β-decay proton emission studies with the Active Target Time Projection Chamber (AT-TPC)

Yassid Ayyad and Wolfgang Mittig

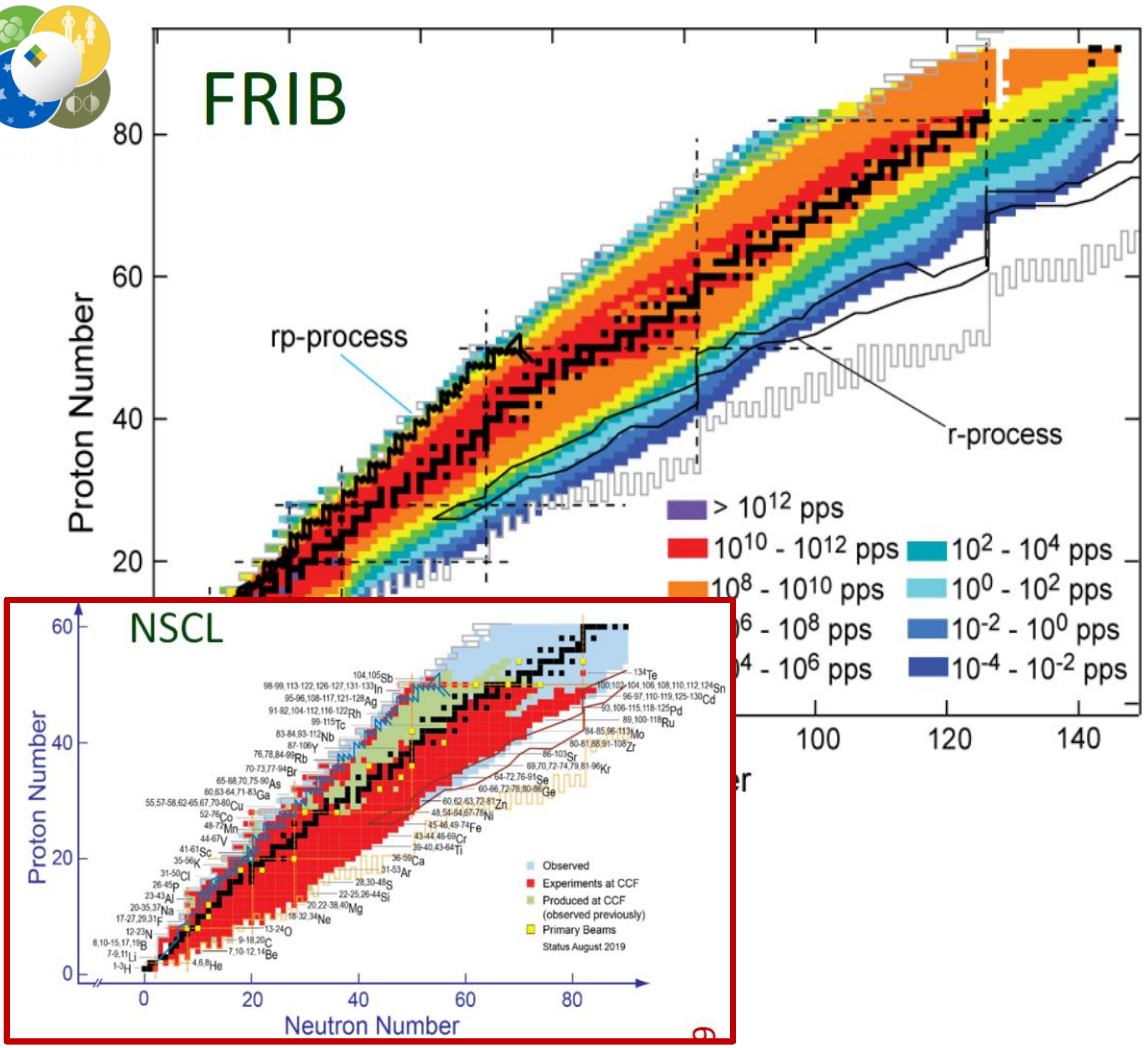
FRIB

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

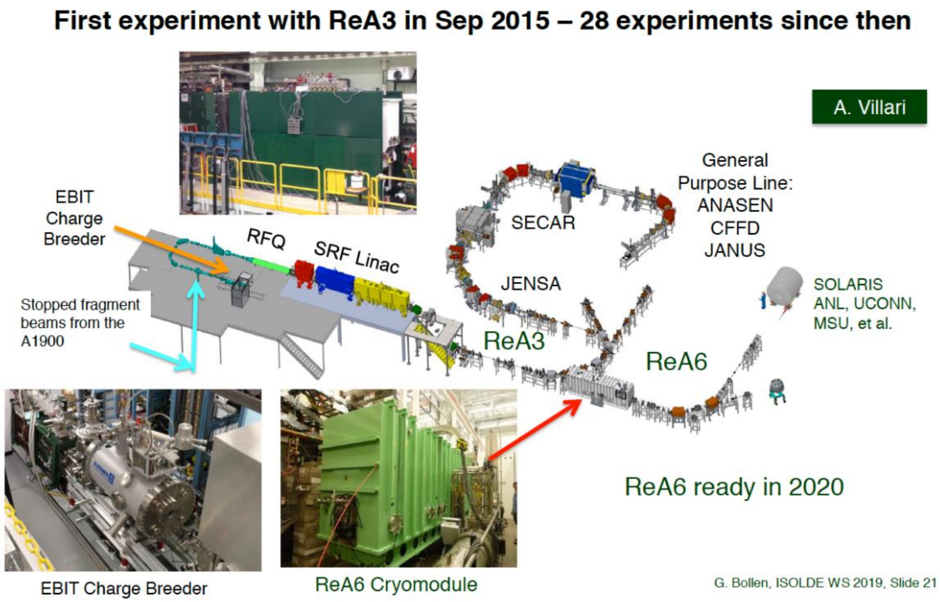
- Studies with rare isotope beams.
- Halo nuclei and β-decay.
- Implantation-decay experiments with the AT-TPC: The case of ^{11}Be.
- Particle (ion) identification at low kinetic energy.
- Outlook and conclusions.

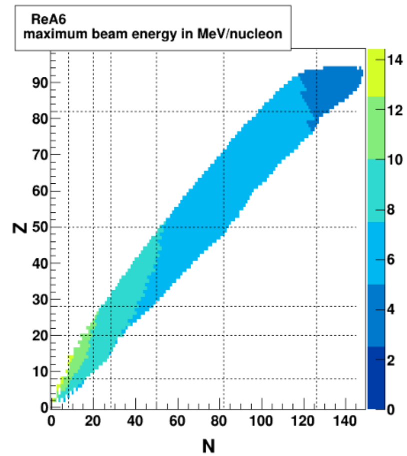
Next-generation facilities for low-energy nuclear physics: FRIB

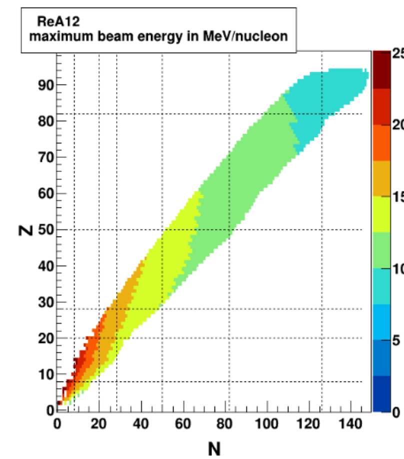


- NSCL produced about 1000 RIBs.
- FY2020 run time is 5,055 hours with 80% CCF availability and 98% for ReA3.
- Primary beams energy ranging from 10A to 175A MeV
- FRIB will increase production by several orders of magnitude. Ions up to Uranium and 400 kW (5 x10^{13} ^{238}U/s).
- Energy upgrade up to 400A MeV.

Next-generation facilities for low-energy nuclear physics: ReA (FRIB)



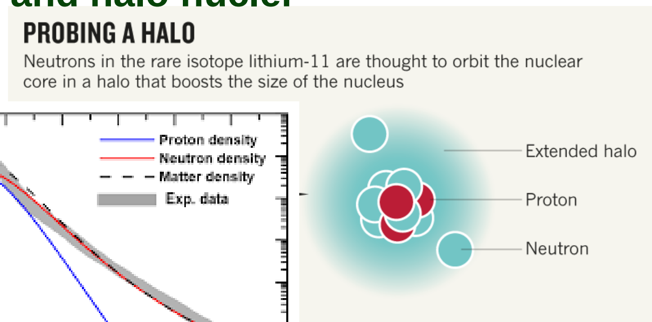


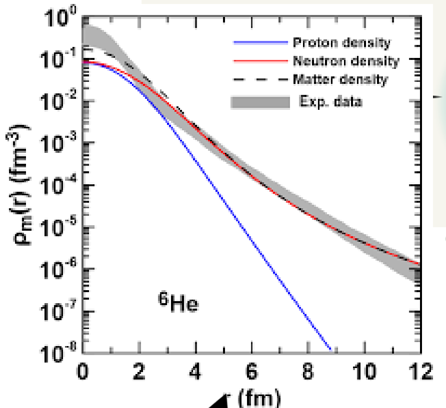


- From 300 keV/u to the maximum of 12 MeV/u for Q/A=1/2.
- Broad range of isotopes can be accelerated depending on: Beam input in ReA(intensity of stopped beam), Beam-Cooler-Buncher efficiency,EBIT efficiency, RFQ efficiency and Transport efficiency = TR.
- Main limitation for light nuclei due to stopping efficiency: Cycstopper provides longer paths and better efficiency

