Physics opportunities with the AT-TPC at ReA

D. Bazin
NSCL / MSU

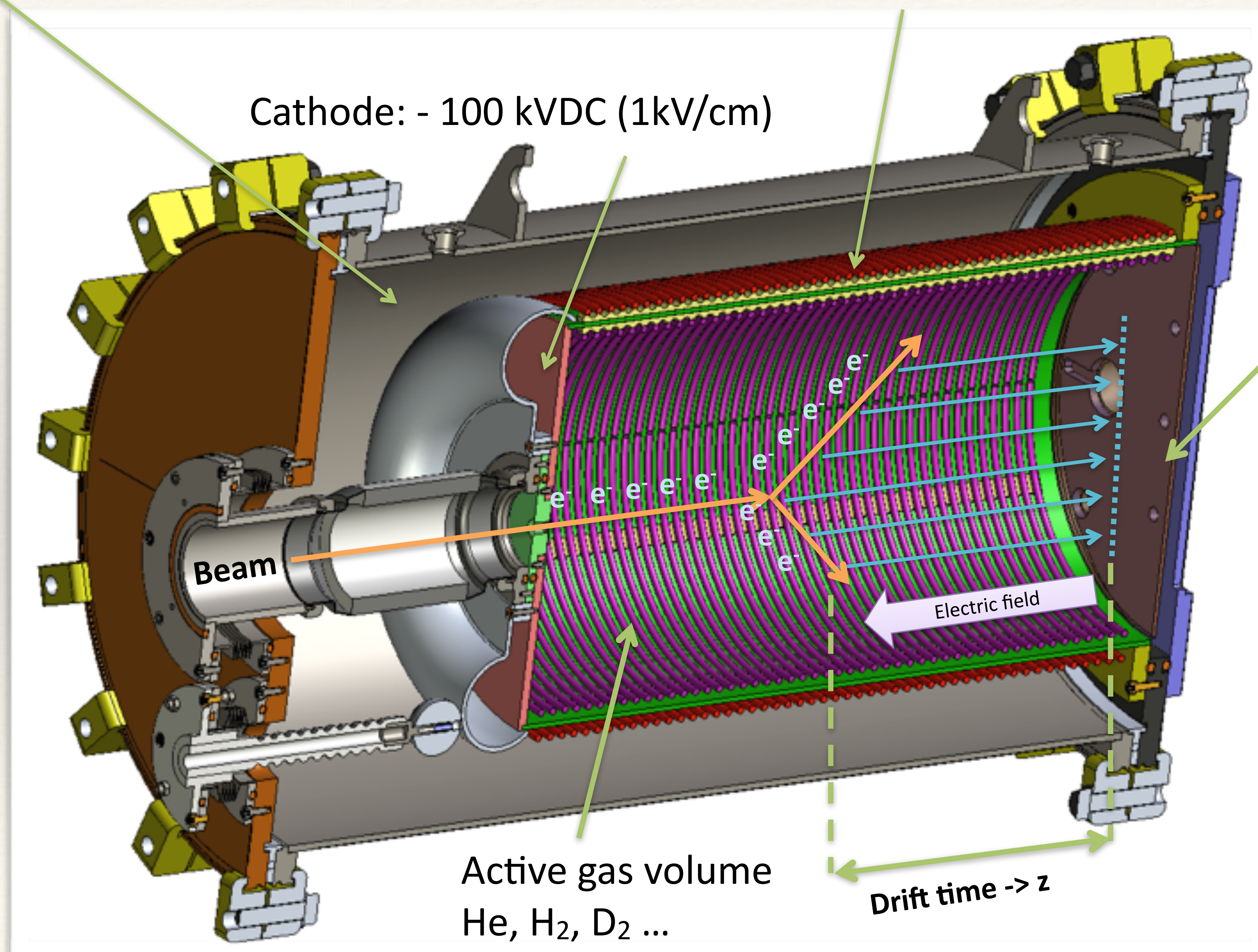
Reaction studies at ReA

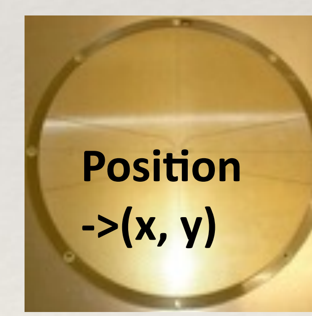
- Radioactive beams are used in inverse kinematics
  - Target is now the (usually light) probe nucleus
  - Scattered particles have low energies
  - Beam intensities are small (from 1 to 10^8 pps)
  - High luminosity needed: large acceptances, thick targets
- New types of instruments needed
  - Active Target Time Projection Chamber (AT-TPC)
  - Gas is both target and detector medium: thick target without loss of resolution
  - Vertex determination, virtually 4π angular coverage, very low energy threshold
  - Excitation functions from beam slow down and vertex determination

AT-TPC physics program at ReA

- Resonant scattering for nuclear cluster structure studies
- Inverse kinematics proton scattering for single-particle structure studies via IAS population
- Fusion cross sections with neutron-rich isotopes below the Coulomb barrier
- Inverse kinematics transfer reactions for single-particle structure such as (d,p), (p,d), (p,t), (^{3}He,d), …
- Excitation functions of reactions of astrophysical interest such as (α,p) for instance
- Exotic radioactive decays (3α decay from ^{12}C Hoyle state, 2p radioactivity, …)
- ReA3 upgrade is crucial to access the full potential of these reaction tools

