Constraining the Electron Capture Rates of Neutron-Rich Nuclei with (d,^{2}He) in Inverse Kinematics

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19th Russbach School on Nuclear Astrophysics

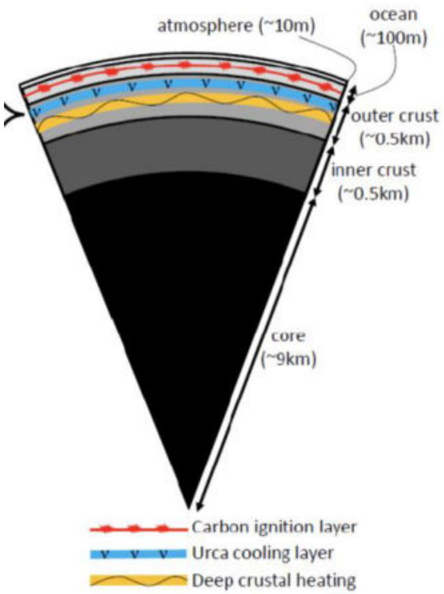
Constraining the Electron Capture Rates of Neutron-Rich Nuclei with (d,^{2}He) in Inverse Kinematics

- The important role of electron captures in astrophysical simulations
- The extraction of Gamow-Teller strengths from charge-exchange experiments
- A new experimental tool for extracting Gamow-Teller strengths in the EC direction from unstable nuclei: the (d,^{2}He) reaction inverse kinematics
- First application: the ^{14}O (d,^{2}He) reaction in inverse kinematics
- Conclusions

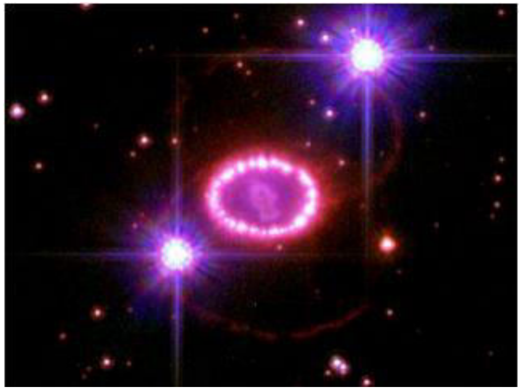
Electron Capture Rates are Important Inputs for Astrophysical Simulation

Electron Capture (EC) Rates are important for:

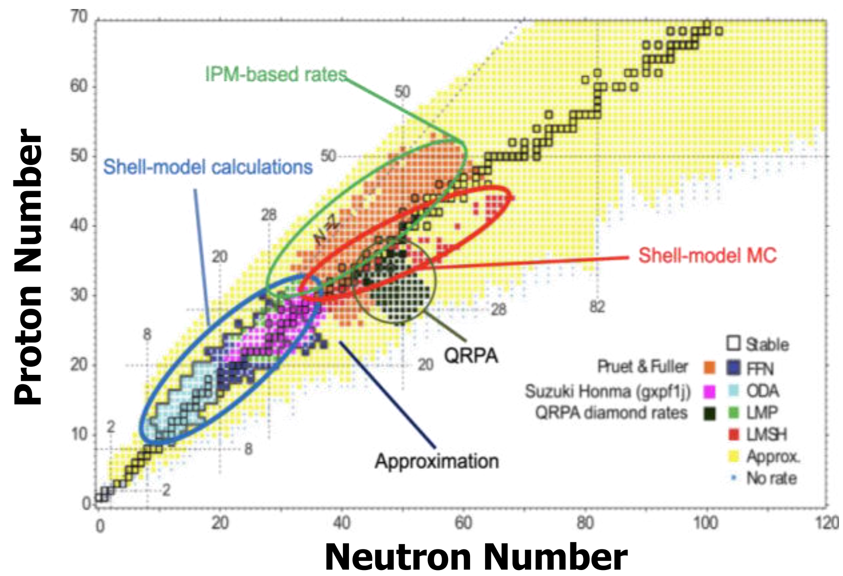
- Core-collapse and thermonuclear supernova
- Crust of accreting neutron stars in binary systems
- Final core evolution of intermediate mass stars
- ....



Courtesy Space Telescope Science Institute/NASA



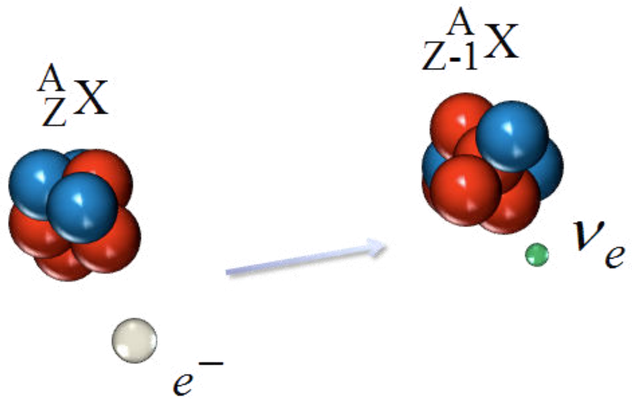
The remnant of supernova 1987a



Weak Rate Library: https://groups.nscl.msu.edu/charge_exchange/weakrates.html
NuLiB : http://www.nulib.org

- Experimental data is needed to benchmark and guide the theoretical models.

Gamow-Teller Transition Strength Necessary for Estimating EC Rates in Stellar Environments

