Multi-nucleon transfers using two-neutron halo ^{6}He on ^{12}C at 30 MeV using the SHARC and TIGRESS arrays at TRIUMF ISAC-II

Fred SARAZIN, **Duane SMALLEY**
Colorado School of Mines

- Motivation
- SHARC + TIGRESS @ ISAC-II
- Data analysis
  - Elastic / inelastic scattering
  - $^{12}C(^{6}He,^{4}He)$
  - $^{12}C(^{6}He,^{8}Be)$
- Conclusion and outlook

(^{6}He,^{4}He): an alternate surrogate reaction for 2n-transfer

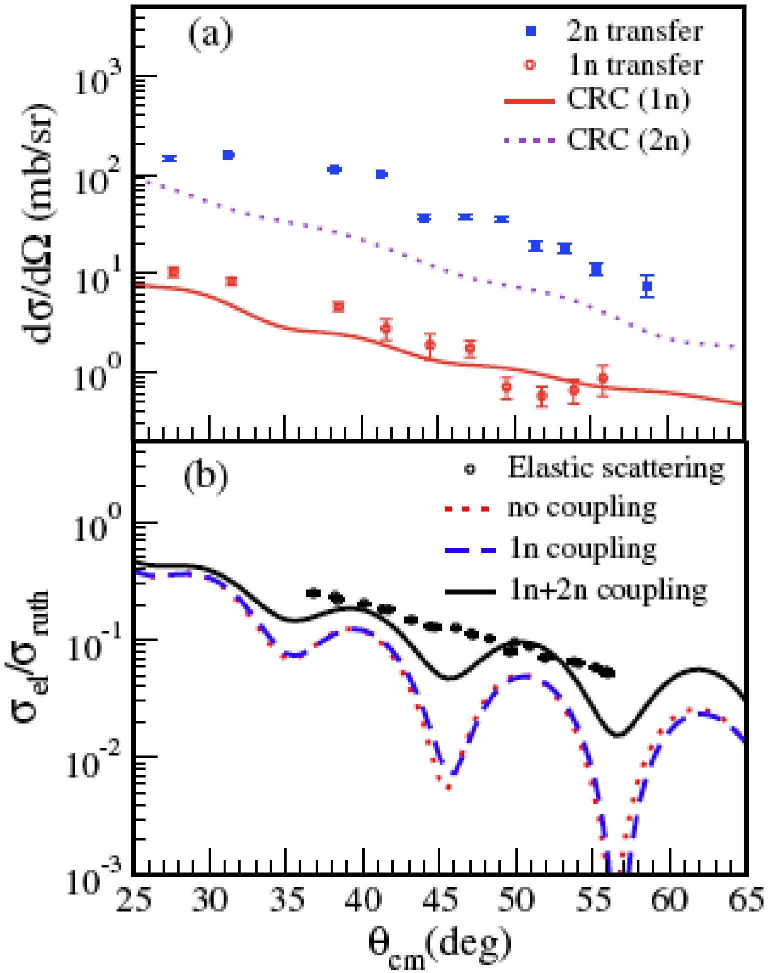
- (t,p):
  - Used very successfully in the past
  - Tritium beams now hard to come by
  - State-of-the-art detectors at RIB facilities
  - Tritium (implanted) target challenging

- (^{6}He,^{4}He):
  - A few RIB facilities now have intense ^{6}He beam (>10^7 pps) in the few A.MeV range
    - Most intense ^{6}He beams likely at SPIRAL and ISAC
  - Potentially more favorable than (t,p)
    - Large Q-value: higher excited states, more direct?
      - ^{6}He S_{2n}=1.867 MeV
      - Triton S_{2n}=6.257 MeV
    - Influence of the ^{6}He halo / study of the 2n-correlation
  - Disadvantages:
    - stable (or long-lived) target
    - More challenging from the reaction theory standpoint

Influence of the ^{6}He halo?

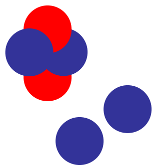
$^{65}Cu(^{6}He,^{4}He)$ @ SPIRAL:

$\sigma_{(6He,4He)} = 10\ \sigma_{(6He,5He)}$



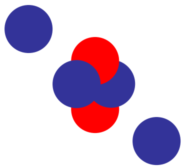
From A.Chatterjee et al., Phys. Rev. Lett. 101 (2008) 032701

Dineutron configuration:



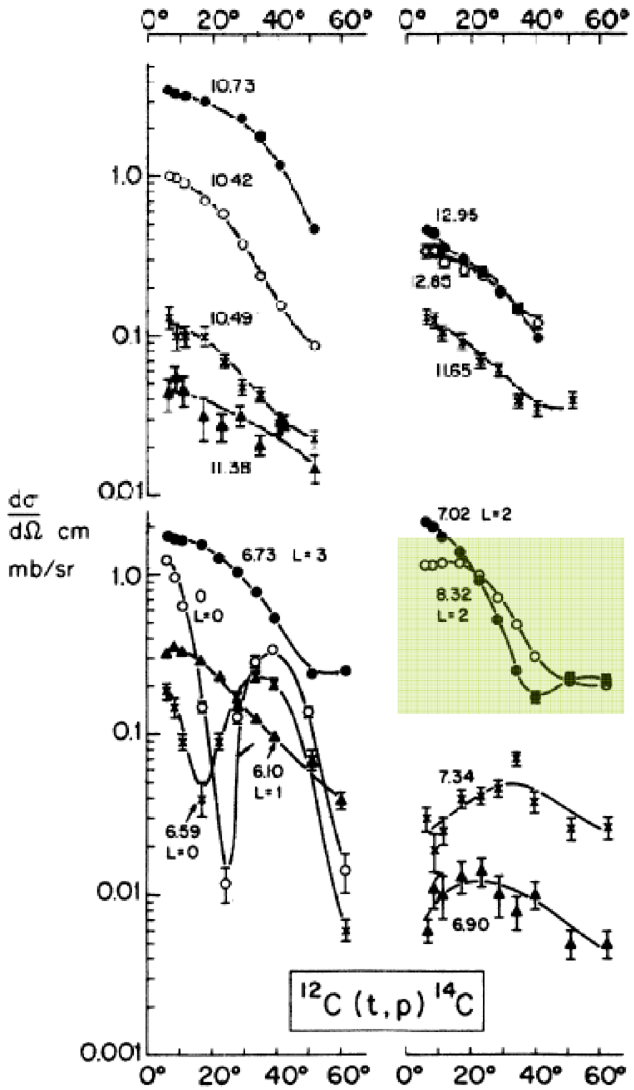
Favors 2n-transfer

Cigar-like configuration:



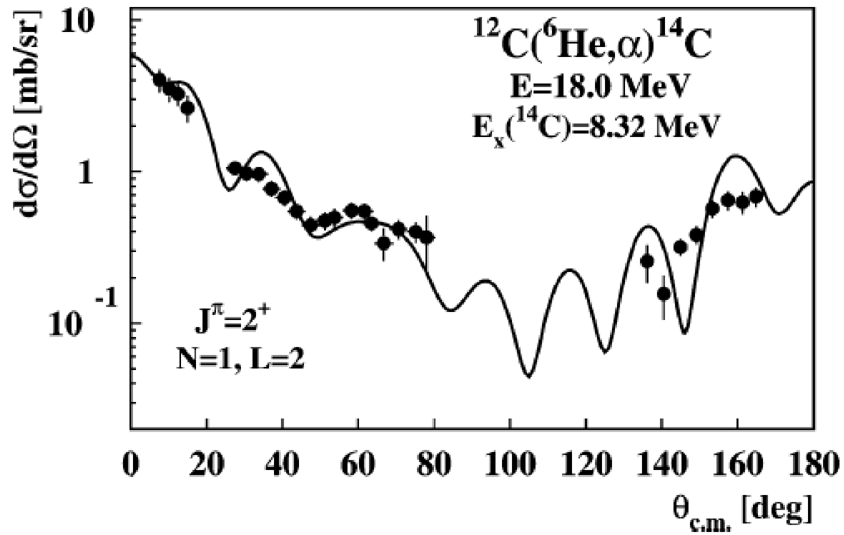
Favors 1n-transfer

Benchmark experiment: $^{12}C(^{6}He,^{4}He)^{14}C^{*}$



From F.Ajzenberg-Selove et al., Phys. Rev. C17 (1978) 1283

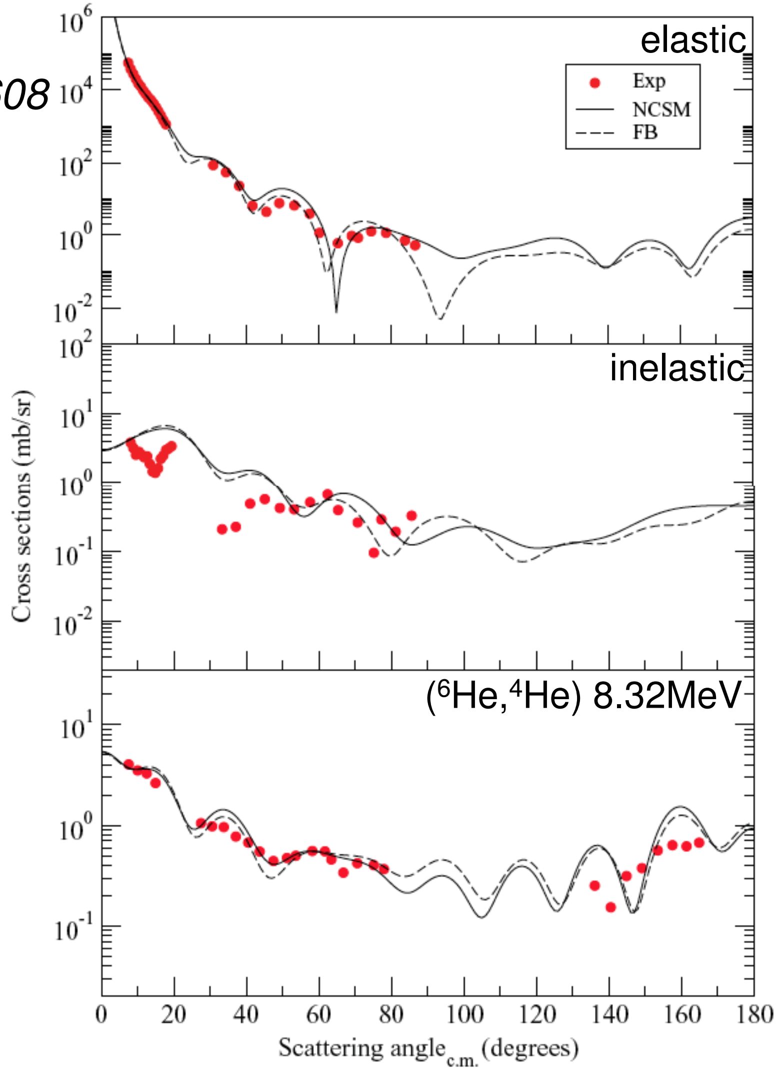
- Use a reaction for which (t,p) was well measured.
- States in the recoil nucleus well known.
- Angular distributions for bound states.



From M.Milin et al., Nucl. Phys. A730 (2004) 285

$^{12}C(^6He,^6He)$ elastic / inelastic scattering

Data: from M.Milin et al., Nucl. Phys. A730 (2004) 285
Fit: from I.Boztosun et al., Phys. Rev. C 77 (2008) 064608



- First minimum not covered by data
- No good fit of the inelastic scattering
  - CCBA calculation: magnitude, but still not shape
  - Need more information

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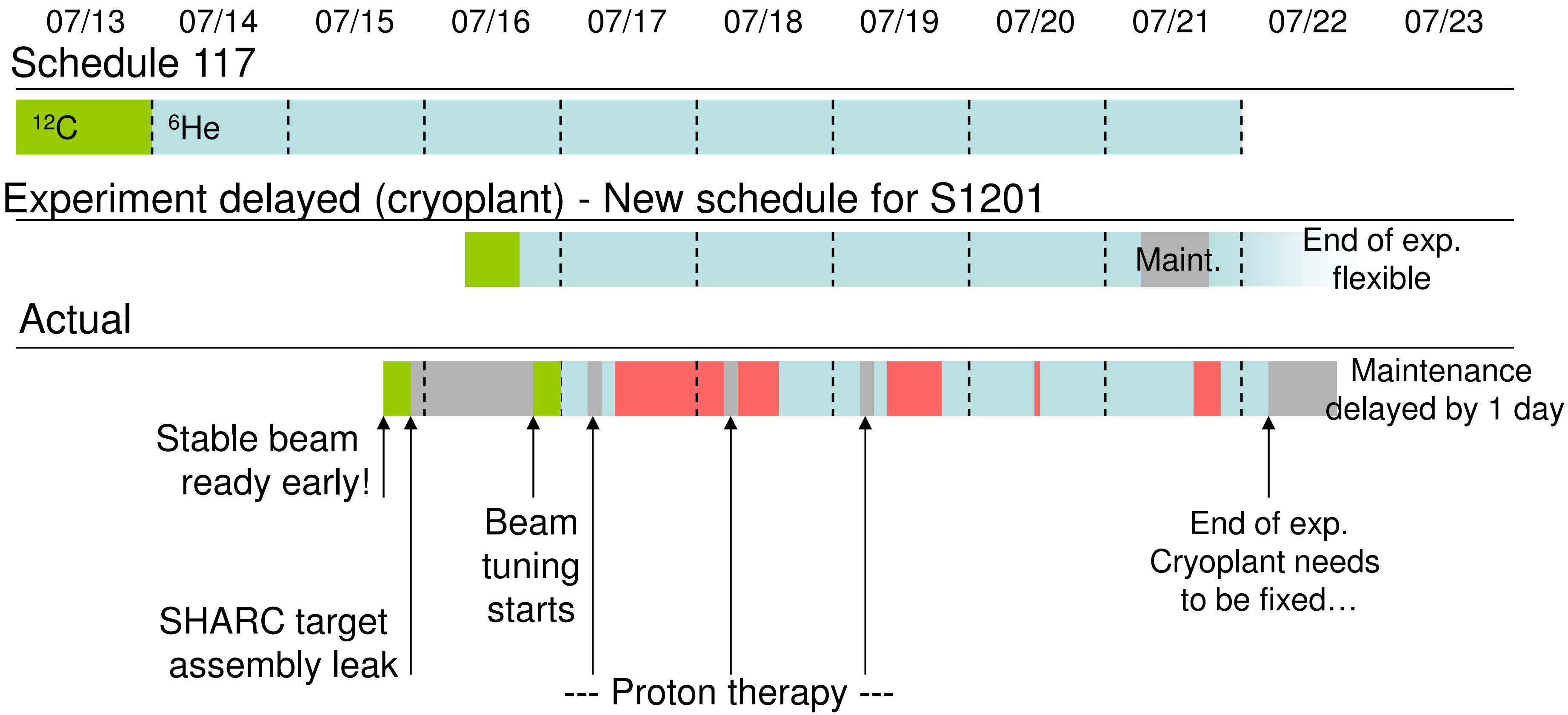
S1201: $^{12}C(^{6}He,^{4}He)$

