Simulation and physics modelling of Active Target TPCs (and solenoidal spectrometers)

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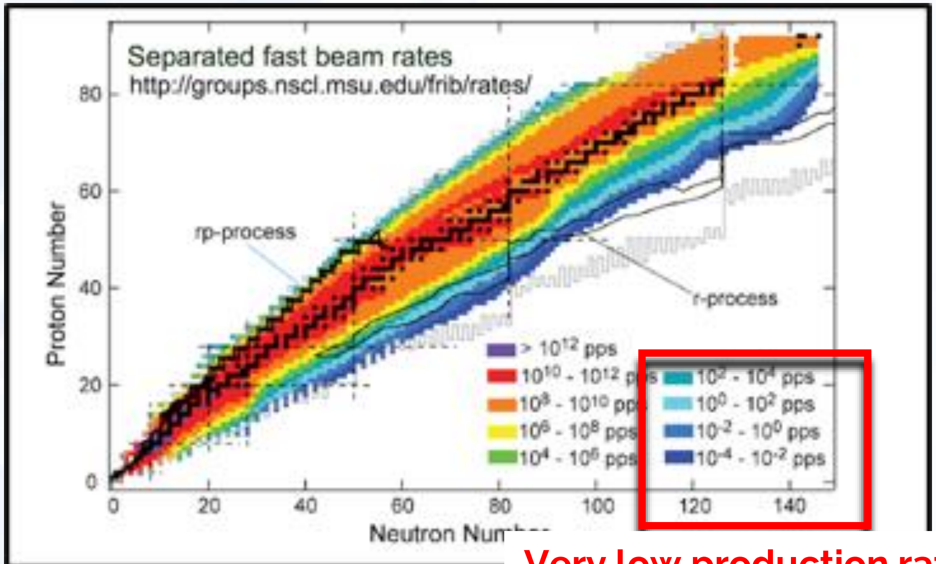
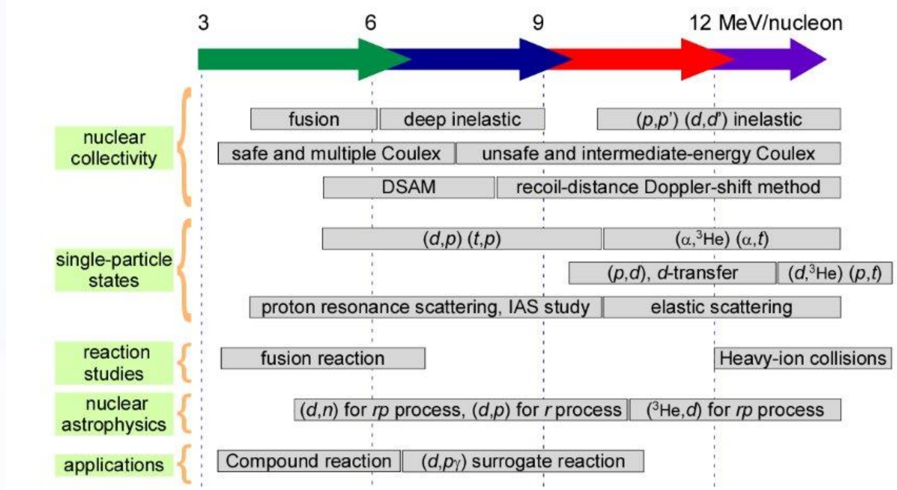
XUNTA DE GALICIA

CENTROS gus
Cofinanciado por la Unión Europea
Fondos Europeos

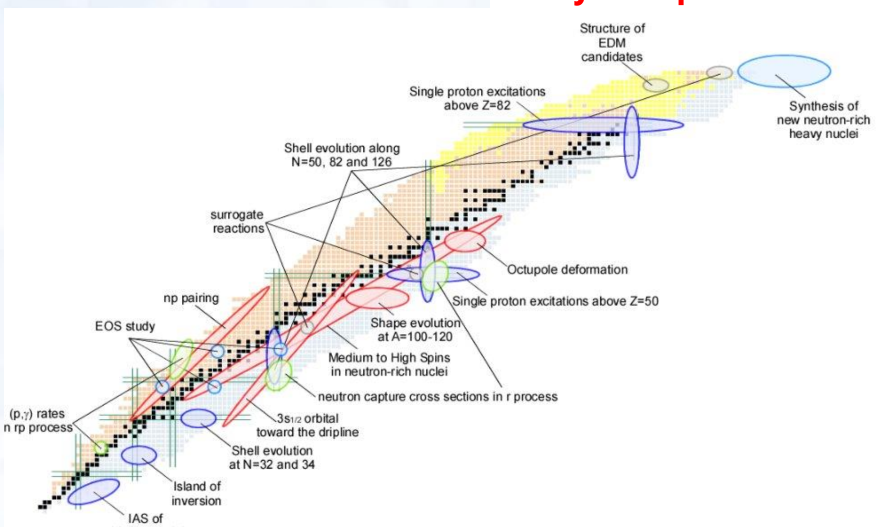
- Why active target time projection chambers (AT-TPC)?
- Low-energy nuclear physics with AT-TPC´s.
- Key aspects for simulation and analysis.
- Some examples with different setups.
- Outlook.

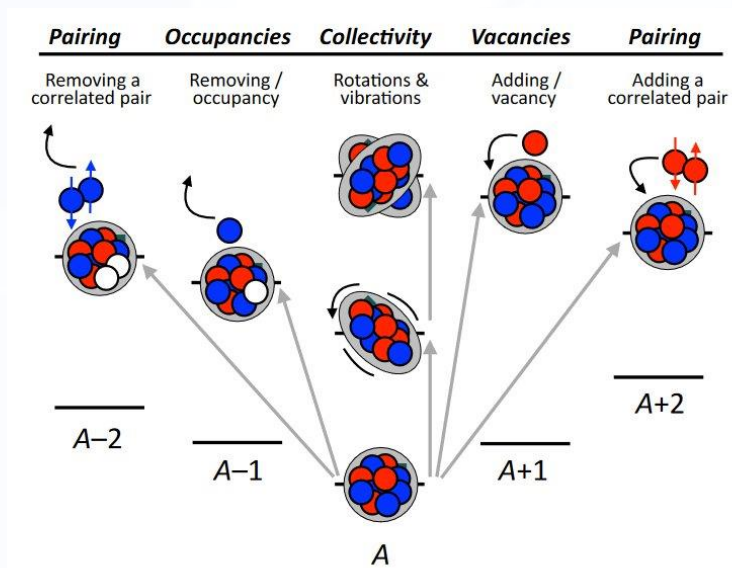
Why active target time projection chambers?





Very low production rates!



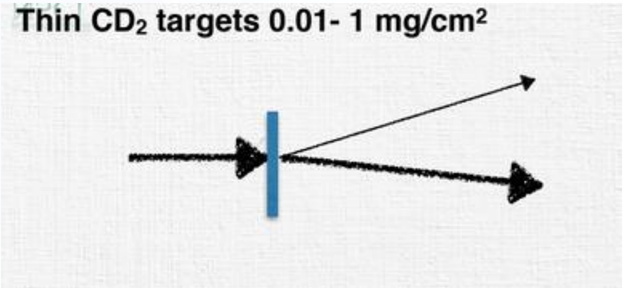


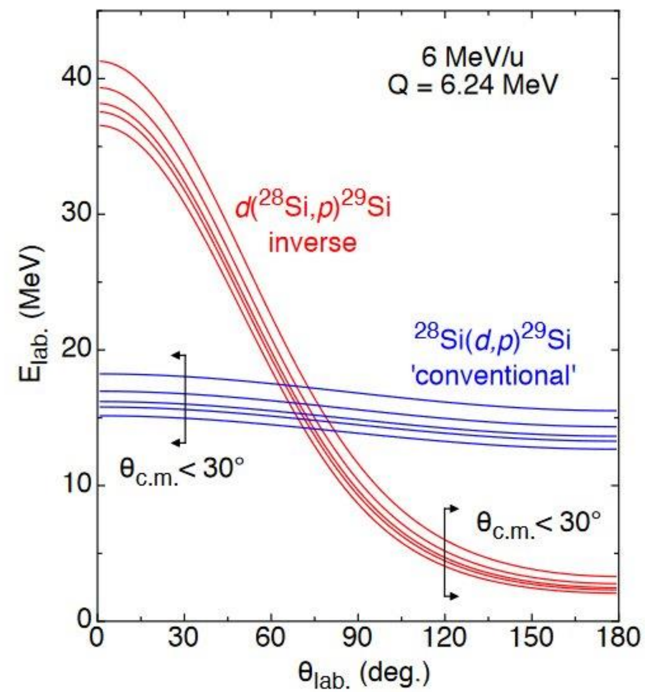
Facility for Rare Isotope Beams
at Michigan State University