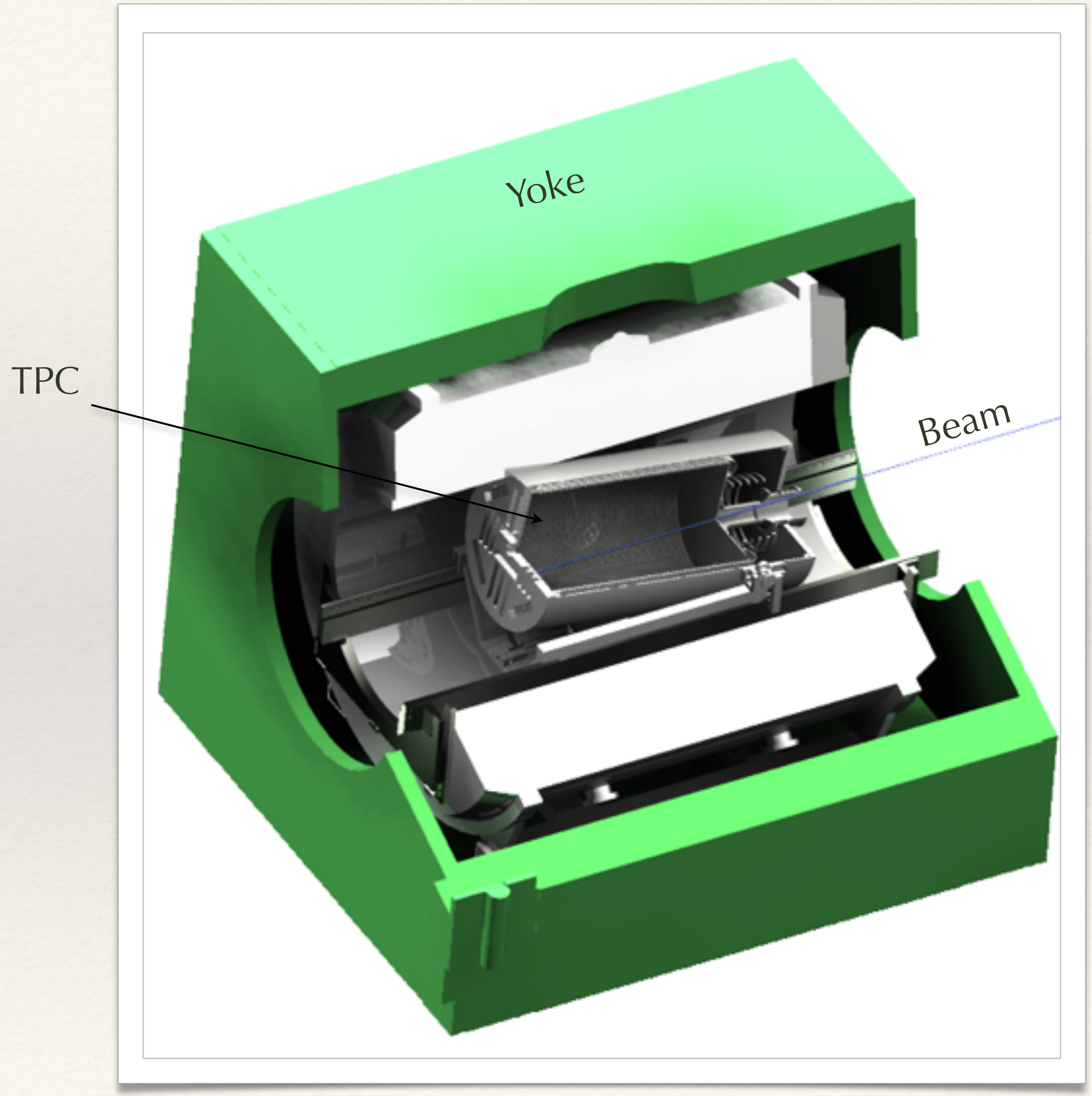
Principle of operation





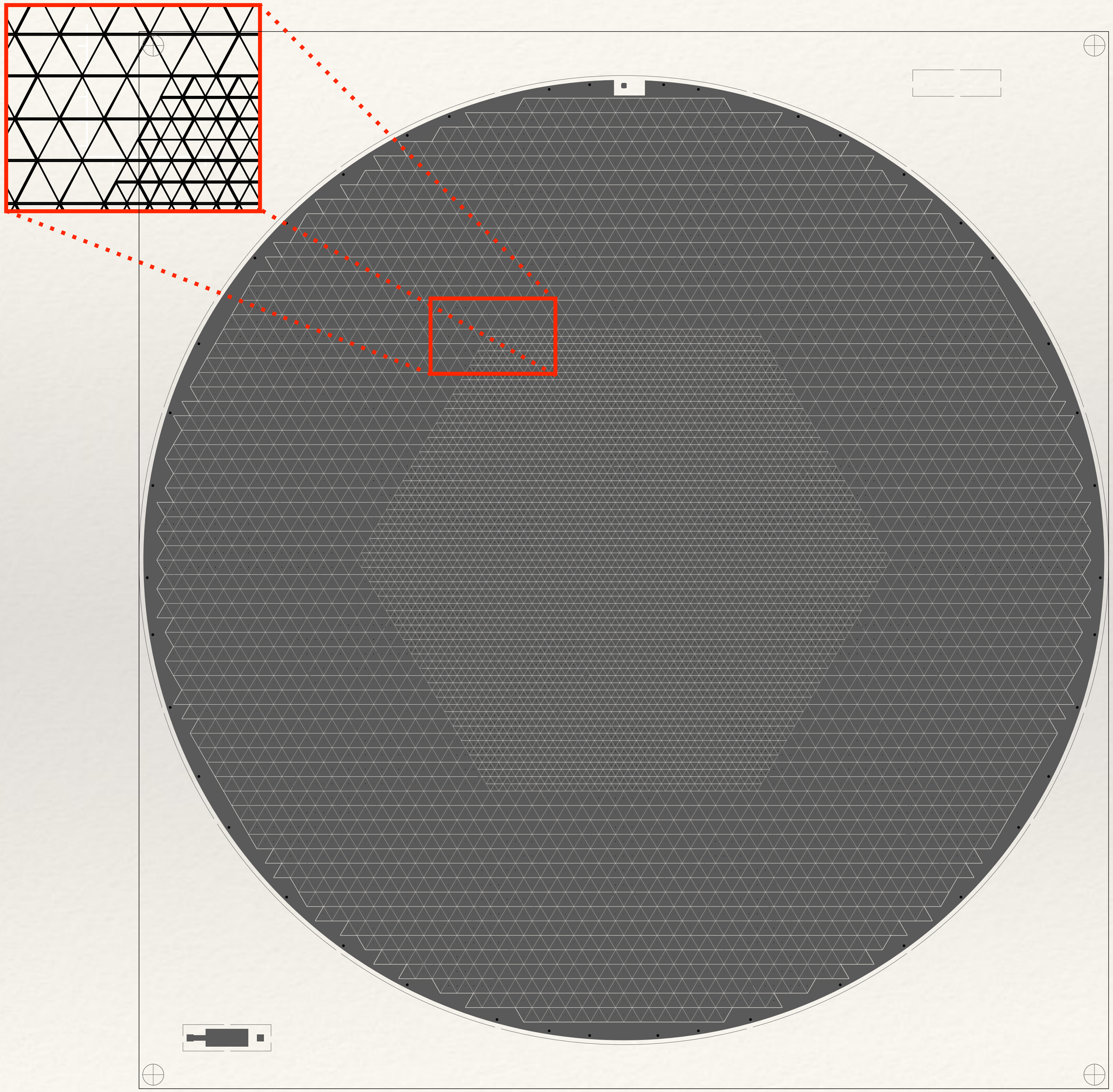
AT-TPC setup

- Straight and tilted (7°) configurations
- Tilt relative to beam axis to increase accuracy for small angles
- Placed inside 2 Tesla solenoid (increase range and measure Brho)
- 250 liters (1 m by 55 cm) active volume
- Financed by NSF-MRI