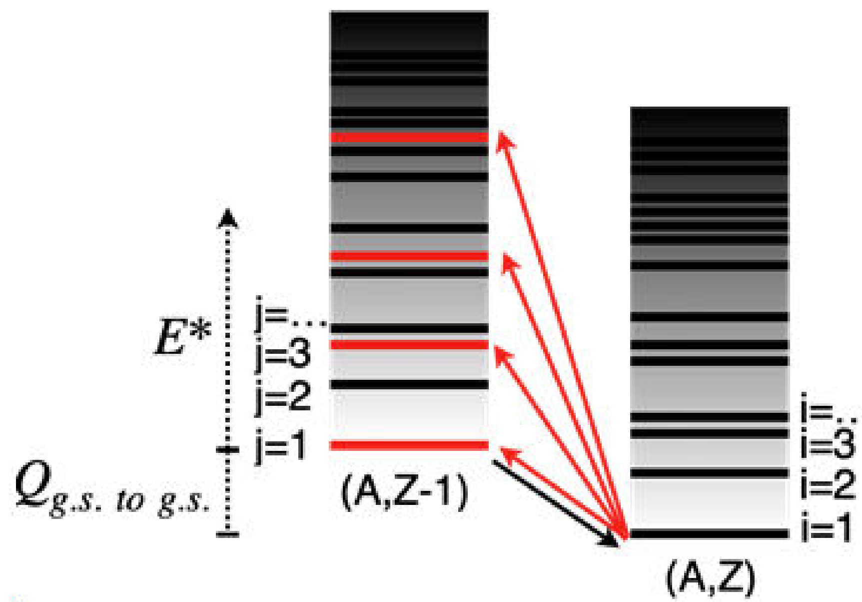


$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

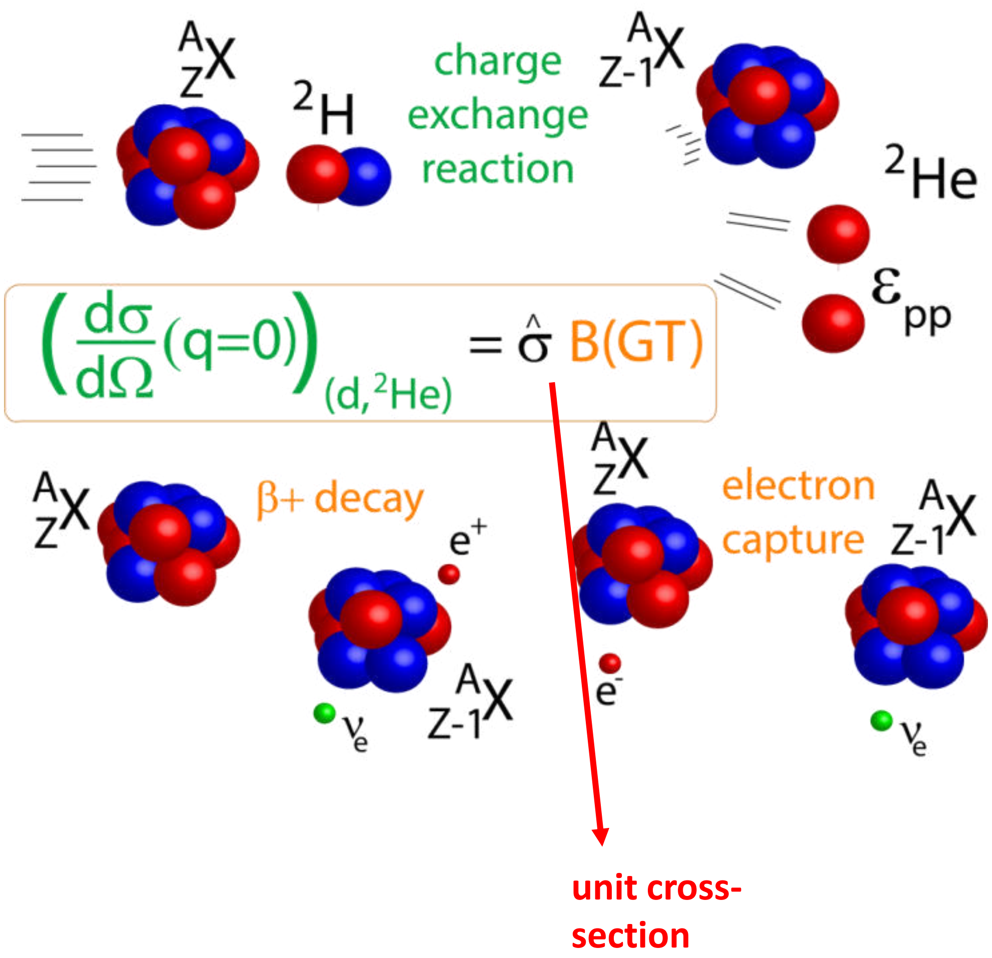
phase space factor

- EC from ground state
- β^- from ground state

- Electron capture is mediated by the weak nuclear force
- EC Rates are dominated by allowed Gamow-Teller (GT) transitions at relatively low temperatures ($\Delta L = 0, \Delta S = 1, \Delta T = 1$)
- Direct measurement possible only for g.s. to g.s. and low-lying states transition through EC/β decay data.

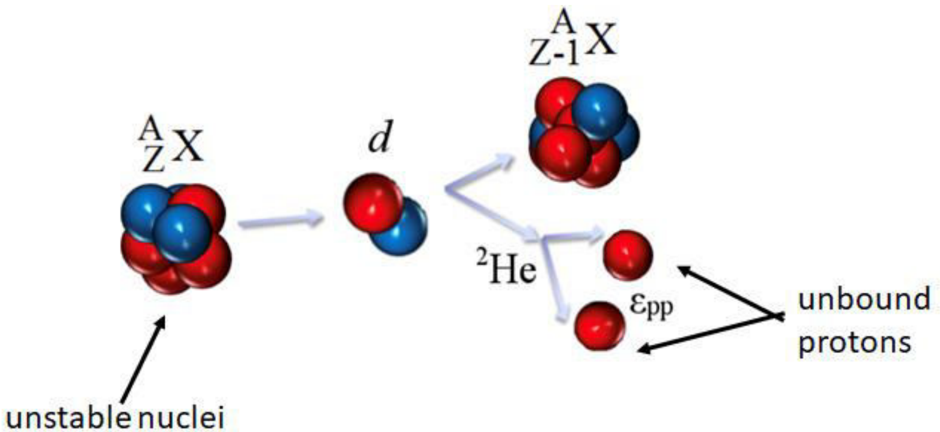


Charge-Exchange Reactions can Extract *B*(GT)



- Indirect measurement of *B*(GT) with (*n,p*)-type charge-exchange reactions at E_{beam}~100 MeV/u.

(*d*,^{2}He) Reaction in Inverse Kinematics can be Used Across the Chart of Nuclei



^{2}He = a pair of protons coupled to $^1S_0$ state:

- Incident deuteron is in $^3S_1$ state, and the (*d*,^{2}He) reaction proceeds almost exclusively by spin transfer (ΔS = 1), if ϵ_{pp} < 2 MeV.
- The proportionality between differential cross section and *B*(GT) for the (*d*,^{2}He) reaction in forward kinematics is well established.

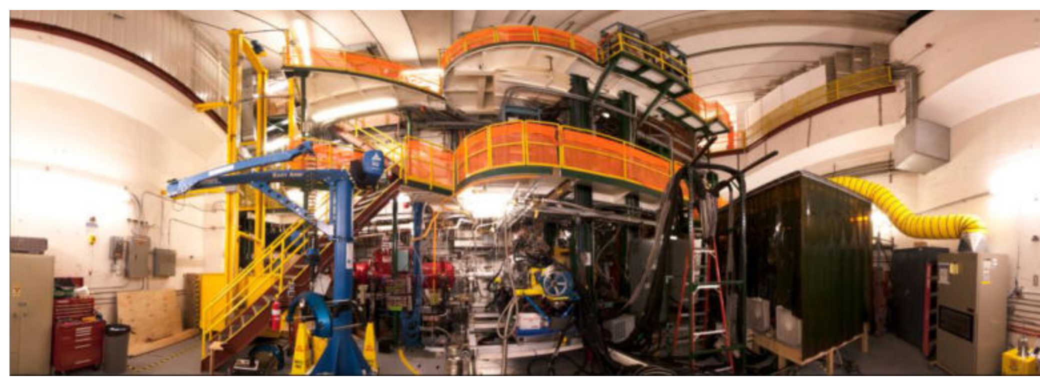
[(GT) transitions ($\Delta L = 0, \Delta S = 1, \Delta T = 1$)]

First Experiment: $^{14}O(d,^{2}He)$ Reaction in Inverse Kinematics

$^{14}O(d,^{2}He)^{14}N$ reaction primary focus of the experiment (Giraud *et al.*)

- Novel use of an Active Target Time Projection Chamber to detect low-energy recoils from inverse kinematics experiment at low momentum transfer (q=0)
- Magnetic Spectrometer is used to detect reaction products (^{14}N, or one of its decay products after decay by particle emission)
- Technique can also be used for other reactions in inverse kinematics, e.g., (p,p'), (α,α'), etc.

AT-TPC (Active-Target Time Projection Chamber) at the target location of the S800 for the experimental setup (before cabling).



S800 without the AT-TPC in its target location.