From nuclear structure to dark matter

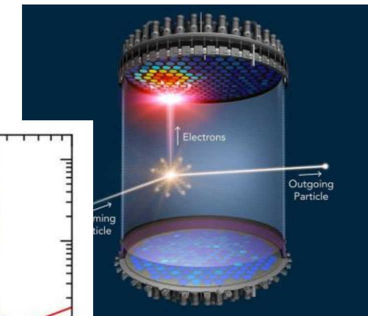
Nuclear structure and halo nuclei

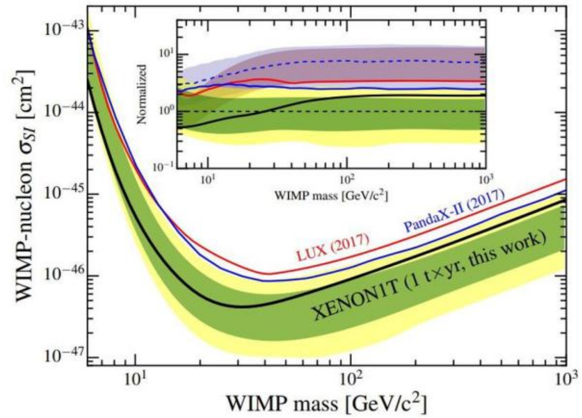


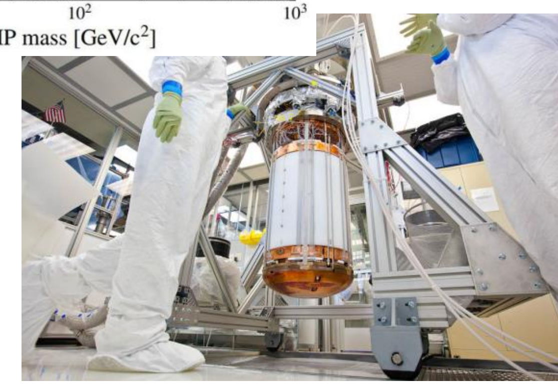


Credit: Nature, February 20, 2018, doi: 10.1038/d41586-018-02221-9

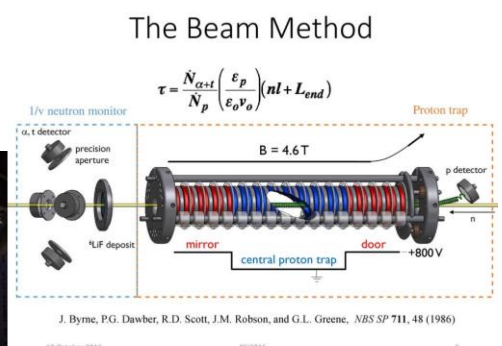
Dark matter

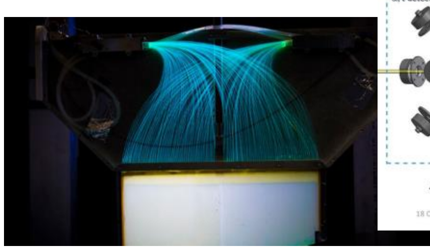




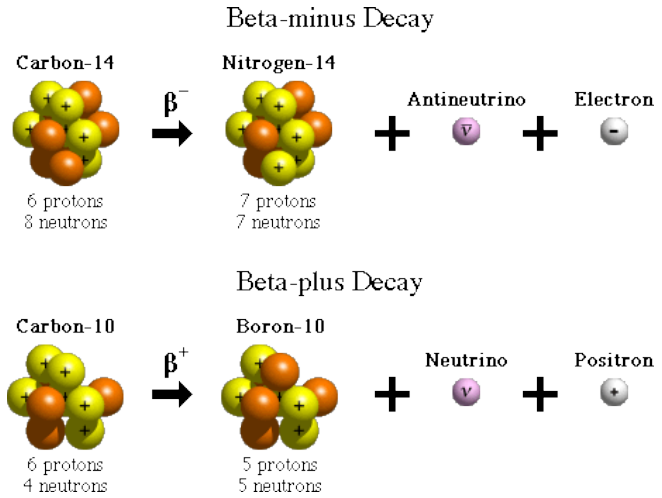


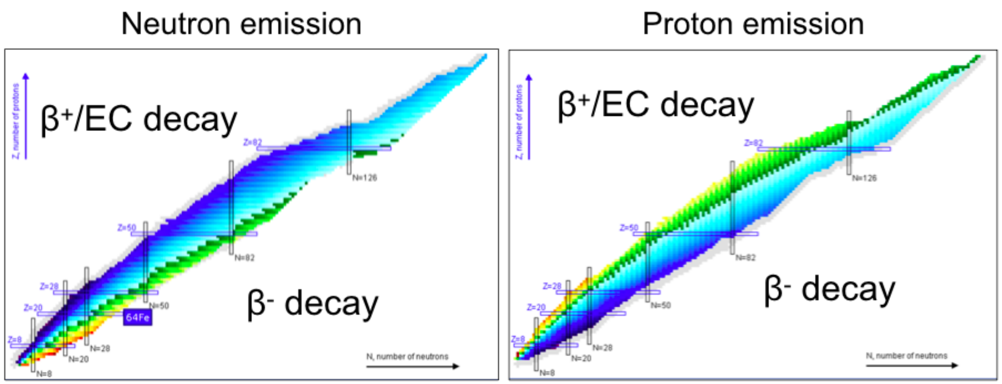
Neutron lifetime



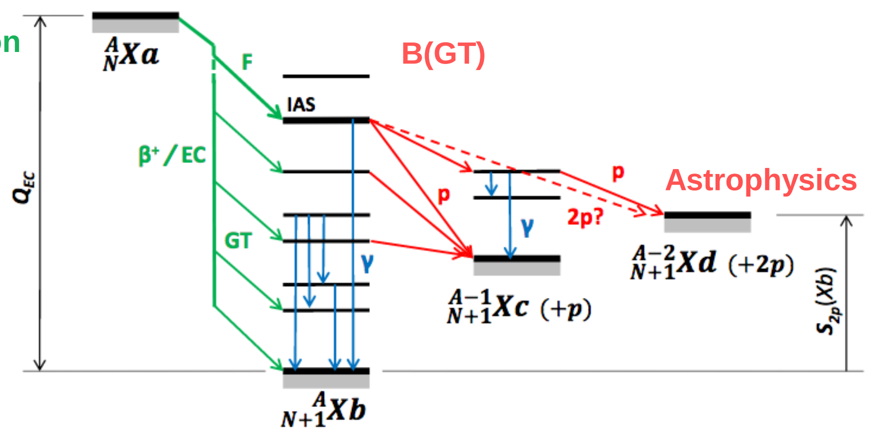


Beta-delayed proton emission



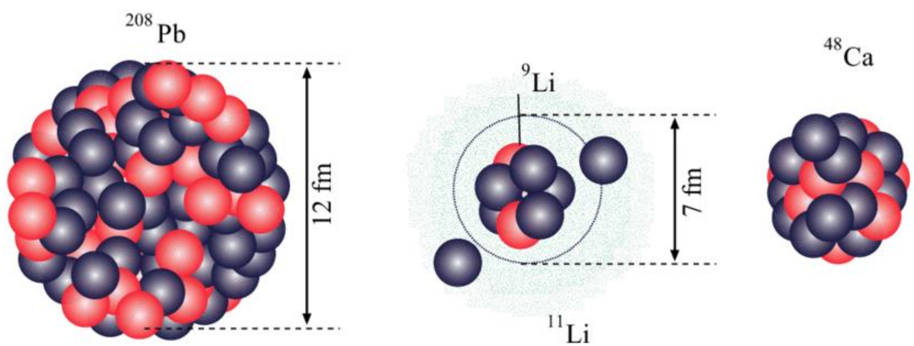


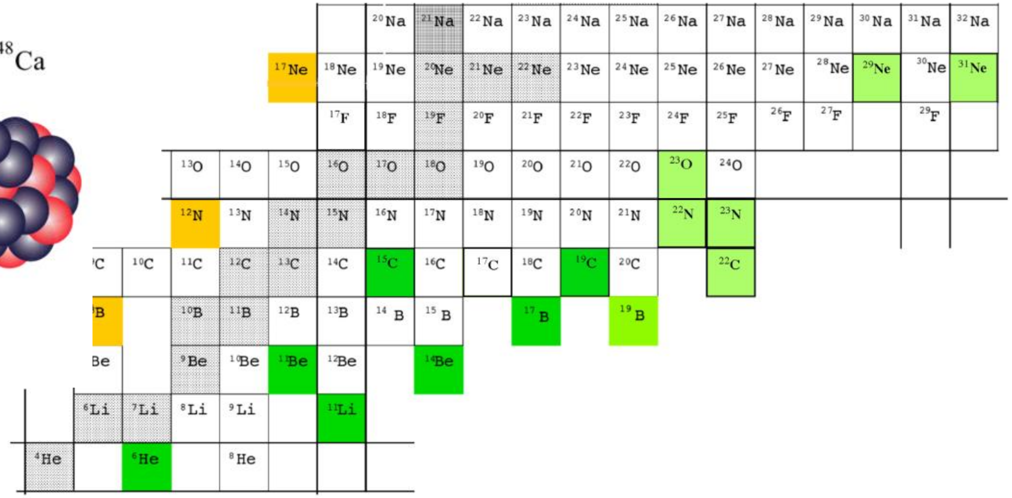
Isobaric Multiplet Mass Equation



Credit: J. Giovinazzo EJC2017

Neutron halo nuclei



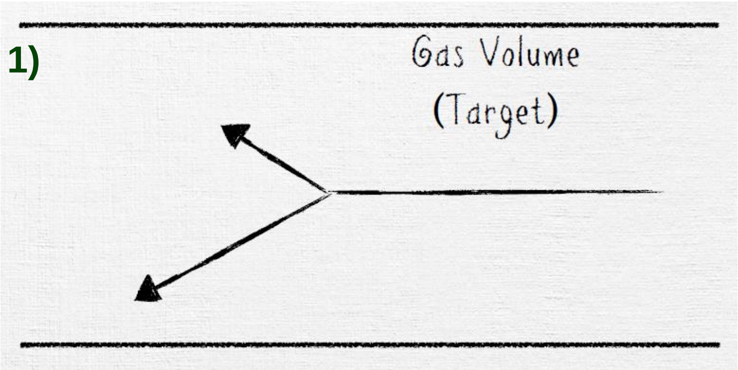


- The halo is a long tail in the density distribution of a nucleus.
- An important concept of a halo is the decoupling of the halo wave function from the core of the nucleus.
- Very weak binding of the last one or two valence nucleons (usually neutrons).
- Single-particle behavior.