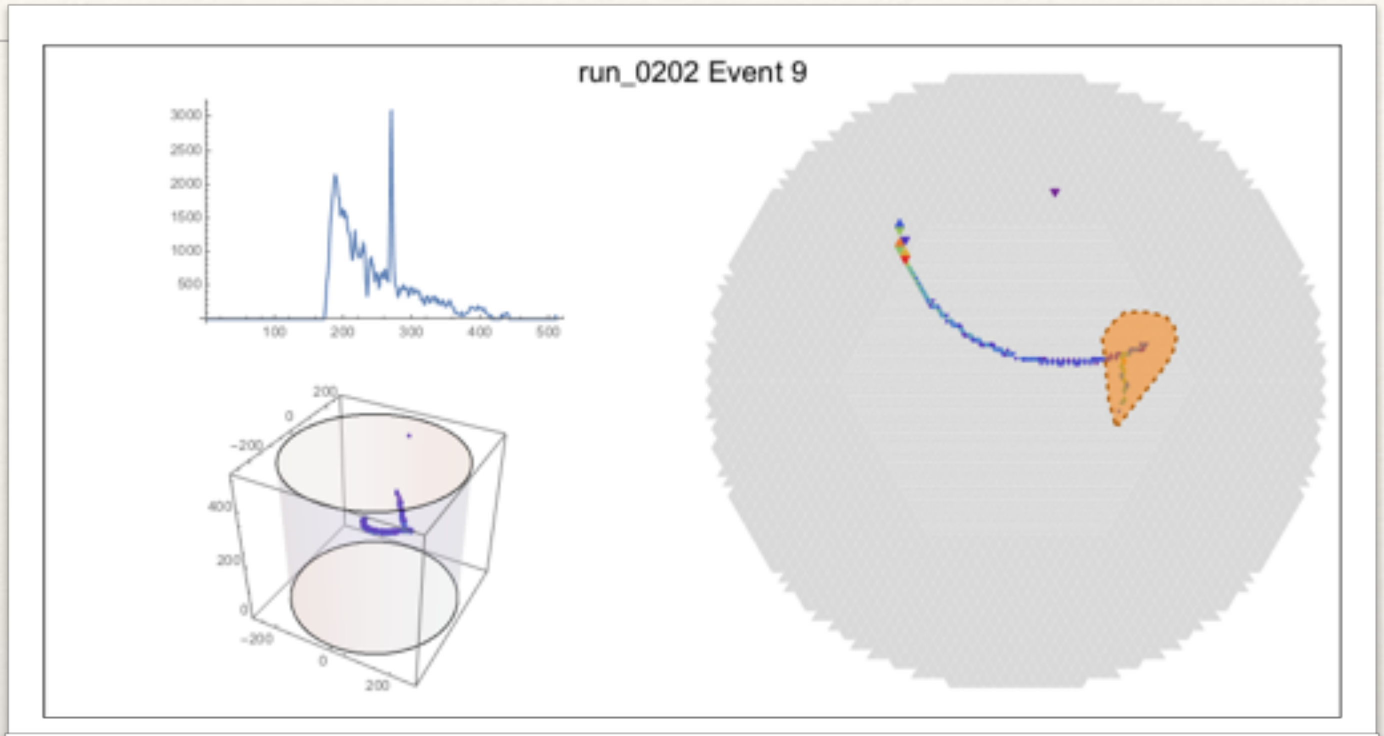
Pad plane and electronics

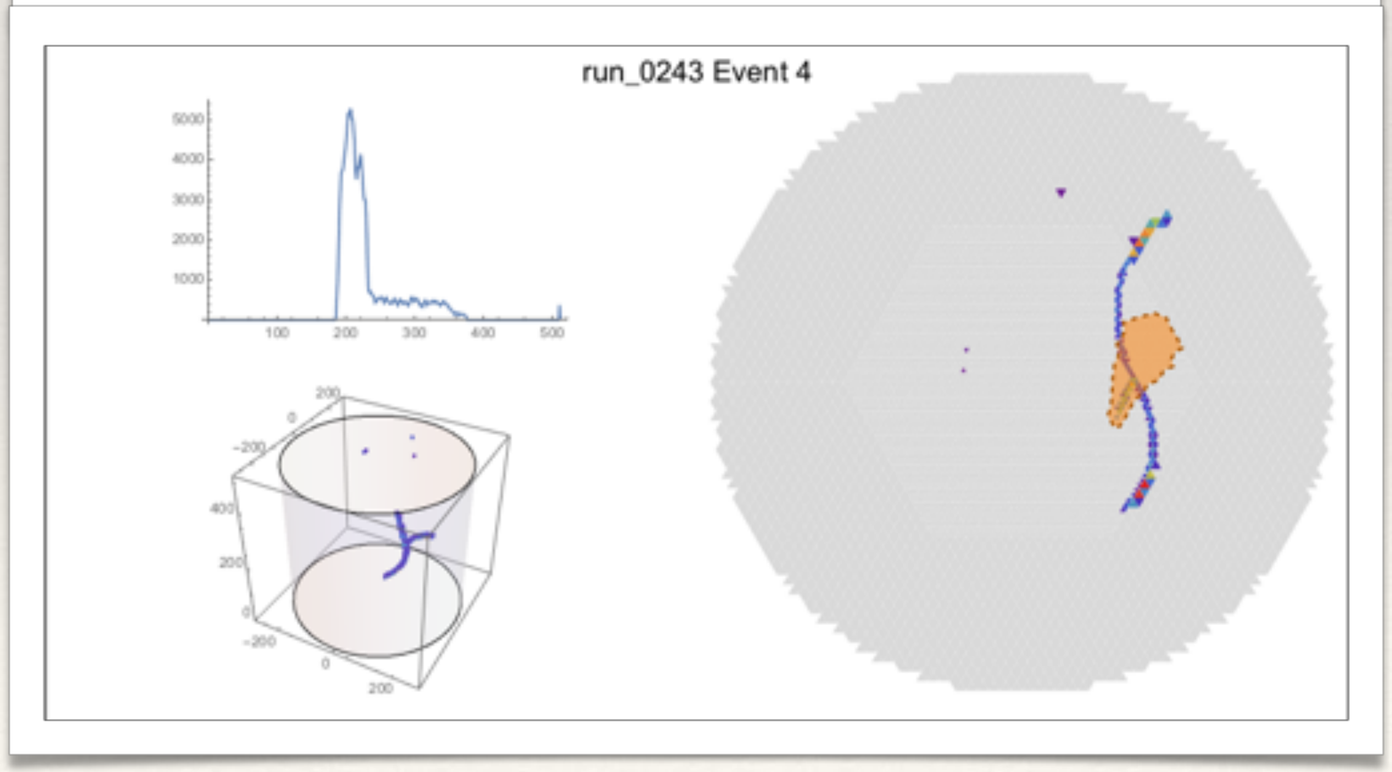
- 10,240 triangular pads
  - Central region density x4 for small angle scattering
- GET (General Electronics for TPC)
  - Digital readout instrumentation of each pad
  - Internal trigger generation using multiplicity signals
  - Data filtering (partial readout, zero suppression, …)



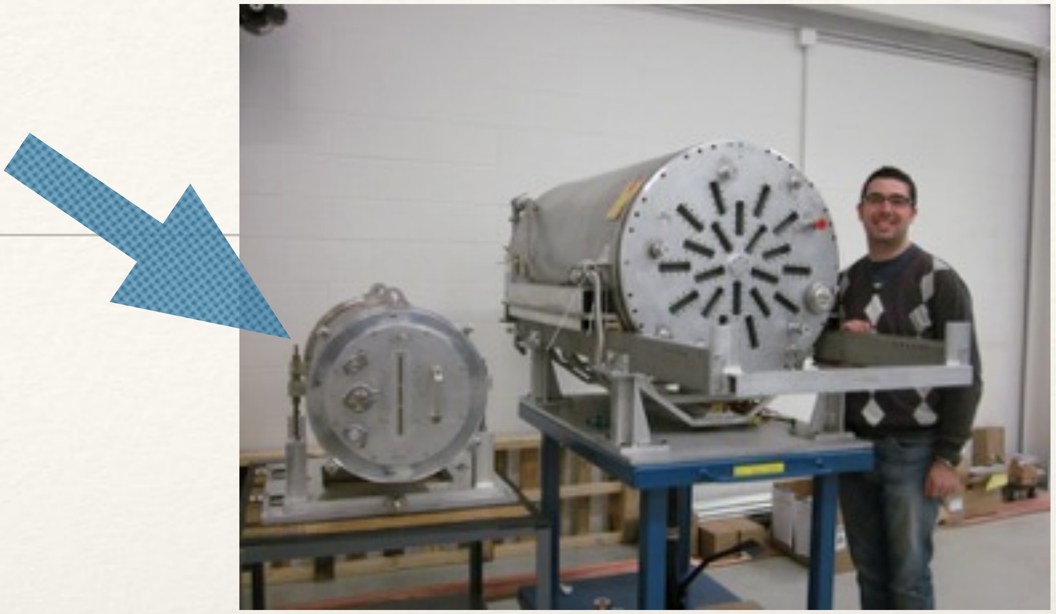
Visualization of nuclear reactions in 3D

- Last commissioning in December 2014
  - Beam: ^4He at 3 MeV/u
  - Target: He(90%) + CO_2(10%) @ 100 Torr
  - Magnetic field: 2 Tesla
- Event displays
  - Right: hit pattern on pad plane, orange region is trigger exclusion zone
  - Top left: integrated time projection
  - Bottom left: 3D reconstruction of event



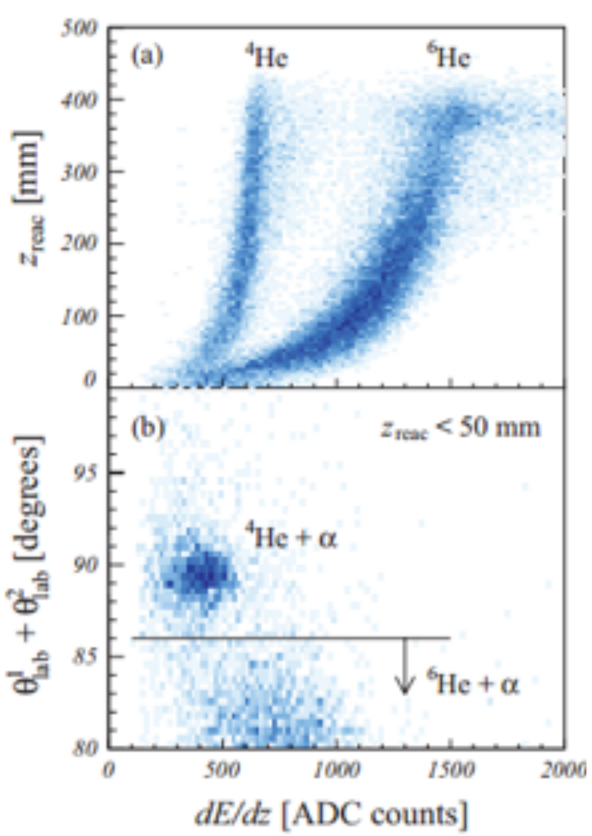


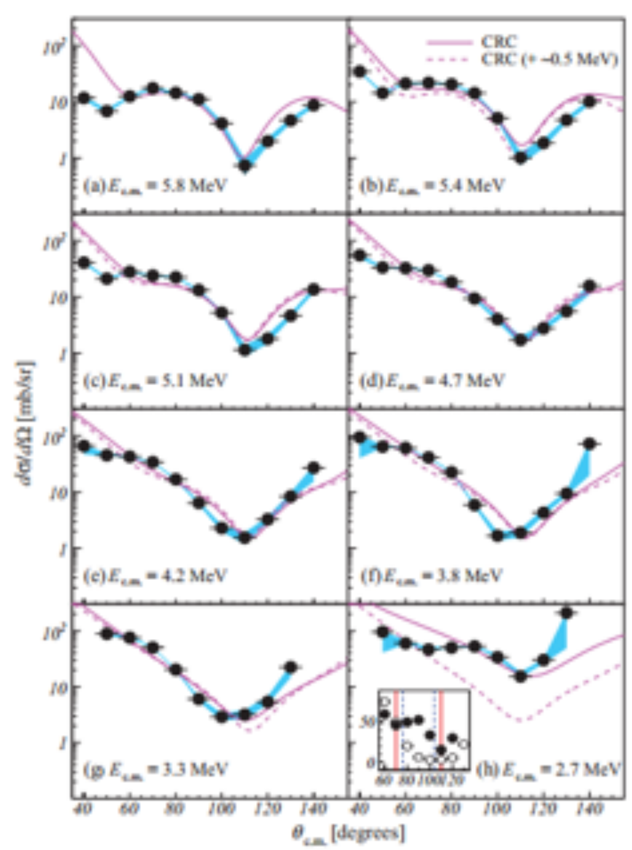
Prototype AT-TPC



Prototype AT-TPC

Scattering ^{6}He + α at Twinsol
- 2000 pps ^{6}He
- Confirm strong α-cluster state in ^{10}Be.