July 15-22, 2010



Intensity requested: 5.10^6pps

Intensity received: $\sim 8.10^5$pps

Beam time requested: 16 shifts

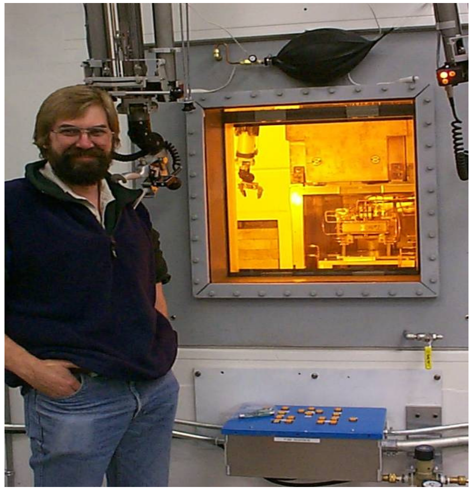
Beam time received: ~7 shifts

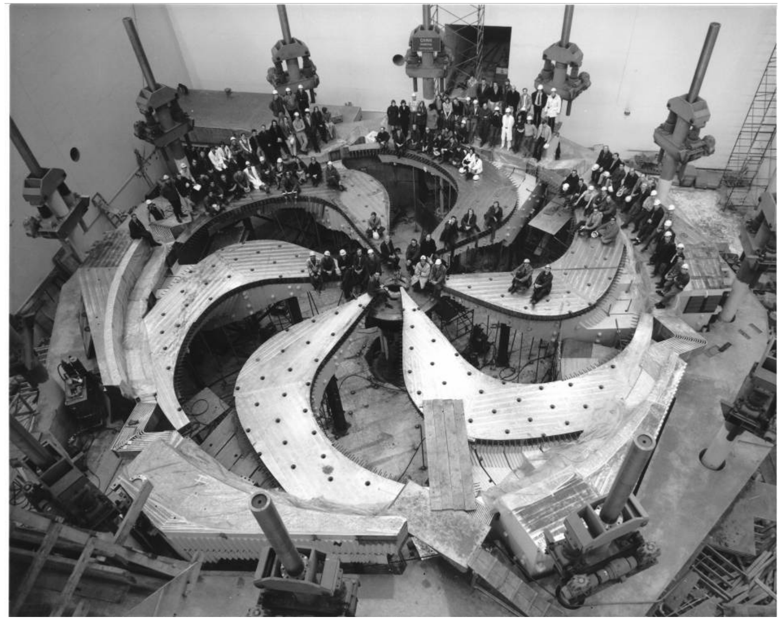
(2 shifts lost by the experimentalists)

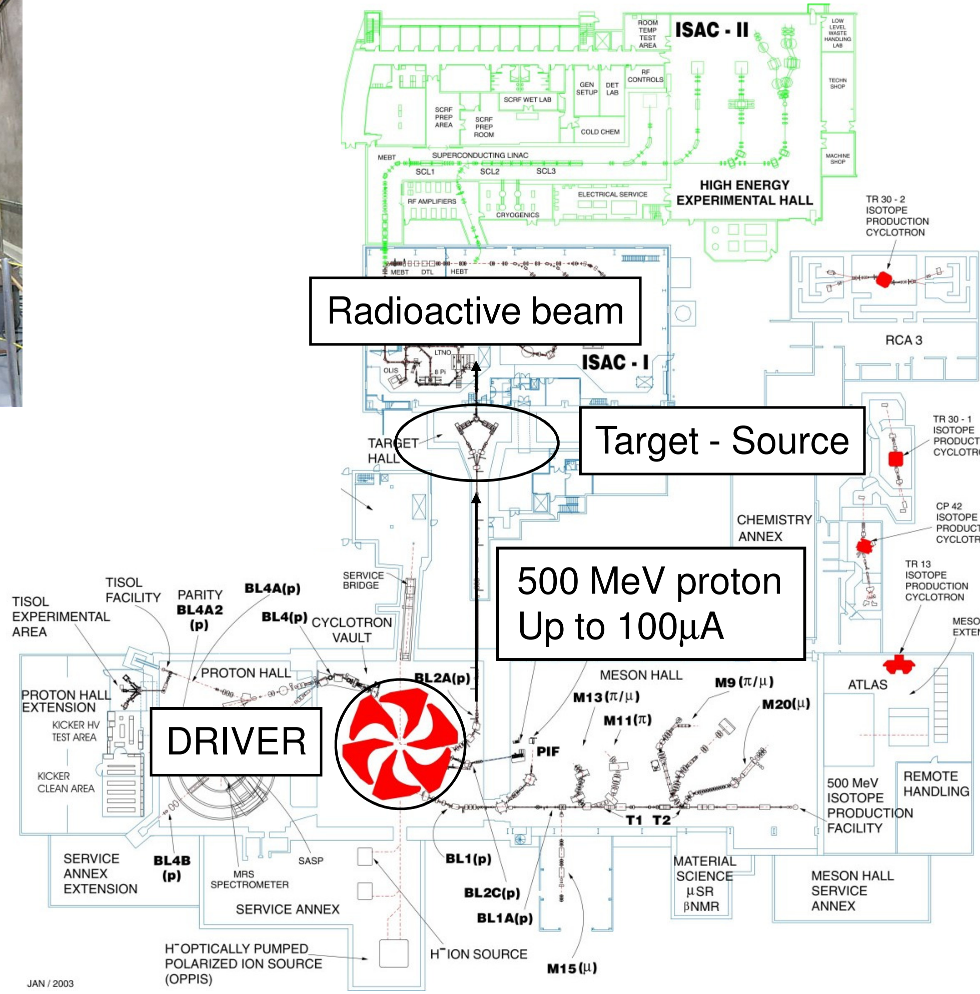
Integrated current requested: 1100 nC

Integrated current received: 77 nC

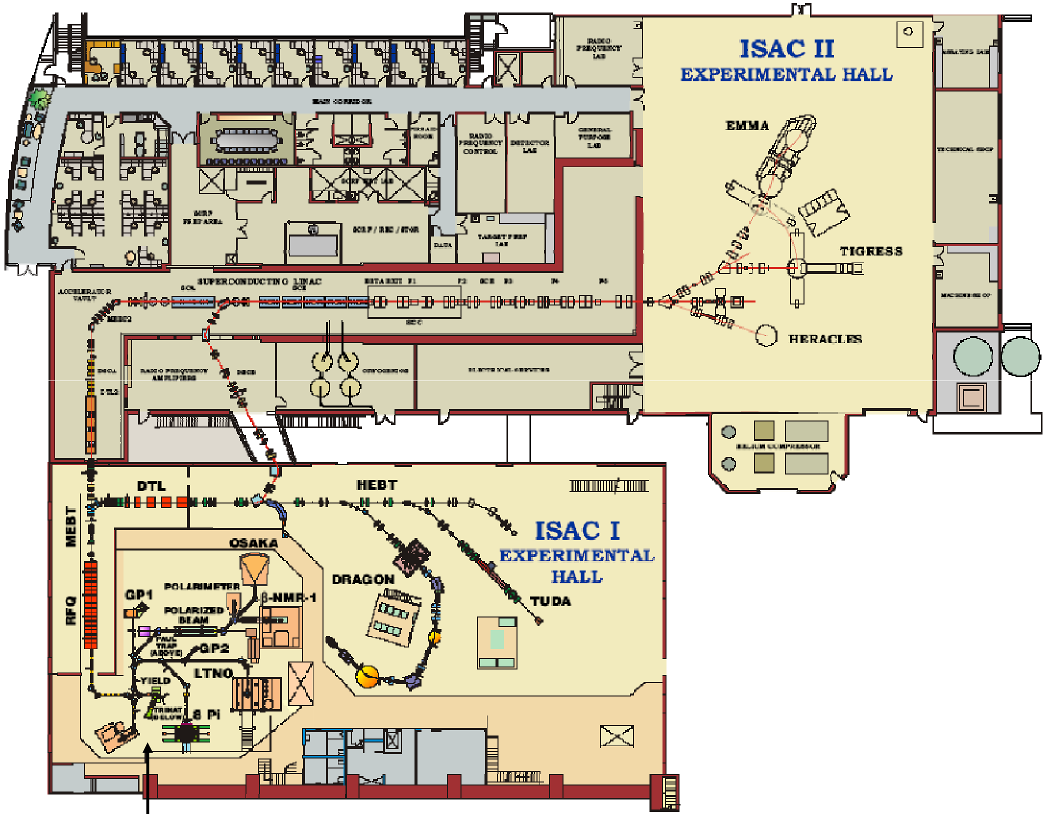
TRIUMF






ISAC - II
HIGH ENERGY EXPERIMENTAL HALL
SUPERCONDUCTING LINAC
TR 30 - 2 ISOTOPE PRODUCTION CYCLOTRON
Radioactive beam
ISAC - I
RCA 3
TARGET HALL
Target - Source
TR 30 - 1 ISOTOPE PRODUCTION CYCLOTRON
CHEMISTRY ANNEX
CP 42 ISOTOPE PRODUCTION CYCLOTRON
TR 13 ISOTOPE PRODUCTION CYCLOTRON
500 MeV proton
Up to 100μA
MESON HALL EXTENSION
TISOL EXPERIMENTAL AREA
TISOL FACILITY
PARITY
BL4A2 (p)
BL4A(p)
BL4(p)
SERVICE BRIDGE
CYCLOTRON VAULT
PROTON HALL
PROTON HALL EXTENSION
KICKER HV TEST AREA
KICKER CLEAN AREA
DRIVER
BL2A(p)
MESON HALL
M13(π/μ)
M11(π)
M9(π/μ)
M20(μ)
ATLAS
PIF
T1
T2
500 MeV ISOTOPE PRODUCTION FACILITY
REMOTE HANDLING
SERVICE ANNEX EXTENSION
BL4B (p)
MRS SPECTROMETER
SASP
SERVICE ANNEX
BL1(p)
BL2C(p)
BL1A(p)
MATERIAL SCIENCE μSR βNMR
MESON HALL SERVICE ANNEX
H⁻OPTICALLY PUMPED POLARIZED ION SOURCE (OPPIS)
H⁻ION SOURCE
M15(μ)
JAN / 2003

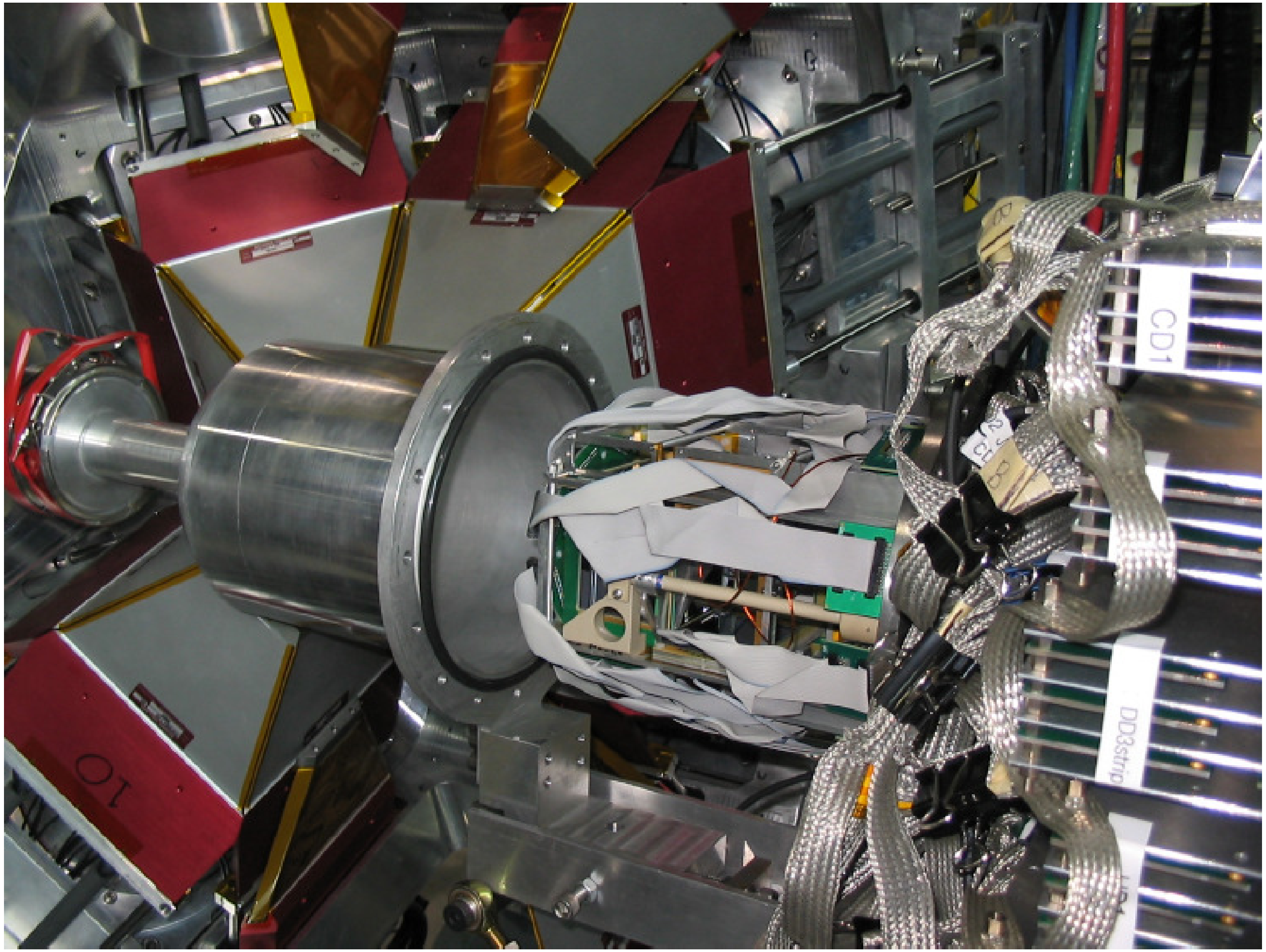
ISAC-I and –II @ TRIUMF



Target/Source + Mass Separator (Underground)

TRIUMF Cyclotron – p^+ 500 MeV ; I<100μA

SHARC + TIGRESS



Target:

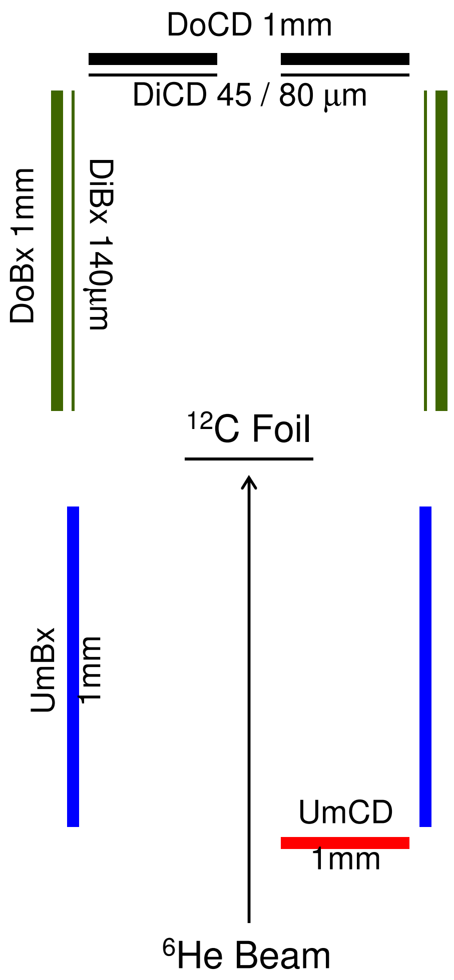
- 200 μg/cm² ^{12}C (~1μm)