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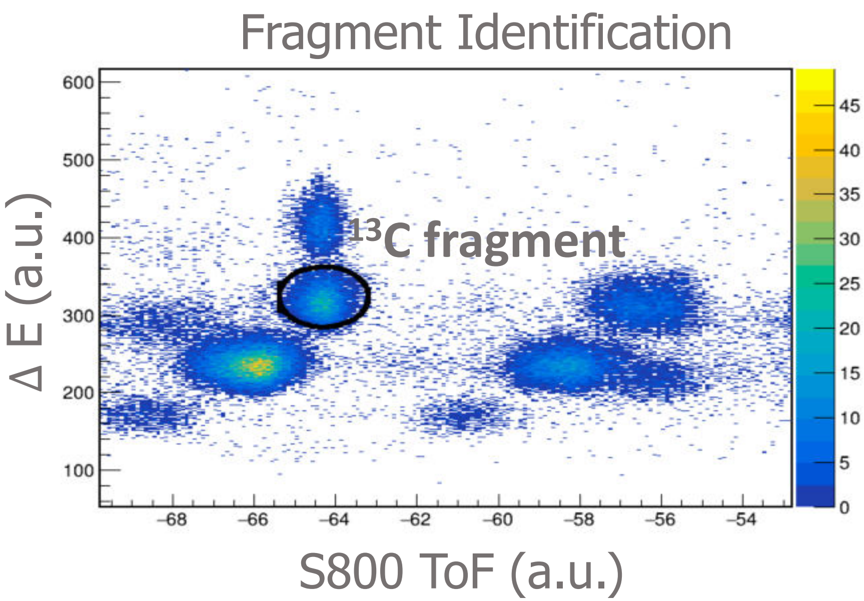
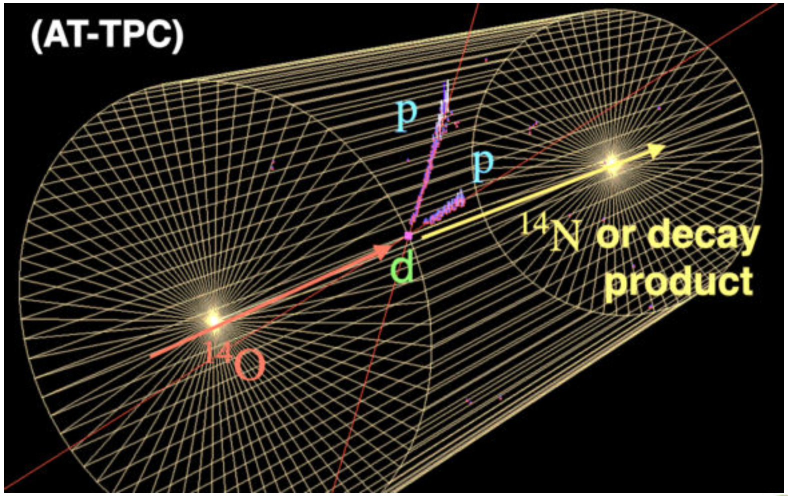
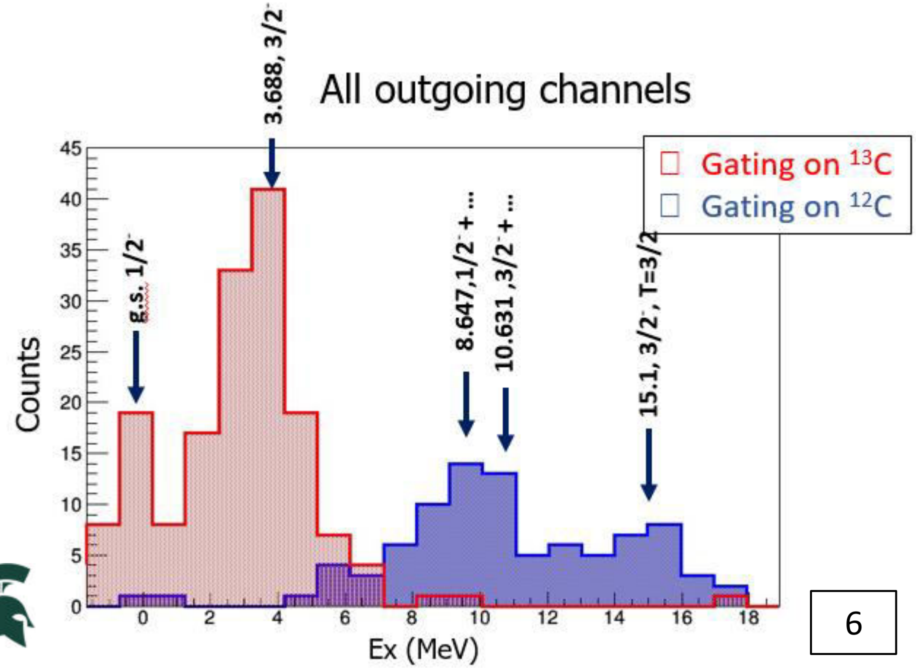
Reconstruction of Excitation Energy from PID and Analysis of Tracks in the AT-TPC



- AT-TPC readout provides the momentum vector of the two protons.
- Momentum and scattering angle of ^{2}He is reconstructed.
- Excitation energy of the residual ^{13}C and center of mass scattering angle is reconstructed.





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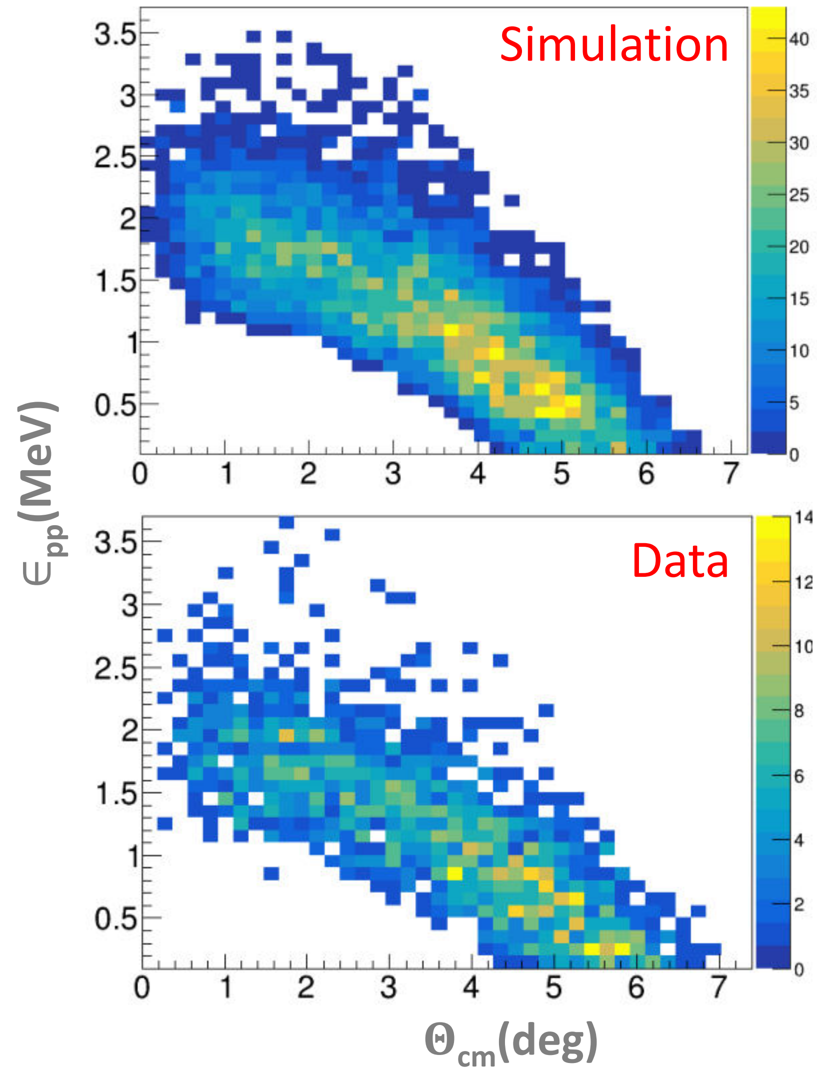
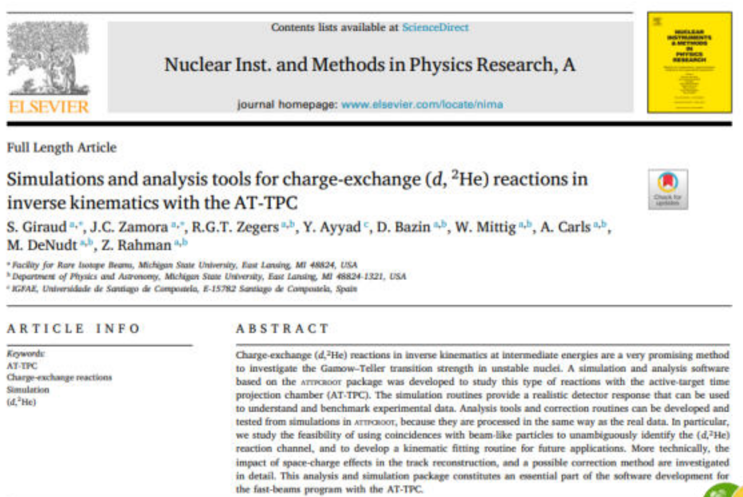
Simulation is Important for Understanding the Detector Response and Correction for Limited Acceptances

- FairRoot framework (GEANT4 + ROOT)
- Simulation is done in three main stages- event generator, digitalization, and reconstruction.
- Same analysis frame works used for data and simulation.
- ε_{pp} acceptance depends on ^{2}He scattering angle
- S800 momentum acceptances also included





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Full Length Article

Simulations and analysis tools for charge-exchange (d, ^{2}He) reactions in inverse kinematics with the AT-TPC

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ABSTRACT

Charge-exchange (d,^{2}He) reactions in inverse kinematics at intermediate energies are a very promising method to investigate the Gamow–Teller transition strength in unstable nuclei. A simulation and analysis software based on the ATTPCROOT package was developed to study this type of reactions with the active-target time projection chamber (AT-TPC). The simulation routines provide a realistic detector response that can be used to understand and benchmark experimental data. Analysis tools and correction routines can be developed and tested from simulations in ATTPCROOT, because they are processed in the same way as the real data. In particular, we study the feasibility of using coincidences with beam-like particles to unambiguously identify the (d,^{2}He) reaction channel, and to develop a kinematic fitting routine for future applications. More technically, the impact of space-charge effects in the track reconstruction, and a possible correction method are investigated in detail. This analysis and simulation package constitutes an essential part of the software development for the fast-beams program with the AT-TPC.