Suzuki et al. PRC 2013

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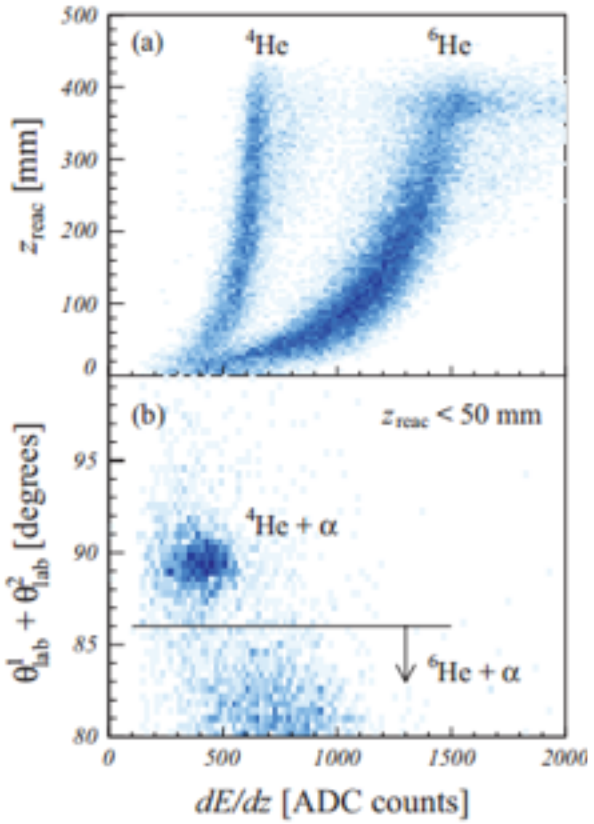

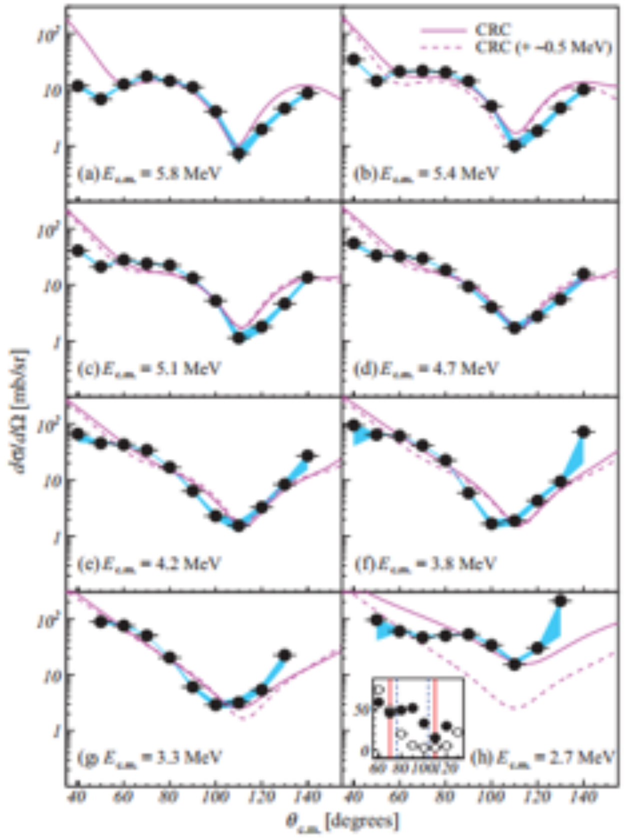

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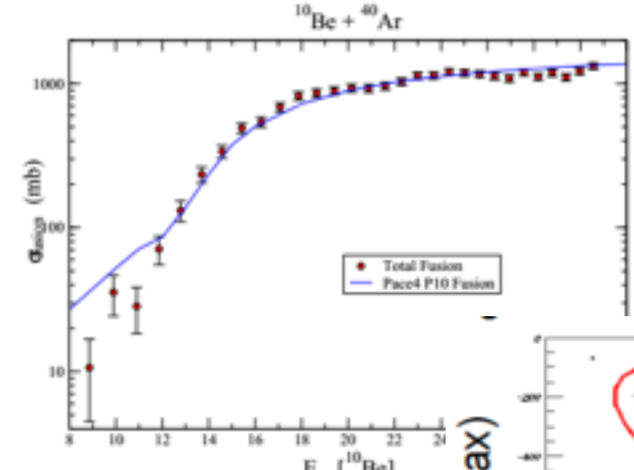
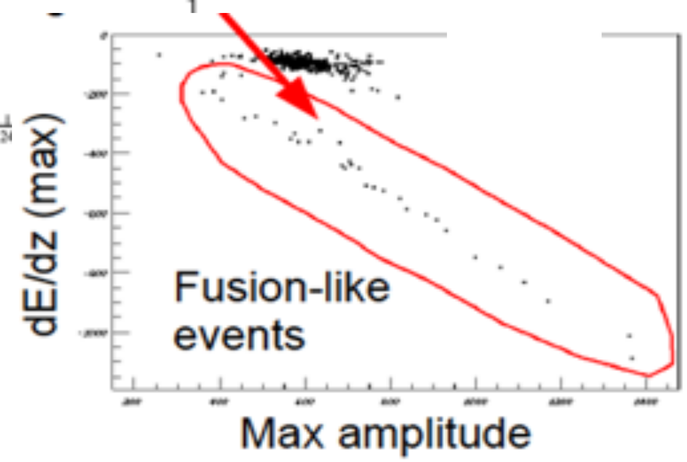
Fusion ^{10}Be + P10 (Ar/Methane)

- Sub-barrier fusion with low-intensity RIBs. (200 cps)