Low-energy nuclear physics with AT-TPCs

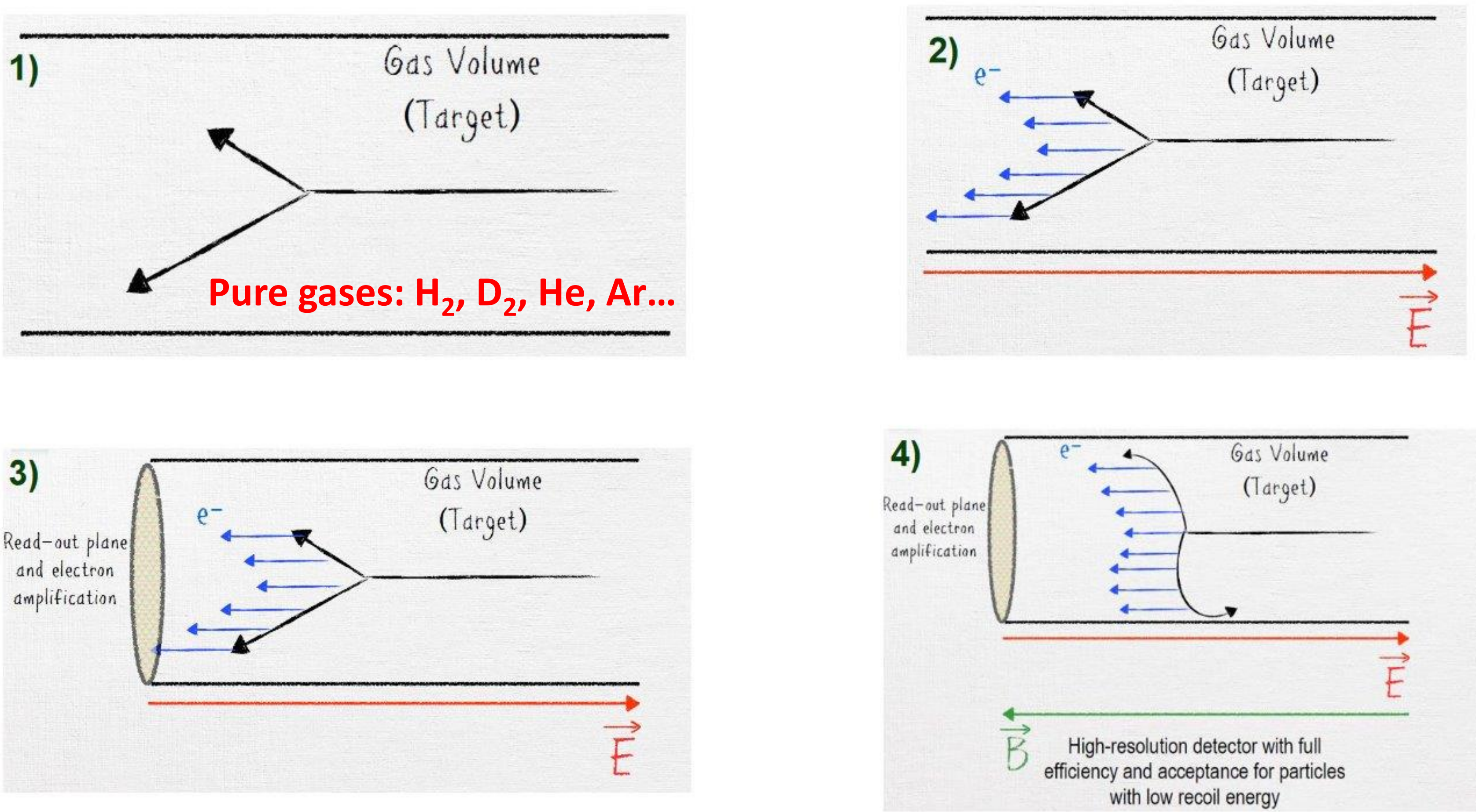
Direct reactions in inverse kinematics

- An essential probe of nuclear structure.
- Small momentum transfer.
- Large impact parameter (surface).
- Cross section focused on forward direction.
- Very short time scale (~10^{-22} s).
- Energies, angular momentum, overlaps.
- Particle identification, ΔE-E techniques more challenging at low energies.
- Strong energy dependence with respect to laboratory angle.
- Typically leading to poor resolution (100s of keV).
- ...and beams a few to 10^6 orders of magnitude weaker.