S. Giraud *et al.* (2023)

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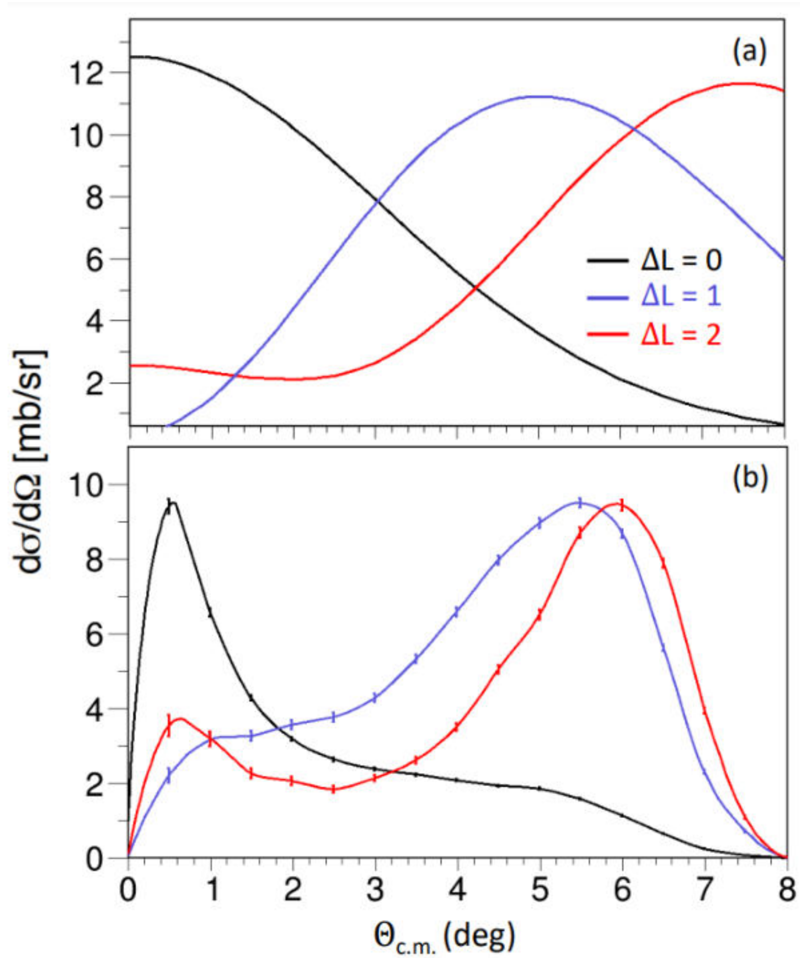
Extraction of the GT (ΔL = 0) Component is Performed Through a Multipole Decomposition Analysis

[(GT) transitions ($\Delta L = 0, \Delta S = 1, \Delta T = 1$)]

$\Delta L = 0$ component extracted with Multipole Decomposition Analysis (MDA) on identified peaks:

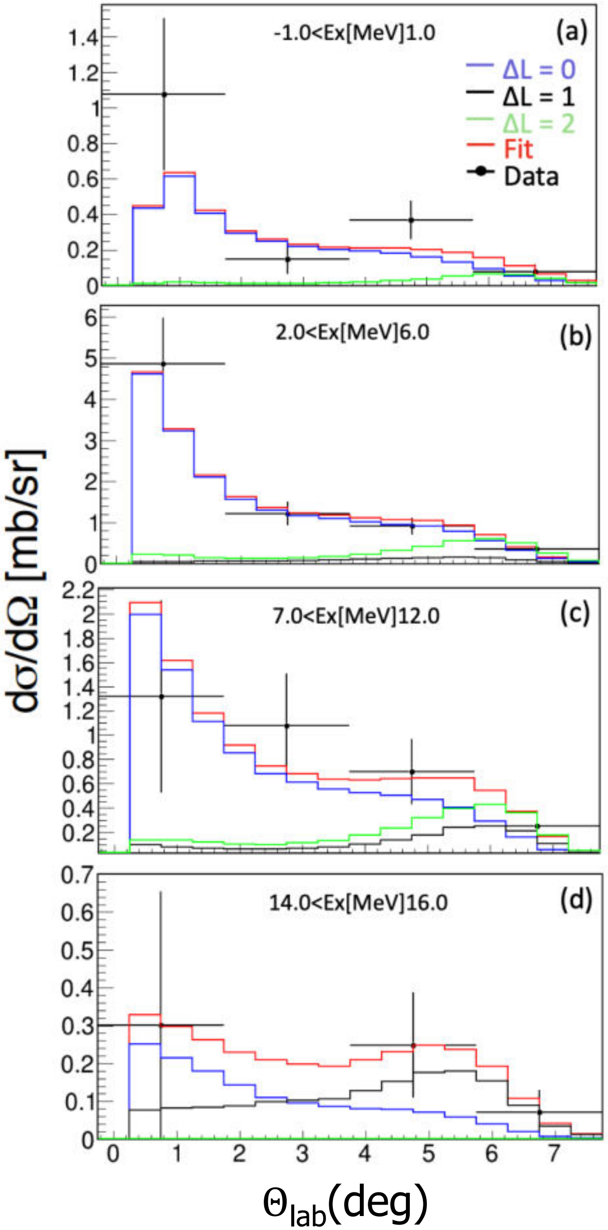
$$\frac{d\sigma}{d\Omega} = a_0 \frac{d\sigma}{d\Omega}\bigg|_{\Delta L=0} + a_1 \frac{d\sigma}{d\Omega}\bigg|_{\Delta L=1} + a_2 \frac{d\sigma}{d\Omega}\bigg|_{\Delta L=2}$$

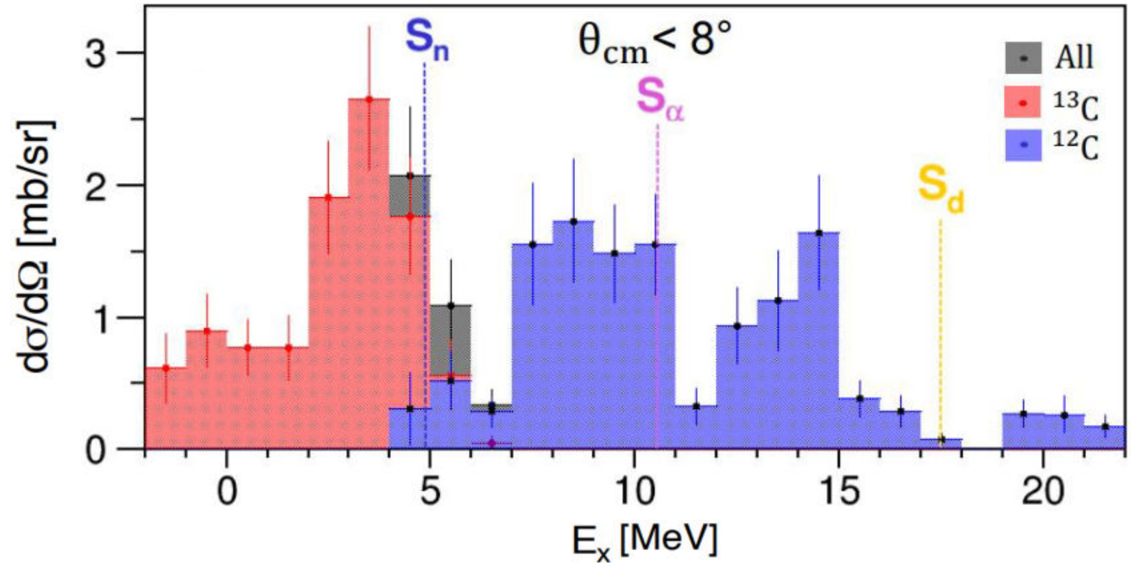
- ACCBA (Adiabatic Coupled-Channels Born Approximation) code is used to calculate theoretical differential cross-section. (H. Okamura (1999))
- $\frac{d\sigma}{d\Omega}$ from ACCBA is used in simulation to account for detector response as a function of ϵ_{pp} and θ_{cm}.