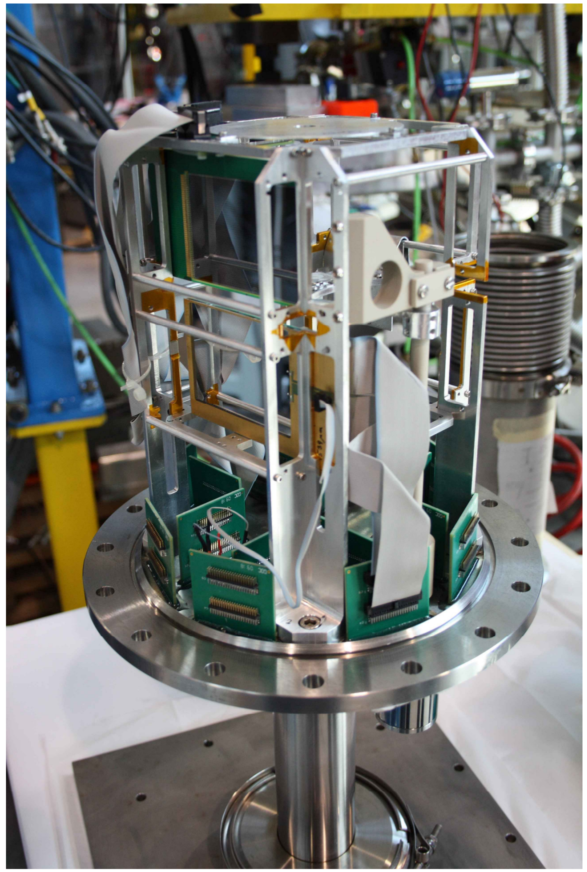
SHARC configuration:

- Upstream, only E
  - 4 x 1mm BB11 box
  - 1 x 1mm QQQ2 CD
- Downstream
  - 4 x 140μm BB1 box (DE)
  - 4 x 1mm pad (E)
  - 3 x 80μm QQQ2 CD (DE)
  - 1 x 45μm QQQ1 CD (DE)
  - 4 x 1mm QQQ1 pad
    - DoCD3 not working

SHARC angular resolution:

- DCD / UCD ~ 1.5°
- DBx / UBx ~ 0.5°





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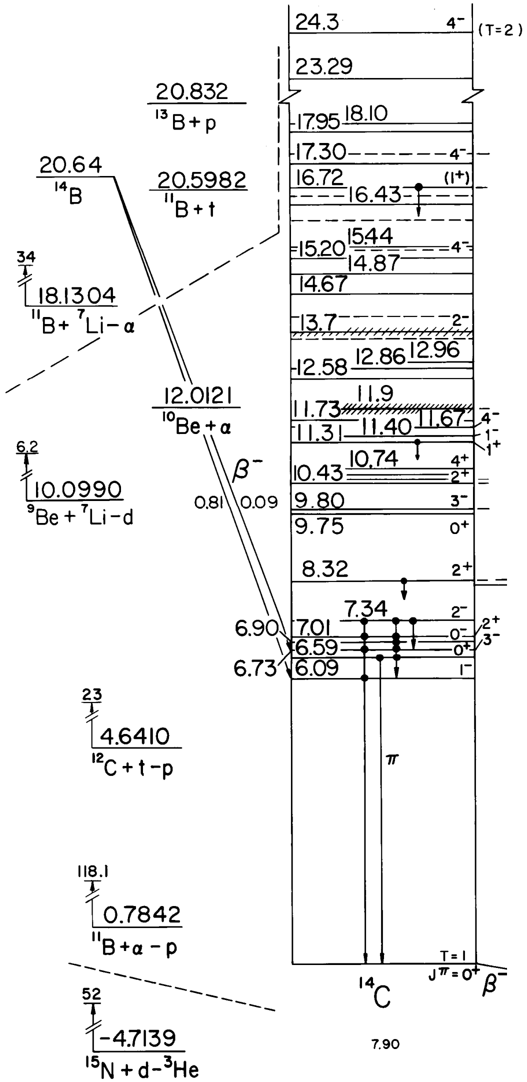
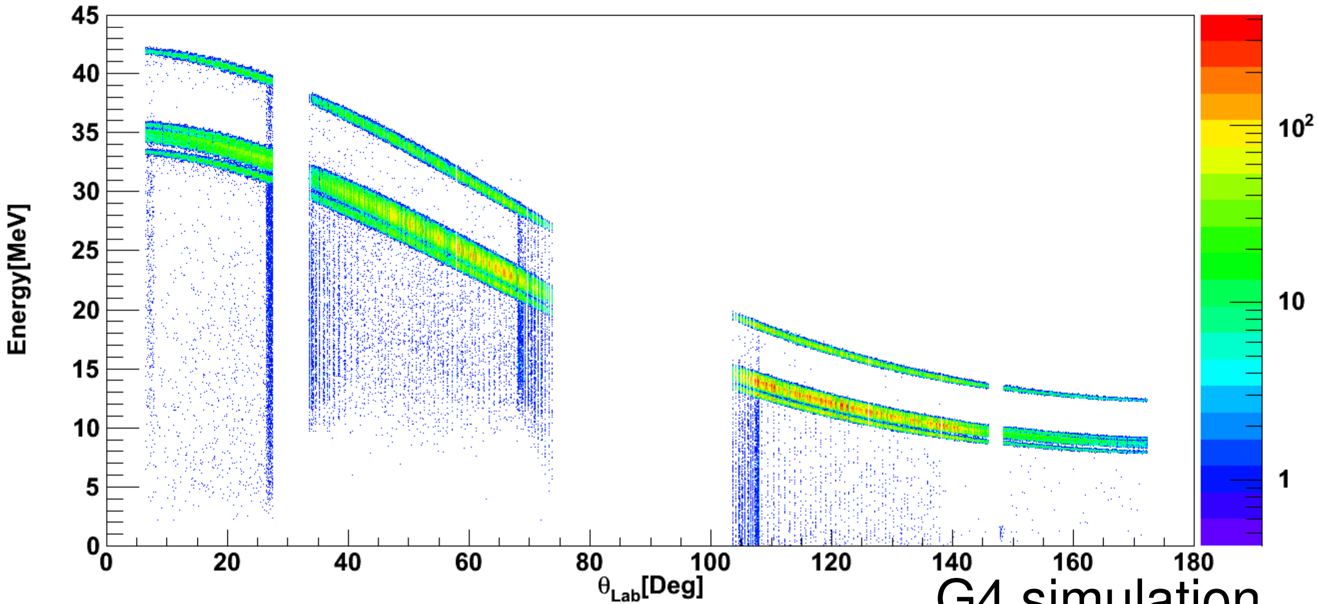
$^{12}C(^{6}He,^{4}He)^{14}C^{*}$ @ 30 MeV

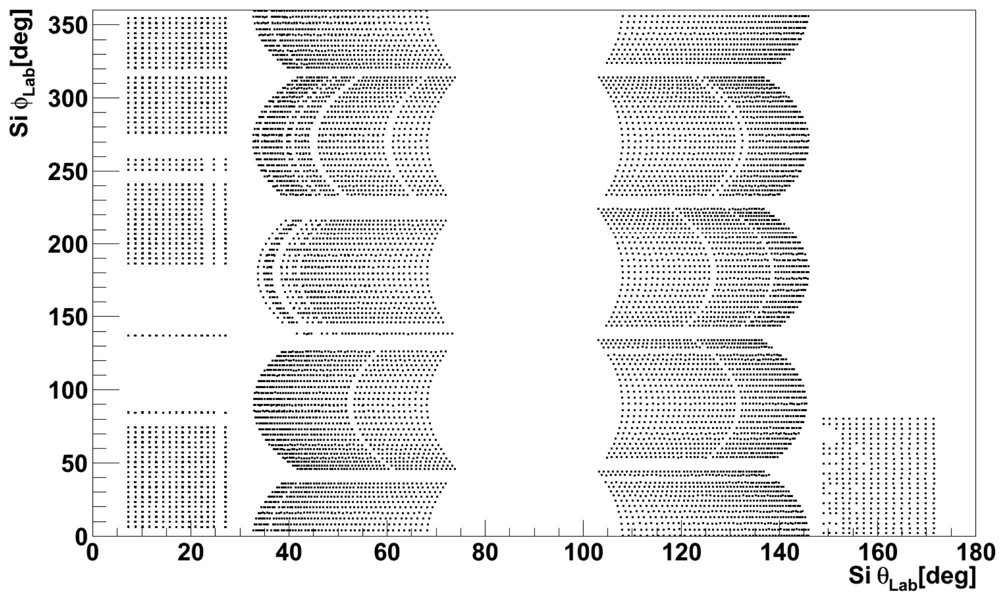


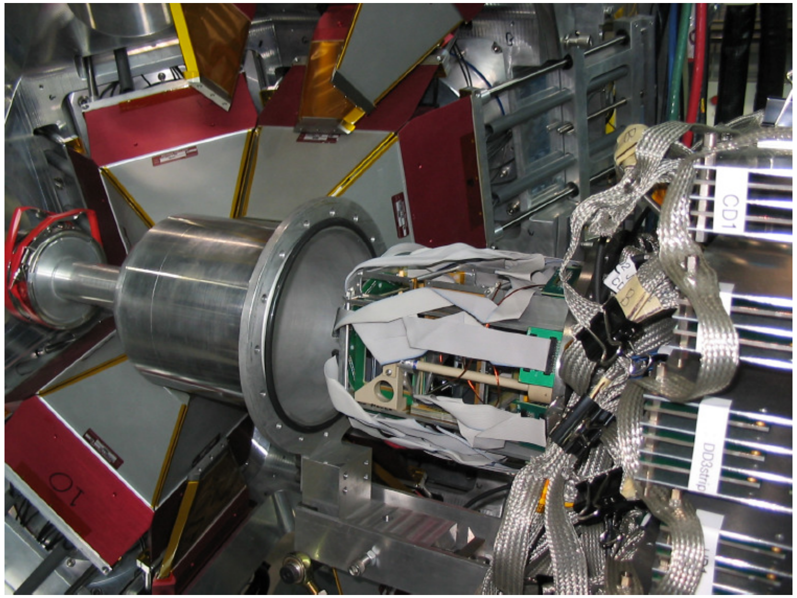
- 6-7.3MeV bound states separation require γ-tagging



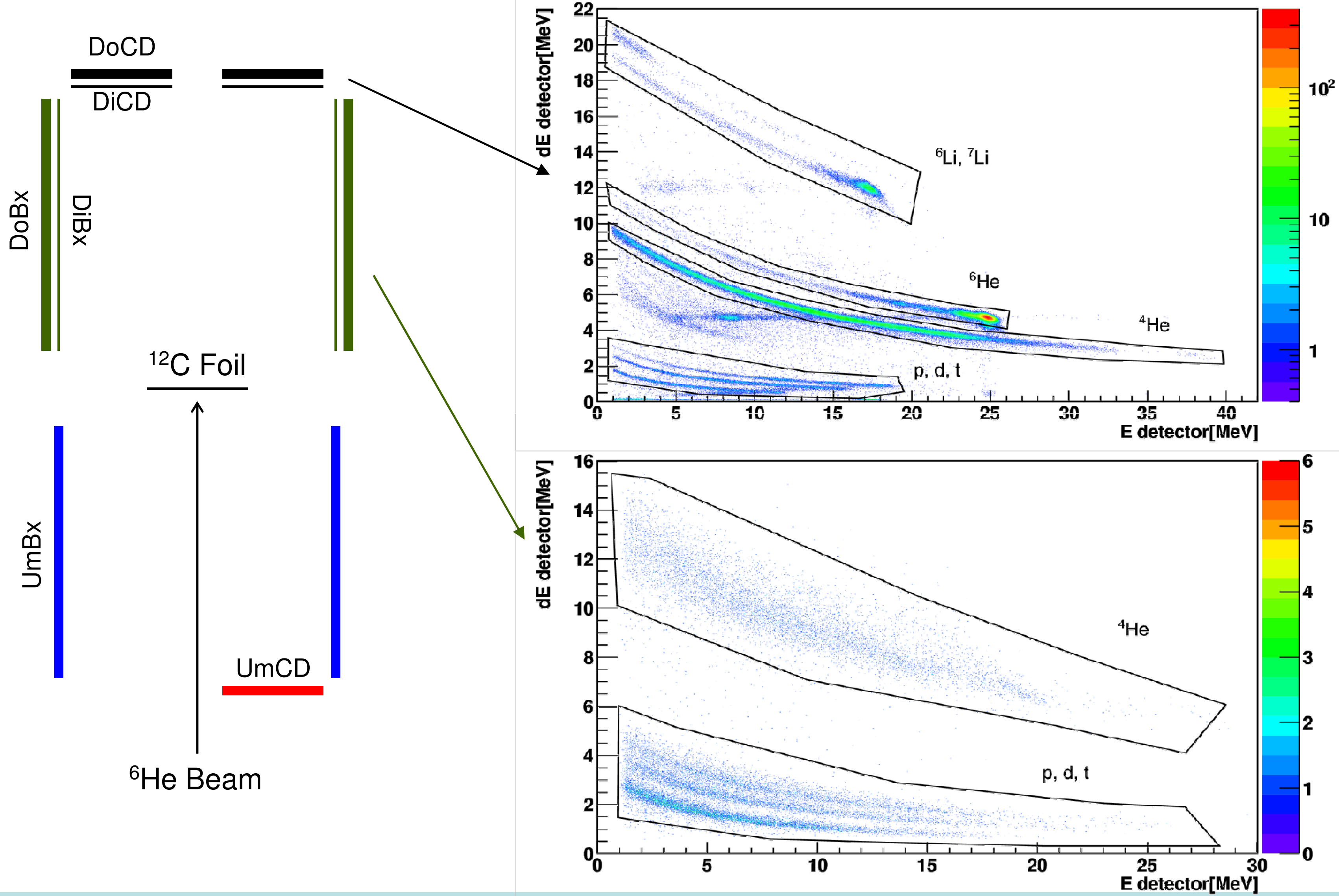
G4 simulation

SHARC angular Coverage





Particle identification (downstream)