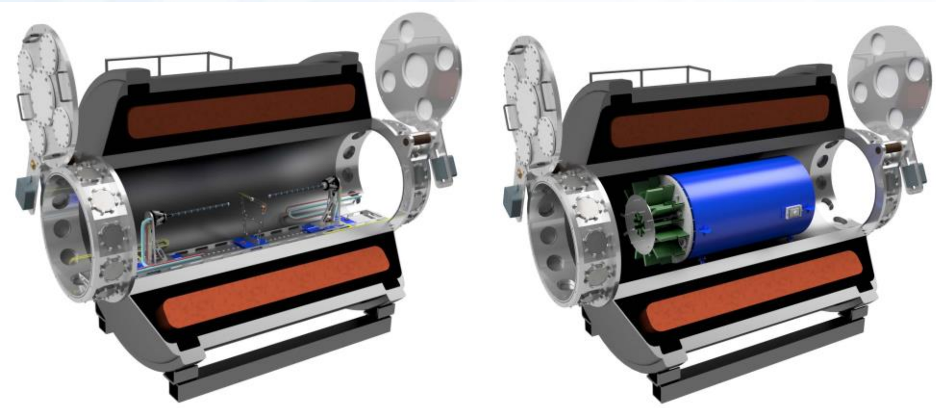


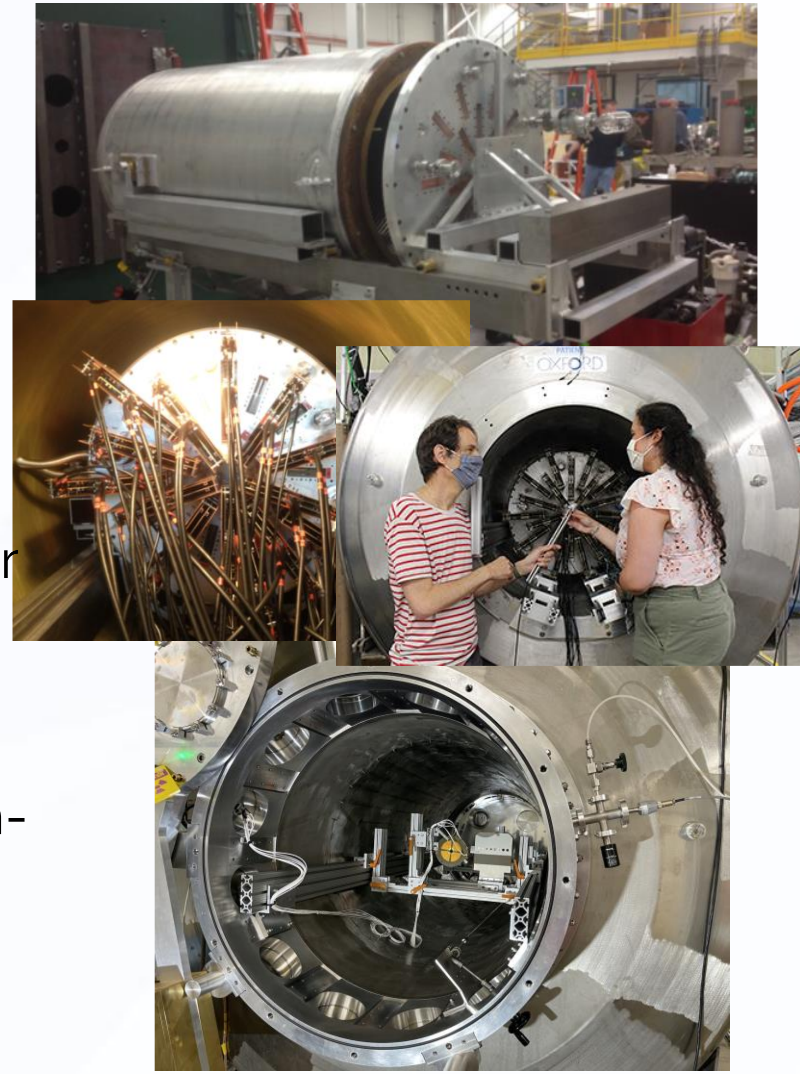
Low-energy nuclear physics with AT-TPCs



Low-energy nuclear physics with AT-TPCs

SOLARIS



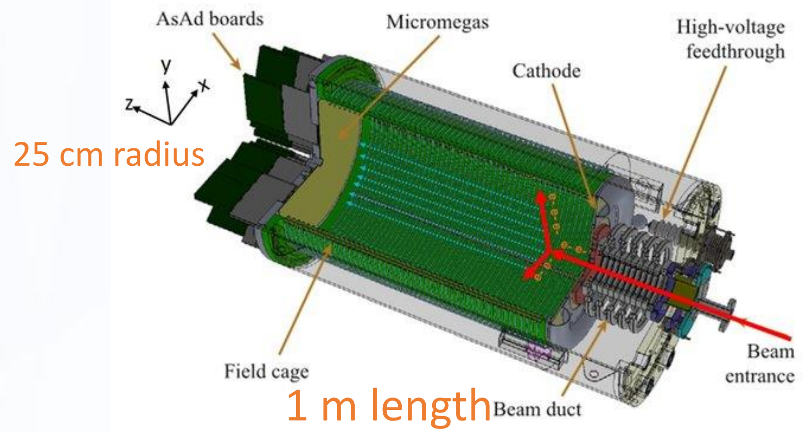


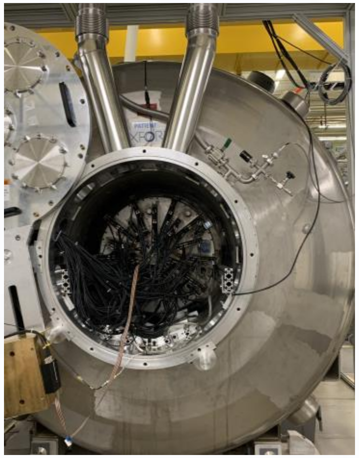
- Next-generation Solenoidal Spectrometer
- Study of direct reactions with radioactive ion beams.
- Two modes of operation: Si array for high-resolution studies of direct reactions and AT-TPC for reactions with weak (most exotic) beams.

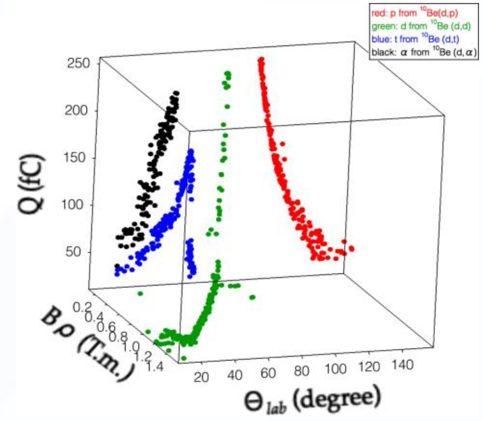
Facility for Rare Isotope Beams
at Michigan State University

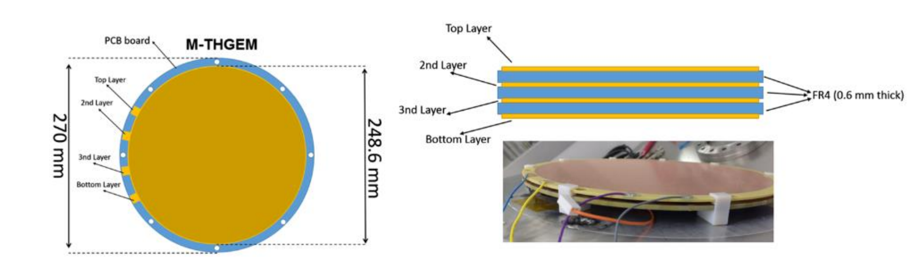
Active Target Time Projection Chamber (AT-TPC)

- High luminosity and large dynamic range.
- High resolution (in principle better than solid state detectors).
- Pure elemental gases.
- Cylindrical configuration: large thickness with moderate cost for electronics.
- Versatile setup for different type of reactions.
- Magnetic field enables rigidity measurement.
- Kinematics reconstruction not trivial…







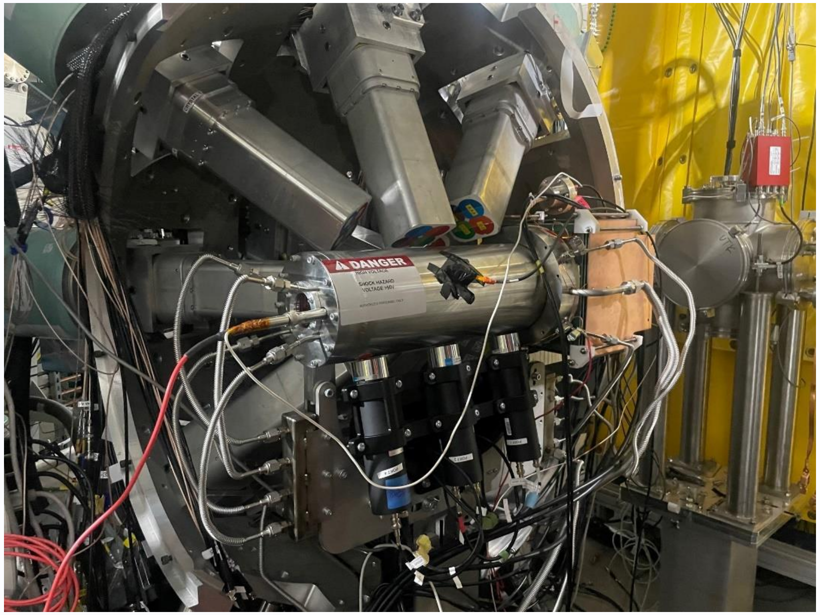


Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)

Low-energy nuclear physics with AT-TPCs

Gaseous Detector with Germanium Tagging II (GADGET II)
Spokesperson: C. Wrede (Michigan State University and FRIB)

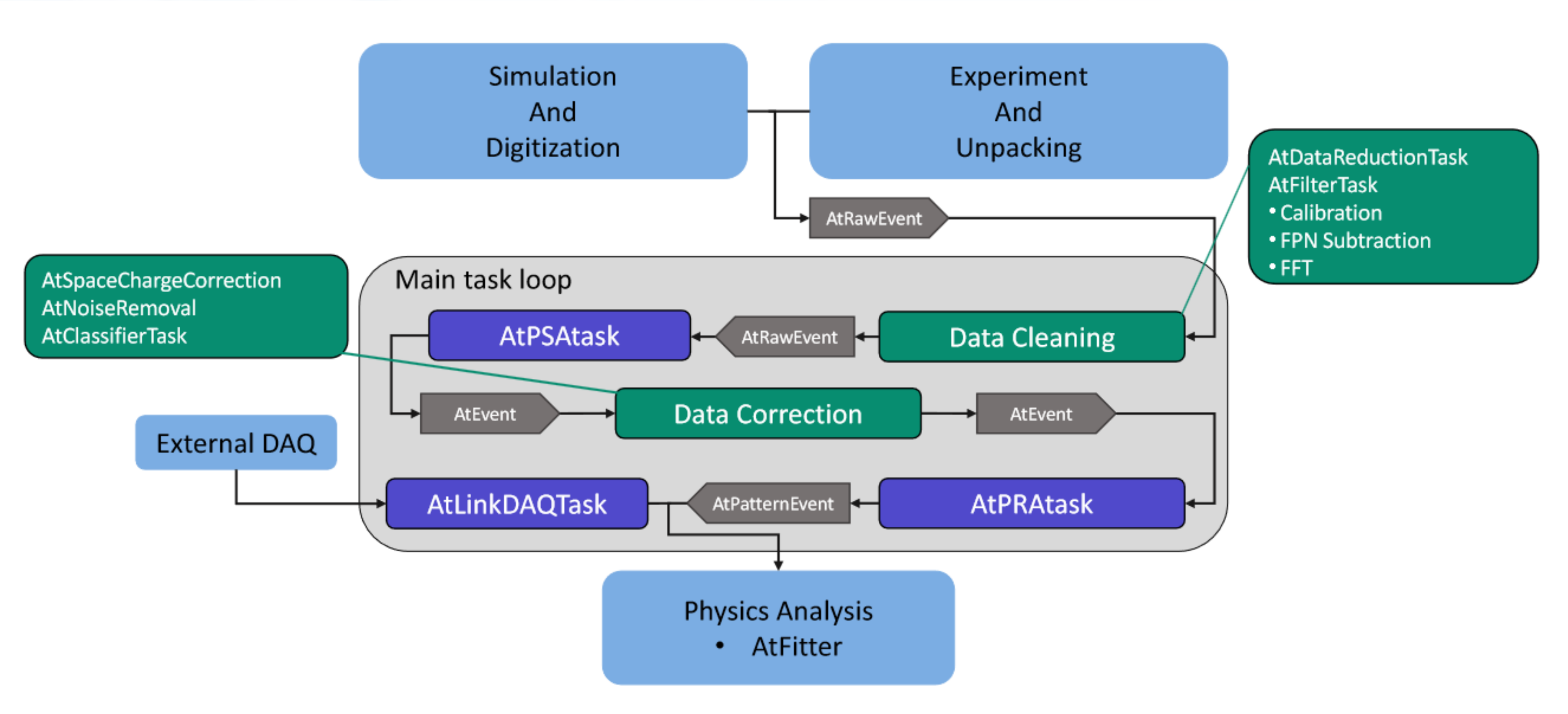
- Used to measure β-delayed charged particles and γ-rays with in-flight radioactive beams at FRIB for nuclear astrophysics
- Compact TPC thermalizes beam and measures charged particles (protons, α particles, …)
- Surrounded by various high-purity germanium arrays for high-resolution γ-ray detection
- First experiment FRIB E21072 ran November, 2022