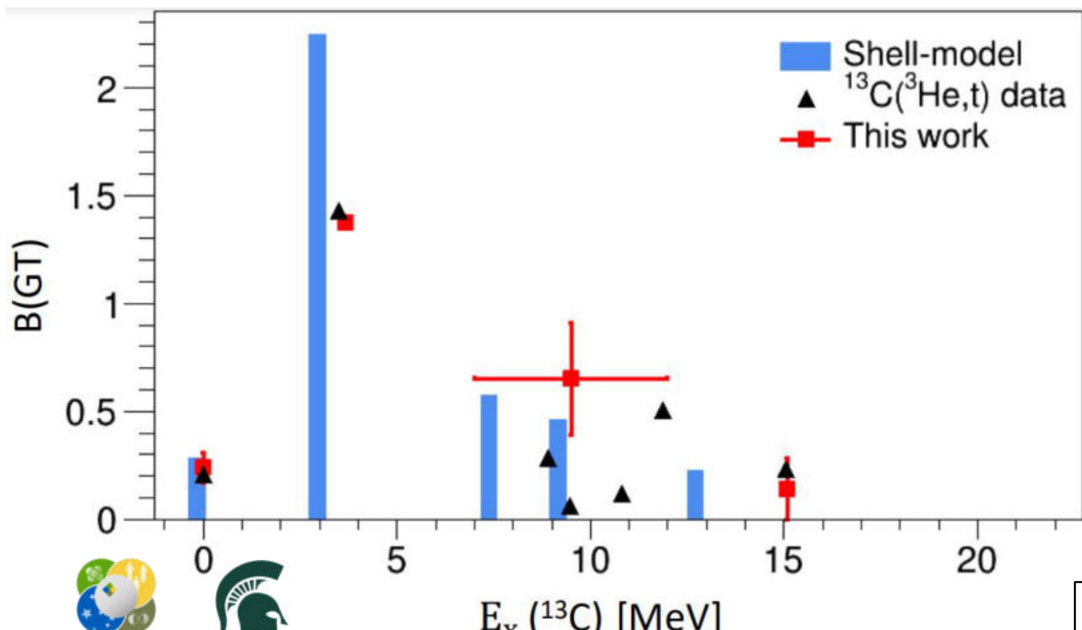


Extracted Differential Cross Section

Multipole Decomposition Analysis







Extracted GT Strengths: $^{14}O(d,{}^{2}He)$

- Unit cross section calibrated to the strong transition to 3.95 MeV, known from β-decay
- Results consistent with $^{14}C(p,n)$ for E_x<15 MeV
- Shell-model calculations reproduce strength-distribution reasonably well after application of a phenomenological quenching factor of 0.67, but does not predict strength for E_x>15 MeV
- CC calculation reproduced strength distribution well, without additional quenching, including high-lying strength E_x>21 MeV)

β^+ Gamow-Teller strengths from unstable ^{14}O via the $(d, {}^{2}\text{He})$ reaction in inverse kinematics

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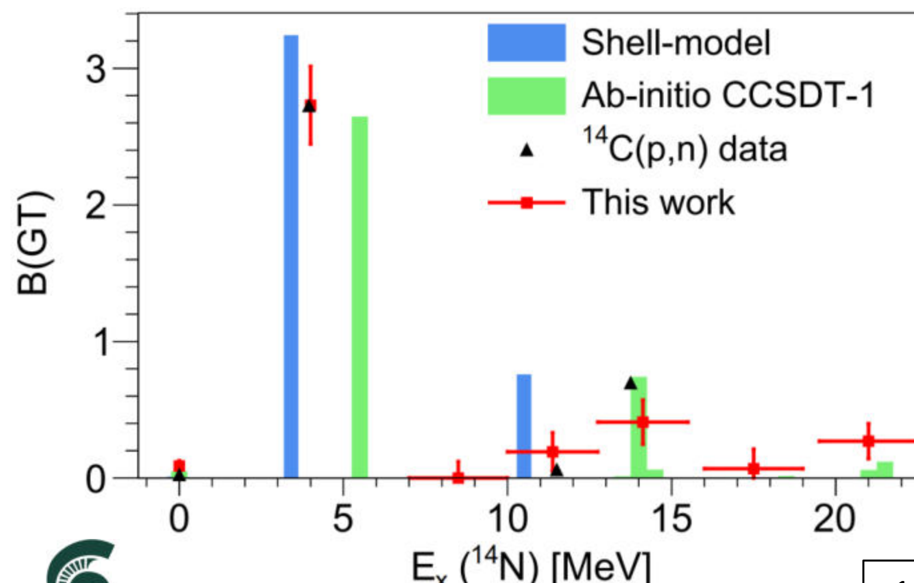
(Dated: May 7, 2023)



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Conclusions and Outlook

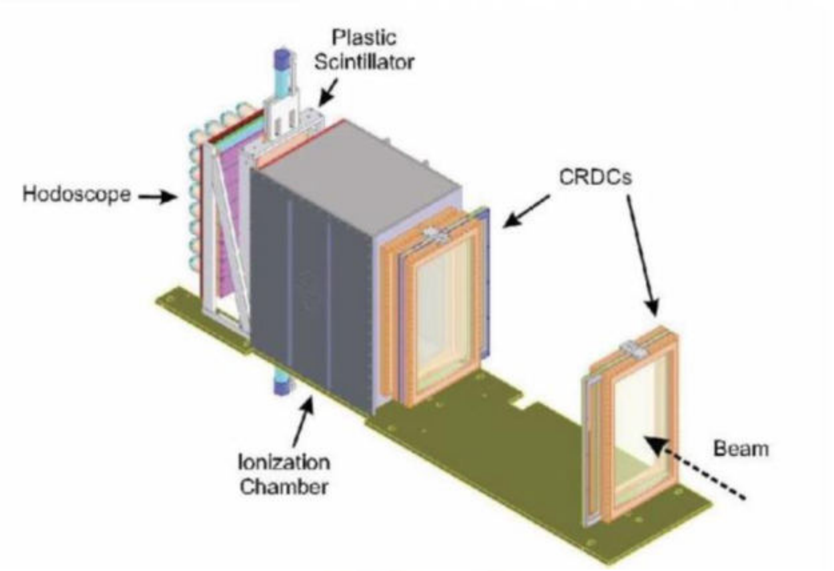
- The (d,^{2}He) reaction in inverse kinematics was developed successfully and used to extract Gamow-Teller strength from an unstable nucleus of to high excitation energies
- The use of an Active Target Time Projection Chamber in combination with a magnetic spectrometer is an effective tool for inverse kinematics experiments with fast beams in which the low-energy recoil particle is used to reconstruct the reaction kinematics
- For ^{14}O It was confirmed that Coupled Cluster calculations based on first principles are able to reproduce Gamow-Teller strength distribution up to high excitation energies without phenomenological quenching -> promising path for heavier nuclei and nuclei far from stability
- The next (d,^{2}He) experiment in inverse kinematics is planned at FRIB – the goal is to perform experiment with gradually increase A and Z, of importance for electron captures in nuclear astrophysics

The S800 Spectrometer is Used for Measuring Ejectiles and Triggering the AT-TPC Data Readout

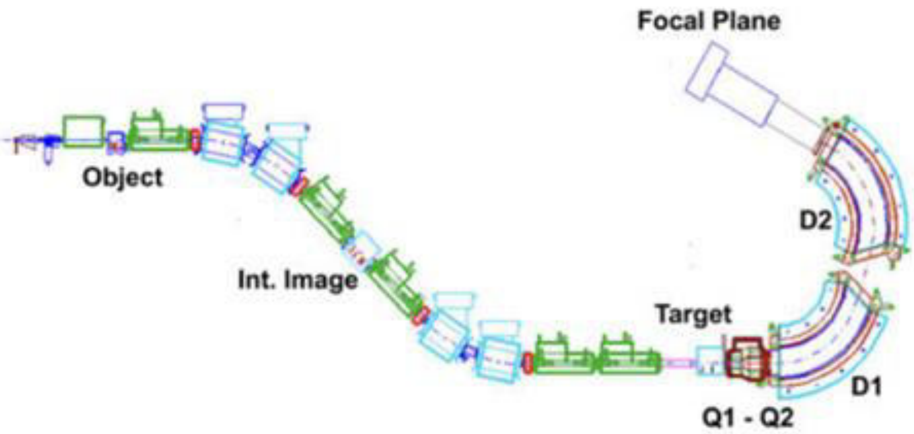
- Cathode Readout Drift Chambers (CRDC) measure the position and angle at the focal plane, providing momentum and scattering angle

- A plastic scintillator gives the trigger for the data acquisition system and is used for particle identification by ToF measurement

- The ionization chamber allows indirect measurement of atomic number based on energy deposition