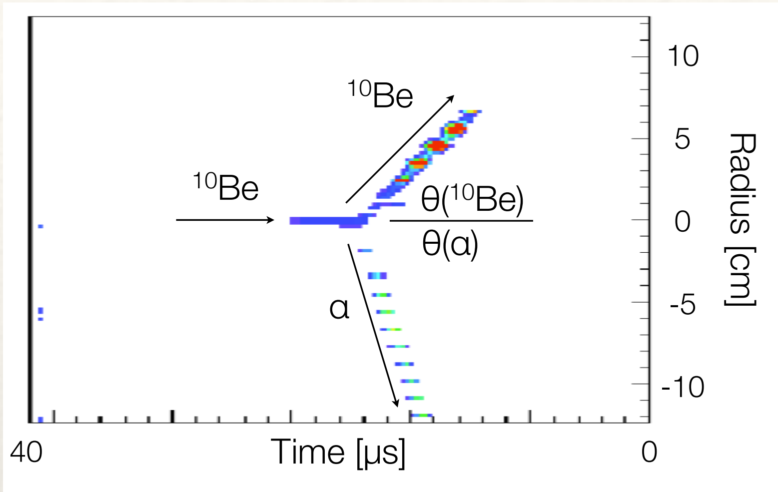


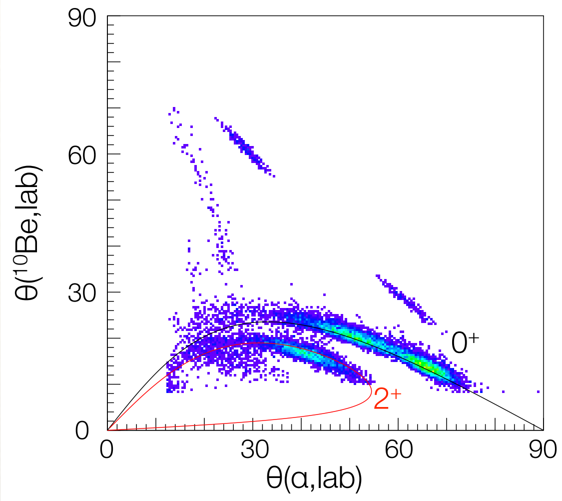


J. Kolata
A. Howard
(Notre Dame)

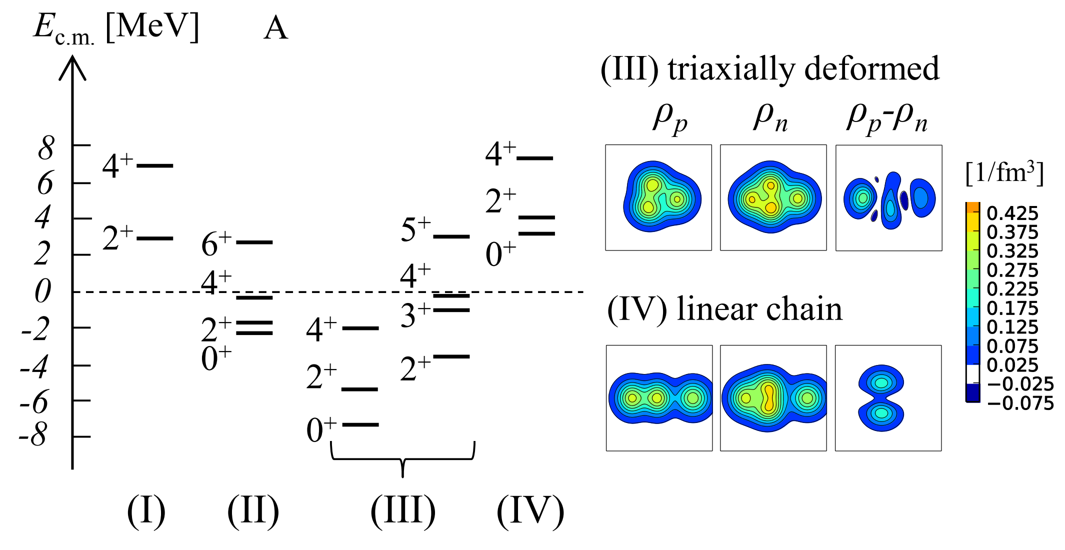
Cluster states in ^{14}C

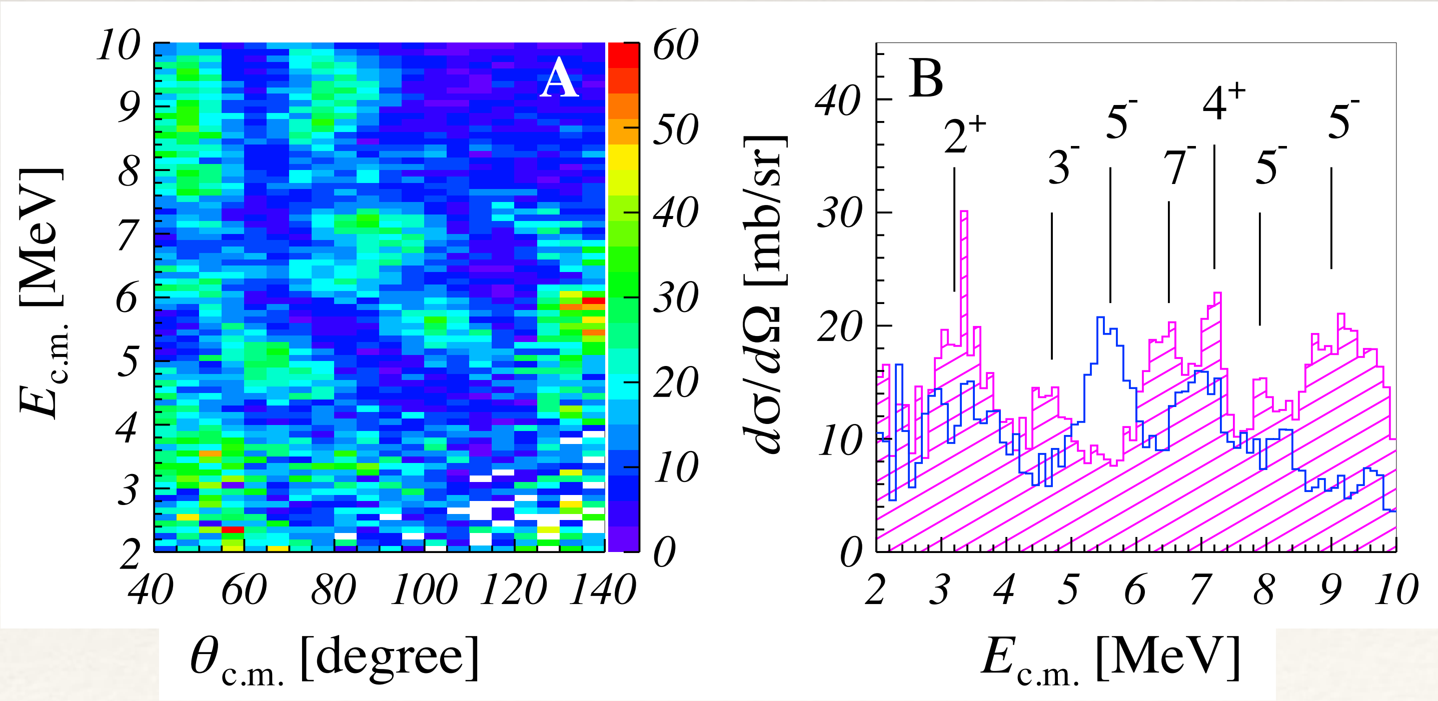
- Resonant scattering of 4 MeV/u ^{10}Be beam (TWINSOL) on ^{4}He
- Observed 2^+ and 4^+ resonances match linear chain calculations (AMD)





- A. Fritsch et al., submitted to PRC





Proton scattering to IAS resonances

- Evolution of neutron orbitals in ^{A}Z can be studied via the $^{A}Z(d,p)^{A+1}Z$ transfer reaction or by populating $T_{>}$ analog states of ^{A+1}Z in $^{A+1}Z+1$ via the $^{A}Z(p,p')$ reaction
- Spectroscopic factors for excited states in ^{A+1}Z can be deduced reliably from cross sections of resonances observed in $^{A+1}Z+1$

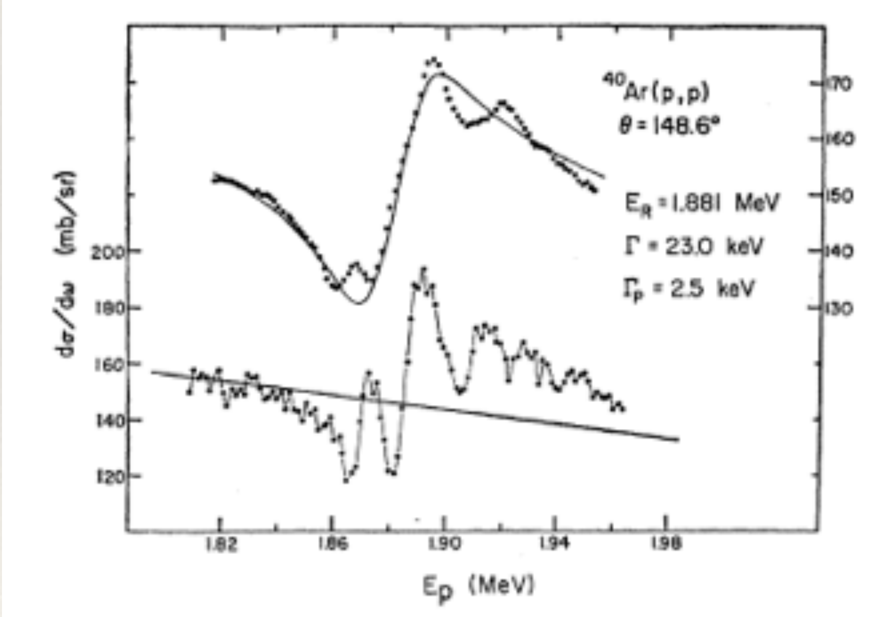


FIG. 1. The 1.88-MeV analog resonance. On this and all subsequent figures the lower set of points are data taken with <3-keV incident energy spread and are referred to the left ordinate. The upper points are the data after averaging over 25 keV, referred to the right ordinate. The smooth curve through the upper data is the resonance fit and the curve through the lower data gives the