Active Targets Time Projection Chambers

How to make a thick target-detector with high-resolution in 4 steps

1)



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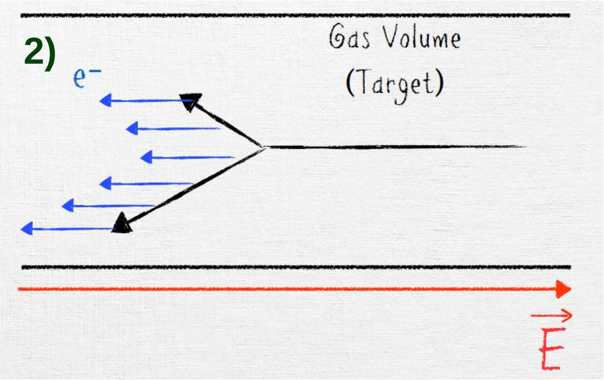

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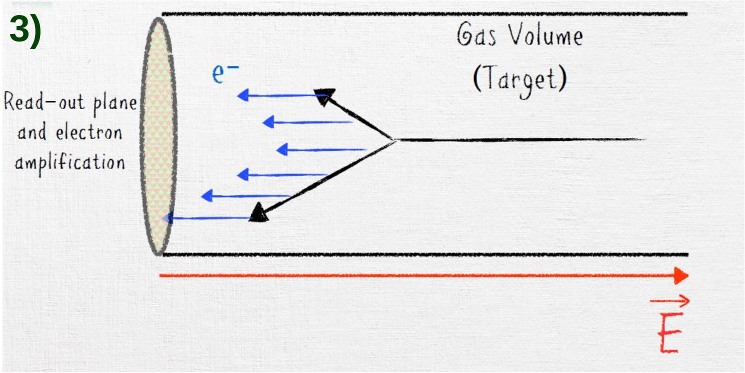

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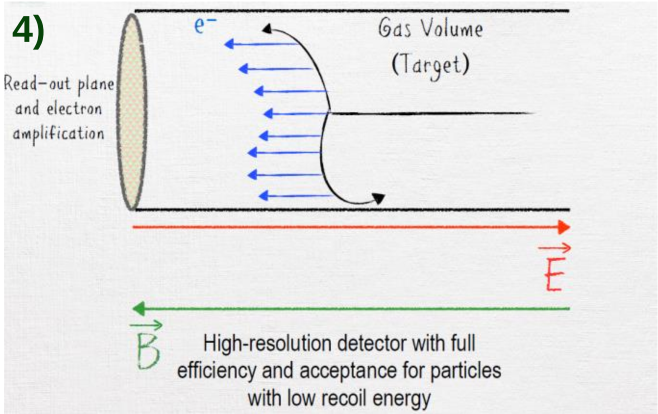
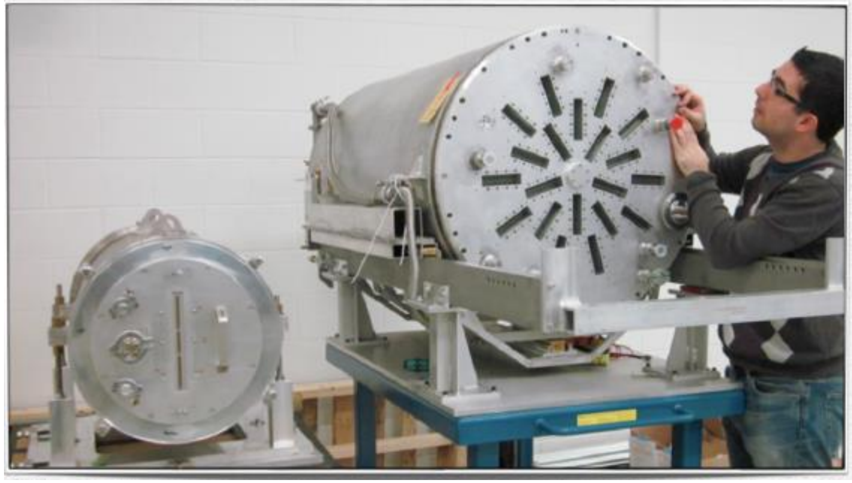
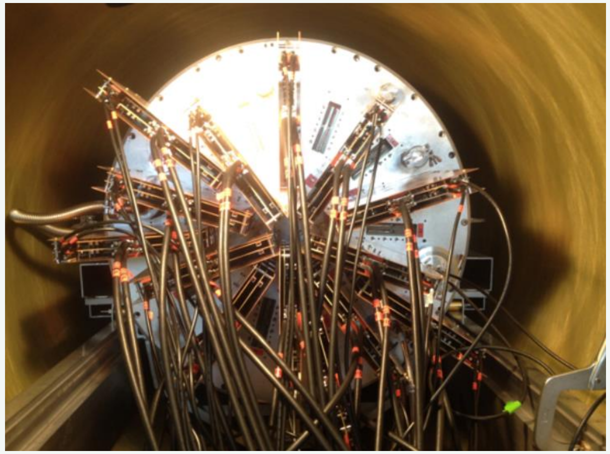
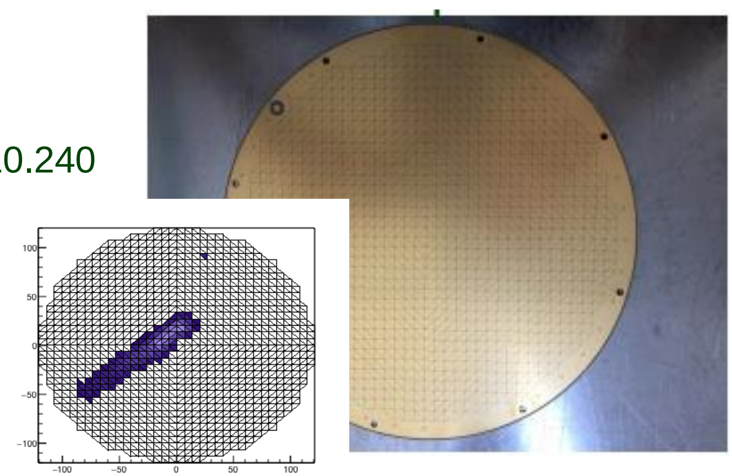
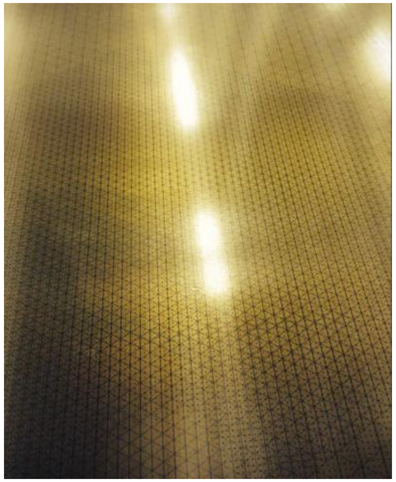


AT-TPC (soon SOLARIS) at NSCL/FRIB



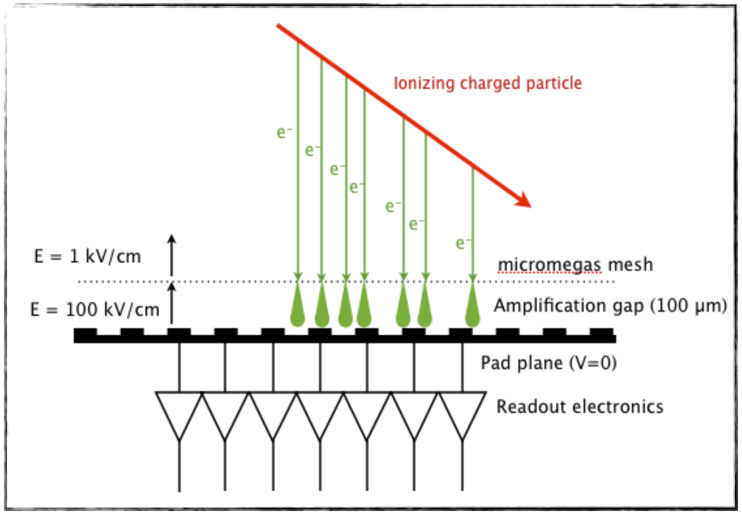


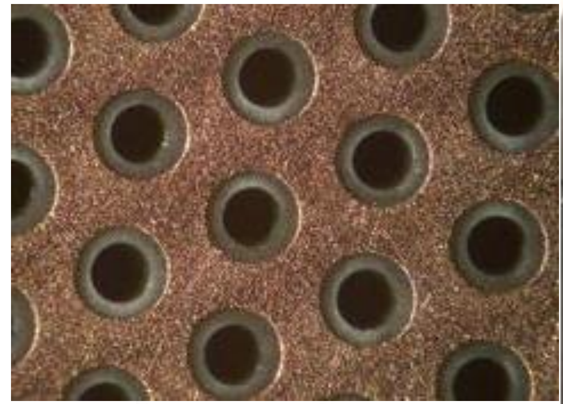




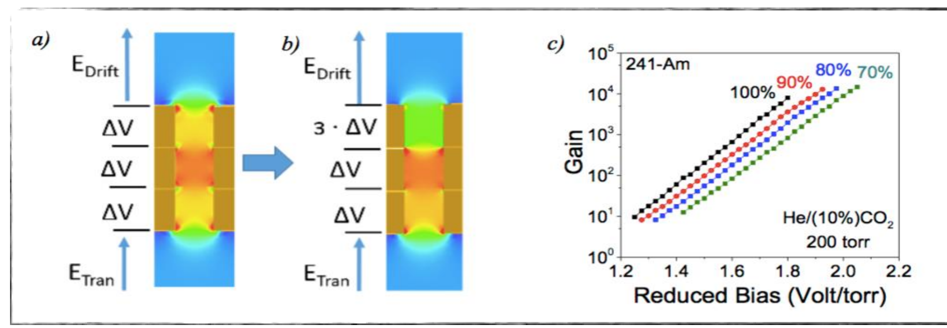
- Cylindrical-radial type.
- Prototype AT-TPC/ AT-TPC – 2.000/10.240
- 50 cm x 12.5 cm/100 cm x 25 cm.
- General Electronics for TPCs (GET)

AT-TPC (soon SOLARIS) at NSCL/FRIB





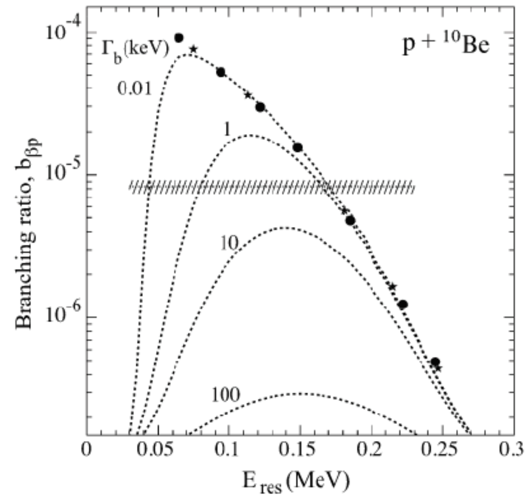
- Micromegas pad plane.
- Multi-Layer THGEM: High-gain for pure elemental gases: H_2, D_2, He..
- Other significant developments going on: MultiMesh MTHGEM, ceramic substrates, ion back flow suppression with layers of electron transparent materials.