The S800 spectrometer



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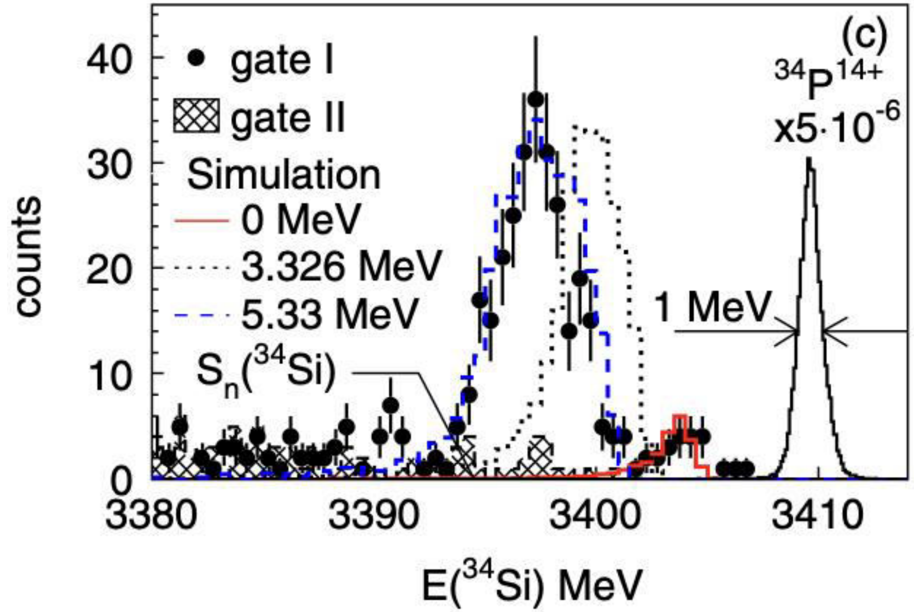
Inverse Kinematics in Charge-Exchange Reactions for Studying Rare Isotope

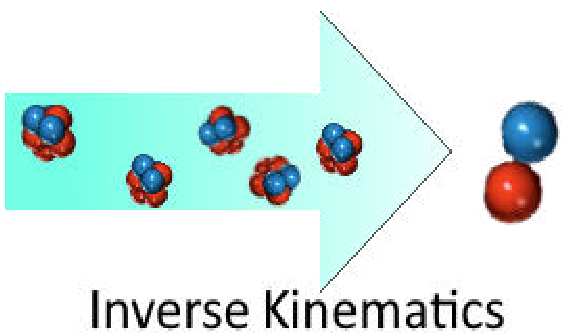
(^{7}Li,^{7}Be) probe has been successfully used to extract *B*(GT) in inverse kinematics for studying unstable nuclei.

Limitation: Method relies on high precision momentum-tracking of the heavy ejectile and is limited to light (A<35) nuclei and excitation energies up to the particle separation energy

^{34}P(^{7}Li,^{7}Be + γ)^{34}Si



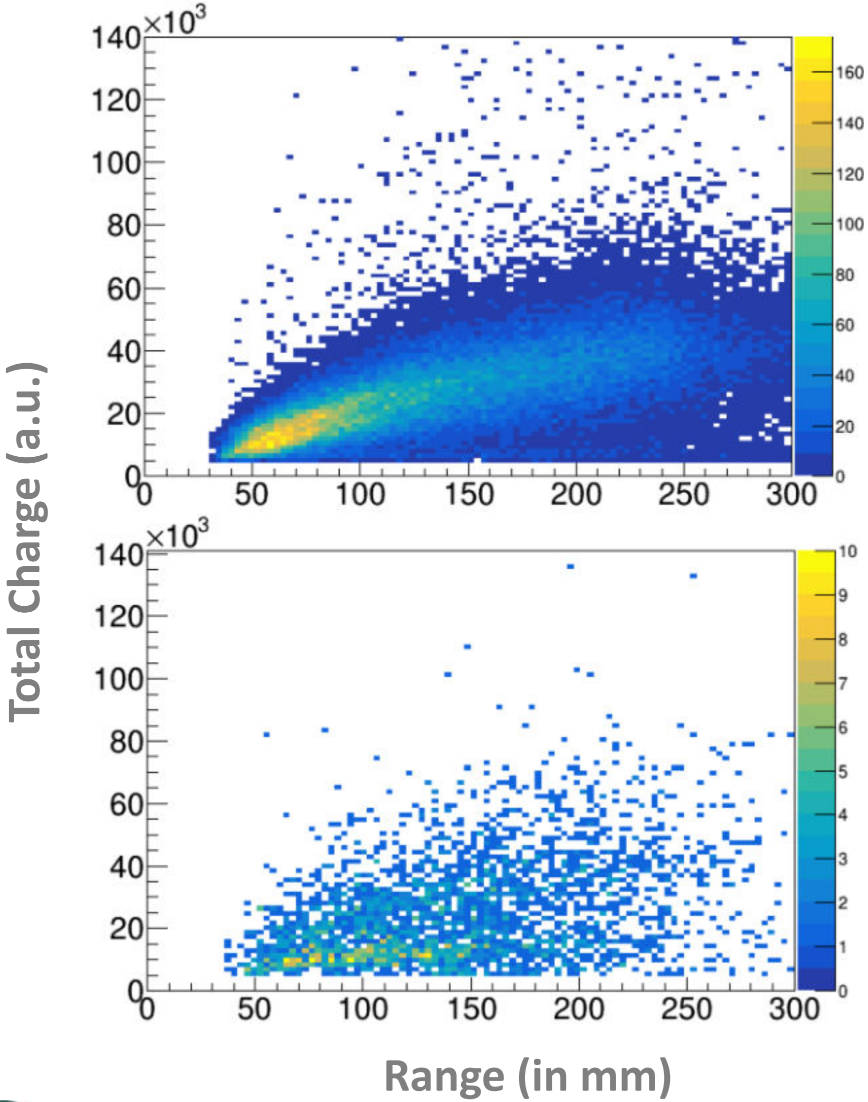
R. G. T. Zegers et al., Phys. Rev. Lett. 104, 212504 (2010)



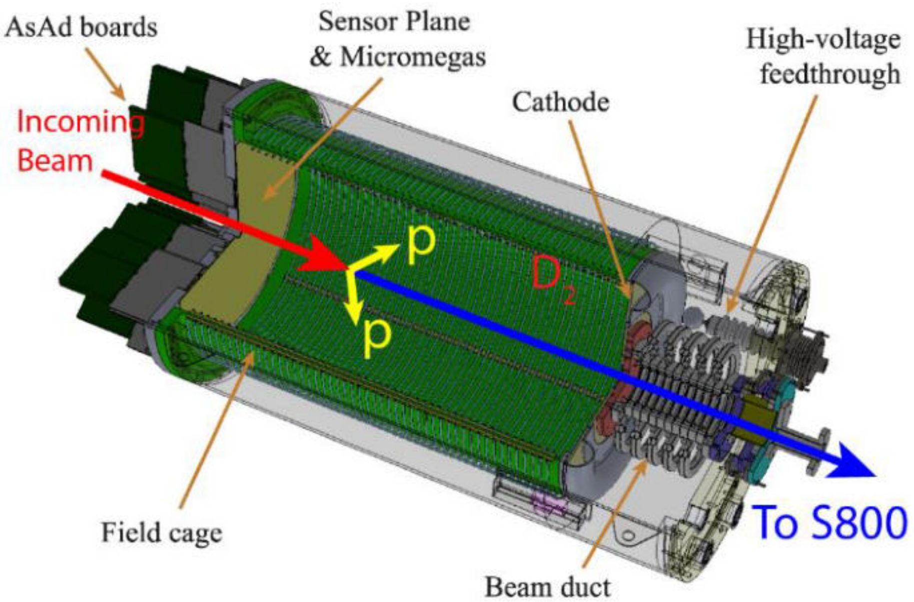
- (*n*,*p*) ?
- (*t*,^{3}He) ?

Background is Suppressed by Several Conditions in the Code

- The code identifies the beam-like particles in coincidence with two protons generated from the vertex.
- Electron events are removed by adding a threshold for total charge.
- A 2D gate on the distribution of the total charge against the particle range in the AT-TPC helps select proton tracks.
- The probability of two (d,p) events with a nearby vertex is in the order of 1% of the probability of a (d,^{2}He) event.
- The combination of all conditions results in a nearly background free spectrum.



AT-TPC is Used for Tracking the Two Protons From Unbound ^{2}He



Allows Target Medium as a Target-Detection System

- Central region of the AT-TPC is insensitive so the beam intensity can be relatively high (0.2-0.7 Mpps).
- Energetic particles react with the gas ionizing it and strip off electrons from the target gas D_2 as they travel.
- The electrons drift with uniform velocity towards the MicroMegas detector.
- Signals transmitted to the AsAd boards via high-density connectors feed the laboratory computer network for analysis.
- X and Y track information is reconstructed based on the location of the activated pad.
- The Z coordinate is the product of the drift velocity and the flight time.