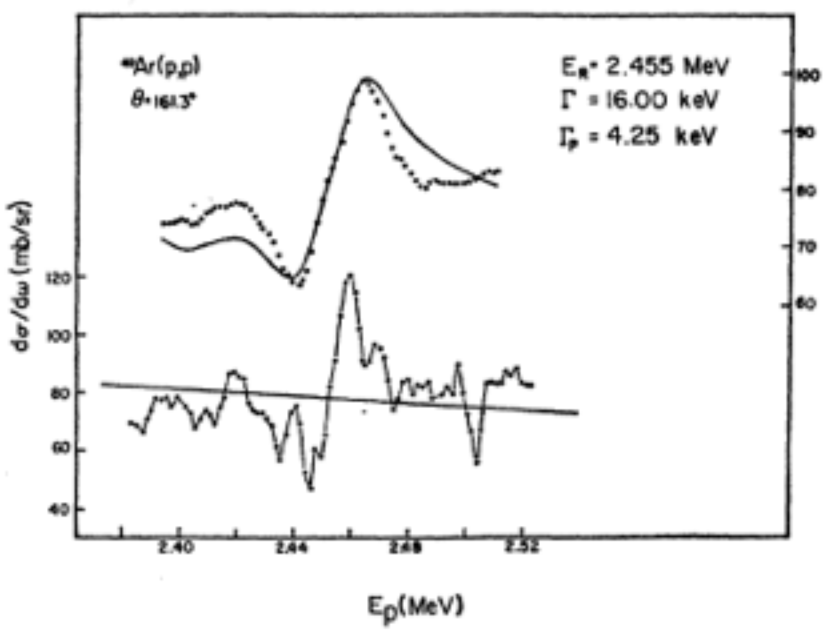
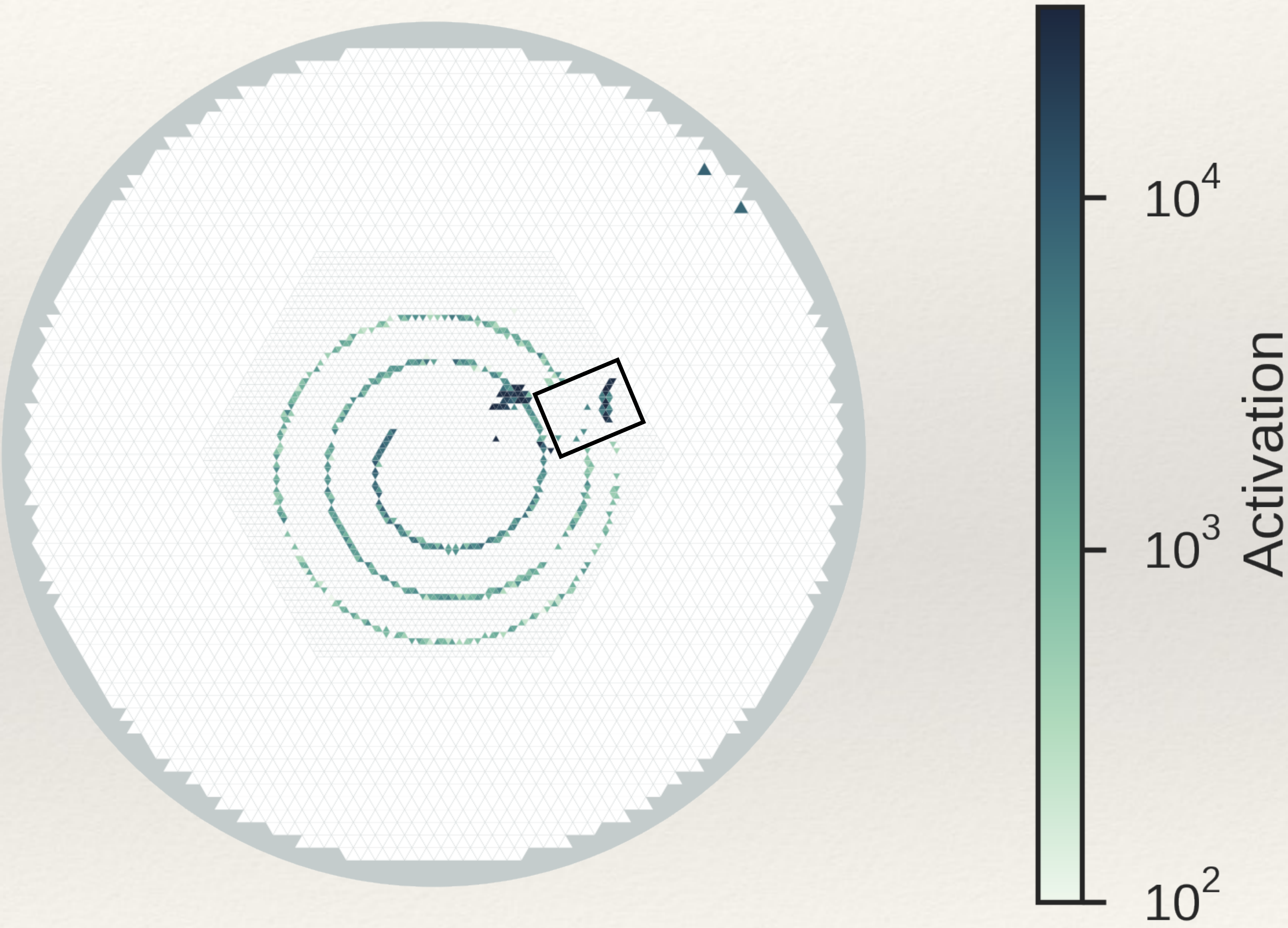


FIG. 2. The 2.46-MeV analog resonance and fit. The caption of Fig. 1 applies to this and all subsequent figures. The abscissa scales are laboratory energies and all indicated angles are laboratory angles.

Inverse kinematics in AT-TPC

- ^{40}Ar beam from ReA3 at 4.5 MeV/u
- Gas target: 20 Torr of C_4H_{10}
- Excitation function from incident energy to 0 (beam stopped)
- Next experiment: ^{46}Ar at 4.2 MeV/u from ReA3 + CCF (9/2015)
- Higher beam energies would allow reaching higher energy states