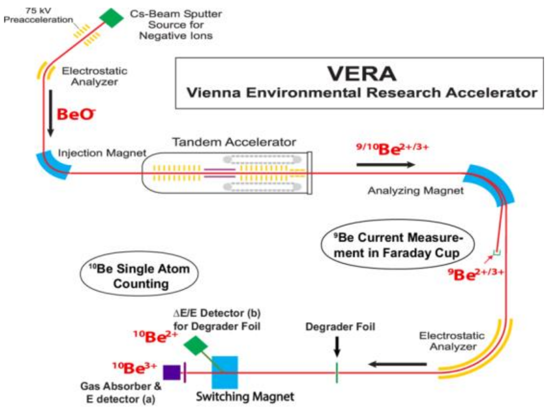


Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)

Beta-delayed proton emission in ^{11}Be

- Beta-delayed proton emission is possible if Sn<(mn−mp−me)c2≈0.782 MeV. In other words, if it is a halo nucleus
- ^{11}Be is halo and its lifetime is 13.7 s and has several beta-delayed channels open. Qbp = 280 keV. **Very low energy protons**.
- An (highly) hypothetical decay of the halo neutron into a dark matter particle would explain the neutron lifetime anomaly.
- Previous branching ratio by an indirect AMS measurement reported 8.3(6)x10^{-6}, explained by an unobserved resonance in ^{11}B.
- Measuring the energy distribution of the protons will yield information in the hypothesized resonance.
- βp energy window allows for the B(GT) extraction.

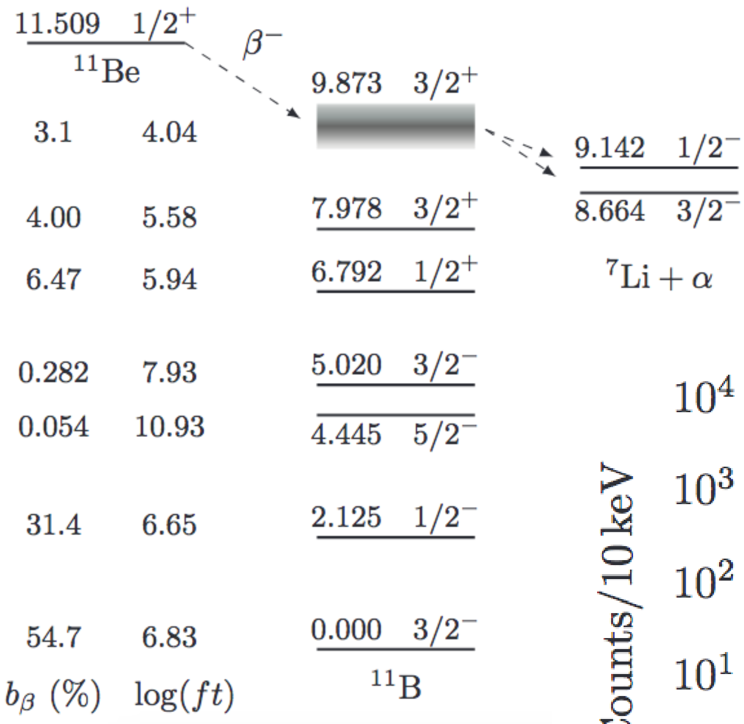


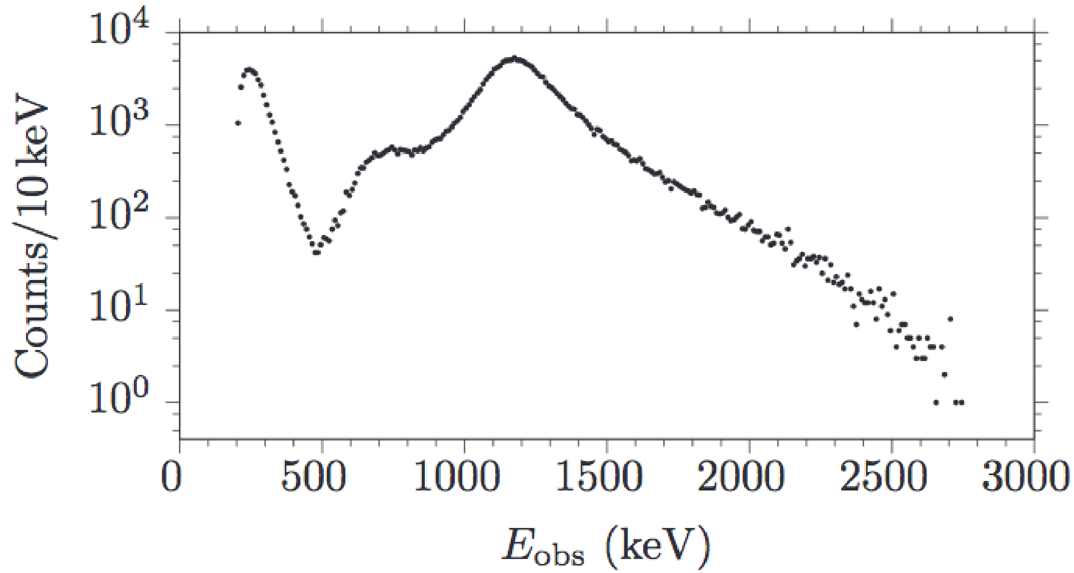


Riisager, PLB **732** 305 (2014)

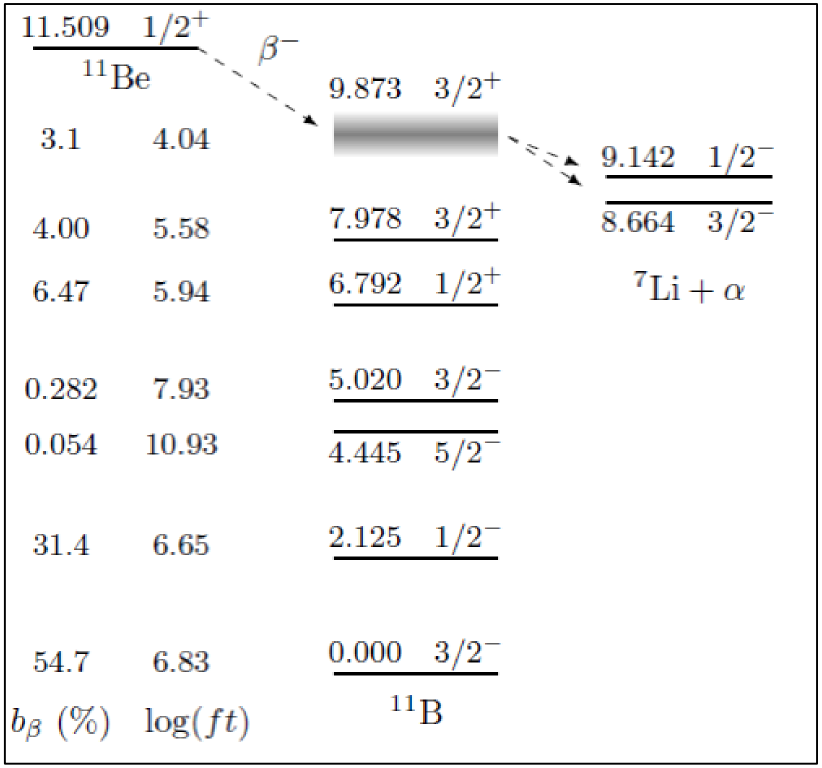
Riisager, Phys. Scr. **T152,** 014001 (2013)