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SUMMARY

- EC rates are important for astrophysical phenomena such as core-collapse and thermonuclear supernovae, the crust of accreting neutron stars in binary systems, and the final core evolution of intermediate mass stars.

- Experiments needed to guide and benchmark the theoretical models.

- Accurate Gamow-Teller strength is necessary to estimate the EC rates in stellar environment.

- (d,^{2}He) in inverse kinematics is the only probe for studying GT strength in unstable nuclei at all excitation energy and across the chart of nuclei.

- First (d,^{2}He) experiment in inverse kinematics was successfully run at the NSCL in 2020 using the AT-TPC and S800 spectrometer.

- Proposal for next (d,^{2}He) reaction in inverse kinematics has been accepted at FRIB.

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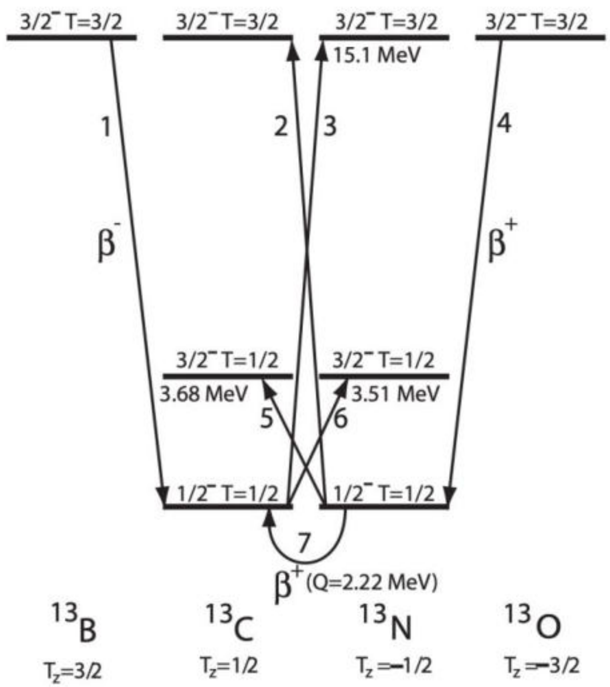
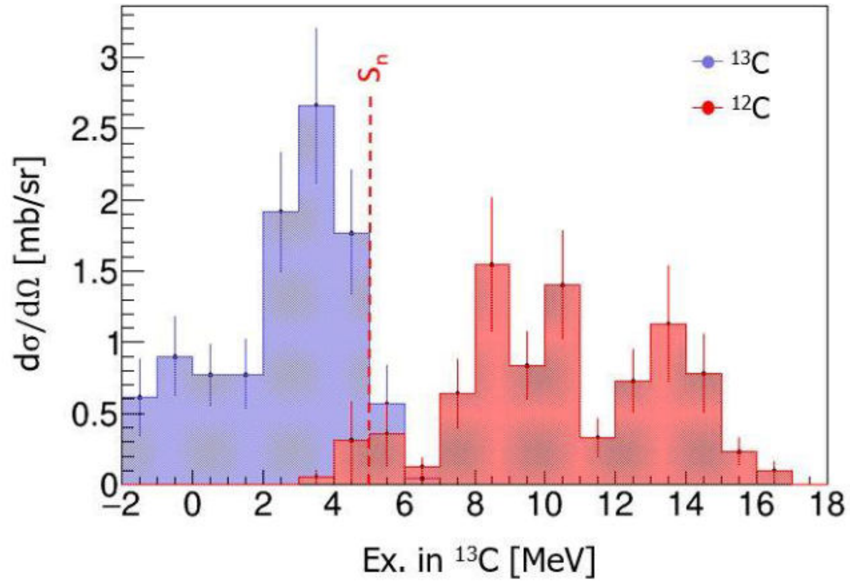
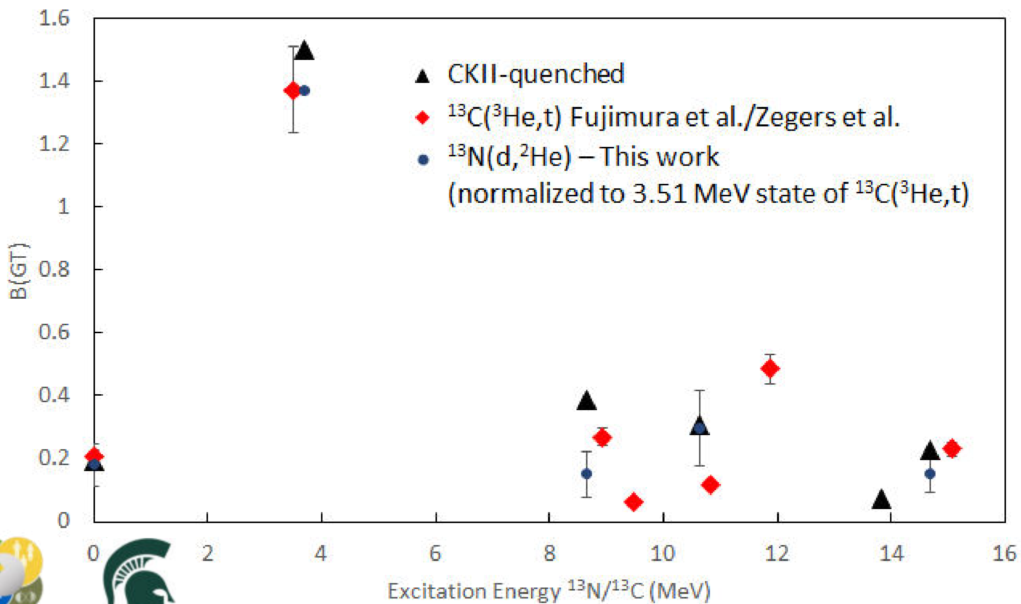
$^{13}N(d,^{2}He)$



Schematic of isospin analogous transitions in the A=13 and $T_z = \pm 1/2, \pm 3/2$.





- $^{13}N(e^-, \nu_e)^{13}C$ reaction plays an Important Role in the Pre-Explosion Convective Phase of Type Ia Supernova

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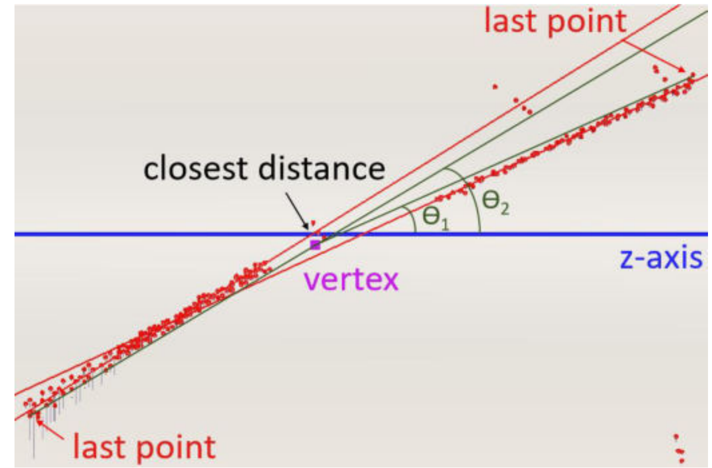
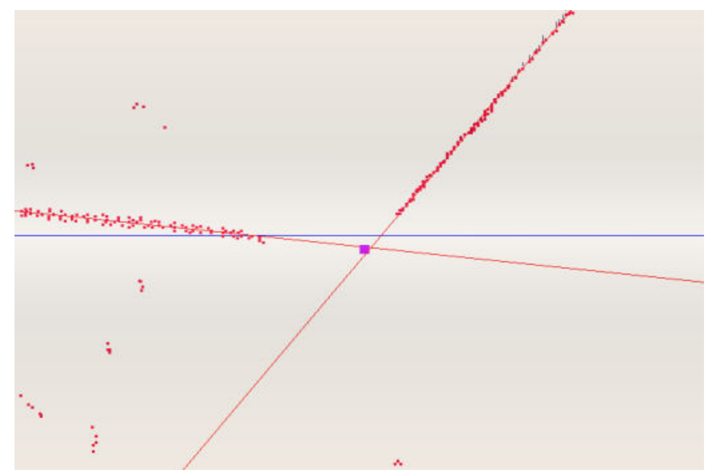
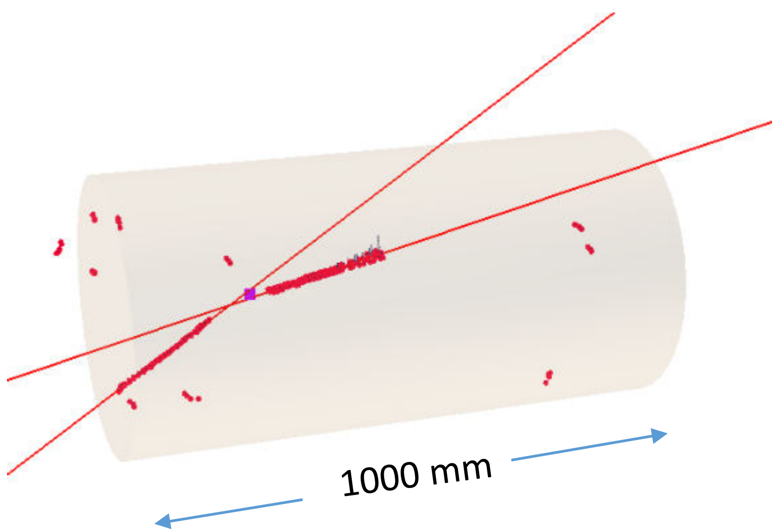
Visualization of AT-TPC Events Inside the Volume

