7}He ground state with $E_r = 0.43(2)$ MeV and $\Gamma = 0.15(8)$ MeV. The dotted line corresponds to an excited state positioned at $E_r = 1.0(1)$ and $\Gamma = 0.75(8)$ MeV. The inset shows the separate resonances excluding any experimental effects in comparison with the data.

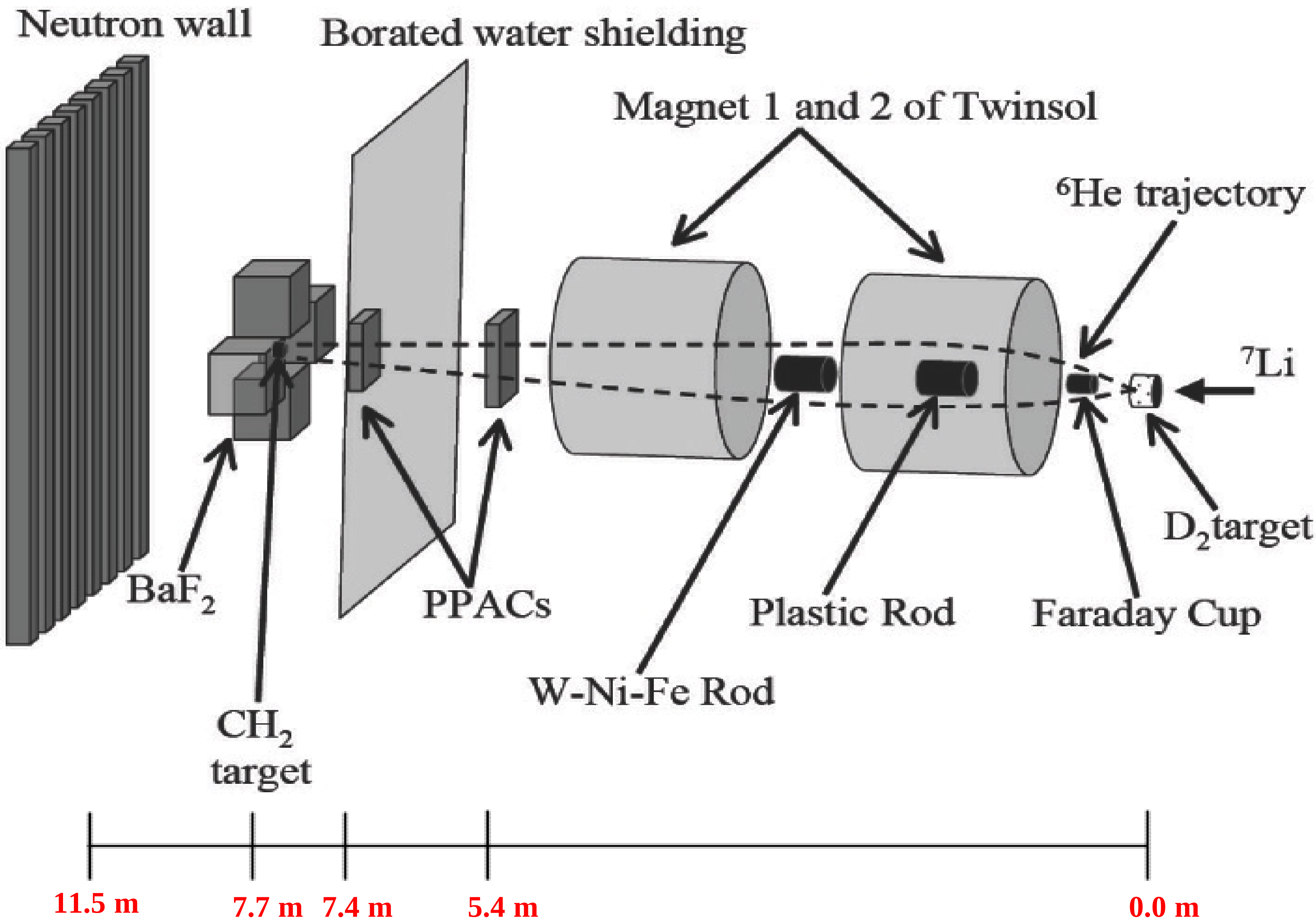


Population:

Resonant (p,n) on ^{6}He to form the analog state in ^{7}Li. Penetrabilities strongly favor low-angular-momentum transfer (L=1).