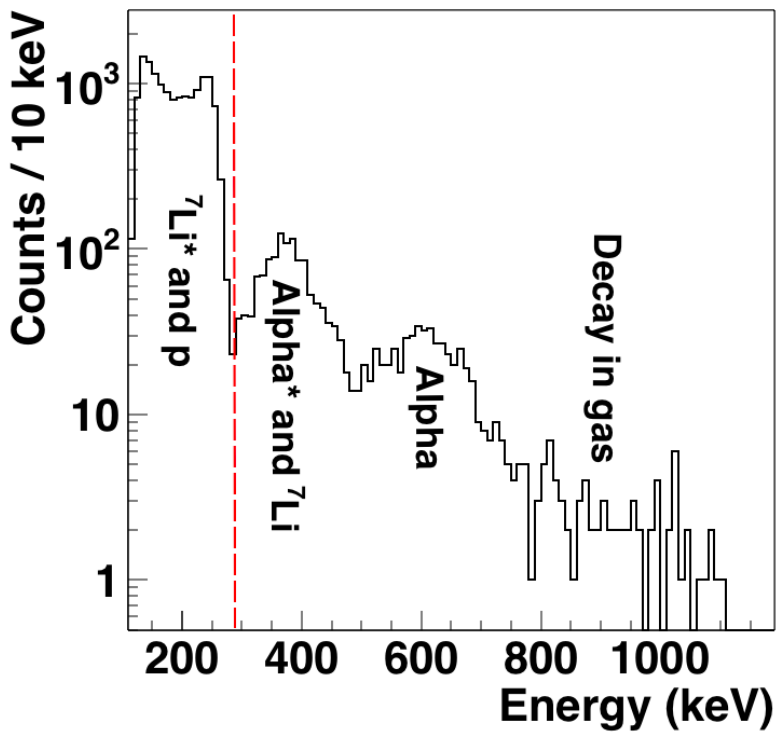
Experimental method: Silicon detectors



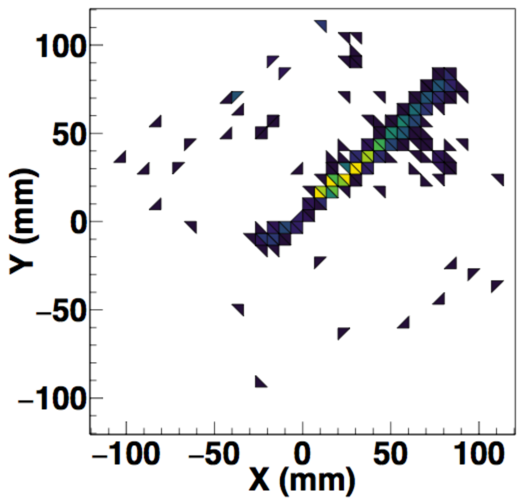


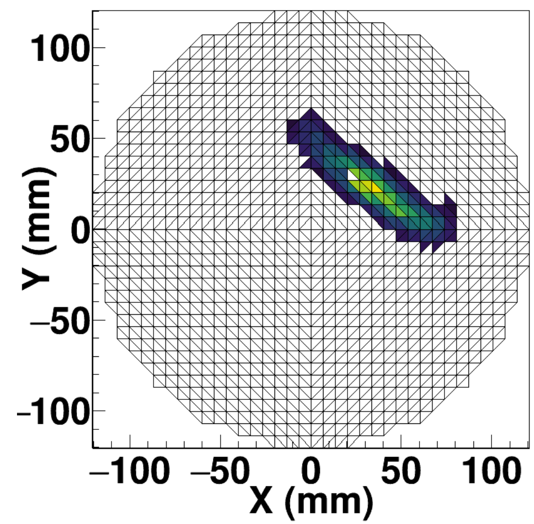
Experimental method: Calorimetry

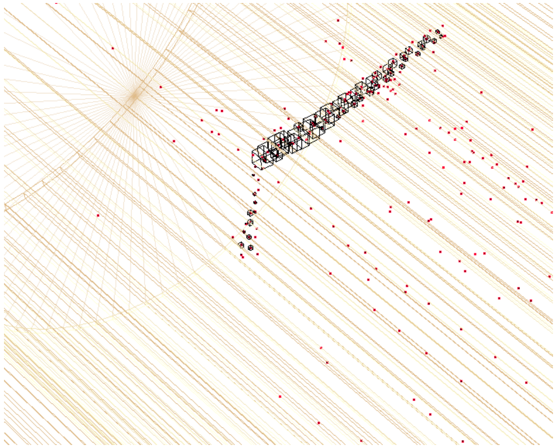


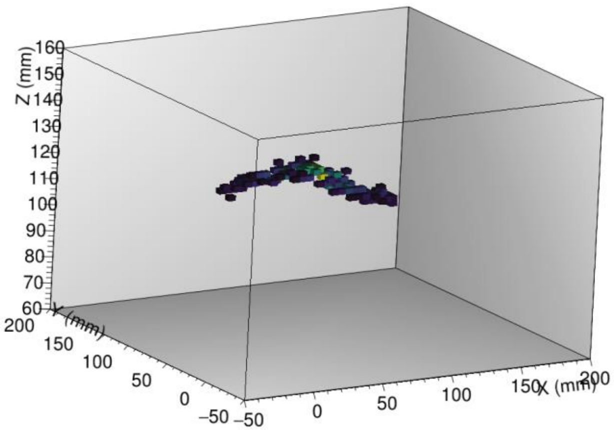


Experimental method

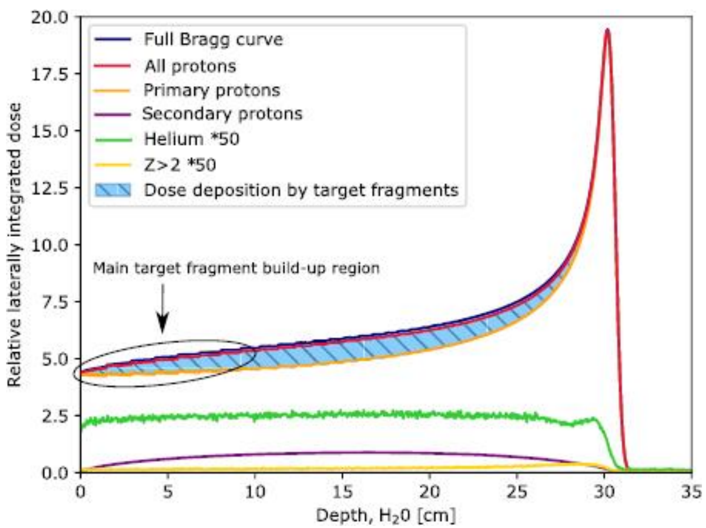


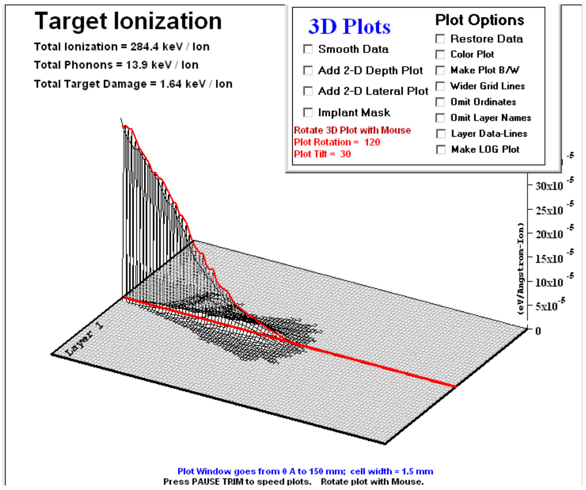


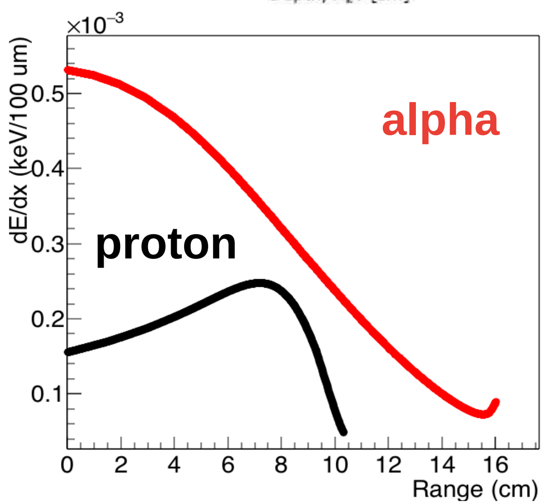


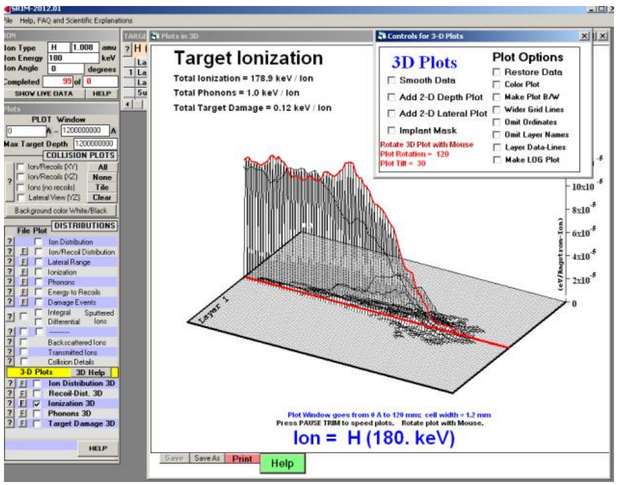


Bragg curve challenges



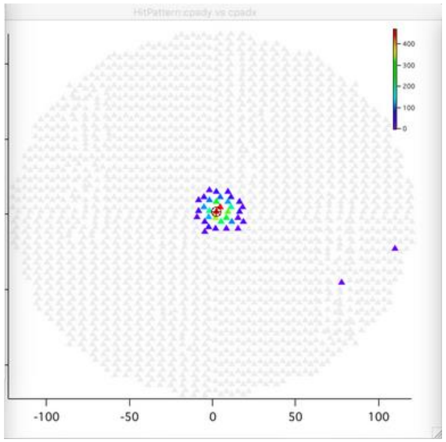


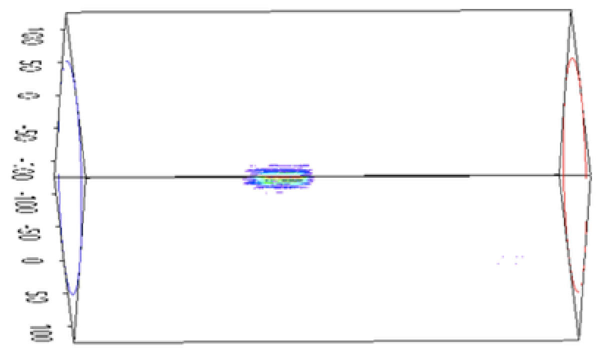


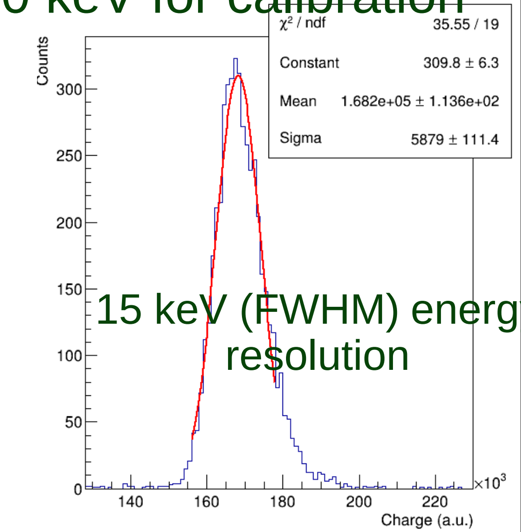


Proton beam calibration

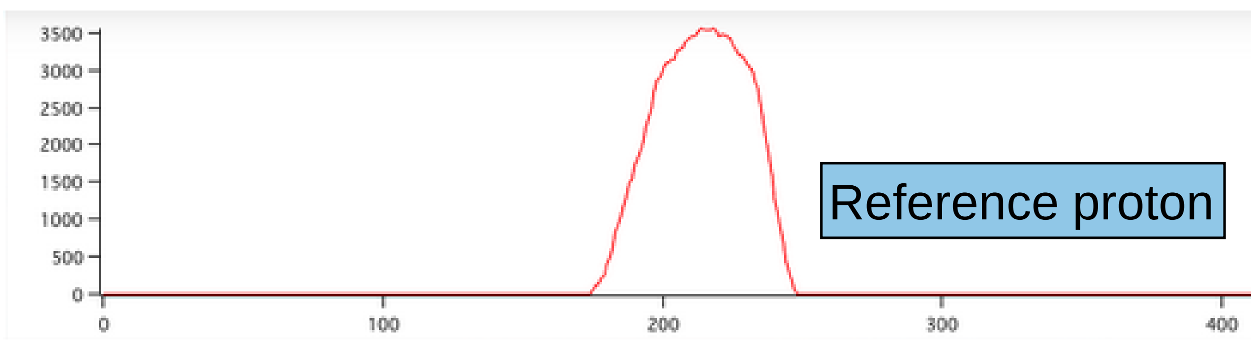
OH- beam from OLIS produced protons of 180 keV for calibration