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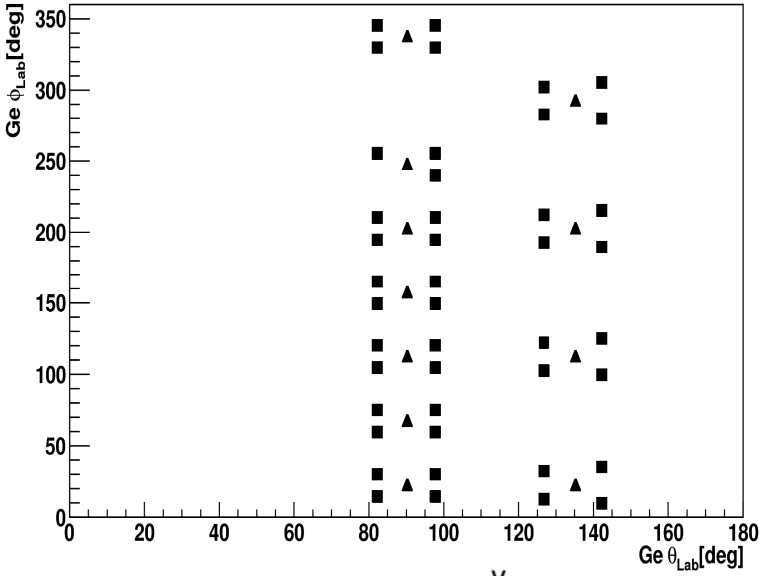
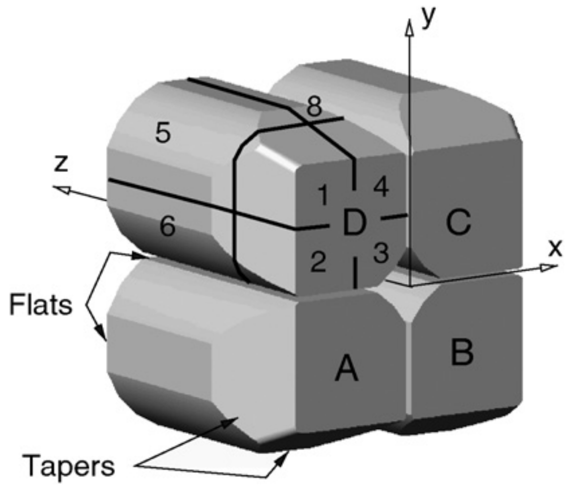
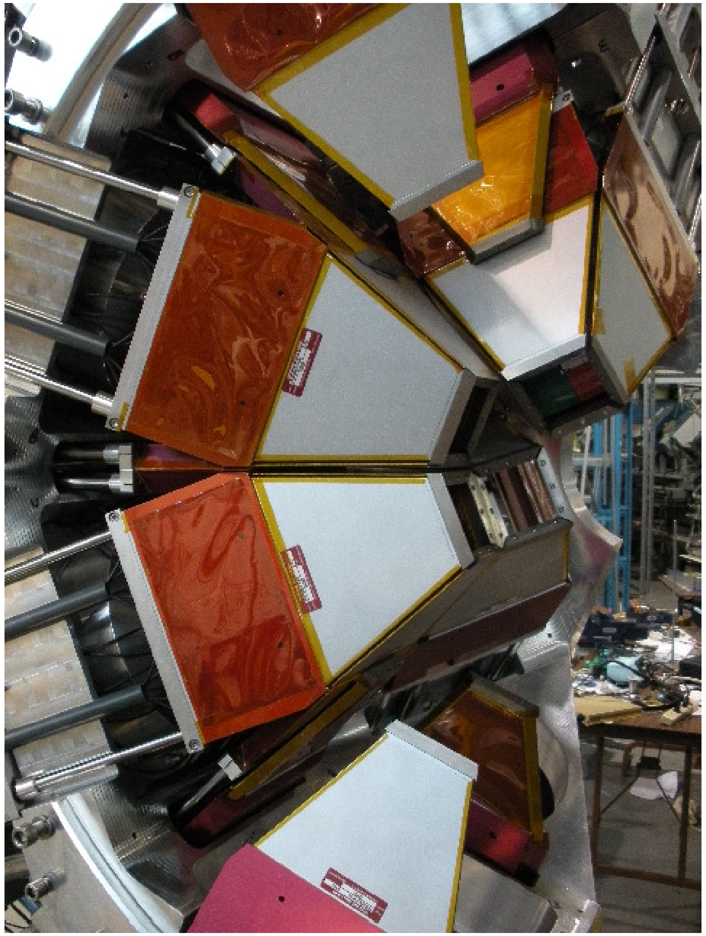
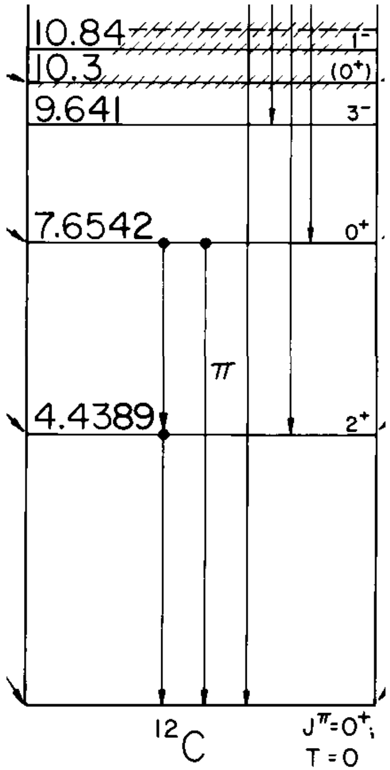
11 HPGe clovers





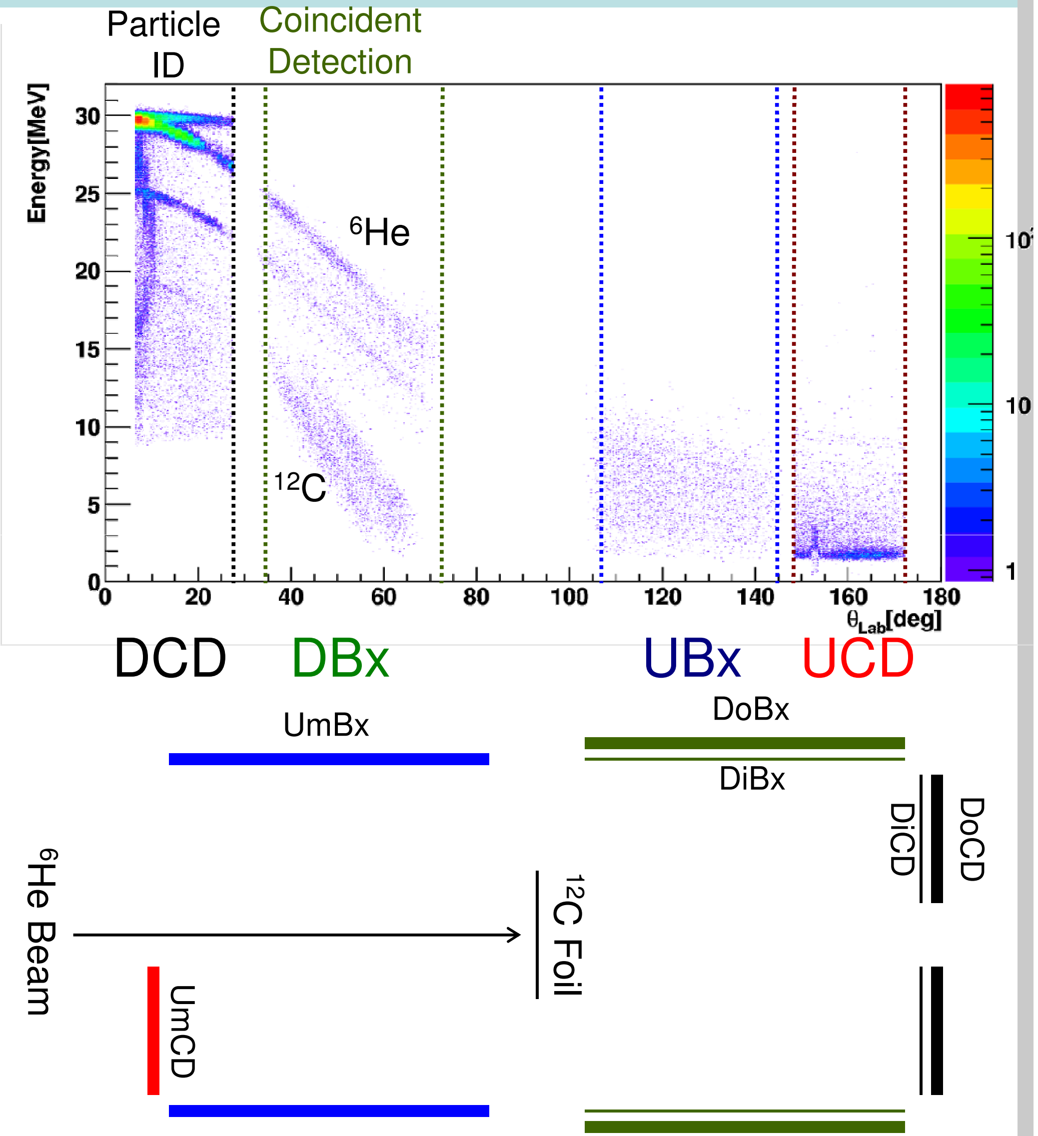


- States expected to be populated
  - 0^+(gs), 2^+ (4.4MeV), 3^- (9.64MeV)
- Fixes microscopic optical potential for $^{6}He+^{12}C$
  - Normalization on elastic scattering data
  - Inelastic gets model parameters for nuclear excitation – challenging!

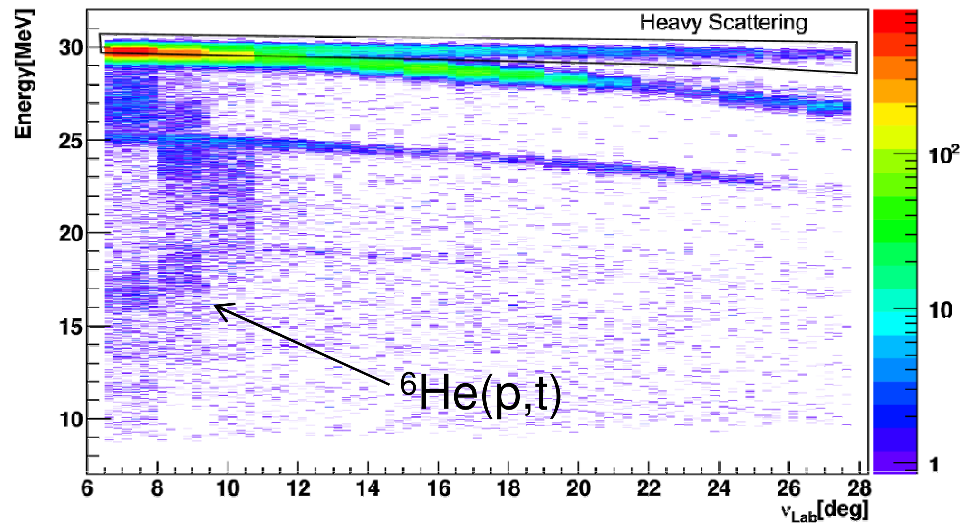


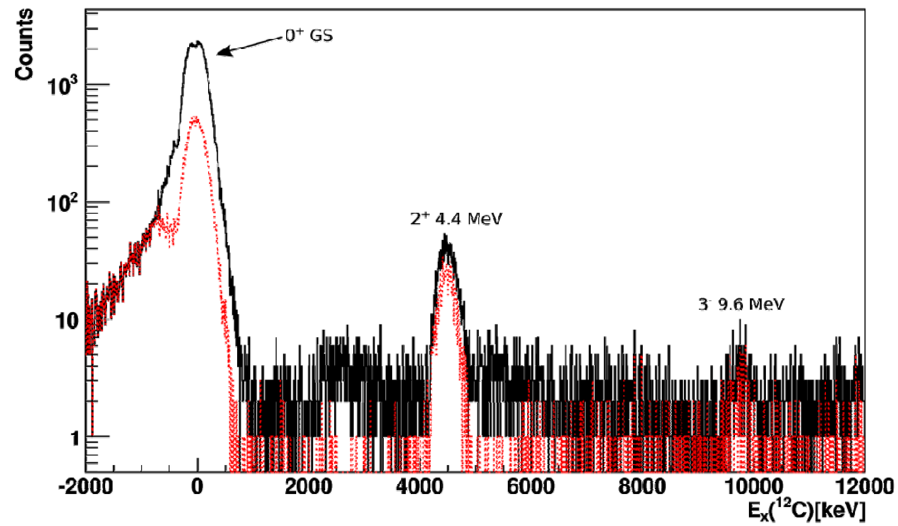
Elastic and inelastic E vs θ

- DCD
  - Particle identification
- DBx
  - ^{6}He elastic don't punch through
  - ^{6}He and ^{12}C detected simultaneously
    - Data cut done on this
- UmBx, UmCD
  - No elastic or inelastic scattering observed past 90°

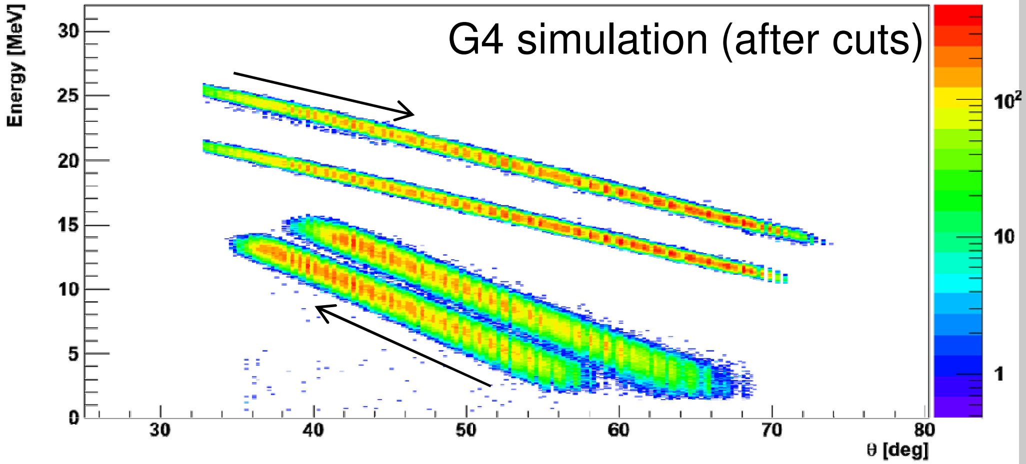


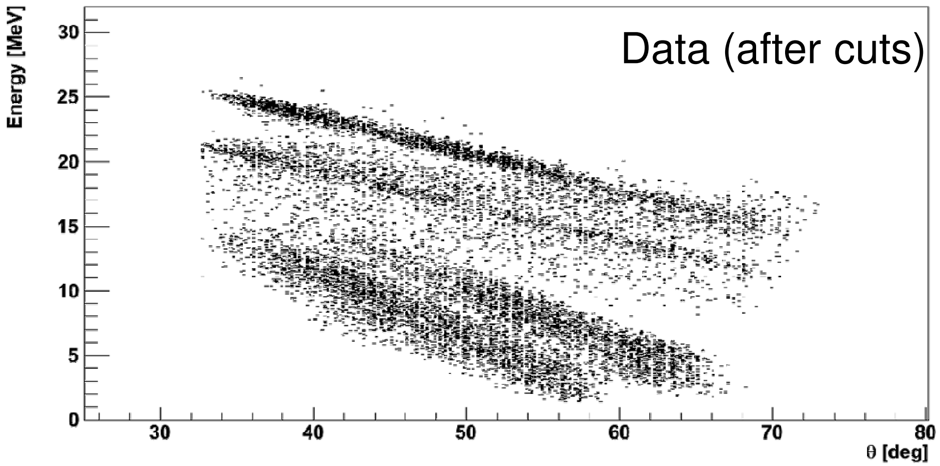
- Particle identification
- As yet undetermined heavy scattering
  - Interferes with first few channels of ground state and one channel in inelastic (4.4MeV)
- $^{6}He(p,t)$
  - Presumably due to water condensation on the target (also evidence of ^{16}O elastic scattering)
- Resolution limited by angular resolution
  - Confirmed with simulations