Facility for Rare Isotope Beams
at Michigan State University

Key aspects for simulation and analysis

ATTPCROOTv2 data analysis and simulation framework



Servicing many detectors in the low-energy physics community!

Analysis techniques for Active Target Time Projection Chambers

Yassid Ayyad[a], Tyler Wheeler[b], Ruchi Mahajan[b], Michelle P Kuchera[c], Raghuram Ramanujan[c], Andreas Ceulemans[d], Tan Ahn[e], Jaspreet Randhawa[e], Juan Carlos Zamora[b], Nabin Rijal[b], Curtis Hunt[b], Chris Wrede[f,b], Bruno Olaizola[g], Adam Anthony[f,b], Christoph Dalitz[h], Juliane Arning[h], Alexandros Kapnidis[h]

^{10}Be + d scattering at 10A MeV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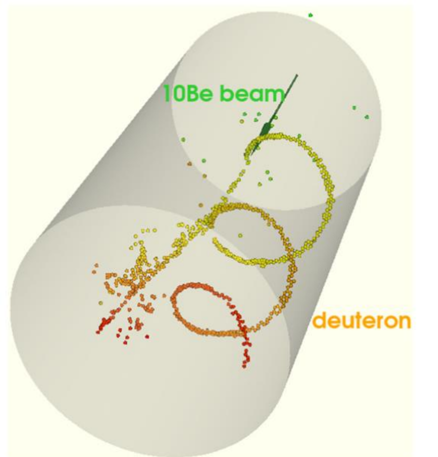
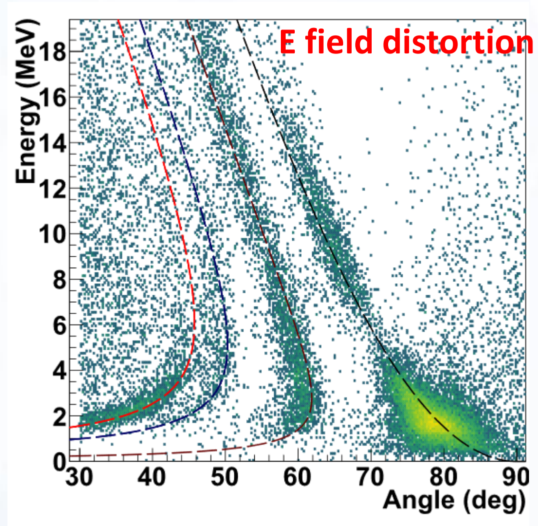
https://doi.org/10.1140/epja/s10050-023-01205-2
THE EUROPEAN PHYSICAL JOURNAL A
Special Article - New Tools and Techniques

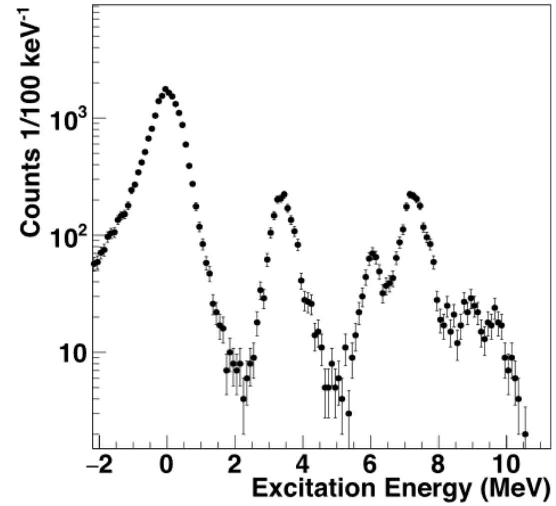
Kinematics reconstruction in solenoidal spectrometers operated in active target mode

Yassid Ayyad[1,a], Adam K. Anthony[2,3,7], Daniel Bazin[2,3], Jie Chen[4], Gordon W. McCann[3], Wolfgang Mittig[2,3], Benjamin P. Kay[5], David K. Sharp[6], Juan Carlos Zamora[2,3]

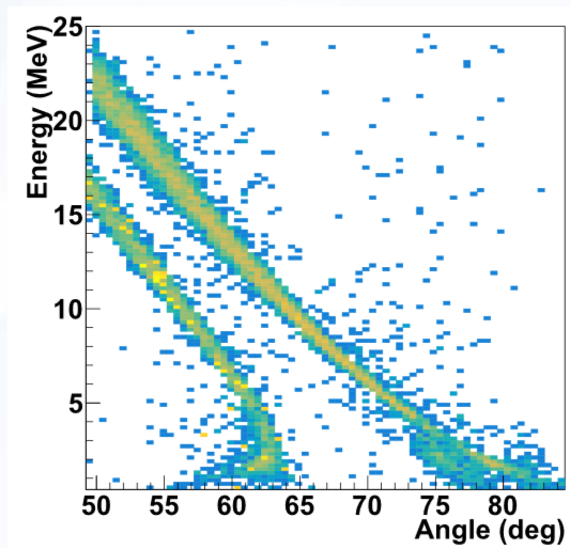


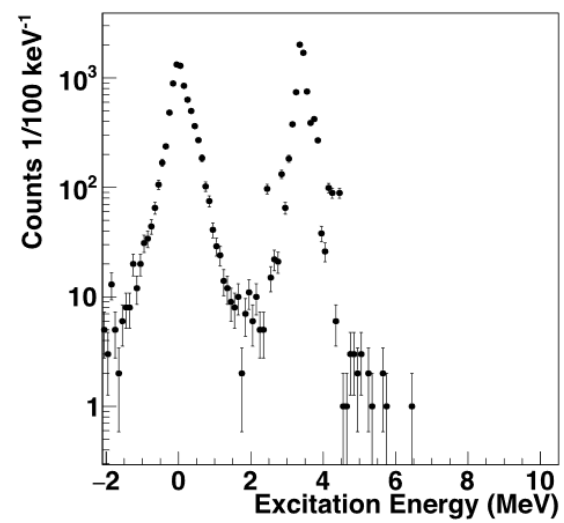
Experiment





Simulation (no cross sections!)

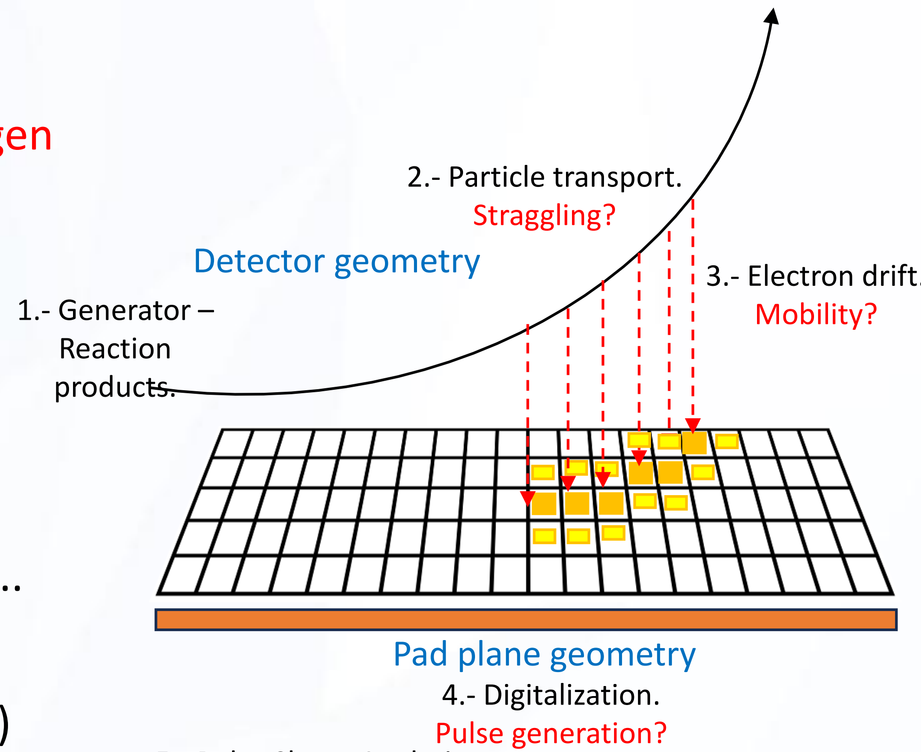




- ^{10}Be 10A MeV provided by ReA6 in stand-alone mode. Around 2000 pps!.
- ^{10}Be material provided by the PSI (Switzerland)
- Pure target of D_2 600 torr.
- Study of negative parity states of ^{11}Be