RANSAC (RANdom SAmple Consensus) algorithm is used to fit the point cloud of the AT-TPC and identify the (d,^{2}He) events.

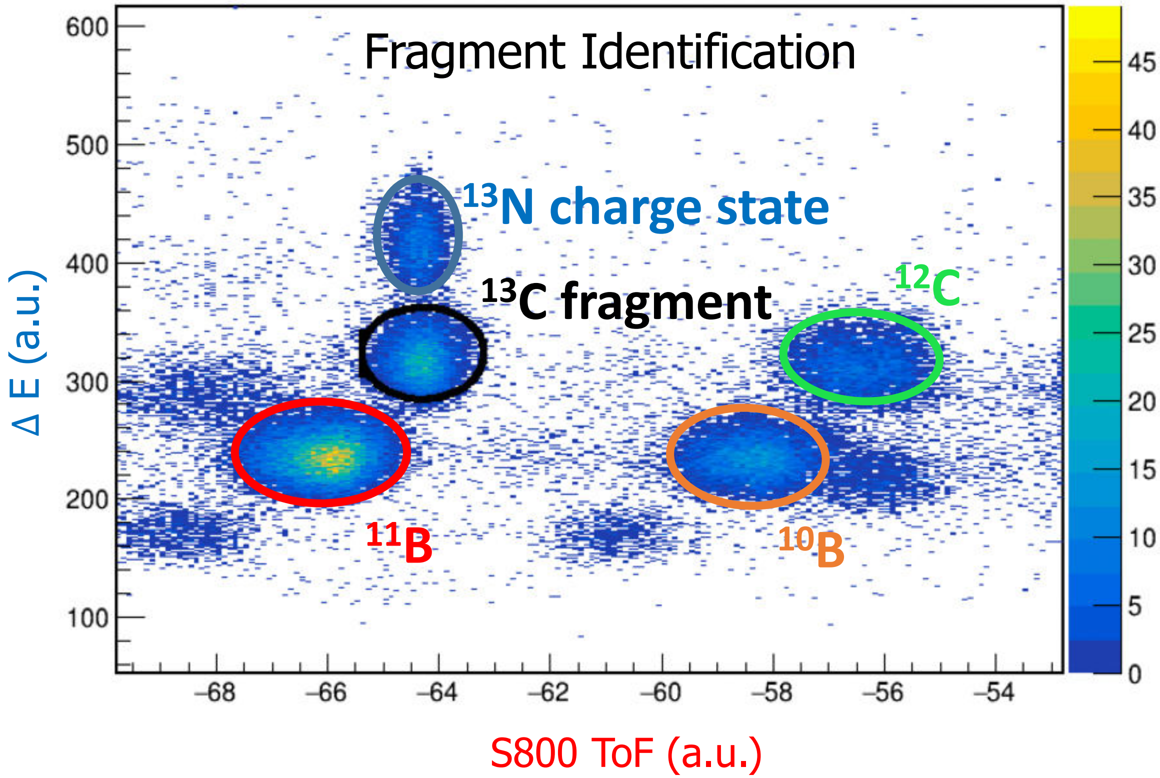
- Vertex is the mean distance weighted by number of hits in each track
- Range is the distance between the position of the vertex and last point on fitted line







Particle Identification using ΔE-ToF method



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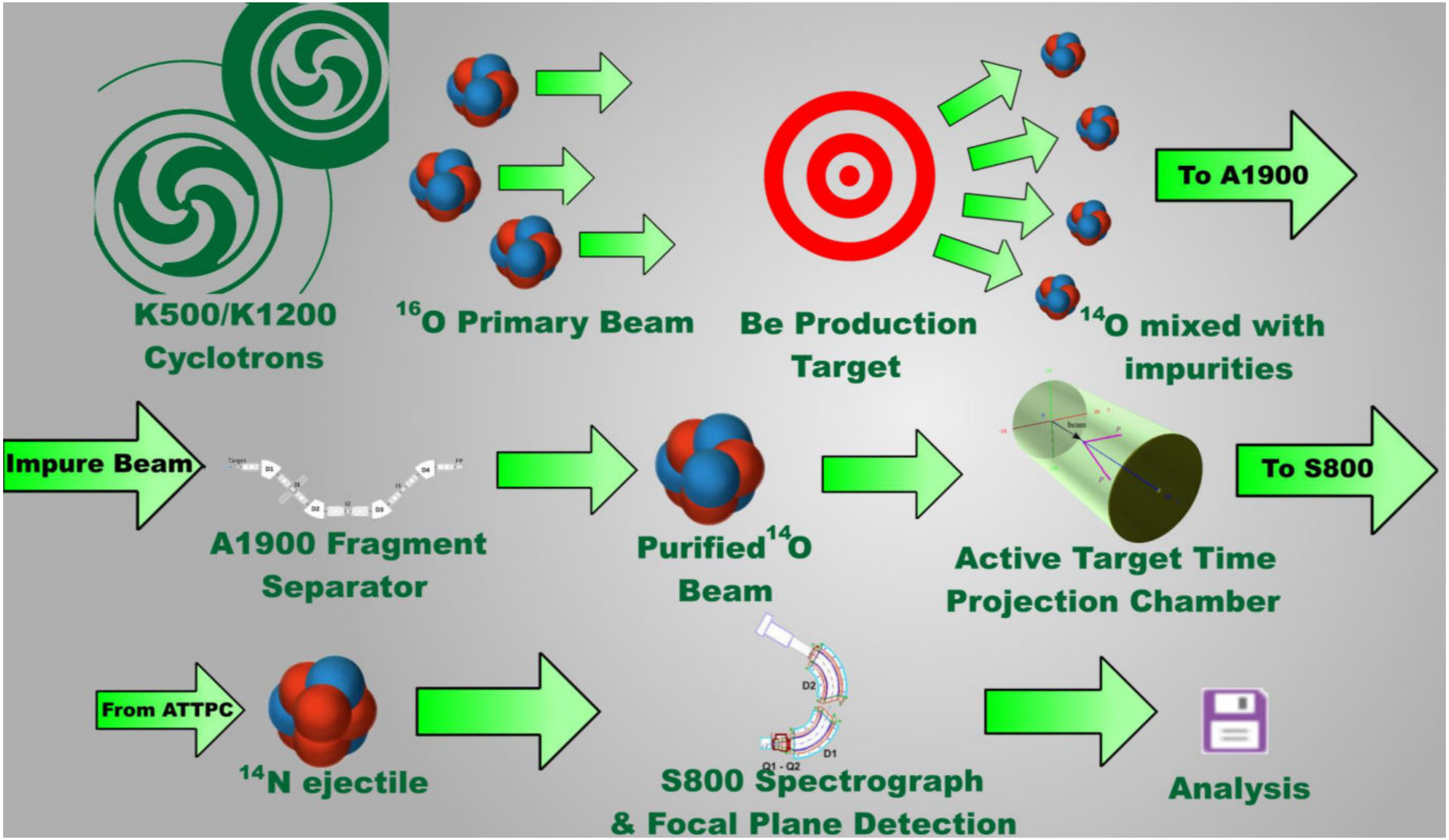
EXPERIMENT



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