- ^{6}He+^{12}C two body reaction in a plane
  - $|\varphi_{6He}-\varphi_{12C}|=\Delta\varphi=\pi$
- Energy of ^{6}He+^{12}C a constant
  - $E_{6He}+E_{12C} = 30$ MeV
  - Energy loss in target foil, dead layers cause $E_{6He}+E_{12C} < 30$ MeV
- Data cuts made to maximize data minimize background
  - $\Delta\varphi = 5^{\circ}$
  - $\Delta E = 3$ MeV GS, 1 MeV 4.4 MeV state
  - Energy spread mainly due to ^{12}C straggling





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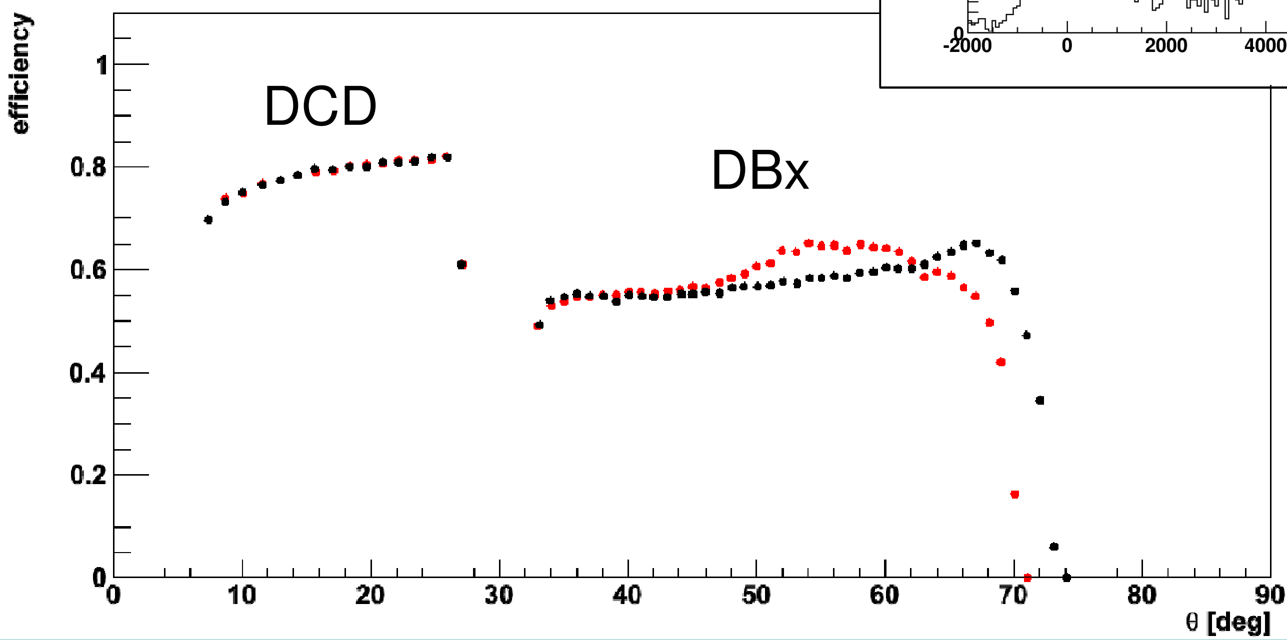
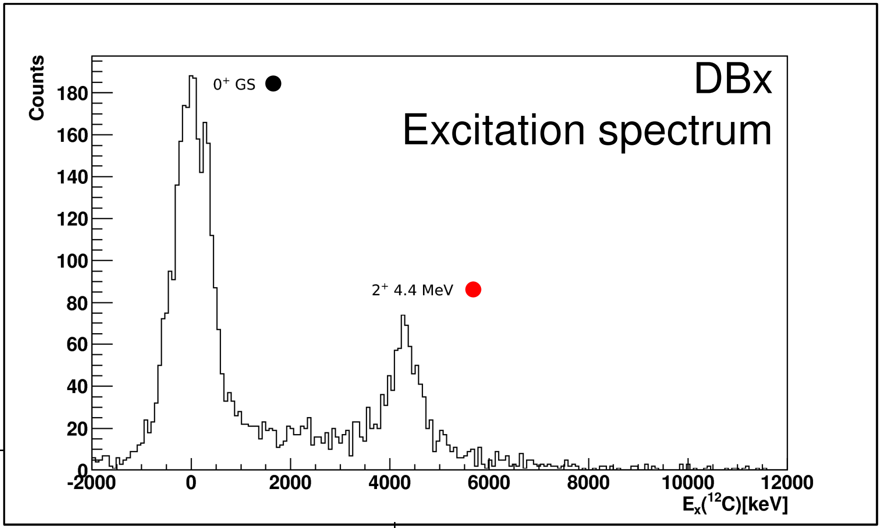
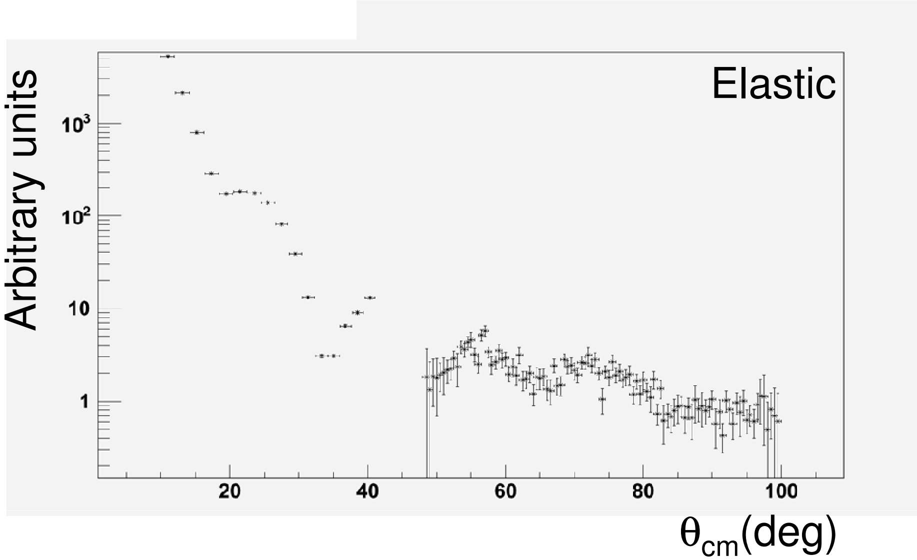
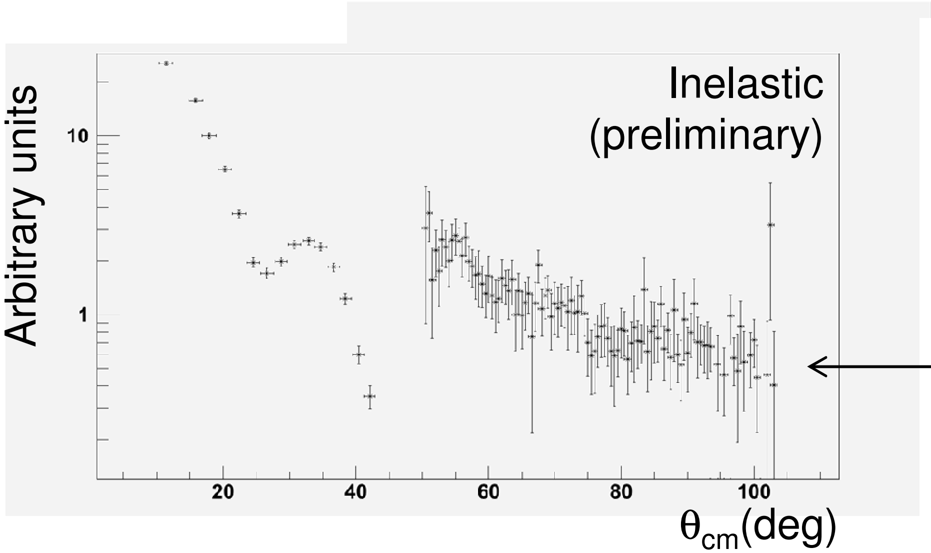
- GS efficiency
  - Little background
  - Mostly interstrip and corner detection effects
- 2^+ 4.4MeV
  - Higher background
  - Stricter ΔE cuts
  - Coincident detection





Elastic/Inelastic angular distributions

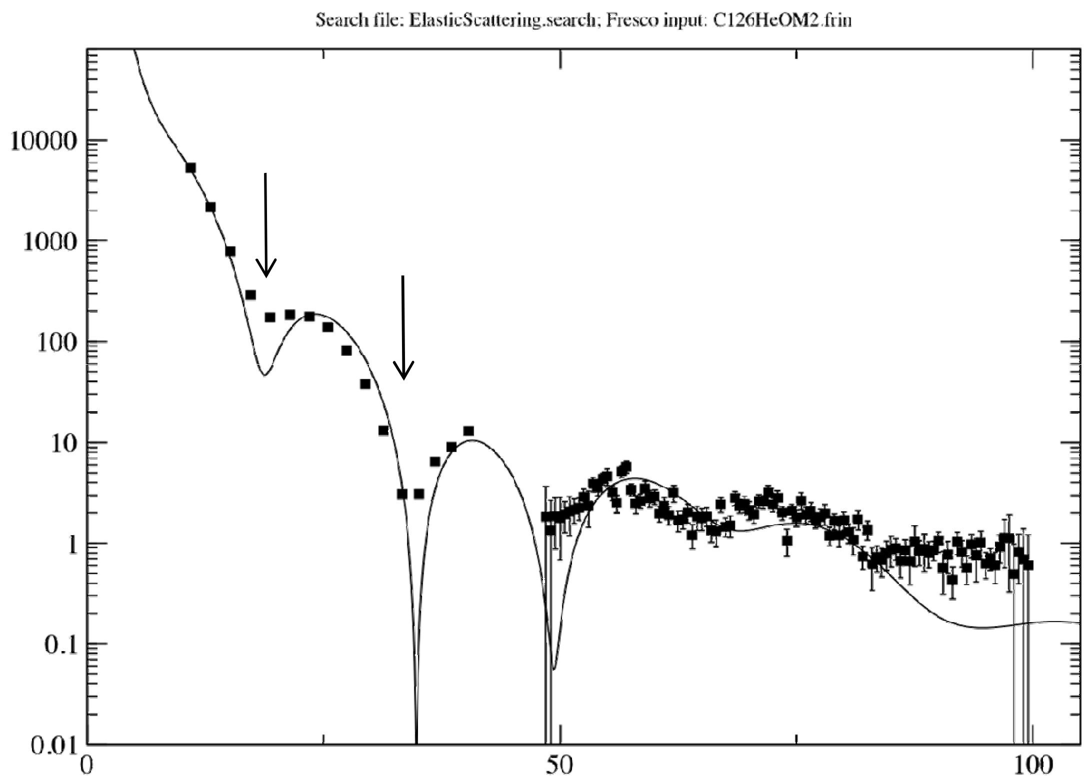




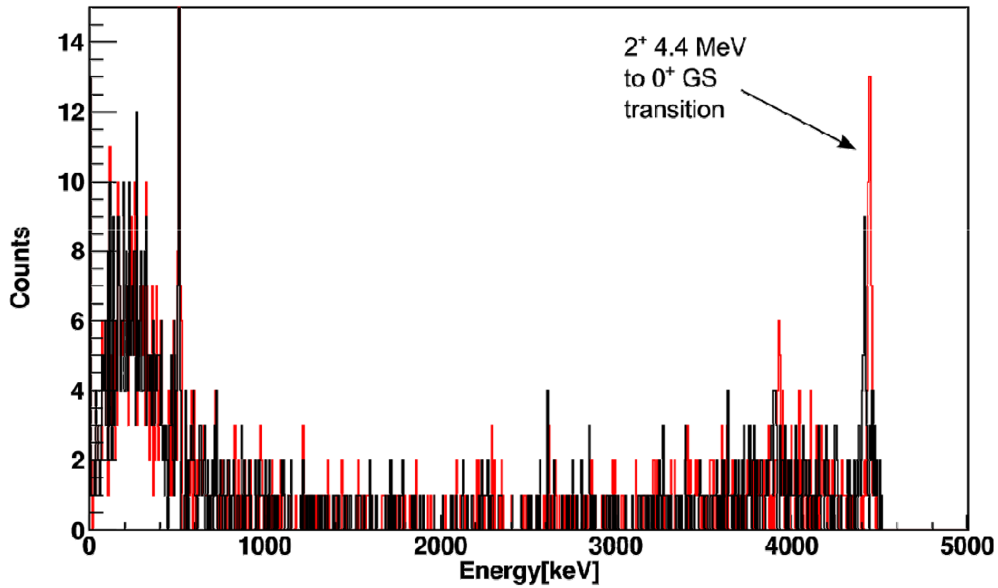
Need further background subtraction

PRELIMINARY

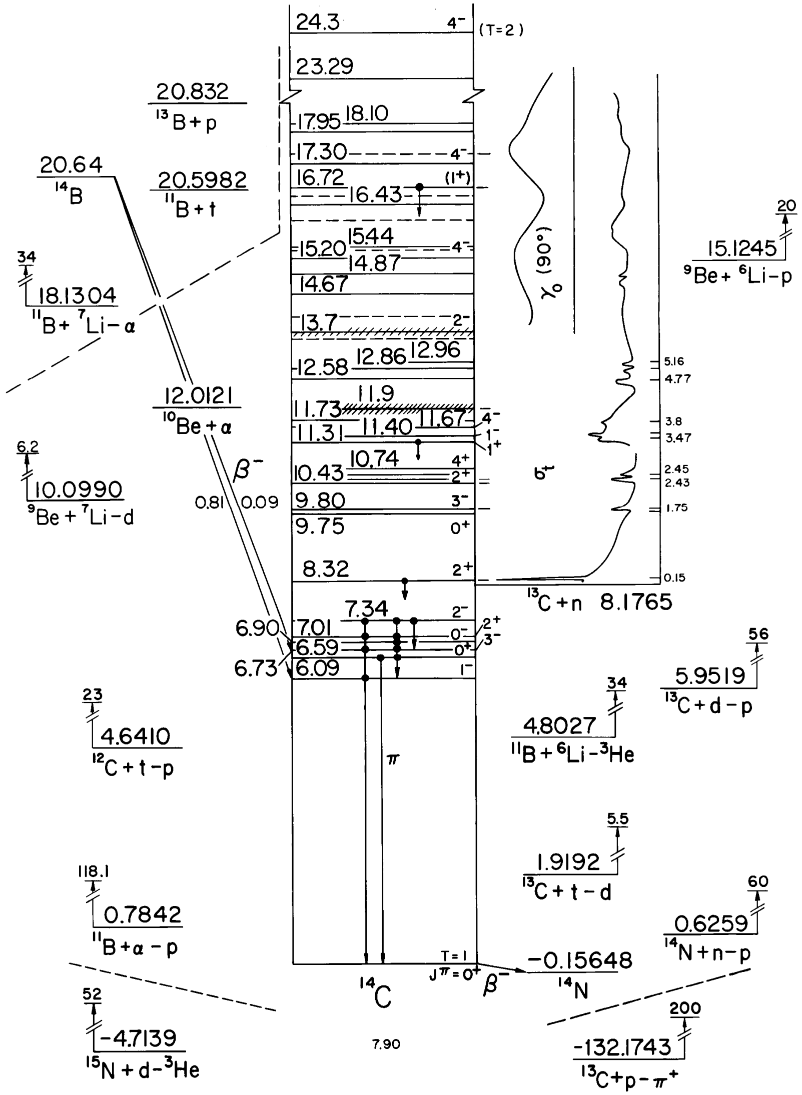
- Optical model from ^{6}Li on ^{12}C at 30MeV
  - Mass adjusted for ^{6}He
  - Normalized