Analog-State Tag:

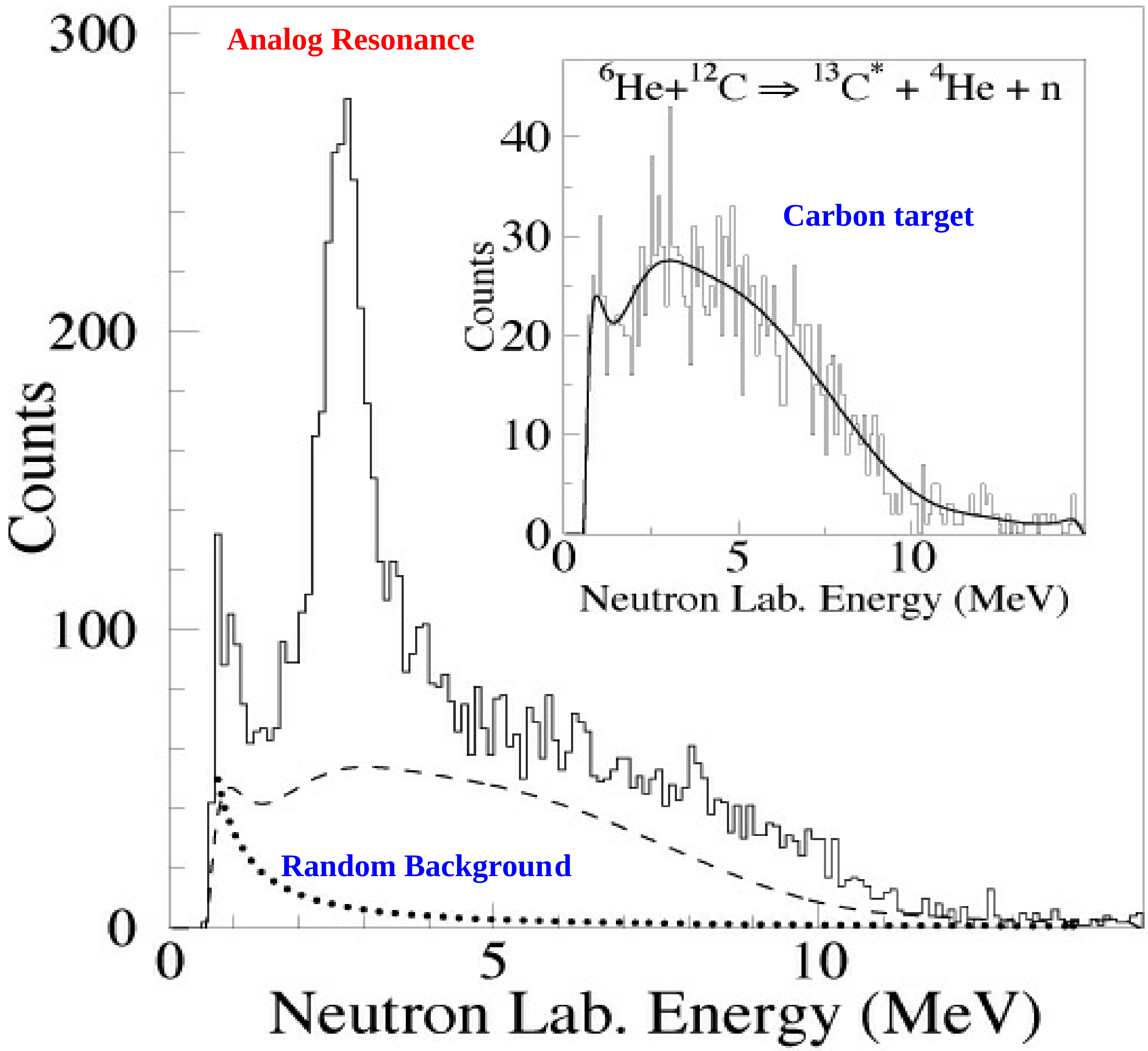
Decay of the $^{6}Li(T=1,0^{+})$ state following neutron decay of the resonance.


Neutron wall
Borated water shielding
Magnet 1 and 2 of Twinsol
^{6}He trajectory
^{7}Li
D_2target
Faraday Cup
Plastic Rod
W-Ni-Fe Rod
PPACs
BaF_2
CH_2 target
11.5 m
7.7 m
7.4 m
5.4 m
0.0 m

Experimental Details

BaF_2 Detectors:

Four large cubes: **15cm on a side.**
Discriminator level at at about 2 MeV
Array efficiency = **8.7% at 3.56 MeV.**



Analog Resonance
Random Background
Counts
Neutron Lab. Energy (MeV)
300
200
100
0
0
5
10
$^{6}He+^{12}C \Rightarrow ^{13}C^{*} + ^{4}He + n$
Carbon target
40
30
20
10

Solid Curve:

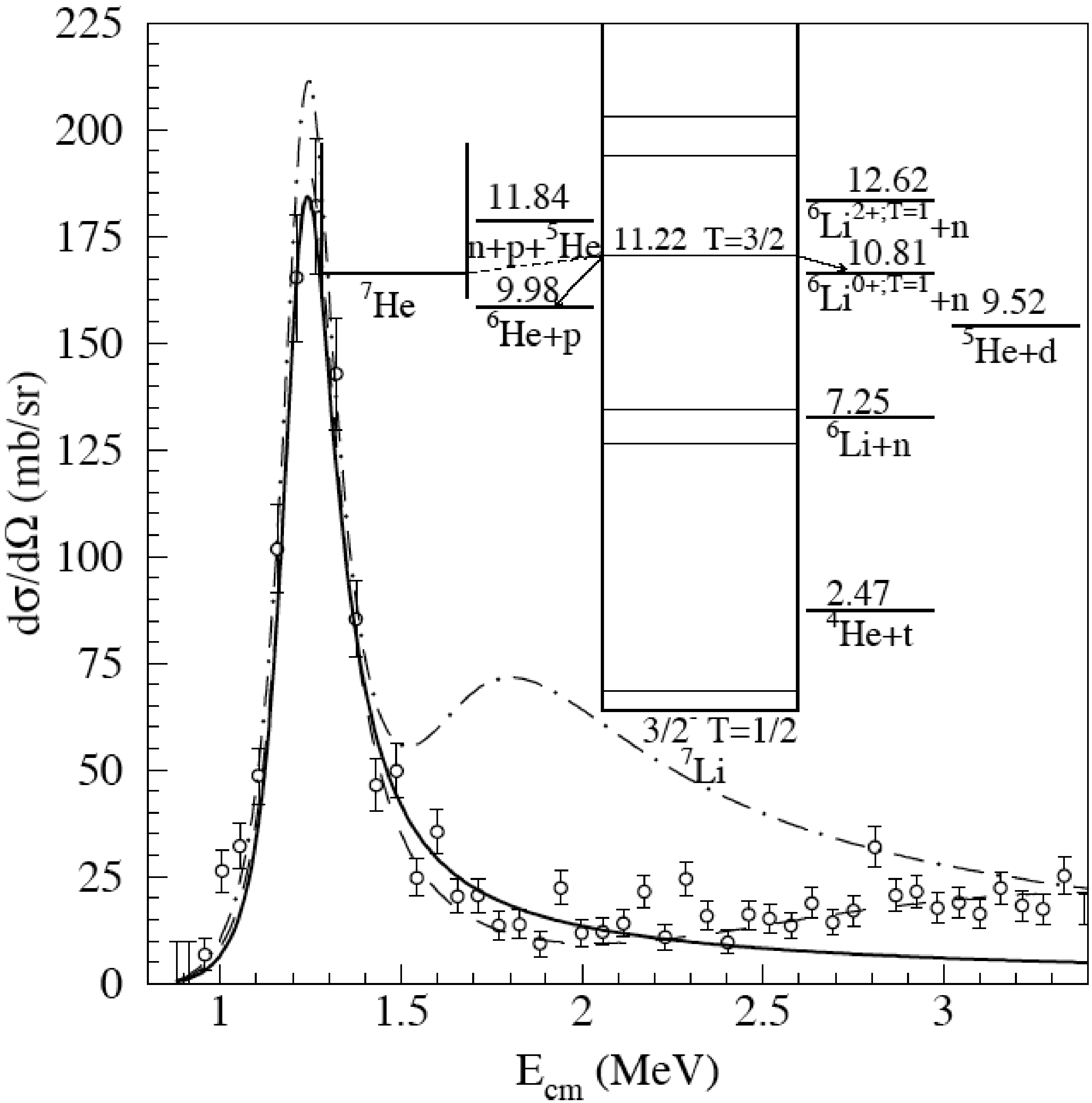
Breit-Wigner (L=1)
R-matrix calculation
E_R = 1.24 MeV
Γ_R = 0.265 MeV
Monte-Carlo using parameters from the experiment.
No renormalization

Dot-dash Curve:

Parameters from the PRL paper.

Dashed Curve:

Two-state fit
E_{R2} = 3.9 MeV
Γ_{R2} = 8 MeV



Conclusions

- The **thick-target inverse kinematics resonance method**, previously applied only for elastic-scattering resonances, works equally well for (p,n) reactions.

2. The **energy resolution is limited only by the properties of the neutron detector** (flight path, timing resolution). The method is independent of the energy profile of the incident beam, and the neutron loses no energy in the target. (We achieved better than 50 keV FWHM in the c.m. system in the present work).

- The **resonant (p,n) reaction on radioactive beams allows access to analog states of very exotic, neutron-rich nuclei** and thereby provides another method to study their properties. (A "tag" for the decay of the analog state is necessary).

- The proposed low-lying spin-orbit partner of the ^{7}He ground state **does not exist**.

- Instead, this $(1/2)^-$ state is at an excitation energy >2.2 MeV **consistent with all standard microscopic-model calculations**.

- The state is quite broad (>6 MeV) due to its high excitation energy. Interestingly, just such a broad $(1/2)^-$ state was proposed by Korsheninnikov, et al. to explain the observed branching ratio of their $(5/2)^-$ state at 2.9 MeV.

Collaborators

I. ^{6}He (p,n) to Analog States of ^{7}He.

Notre Dame: **G.V. Rogachev, P. Boutachkov, A. Aprahamian, B.B. Skorodumov, M. Quinn, A. Wohn**
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Hope College: **P.A. DeYoung, G.F. Peaslee**
Texas A&M Univ.: **V.Z. Goldberg, G. Chubarian**

II. Transfer/Breakup Modes in the ^{6}He+^{209}Bi Reaction.

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Indiana Univ.-South Bend: **J.D. Hinnefeld, A. Vida**
Univ. of Wisconsin-Green Bay: **M. Hencheck**