Simulation details

- Large dE/dx dynamic range: beam (1-100 GeV) and reaction products (few MeV).
- Slow drift velocities for gases such as hydrogen or deuterium.
- Two Monte Carlo Engines: Geant4 and a proprietary energy loss manager (multiple scattering).
- Modular detector geometry.
- Generators: two body, decay, fission, fusion...
- Digitalization: Single-electron drift taking diffusion into account (under magnetic field)
- Realistic management of charge spreading in the pad plane.
- Amplification stage NOT simulated in real time (usually Multilayer THGEM and Micromegas, including resistive mode)
- Response of the pad plane: Micromegas coupled with GET electronics.



5.- Pulse Shape Analysis.
6.- Pattern Recognition Analysis.
7.- Tracking and fitting.
8.- Analysis

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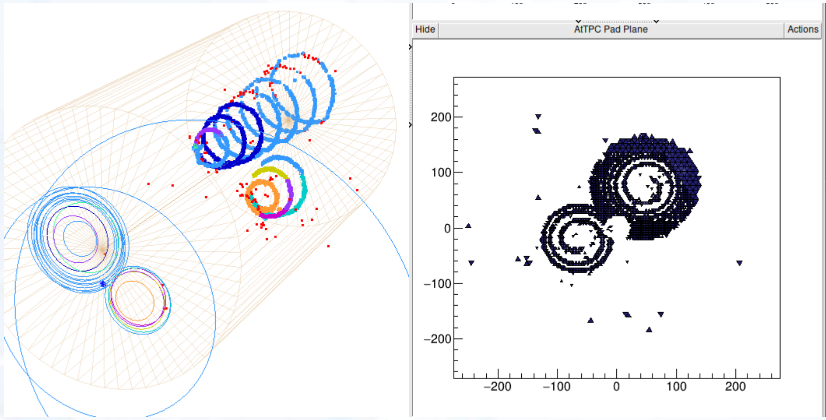
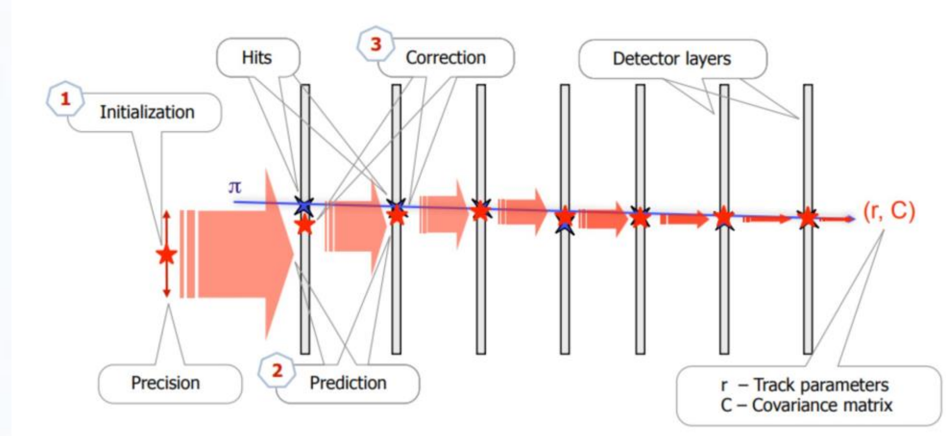
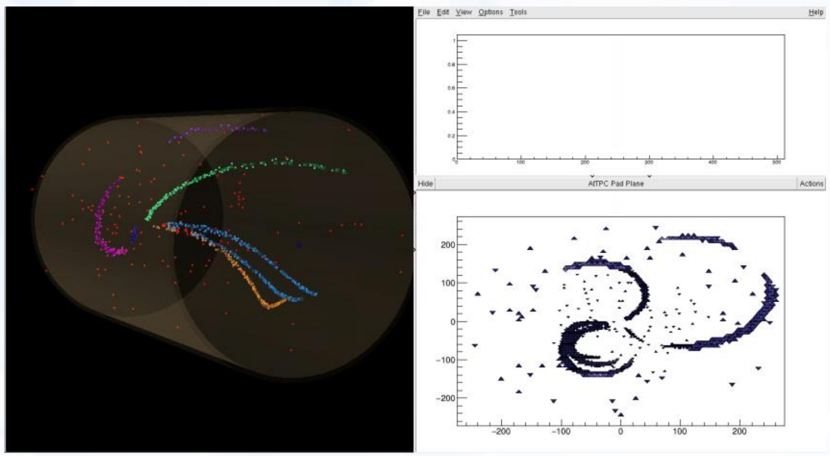
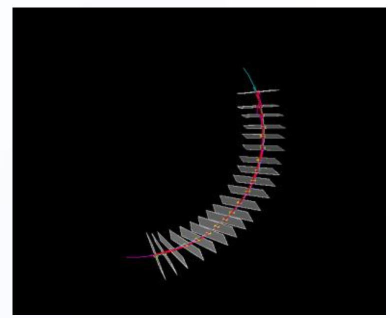
[AtDigiPar]
EField:Double_t              70000   # V/m
BField:Double_t                0.0   # Tesla
TBEntrance:Int_t               457   # Beam position at detector entrance in TB
ZPadPlane:Double_t          1000.0   # Position of the micromegas pad plane
EIonize:Double_t             42.70   # Ionization energy of gas in eV
Fano:Double_t                 0.24   # Fano factor of the gas
CoefL:Double_t              0.0055   # Longitudal coefficient of diffusion [cm^2/us]
CoefT:Double_t              0.0038   # Transverse coefficient of diffusion [cm^2/us]
GasPressure:Double_t           800   # Gas pressure in torr
Density:Double_t             0.175   # Gas density (kg/m3 or mg/cm3)
DriftVelocity:Double_t        0.815  # cm/us
Gain:Double_t                 1000   # Average gain of micromegas