- 2^+ to 0^+ 4.438MeV γ-ray transition observed
  - Black: raw spectrum
  - Red: Doppler corrected
- A few % efficiency at 4MeV
- Not enough statistics for α–γ tagging for angular distribution



- 6.09MeV to 7.34MeV excited states
  - α–γ tagging required
  - High γ-efficiency
- $^{12}C(^{6}He,^{4}He)$ angular distribution only measured for 8.32MeV (unbound) state



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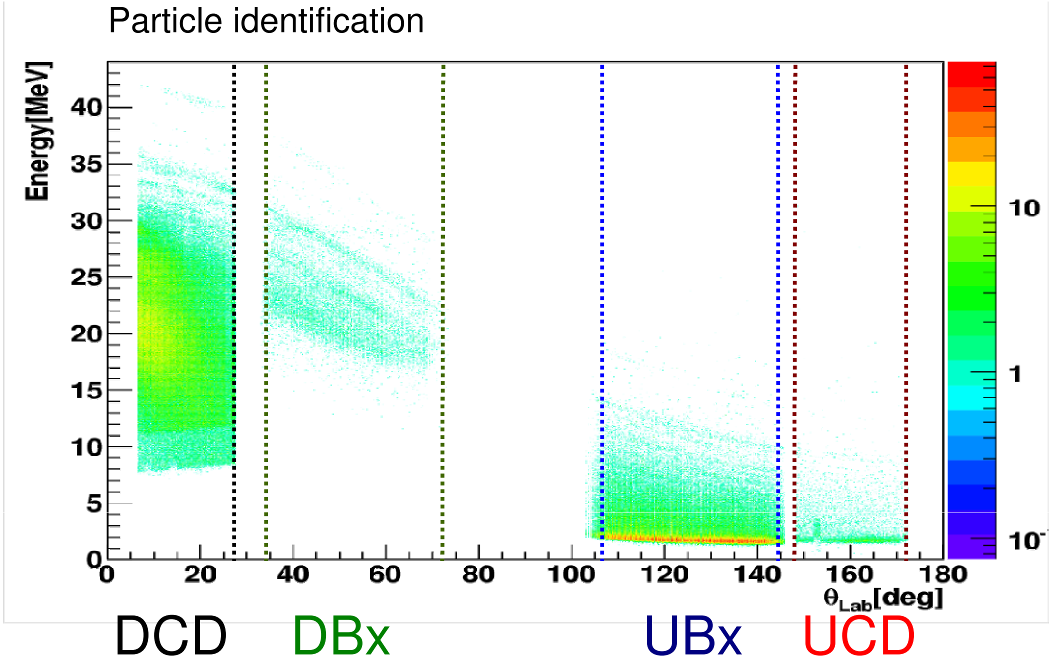
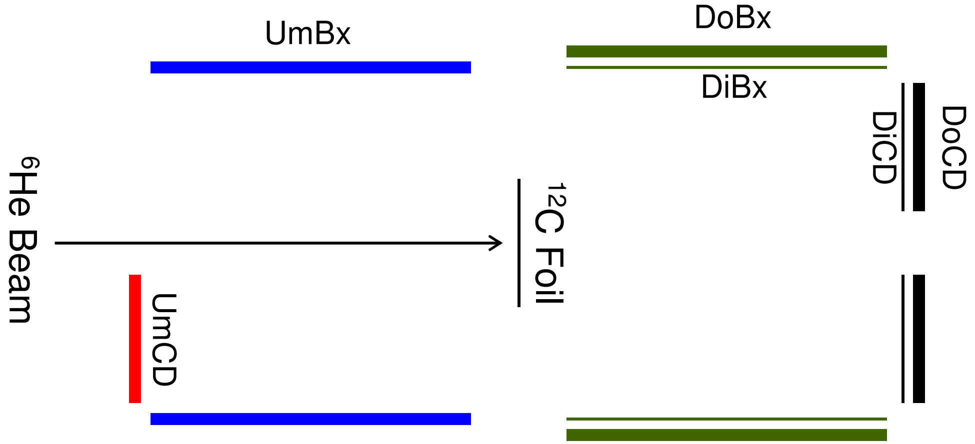


- DCD
  - Particle ID
  - Fusion-evaporation
- DBx
  - Particle ID
  - Only the highest energy 4He punch through
- UmBx / UmCD
  - Large Q-value (Q=12.15MeV): few contaminants



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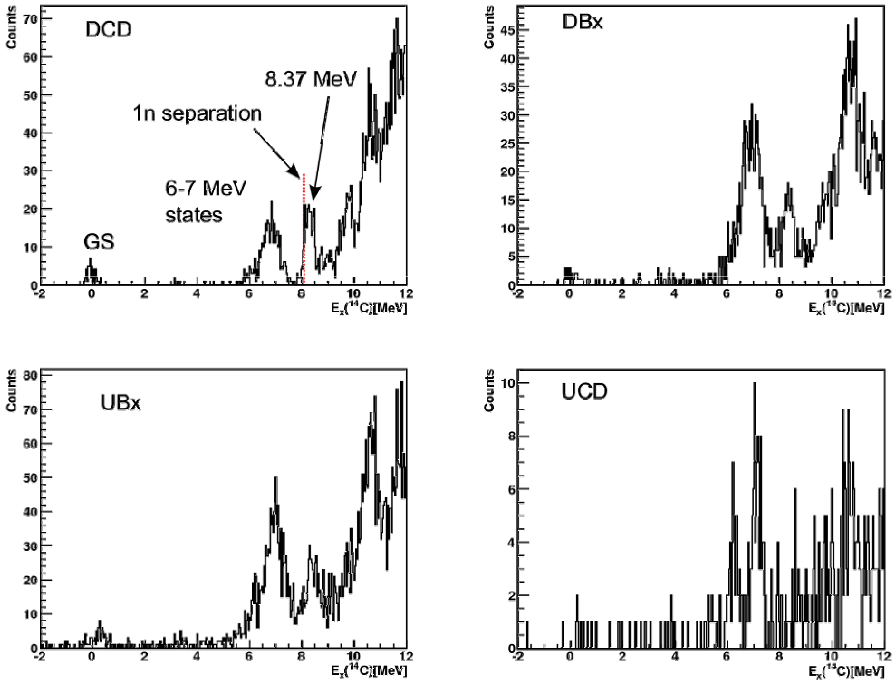
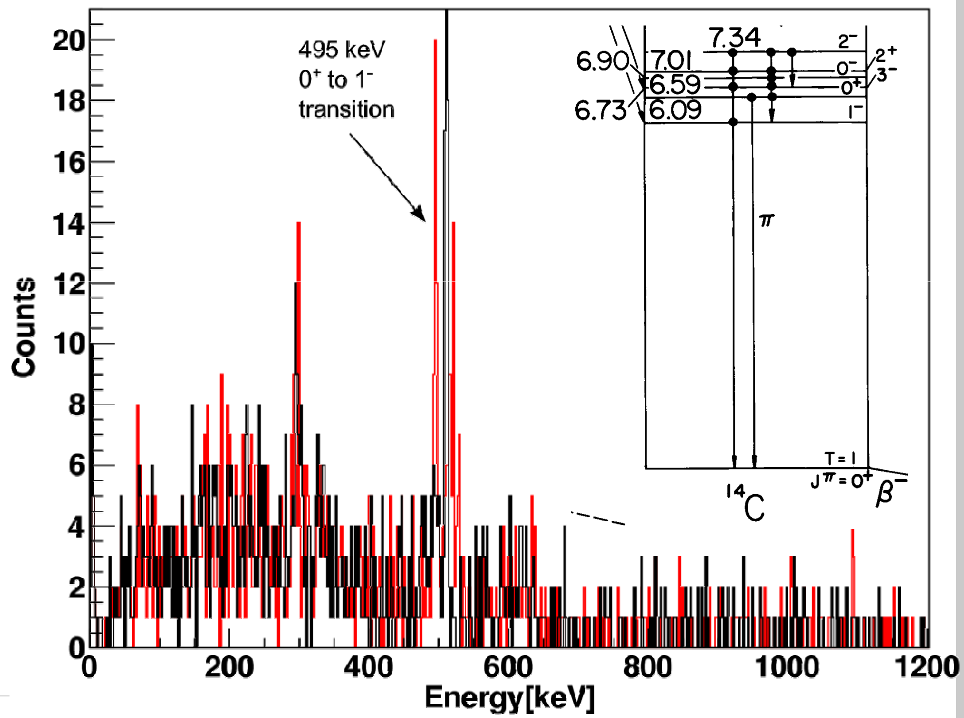
$^{12}C(^{6}He,^{4}He)^{14}C^{*}$ excitation and γ spectra

SHARC



SHARC + TIGRESS



Proof of principle

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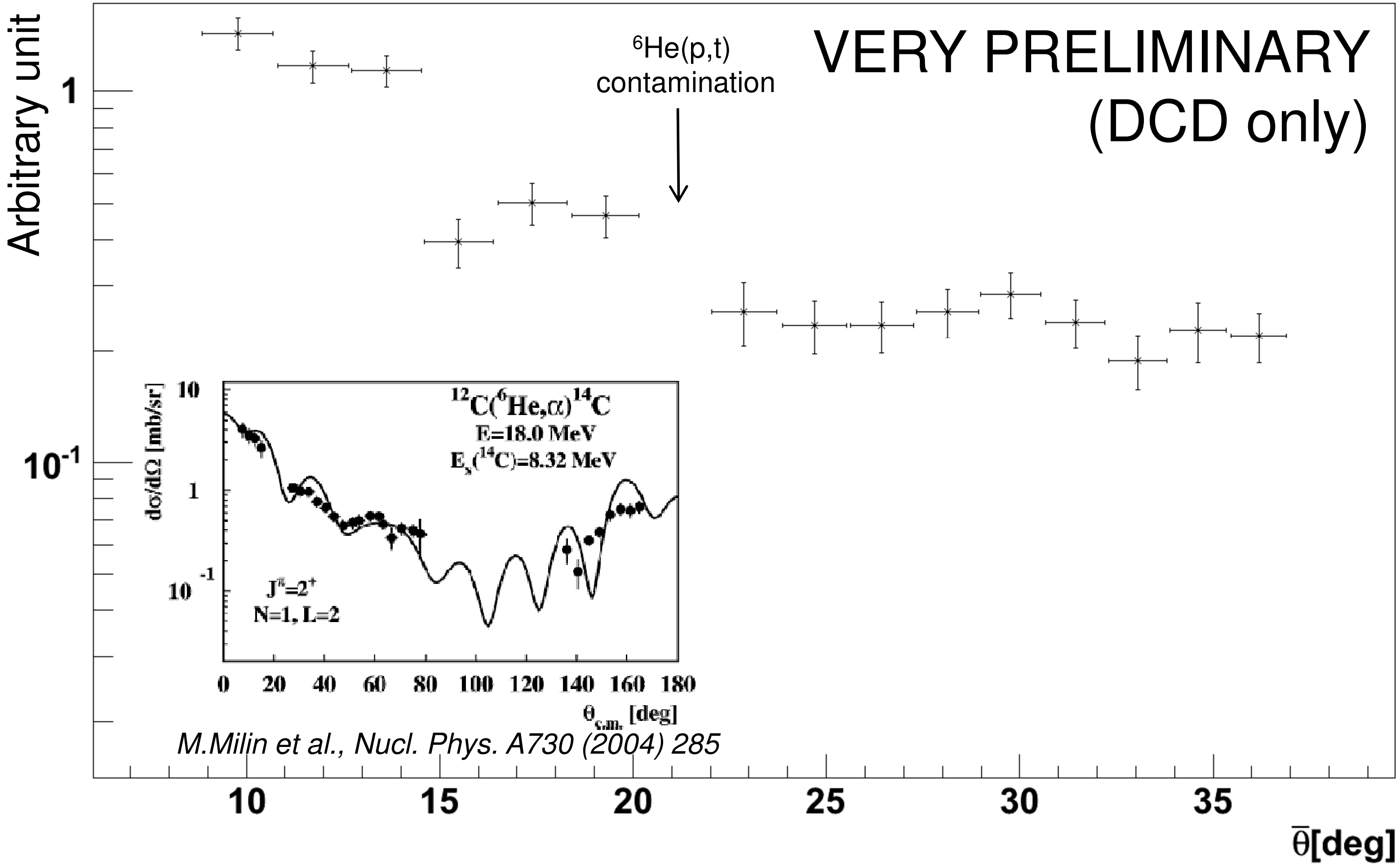
8.32MeV angular distribution