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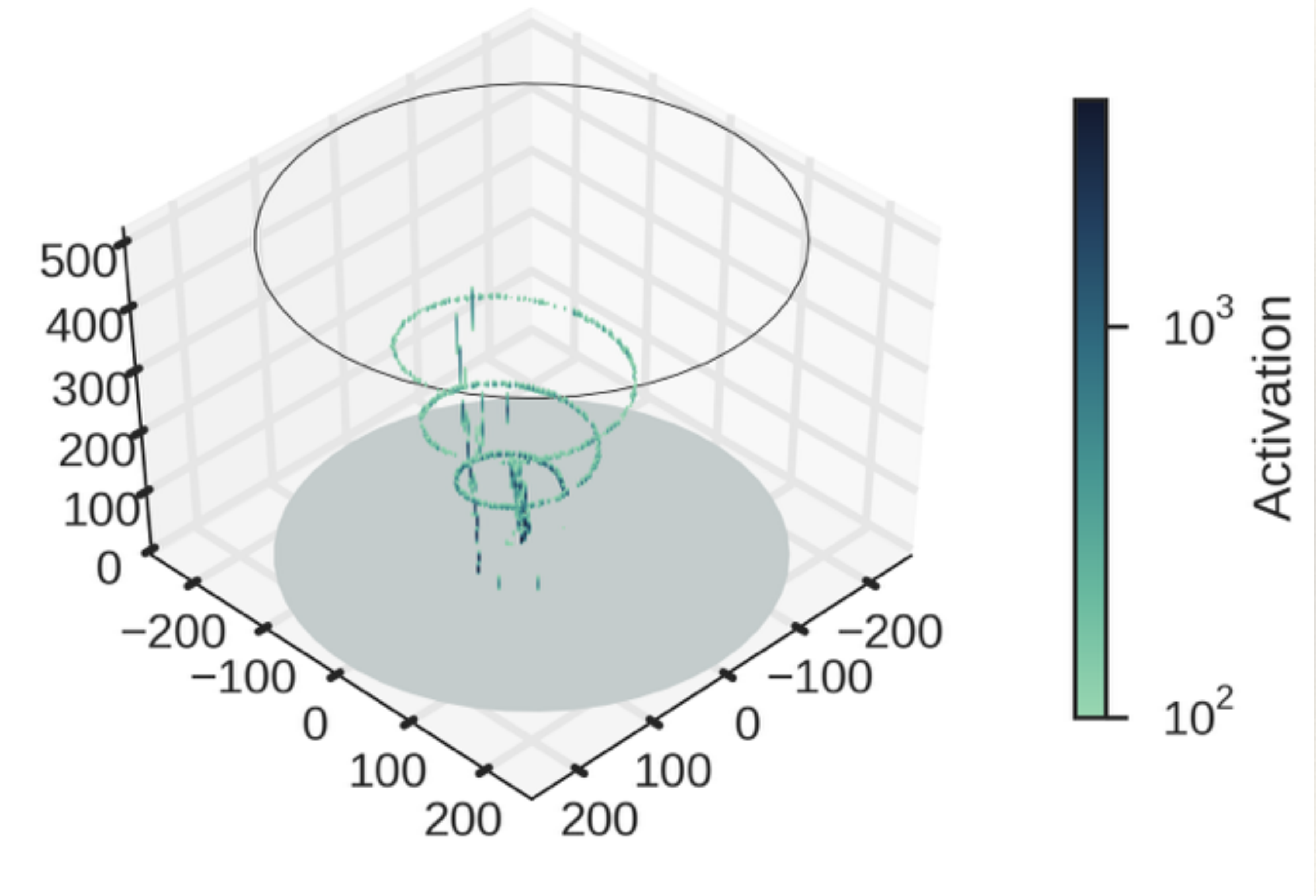
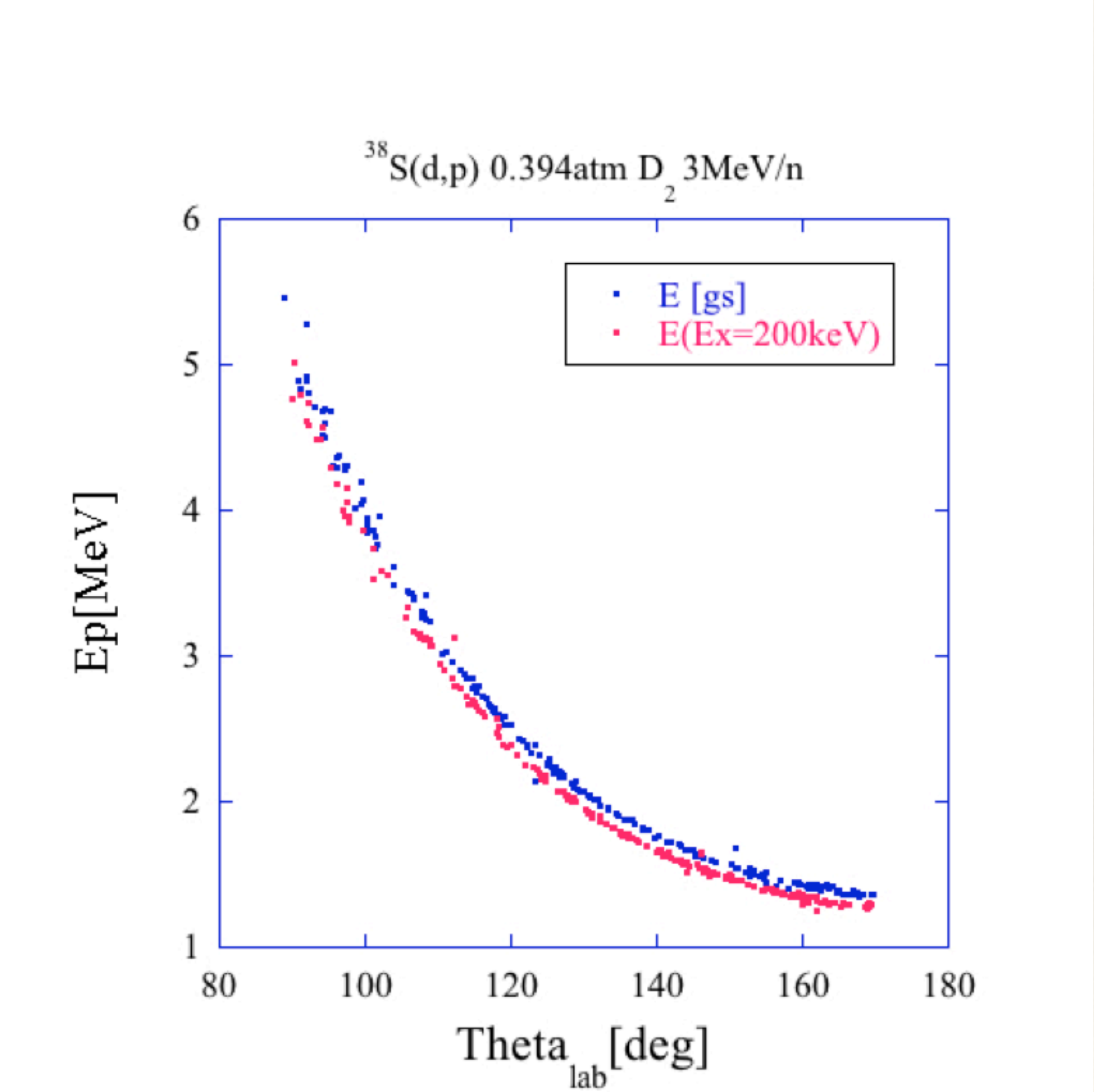


Transfer reactions

- ReA3 energies too low for most cases (Q-value, momentum matching)
- AT-TPC can provide highest luminosity, can detect both light and heavy particles with close to 4π coverage and good resolution
- Elastic cross section of entrance channel measured simultaneously
- H_2 and D_2 gas targets can be made significantly thicker than CH_2 and CD_2 foils
- Reaction energy known for each event (vertex), allows to sum angular distributions measured at different energies

Example: $^{38}S(d,p)$

- Study shell quenching between N=20 and N=28 below the Z=20 closure
- Simulations show 200 keV resolution achievable



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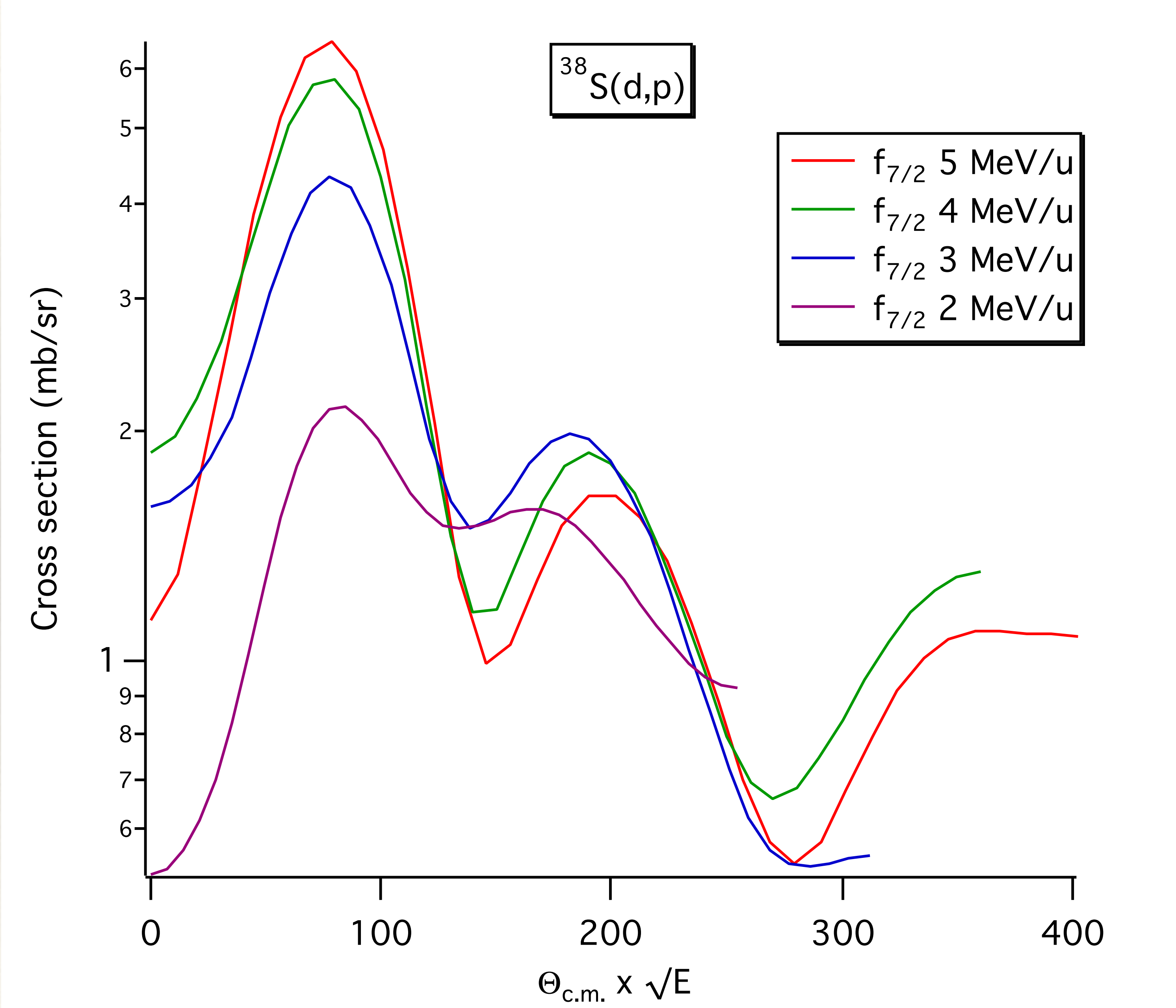