SamplingRate:Int_t             3.125 # Real value is 6.25 MHz
GETGain:Double_t              1000   # Gain of the GET electronics in fC
PeakingTime:Int_t              720   # Electronic peaking time in ns
```

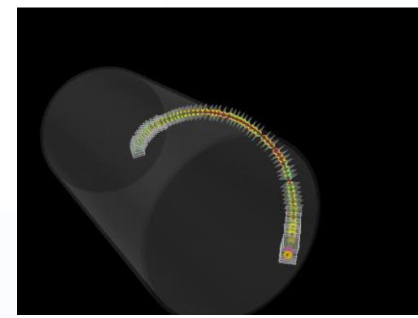
Reconstruction of simulated data

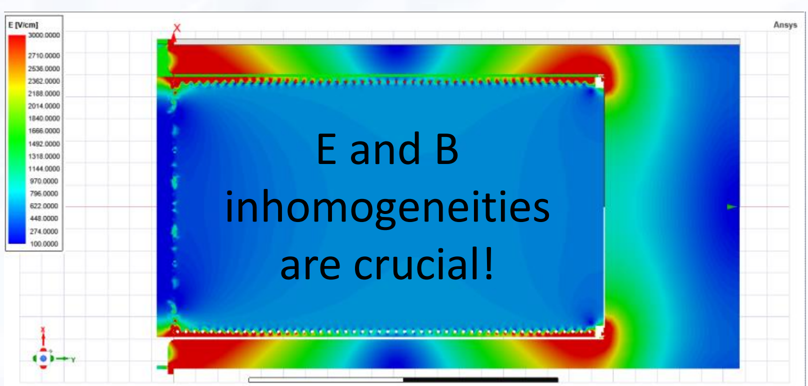






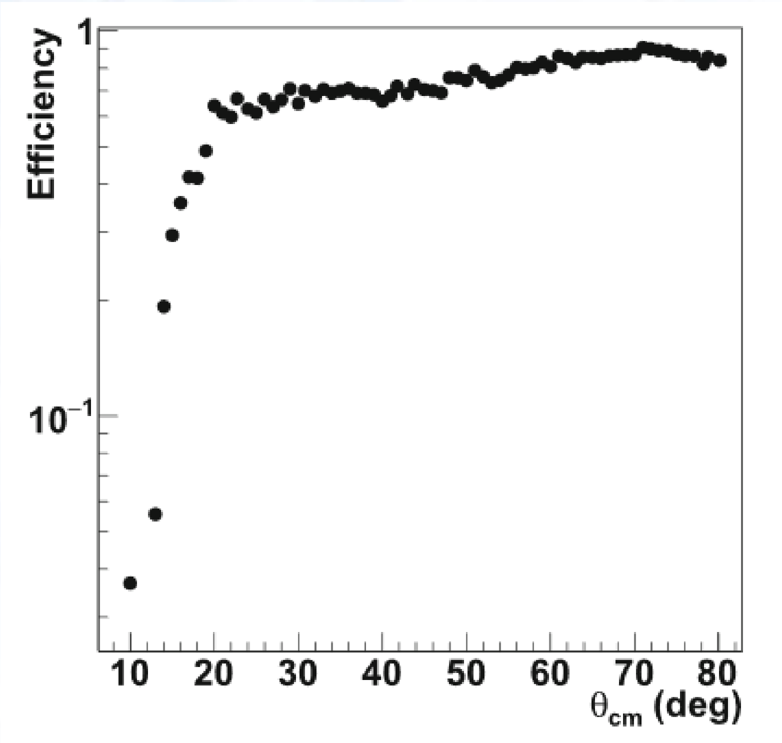




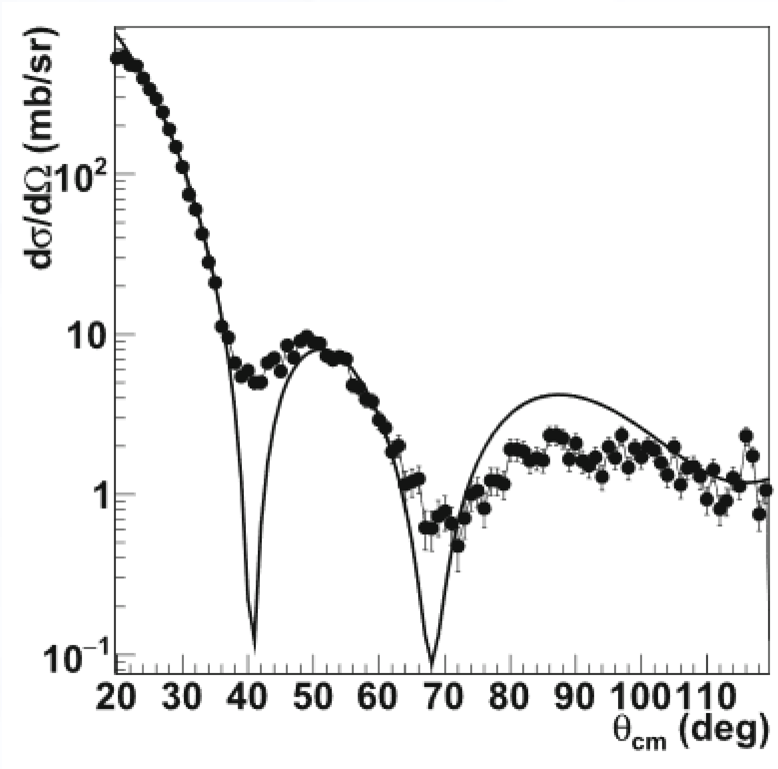


- Non-linear trajectories.
- Reconstruction using Kalman filter adapted to a large energy loss scenario.
- Improving resolution requieres a precise implementation of multiple scattering and straggling effects of heavy ions.
- What about charge exchange?

Deducing physics using the simulation



Efficiency correction function for the ^{10}Be+d elastic scattering



Angular distribution of the ^{10}Be + d elastic scattering corrected by efficiency. The solid circles and the solid line are the experimental data and the DWBA theoretical distribution.

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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

S. Giraud [a,*], J.C. Zamora [a,*], R.G.T. Zegers [a,b], Y. Ayyad [c], D. Bazin [a,b], W. Mittig [a,b], A. Carls [a,b], M. DeNudt [a,b], Z. Rahman [a,b]
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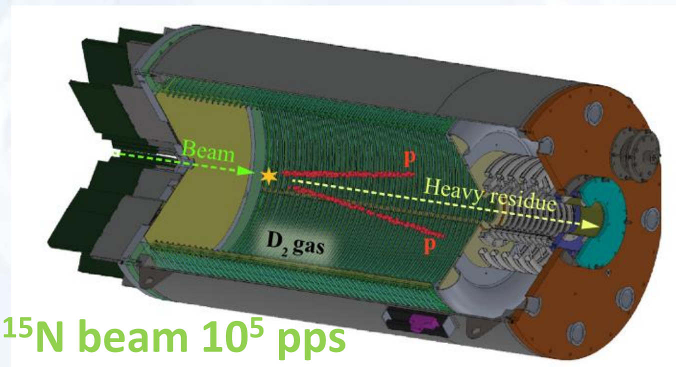
[b] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1321, USA
[c] IGFAE, Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Spain

PHYSICAL REVIEW LETTERS 130, 232301 (2023)

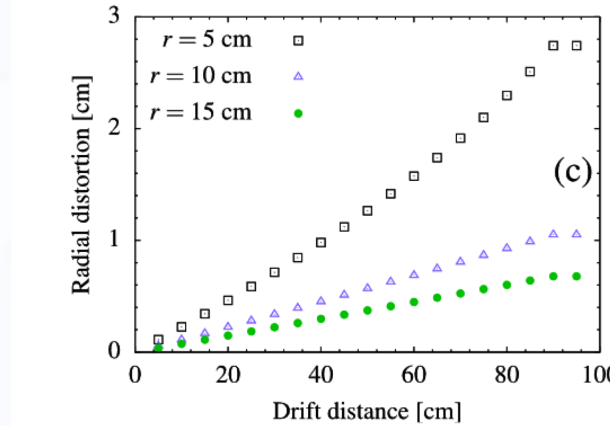
β^+ Gamow-Teller Strengths from Unstable ^{14}O via the (d, ^{2}He) Reaction in Inverse Kinematics

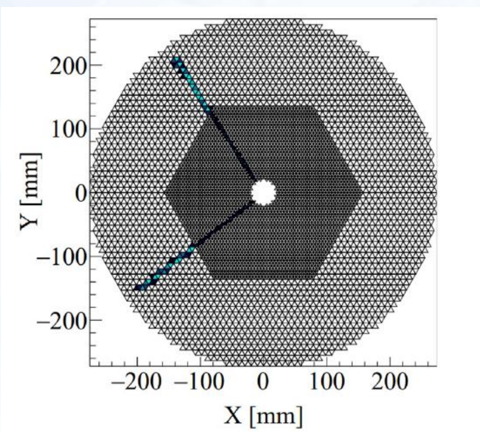