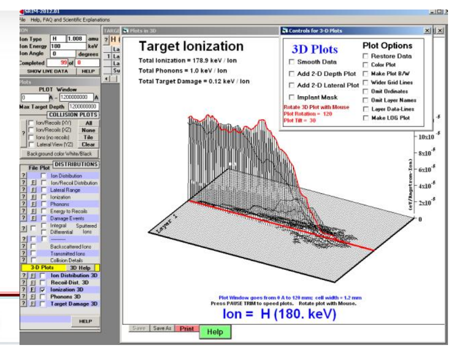




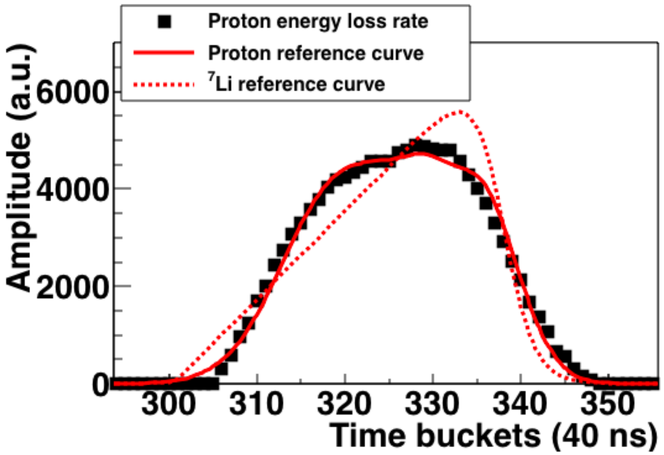
15 keV (FWHM) energy resolution

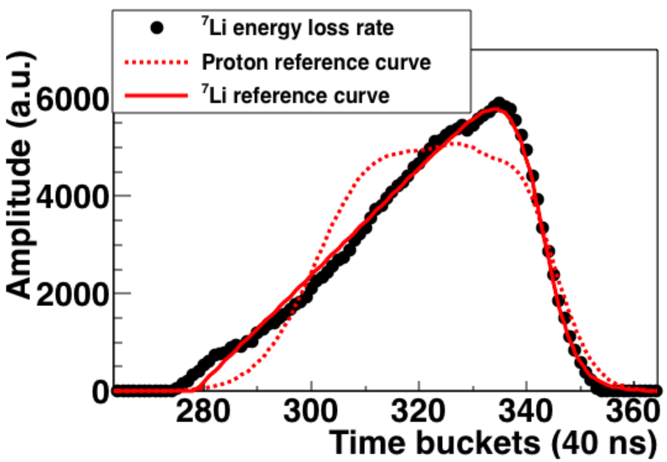


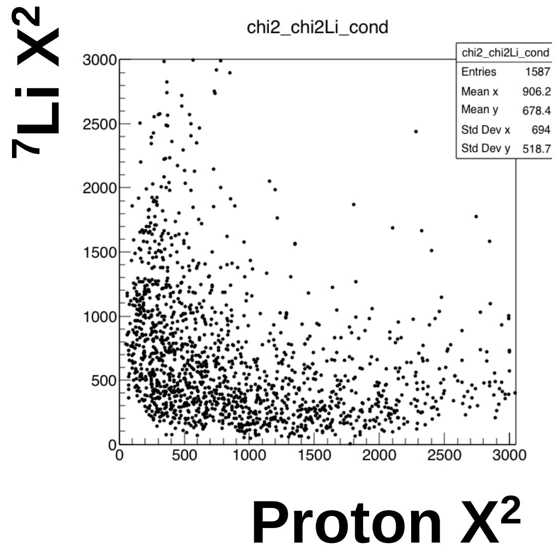
Reference proton

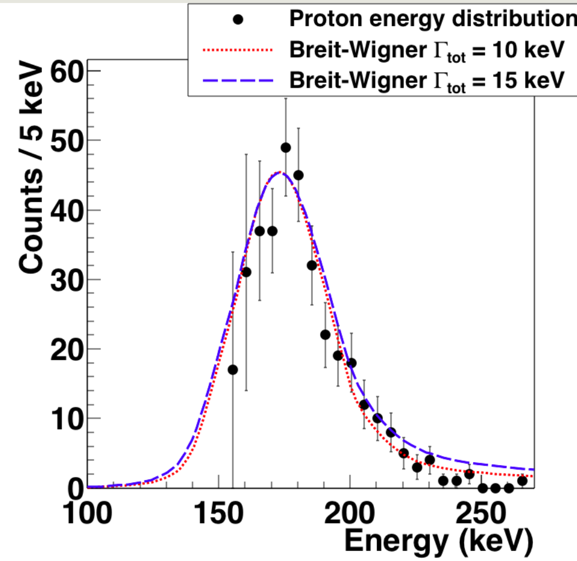


Analysis of Bragg curves







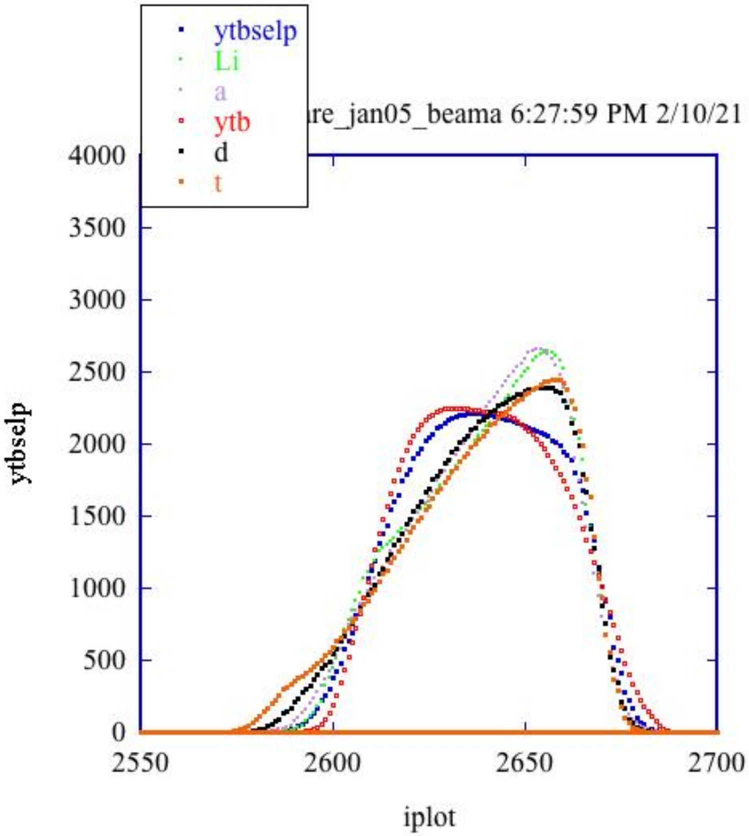


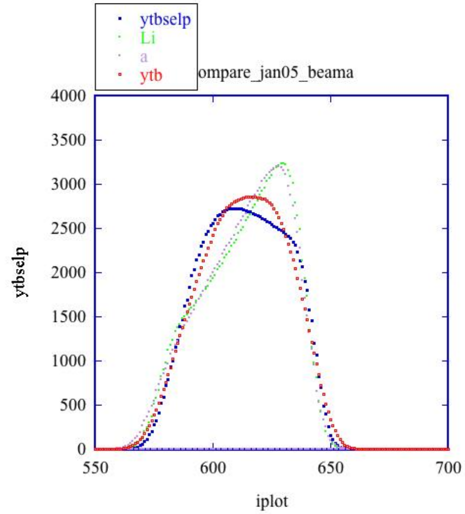
- First direct observation of β⁻p in a neutron-rich nuclei.
- Branching ratio is 1.2×10^{-5} , with 30% uncertainty… Theoretical calculations yield 8.0×10^{-6}.
- A narrow resonance (12 keV) in ^{11}B was inferred. E = 11425(20)keV, Γ=12(5) keV, Jπ = 1/2;3/2+
- Decay into the continuum would be characterized by a much shorter branching ratio (10^{-10}).