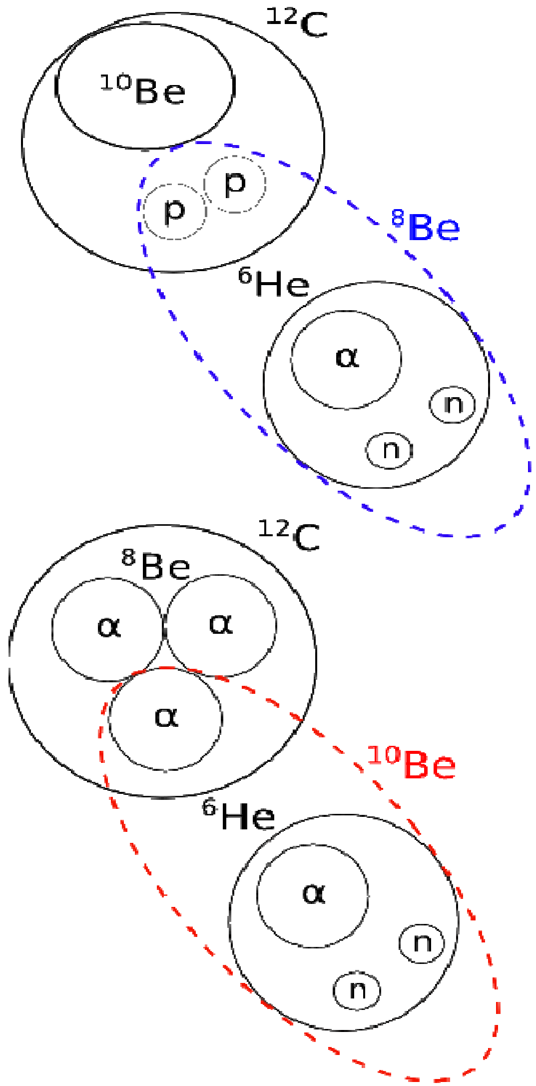


M.Milin et al., Nucl. Phys. A730 (2004) 285

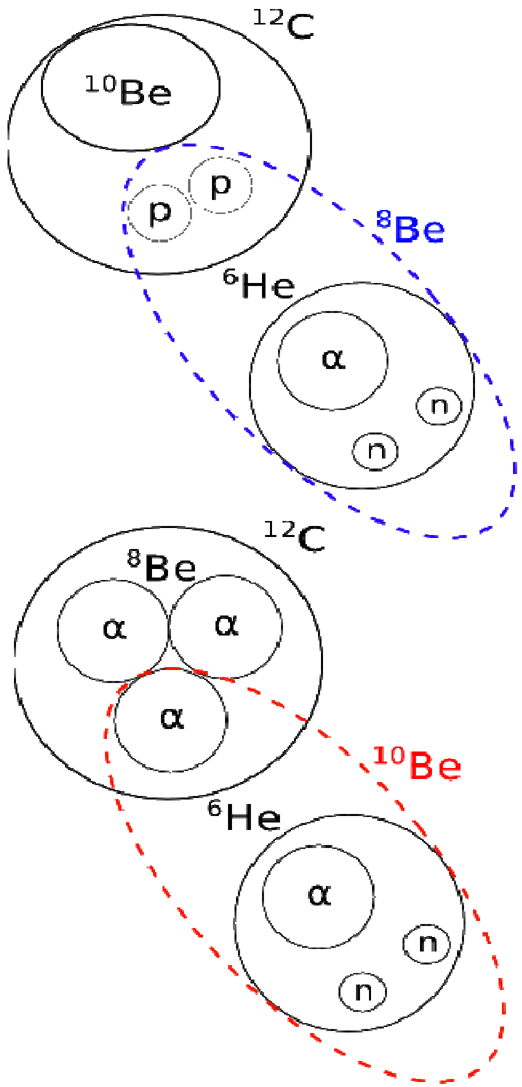
$^{12}C(^{6}He,^{8}Be)$ Q=0.140MeV

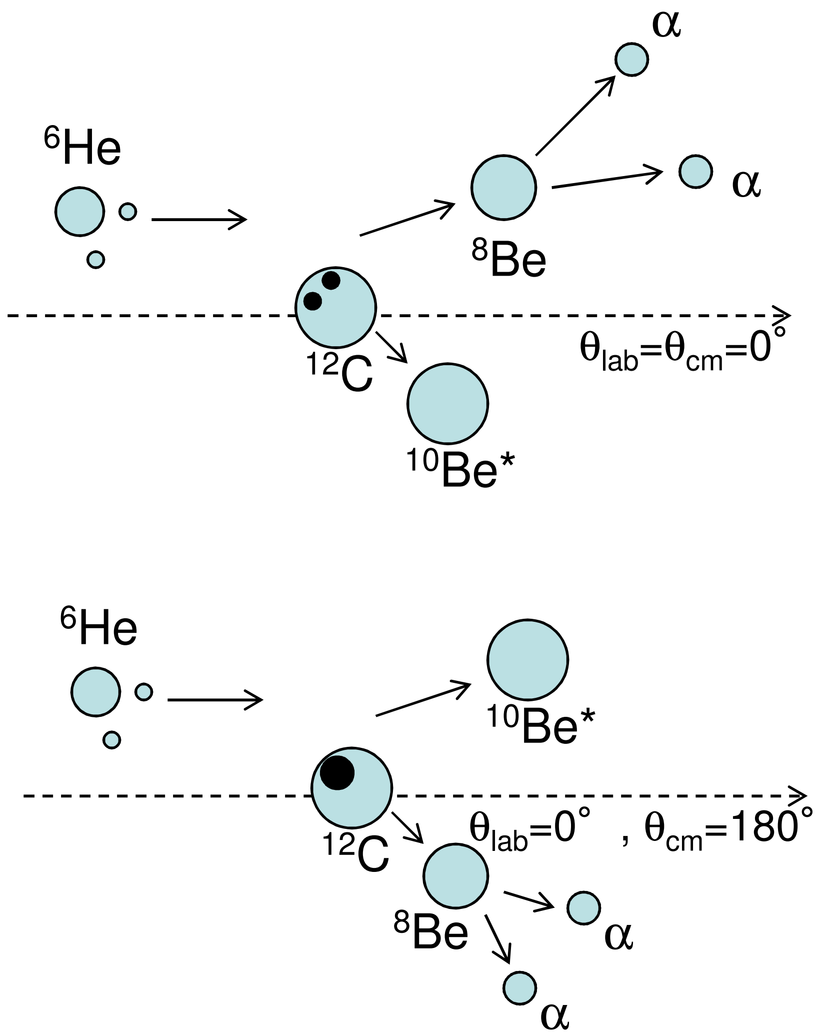
- Suggested a 2p direct transfer by Milin et al., PRC 70 (2004) 044603
  - $S_{2p}(^{12}C)$=27.2 MeV
  - Differential cross section with a factor of 20 larger than $^{12}C(^{6}Li,^{8}B)$ at 80 MeV lab beam energy

- Alternate possibility: α-transfer on ^{6}He?
  - $S_{\alpha}(^{12}C)$=7.4 MeV
  - A look at the 3α-like structure of $^{12}C_{gs}$? Reaction mechanism involving excitation through the Hoyle state?



$^{12}C(^{6}He,^{8}Be)^{10}Be^{*}$ kinematics





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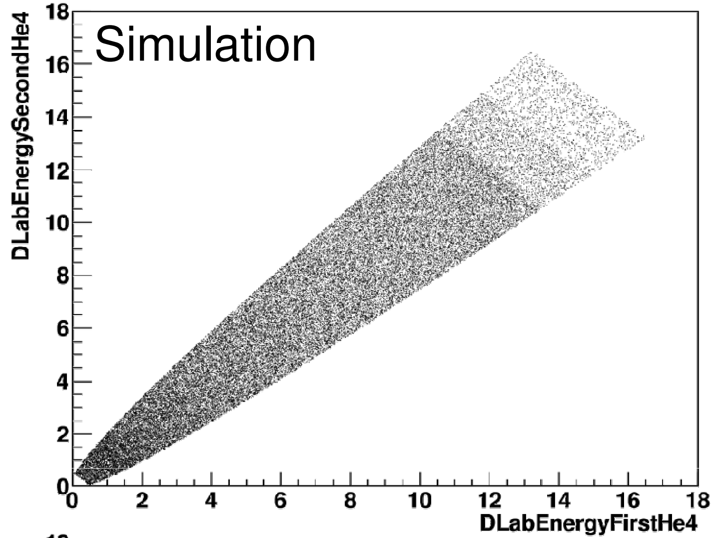
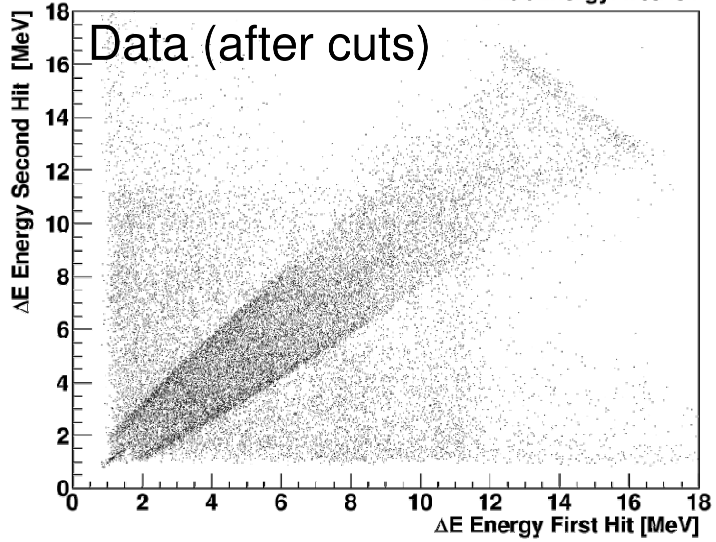
Simulation:
- Kinematics of $^{12}C(^{6}He,^{8}Be)^{10}Be$ and ^{8}Be breakup at 30MeV

Data – reconstruction from multiple cuts
- α-energy < 11.5MeV, αs don't punch through
  - 2 hits in ΔE
- α-energy > 11.5MeV, αs punch through
  - Recoverable events:
    - 2 hits in different front strips
    - 2 hits in same front / different back strips
  - Non-recoverable events:
    - 2 hits in the same front / back strips
    - Just one alpha detected





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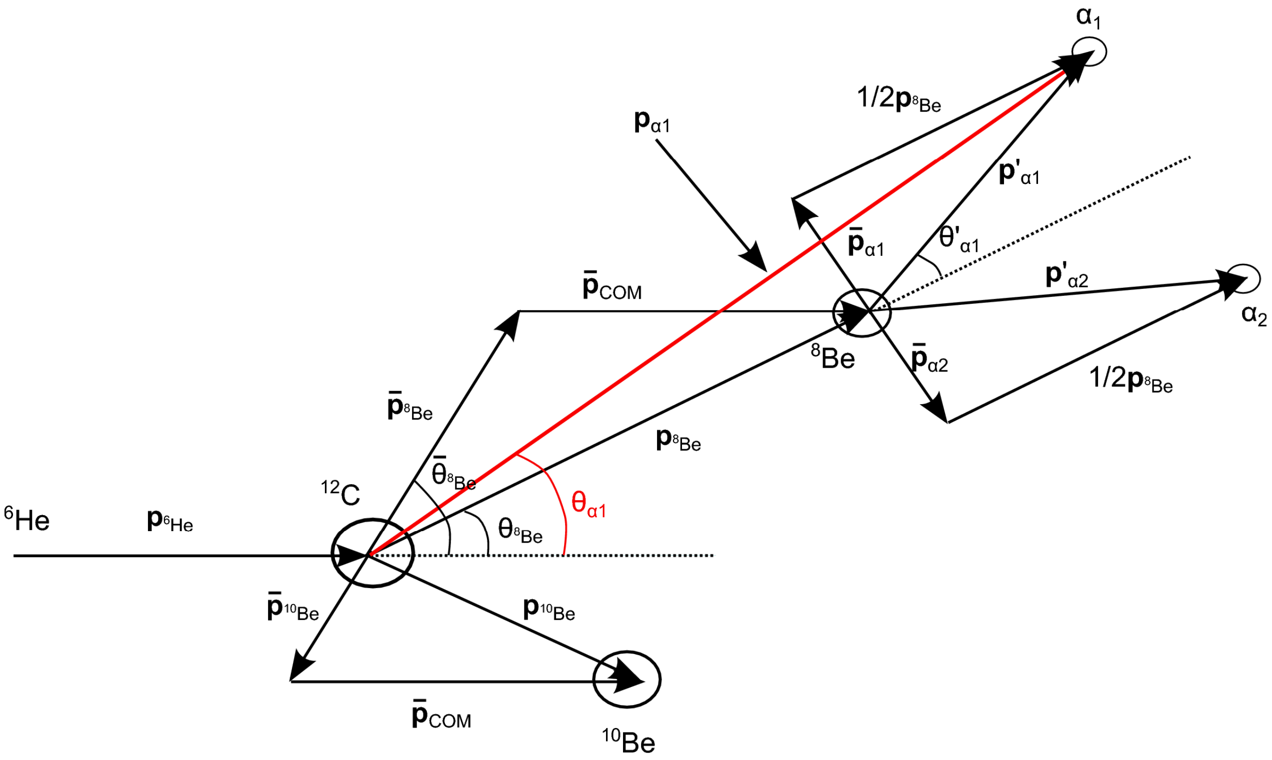
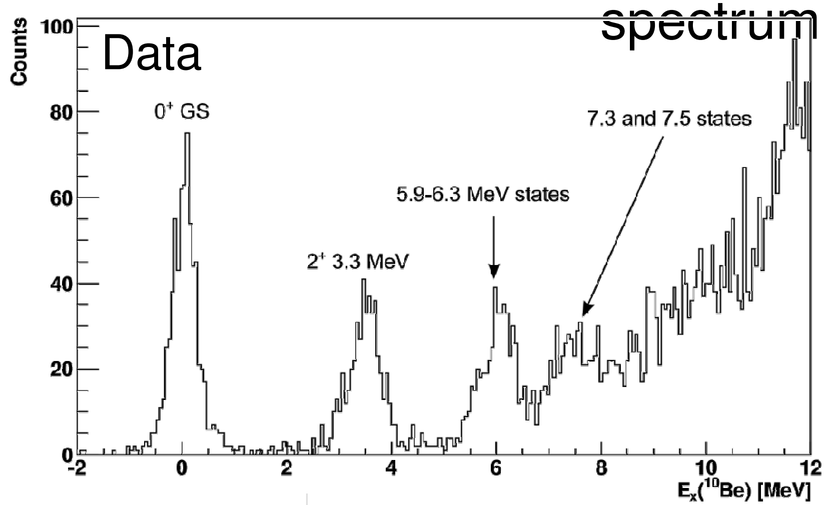
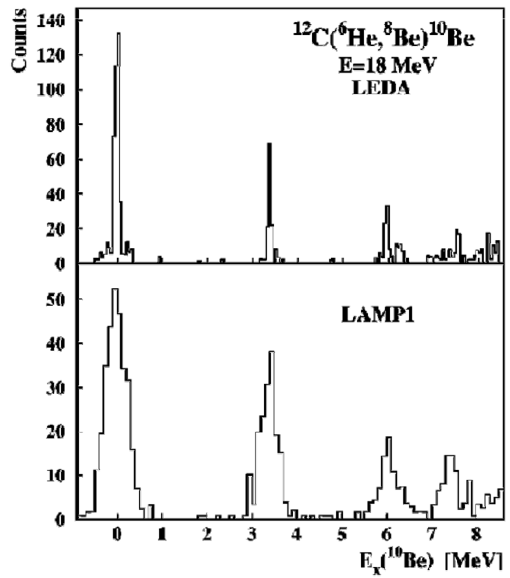
$^8Be \rightarrow 2\alpha$ (Q=92keV – assuming $^8Be_{gs}$)



^{10}Be excitation spectrum



- GS and 2+ 3.3 MeV states clearly separated
  - Angular distributions OK, but requires 2α detection efficiency calculation
- 5.9 MeV to 6.3MeV region
  - Observed, but individual states not separable with SHARC only
  - Not enough statistics for TIGRESS γ-tagging
- Beyond 6.3MeV (S_n=6.8MeV)
  - Neutron unbound states
  - Fusion-evaporation background



From M.Milin et al., Phys. Rev. C70, 044603 (2004)