S. Giraud,[1,2,3,*] J. C. Zamora,[1] R. G. T. Zegers,[1,2,3,†] D. Bazin,[1,3] Y. Ayyad,[4,1] S. Bacca,[5,6] S. Beceiro-Novo,[3,7] B. A. Brown,[1,2,3] A. Carls,[1,2,3] J. Chen,[1,8] M. Cortesi,[1] M. DeNudt,[1,2,3] G. Hagen,[9,10] C. Hultquist,[1,2,3] C. Maher,[1,2,3] W. Mittig,[1,3] F. Ndayisabye,[1,2,3] S. Noji,[1] S. J. Novario,[9,10] J. Pereira,[1,2] Z. Rahman,[1,2,3] J. Schmitt,[1,2,3] M. Serikow,[1,2,3] L. J. Sun,[1,2] J. Surbrook,[1,2,3] N. Watwood,[1,2,3] and T. Wheeler[1,2,3]

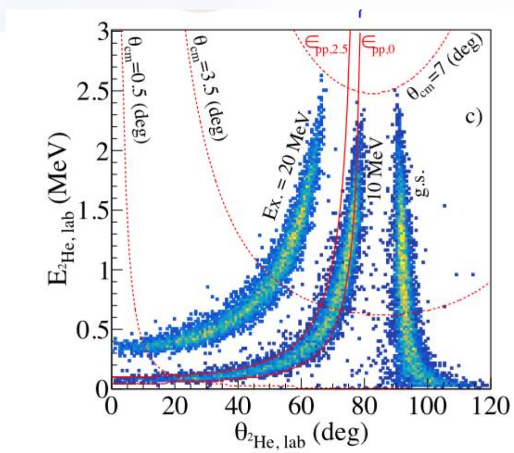
AT-TPC + S800 spectrometer (FRIB)

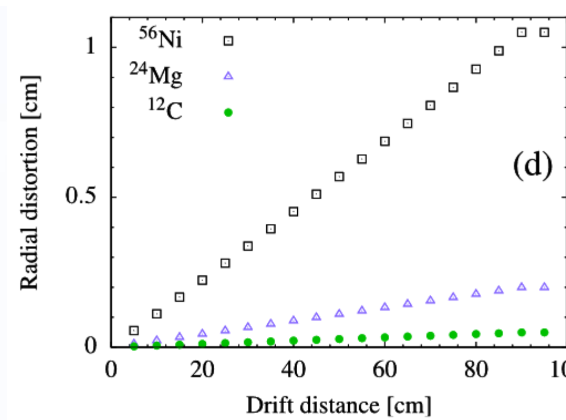


^{15}N beam 10^5 pps









Recombination loss and electron-ion production rate in a deuterium gas at 500 Torr and 500 V/cm. Three different beams were assumed at 100 MeV/u and 10^5 pps.

Ion beam	$\dot{N}$ [ions/(cm^3 s)]	f [%]
^{12}C	5.5×10^7	0.5
^{24}Mg	2.1×10^8	1.7
^{56}Ni	1.1×10^9	9.1

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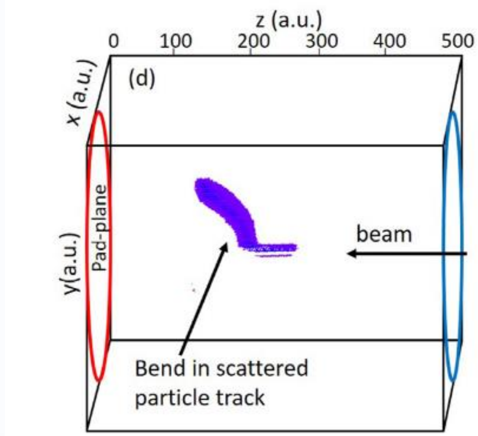
journal homepage: www.elsevier.com/locate/nima

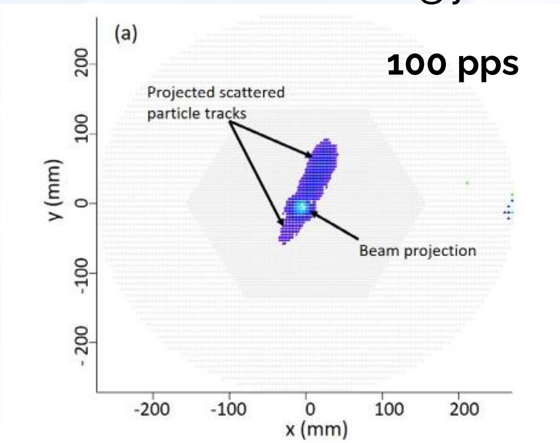
Beam-induced space-charge effects in time projection chambers in low-energy nuclear physics experiments

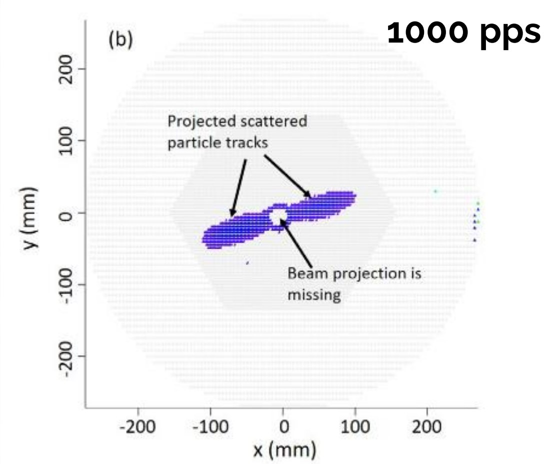
J.S. Randhawa[a,*], M. Cortesi[a], Y. Ayyad[a], W. Mittig[a,b], T. Ahn[c], D. Bazin[a], S. Beceiro-Novo[a], L. Carpenter[a], K.J. Cook[d,e], M. Dasgupta[d], S. Henderson[c], D.J. Hinde[d], J.J. Kolata[c], J. Sammut[b], C. Santamaria[a,f], N. Watwood[a], A. Yeck[b]

[a] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[b] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1321, USA
[c] Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670, USA
[d] Department of Nuclear Physics, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 2601 Australia