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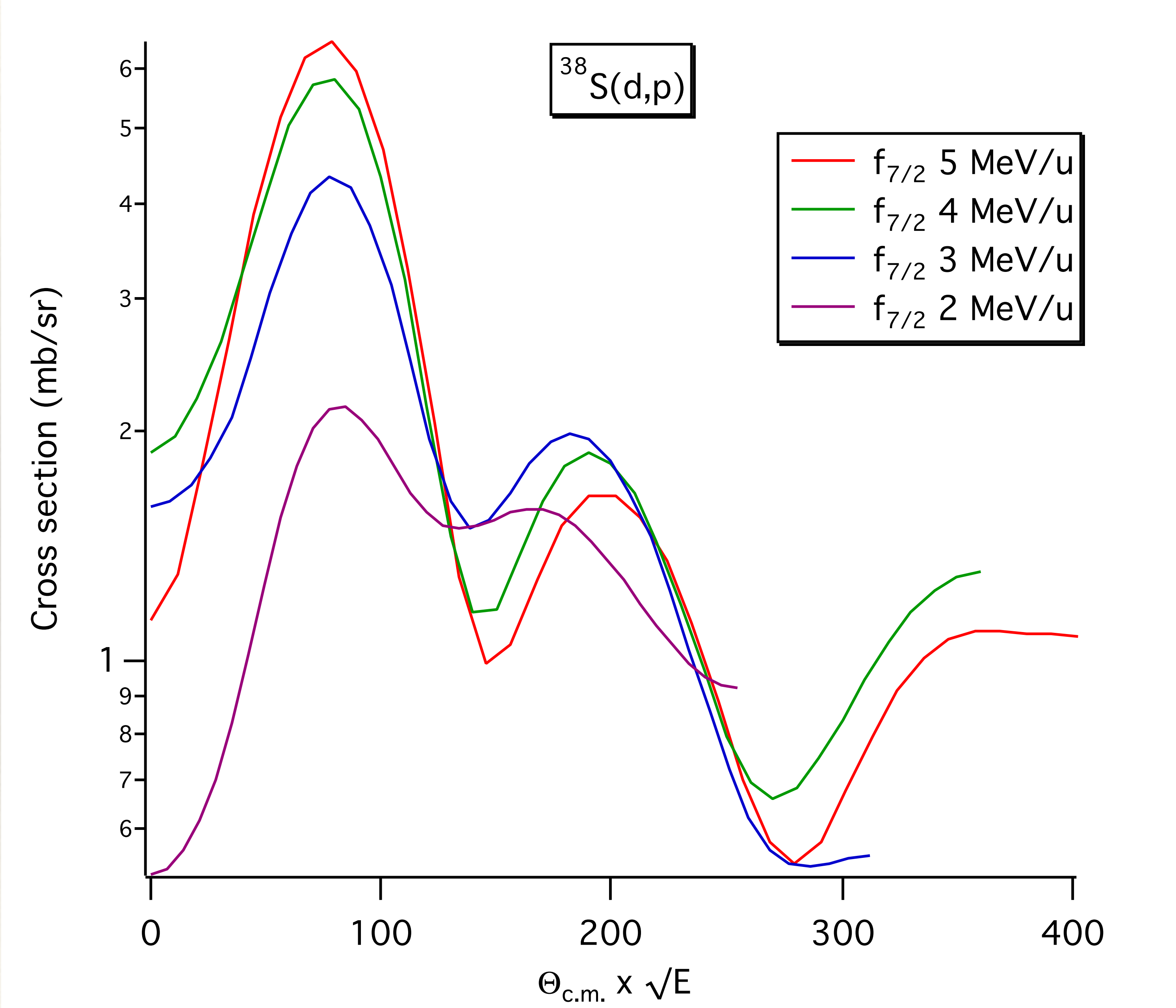

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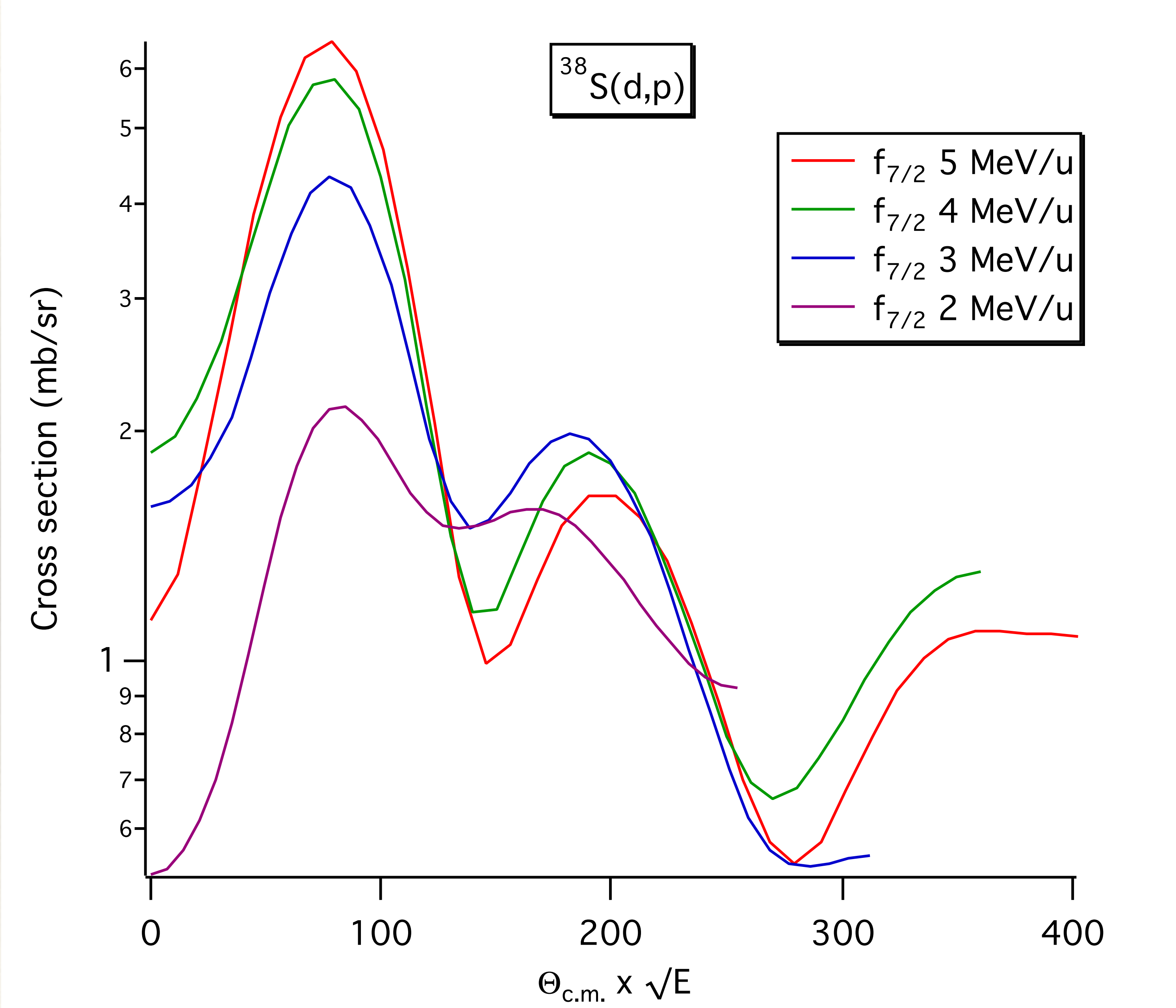
- Energy should be 10-12 MeV/u! Needs ReA12!



Outlook

- ReA3 upgrade to energy range 10-15 MeV/u would open great opportunities for experiments with the AT-TPC
- The AT-TPC can provide high luminosity without compromising resolution
- This is paramount because of the low intensities of re-accelerated radioactive beams
- Simple transfer reactions such as (d,p), (p,d), (d,^{3}He) are of particular interest

AT-TPC collaboration

- NSCL team
  - D. Bazin, W. Mittig, W. Lynch, S. Beceiro-Novo, Y. Ayyad, J. Bradt, L. Carpenter, J. Manfredi, S. Rost, M. Cortesi, J. Yurkon
- Other institutions
  - T. Ahn, J. Kolata, Z. Chajecki, D. Suzuki, U. Garg, R. Kanungo