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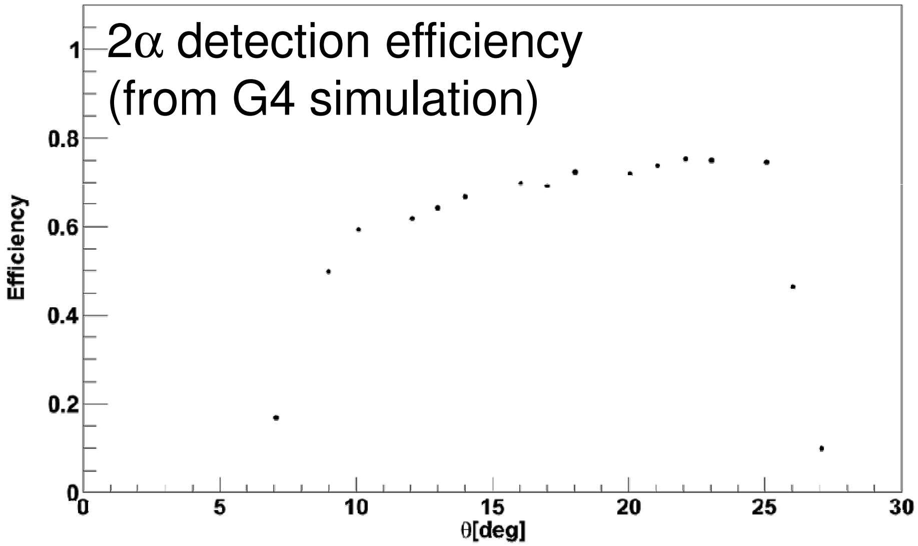
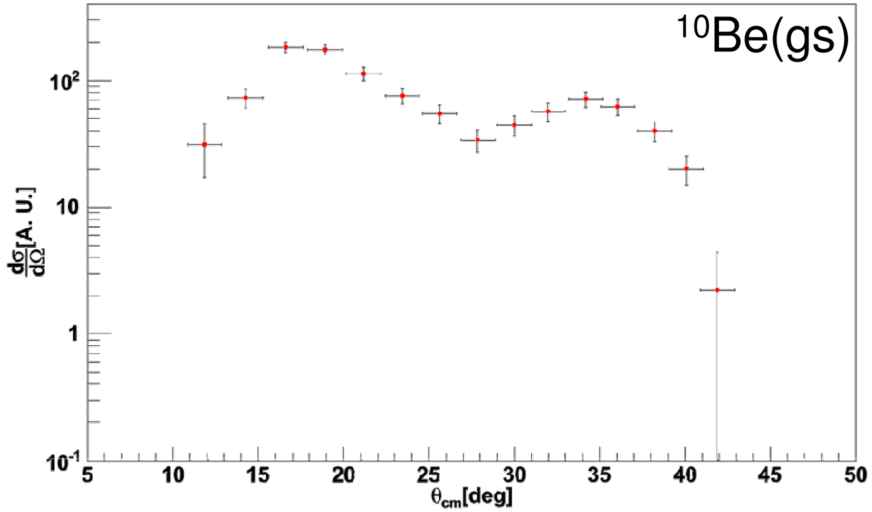
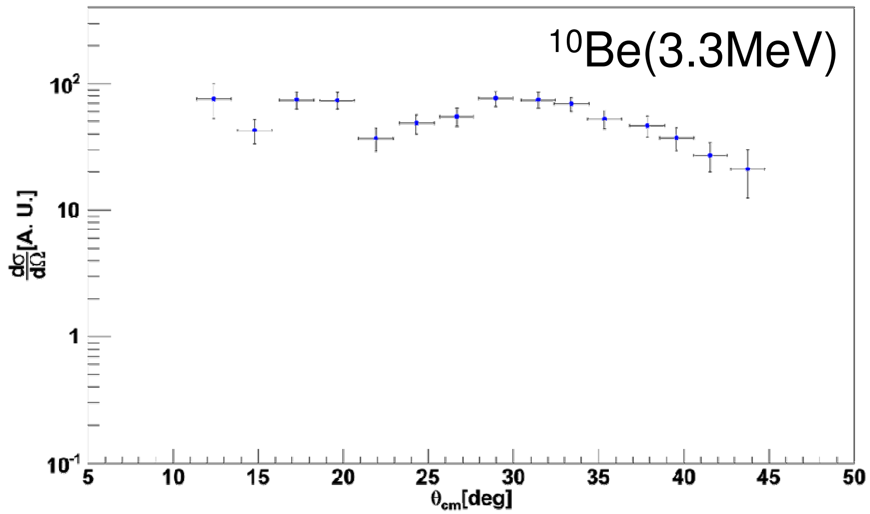
2α detection efficiency and angular distributions (DCD only)

PRELIMINARY







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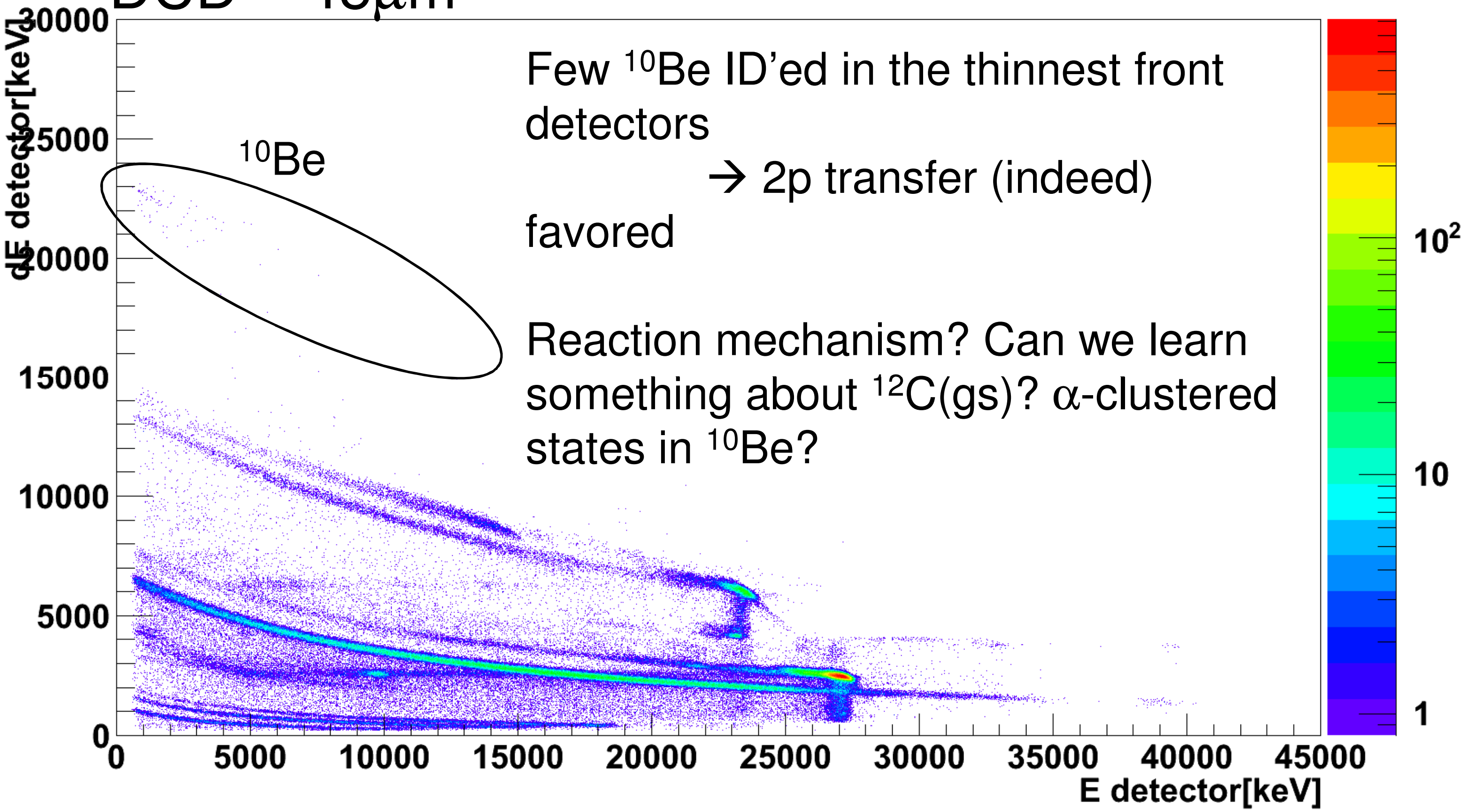
DCD – 45µm



Few ^{10}Be ID'd in the thinnest front detectors

→ 2p transfer (indeed) favored

Reaction mechanism? Can we learn something about ^{12}C(gs)? α-clustered states in ^{10}Be?

$^{6}He+^{12}C$ @ 30 MeV with SHARC + TIGRESS

- Elastic / inelastic scattering
  - Angular distributions extracted for elastic and inelastic (4.4MeV)
  - First fit on elastic, more work to be done on inelastic

- $^{12}C(^{6}He,^{4}He)^{14}C^*$
  - Proof-of-principle of a-g tagging with SHARC+TIGRESS
  - Angular distribution of 8.32 MeV (unbound) state in 14C*
  - Not enough energy resolution with SHARC only (expected) to extract individual angular distributions of the states in 6-7MeV range.
  - Not enough statistics to produce γ-tagged angular distributions

- $^{12}C(^{6}He,^{8}Be)^{10}Be^*$
  - Angular distributions extracted for gs and first excited (3.3MeV) states
  - Two-proton transfer favored, need angular distribution fits
  - Something to be learned on $^{12}C_{gs}$? α-clustered states in the ~6MeV region?

Millicent Audrey Smalley (b. Mar 22, 2012)

Duane Smalley
(PhD student)

The SHARC / TIGRESS Collaboration:

University of York
University of Manchester
University of Surrey
University of Birmingham
University of Liverpool
Daresbury Laboratory

Colorado School of Mines
Louisiana State University

TRIUMF
Mc Master University
Simon Fraser University
St Mary's University
Université de Montreal
University of Guelph

LPC Caen

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THE END

BACKUP SLIDES

Elastic/Inelastic Future Work

- Link inelastic scattering of DCD to DBx
- Create theory model
  - Current model is adjusted mass parameters of $^{6}Li + ^{12}C$ optical potential
  - Create model of $^{6}He + ^{12}C$
  - Collaboration with F. Nunes at NSCL/MSU
- Theory model then basis for further transfer reaction studies
  - Elastic scattering fits normalization parameter
  - Inelastic fits nuclear excitation model

Future Work

- Complete analysis of 8.32 MeV angular distribution
- Add the 2n transfer to the reaction model
  - Can compare to Milin et al.
  - Will help expand transfer model
- Reaction can be compared to (t,p) reaction
  - Enhance of transfer?
  - Population of states

Work Time line

- February 2012
  - Defend Thesis proposal
- Winter 2012
  - Continue data analysis
  - Extract all angular distributions
    - 2^+ 4.4 MeV inelastic
    - 2^+ 8.32 MeV 2n transfer
    - 0^+ ground state (^{6}He,^{8}Be)
    - 2^+ 3.3 MeV (^{6}He,^{8}Be)
- Winter/Spring 2012
  - Develop microscopic model in collaboration with F. Nunes
  - Use microscopic model to test hypothesis of ^{12}C(^{6}He,^{8}Be)^{10}Be reaction mechanism
- Spring/Summer 2012
  - Make final conclusions
- October 2012
  - Defend thesis

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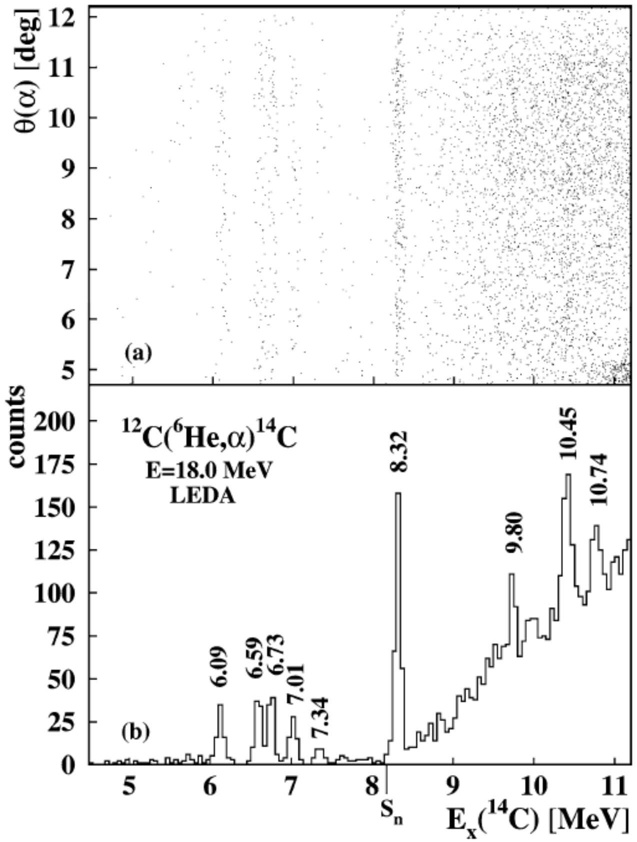
Benchmarking (^{6}He,^{4}He) against (t,p)

- Goal:
  - Compare cross-sections & angular distributions for selected states in a nucleus well studied by (t,p)
    - Enhancement due to ^{6}He halo?

^{12}C(t,p) studied by F.Ajzenberg-Selove et al., Phys. Rev. C17 (1978) 1283

^{12}C(^{6}He,^{4}He) measured once by Milin et al., Nucl. Phys. A730 (2004) 285

- Same states populated
- Different intensities for some states
- Only one angular distribution extracted by Milin et al. (8.32MeV)



From M.Milin et al., Nucl. Phys. A730 (2004) 285

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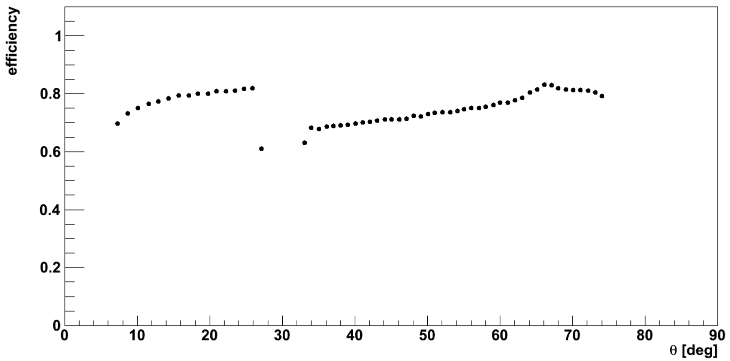
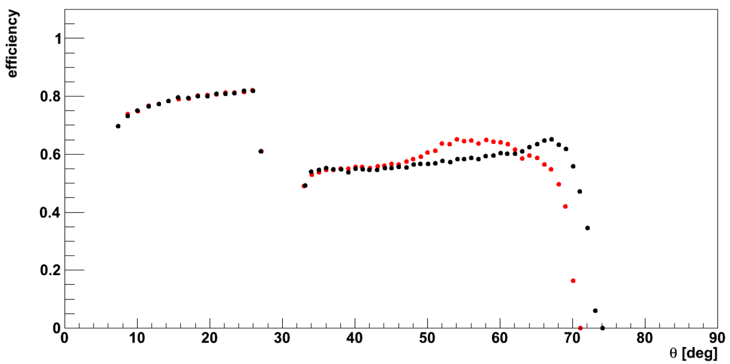
Efficiency Cuts

- Inter-strip distance between strips taken into account
  - Simulations distribute charge collected proportionally according to distance between inter-strip
  - DCD lower efficiency at low angles because of greater surface area of inter-strip to total surface area of strip ratio
    - 24 back strips of 0.1 mm distance over a smaller surface area
- Coincident cuts lower efficiency due to dual detection of particles inter-strip efficiency Ex. At ~32 deg 6He efficiency is .70 and 12C eff at .8, coincident eff is .7*.8 = 0.55





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