[e] Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro City, Tokyo 152-8551, Japan
[f] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

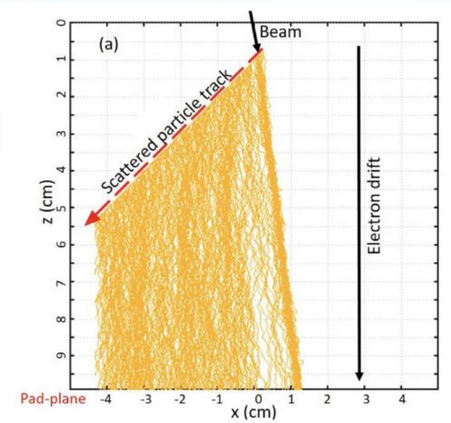


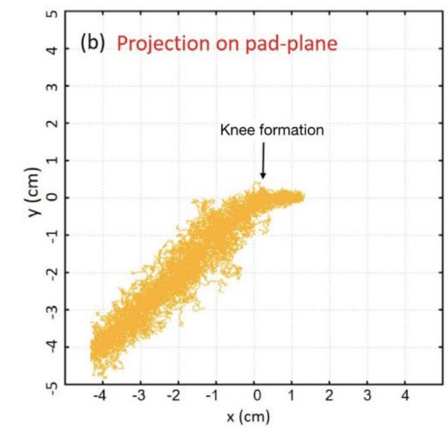
^{46}K beam at an energy of 4.6 MeV/u

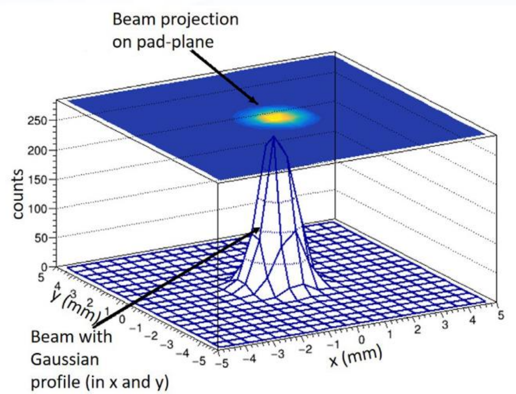


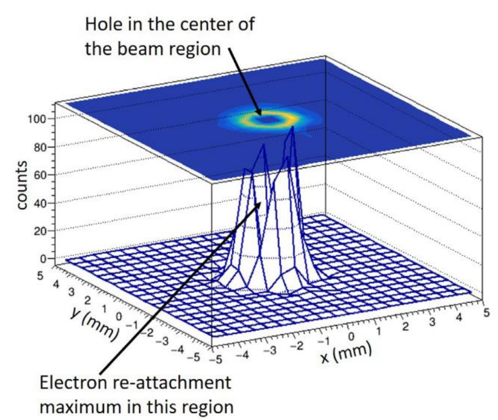


Simulation with Maxwell + Garfield



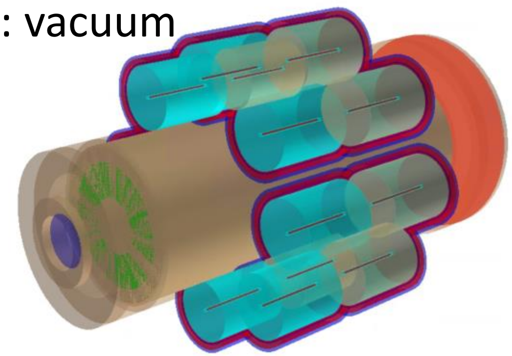


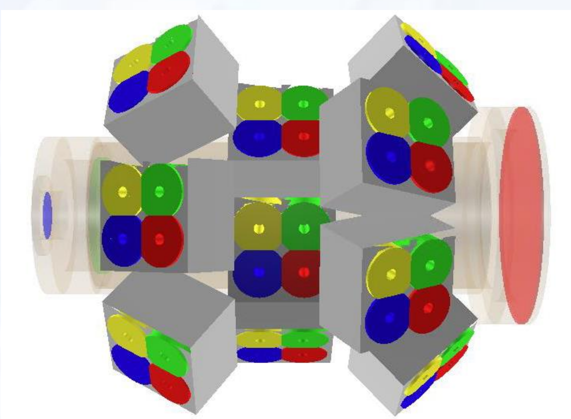


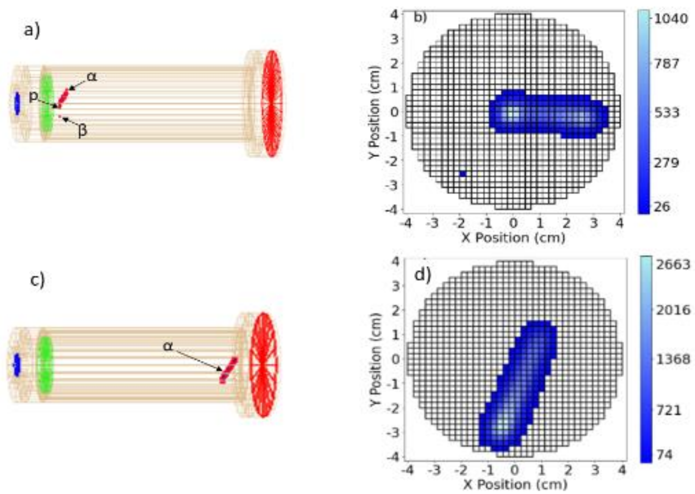


Full geometry and physics integrated in ATTPCROOTv2, including TPC and Ge arrays (eg. SeGA and DeGAi below)

Blue: cryostat (aluminum)
Cyan: active layer (germanium)
Red: vacuum

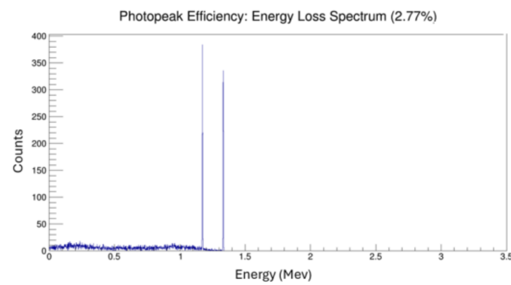


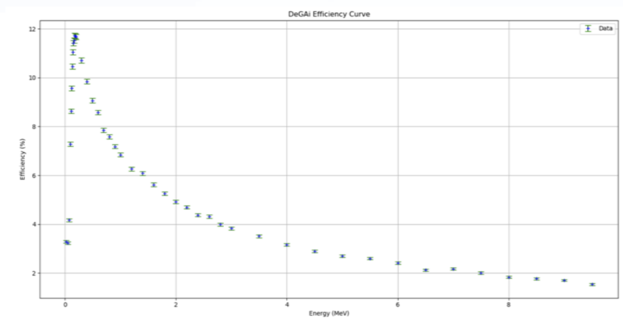




Panel (a) and (b)- ATTPCROOT simulation of the GADGET II TPC for 20Mg(βpα)15O, 3D render and 2D projection.

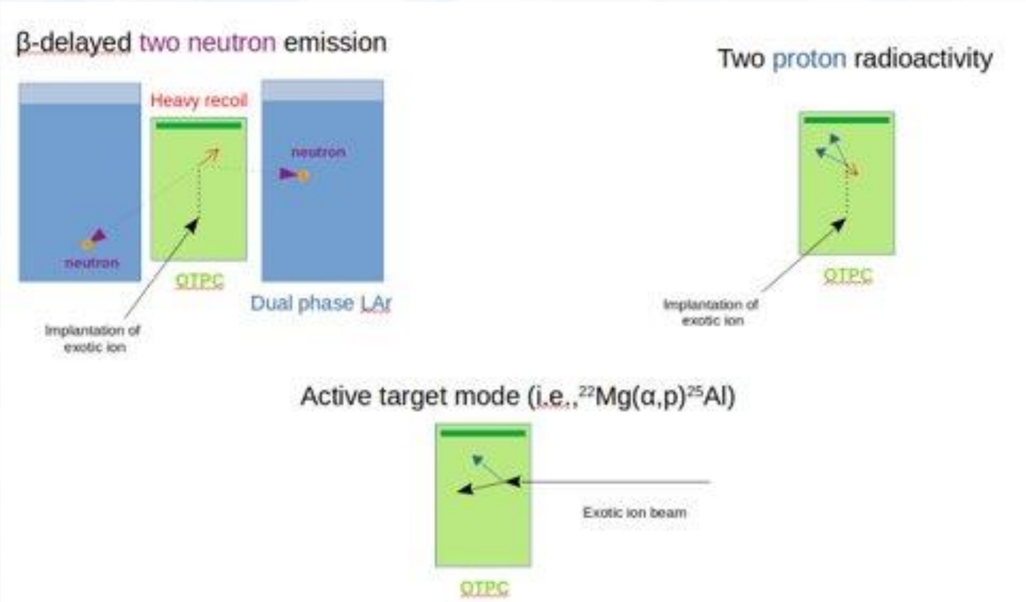
Panel (c) and (d)- ATTPCROOT simulation of the GADGET II TPC for 220Rn α-decay, 3D render and 2D projection.

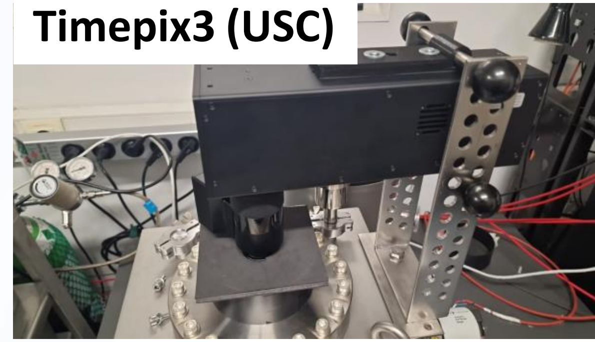


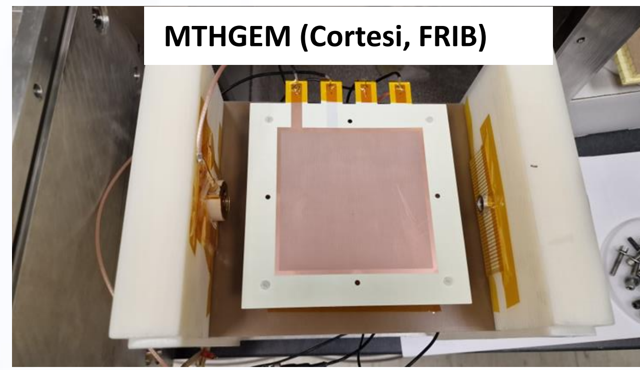


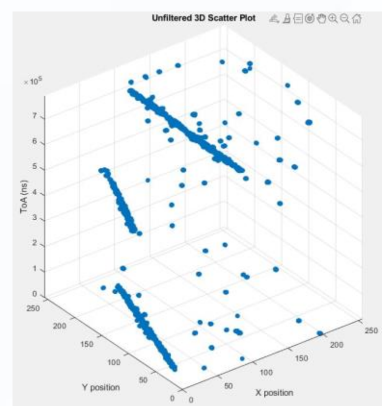
R. Mahajan, T. Wheeler *et al*., submitted, arXiv:2401.01904
Figure credit and g-ray simulations: A. Andalib

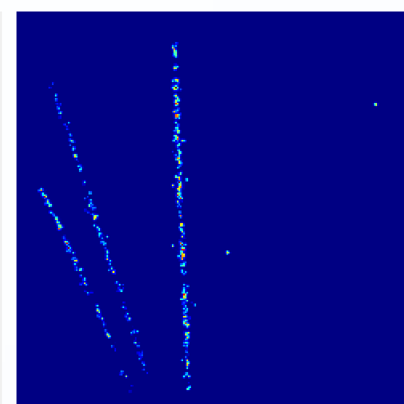
Development of 3D Optical Active Target











- First measurement done at FRIB using a MTHGEM and a Timepix3 camera with 30 torr pure CF_4 (USC-ANL-FRIB collaboration).
- Development of a simulation framework for Optical TPCs (USC-WIS collaboration). Include optical photons.
- Experiment approved at TRIUMF: Implant-decay of ^{16}C and ^{9}C.
- Future: OTPC for neutron scattering studies.

Thank you!

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