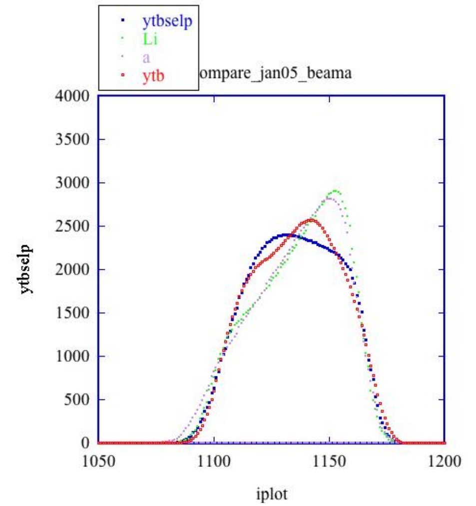
Beta-delayed proton emission in ^{11}Be: reanalysis and outlook

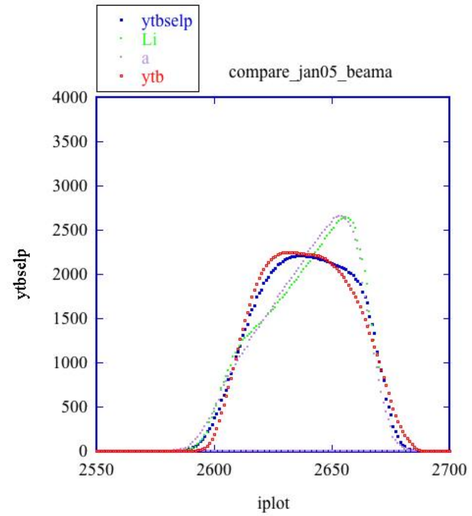
- A new particle ID has been developed including d, t and ^{4}He energy loss curves.
- The Chi-squared test has been redefined: normalization to the number of points (it didn't actually change anything).
- Instead of projecting the calculated energy loss curves, we have projected the one of the particle to analyze into its direction.
- We have obtained a very similar branching ratio.
- This does NOT rule out the possibility of populating the IAS of ^{11}B
- But answers most of the criticisms.
- Manuscript in preparation (W. Mittig, Y. Ayyad and D. Bazin)

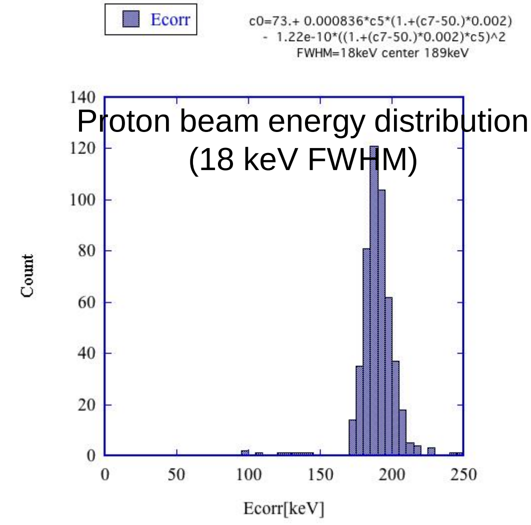
Particle identification: p,d,t,alpha and ^{7}Li





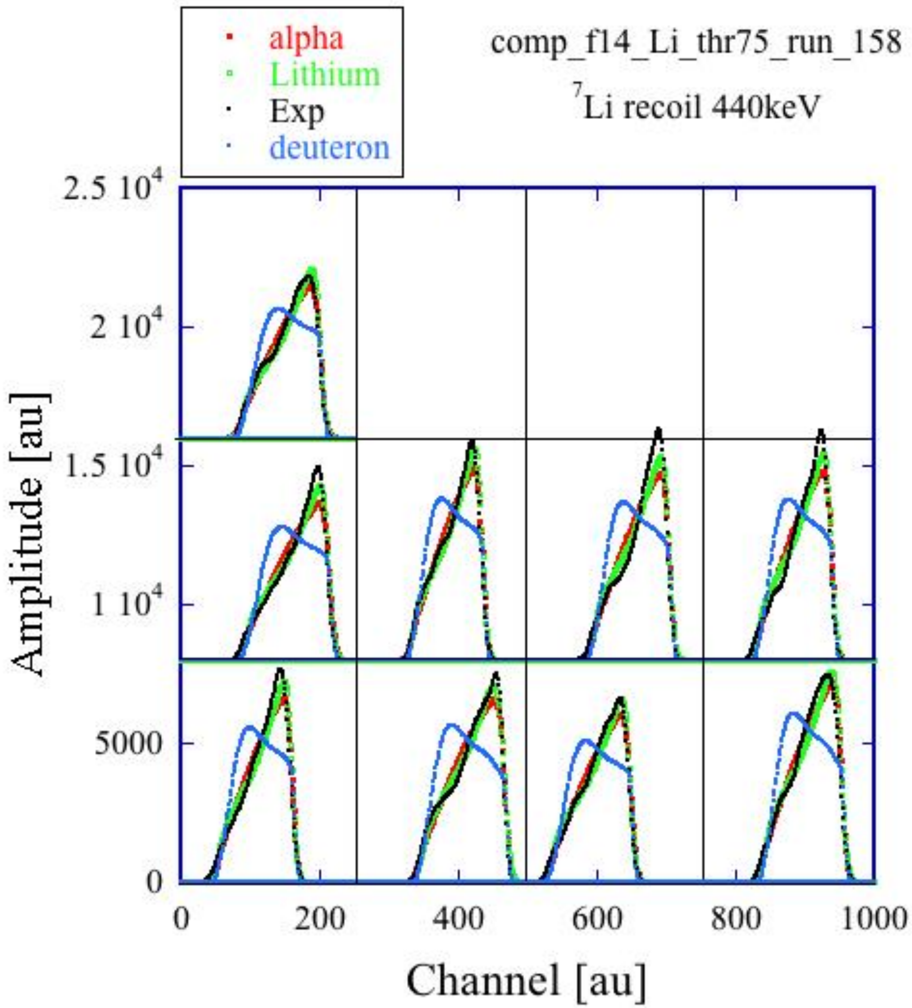






Proton beam energy distribution
(18 keV FWHM)

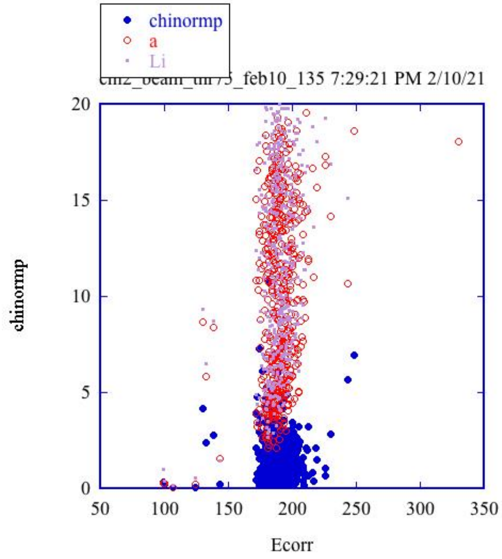
Particle identification: p,d,t,alpha and ^{7}Li



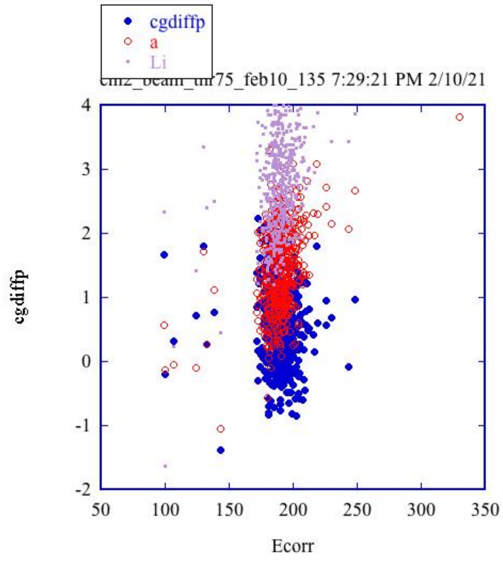
Criteria for proton event selection

- Proton beam events are used to assess the selection parameters.
- Chi2, center of gravity (shape of the pulse) and stretch factor.

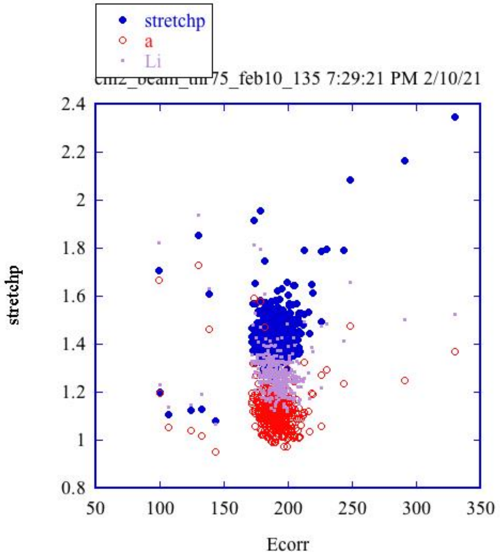
Chi2



Center of gravity

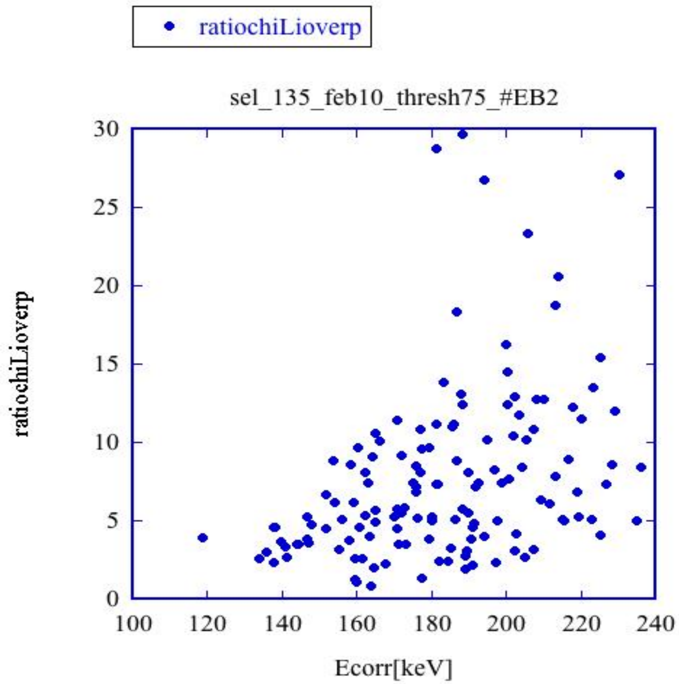


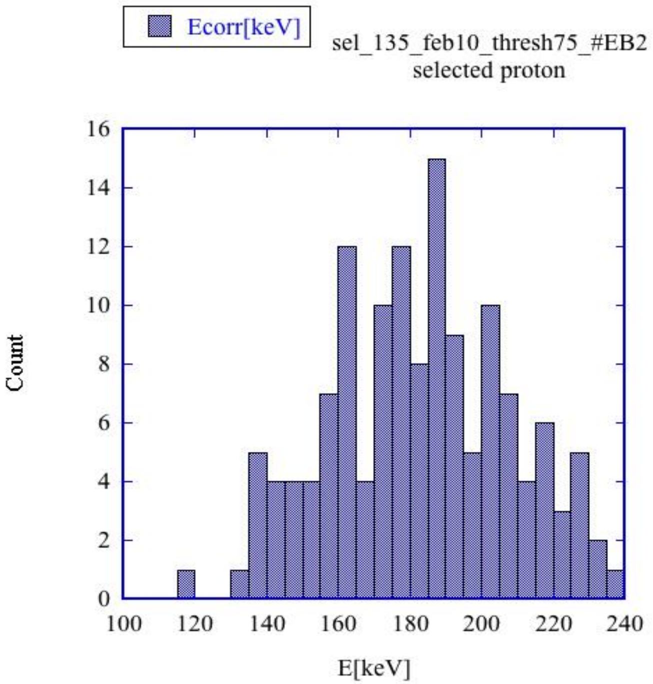
Stretch



Criteria for proton event selection

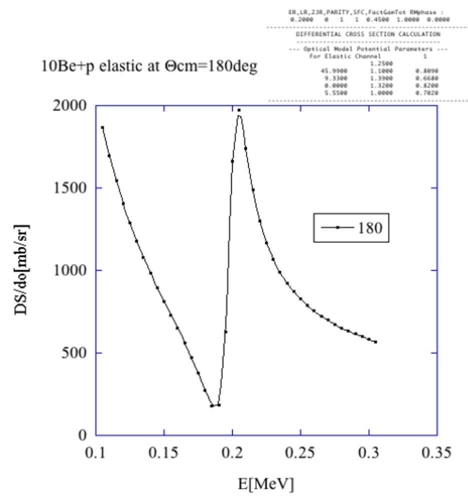
- Proton beam events are used to assess the selection parameters.
- Chi2, center of gravity (shape of the pulse) and stretch factor.
- This method is complementary to the one we used before: no selection in chi2.
- The energy distribution obtained in the last analysis is compatible with the published result.

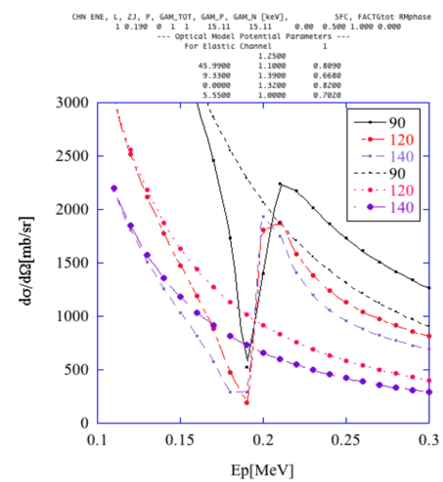




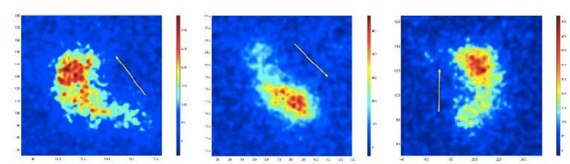
Beta-delayed proton emission in ^{11}Be: reanalysis and outlook

- Direct measurement of 10Be+p at 400 keV/u at ReA3 (Y. Ayyad. Search for near-threshold narrow resonances)
- Very simple setup consisting of an ionization chamber coupled to a Surface Barrier detector (Developed by the NSCL detector lab).
- 2 um CH_2 target used for “thick” target method.
- Possibility of measuring the ^{10}Be recoil (20 keV) with a Optical TPC for directional dark matter search.
- Development of a MTHGEM with finer pitch to increase primary luminescence in CF_4. This will enhance electron-heavy recoil rejection capabilities (production started by CERN MPGD team).
- Other opportunities: Combined measurement of heavy recoil and neutron in beta-delayed neutron emission.
- Other proton radioactivity studies at ReA

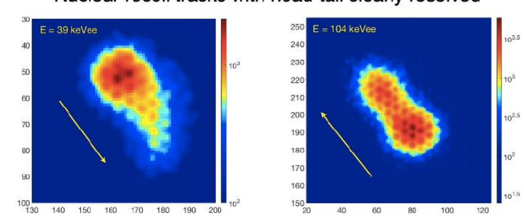




Low energy, ~5-6 keV electron tracks – 6-7 mm long



Nuclear recoil tracks with head-tail clearly resolved



D Loomba, UNM

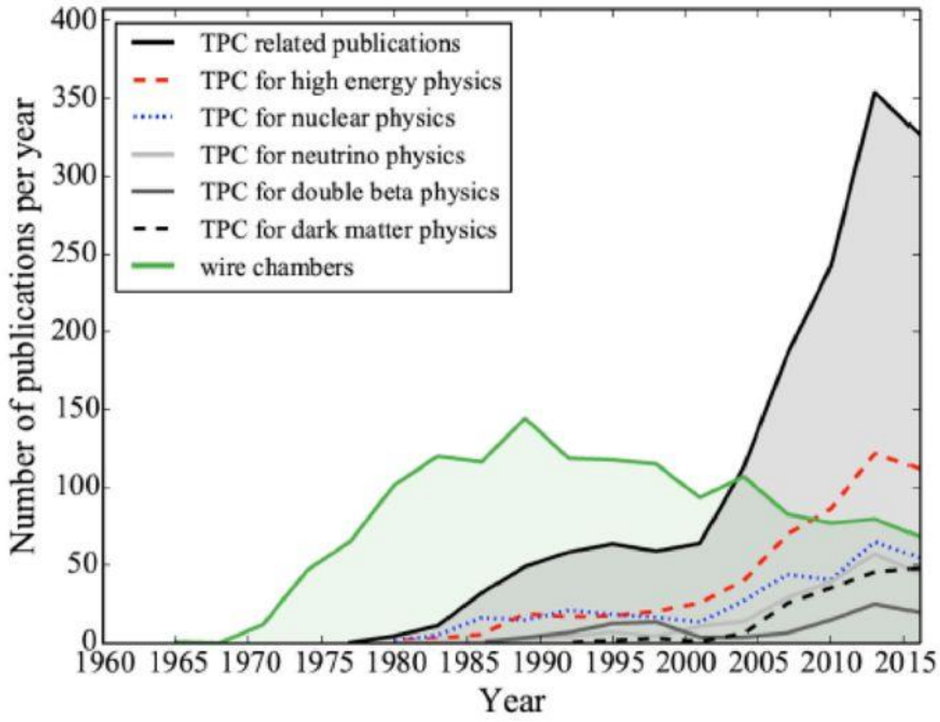
Conclusions and outlook

- We have observed the emission of protons in neutron-rich nuclei after β-decay.
- The particle identification was done using the characteristic Bragg curves for the detected particles.
- We have obtained consistent results using two complementary methods.
- Future experiments to improve the sensitivity of our detection setup are planned.
- Collaborators are always welcome!

Thank you for your attention!

Backup slides

Active Targets Time Projection Chambers



from scopus (efficiency and purity of selections verified to be within 20%)

Table 1
Active targets in operation or being constructed.

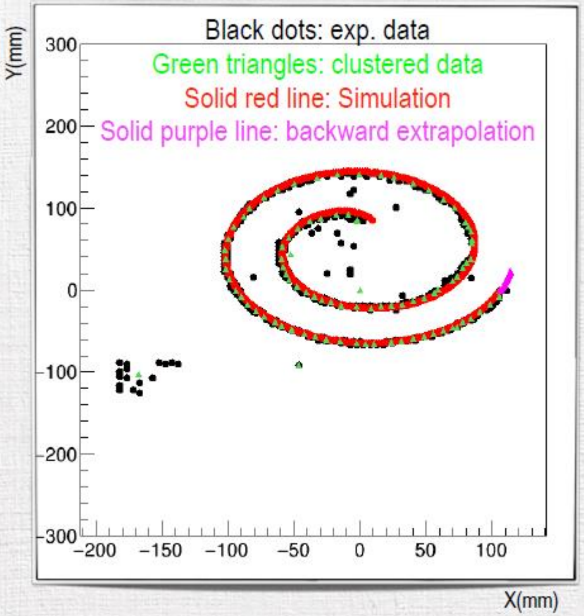
Name	Lab	Gas ampl.	Volume (cm^3)	Pressure (atm)	Energy (MeV/n)	Electronics	Number of chan.	Status[a]	Ref.
Ikar	GSI	NA	$60 \cdot 20^2\pi$	10	$\gtrsim$700	FADC	6*3	O	[6]
Maya	GANIL	Wire	$30 \cdot 28.3^2$	0.02–2	2–60	Gassiplex	1024	O	[7]
ACTAR	GANIL	μmegas	20^3	0.01–3	2–60	GET	16,000	C, P	[8]
MSTPC[b]	CNS	Wires	$70 \cdot 15 \cdot 20$[c]	<0.3	0.5–5	FADC	128	O	[9,10]
CAT	CNS	GEM	$10 \cdot 10 \cdot 25$	0.2–1	100–200	FADC	400	T	[11]
MAIKo	RNCP	μ-PIC	14^3	0.4–1	10–100	FADC	2×256	T	[12]
pAT-TPC	MSU	μmegas	$50 \cdot 12.5^2\pi$	0.01–1	1–10	GET	256	T, O	[13]
AT-TPC	FRIB	μmegas	$100 \cdot 25^2\pi$	0.01–1	1–100	GET	10,240	O	[14]
TACTIC	TRIUMF	GEM	$24 \cdot 10^2\pi$	0.25–1	1–10	FADC	48	T	[15]
ANASEN	FSU/LSU	Wires	$43 \cdot 10^2\pi$	0.1–1	1–10	ASIC	512	O	[16]
MINOS	IRFU	μmegas	6000	1	>120	Feminos	5000	O	[17]
O-TPC	TUNL	Grid	$21 \cdot 30^2$	0.1	~10	Optical CCD	$2048 \cdot 2048$ pixels	O	[18]

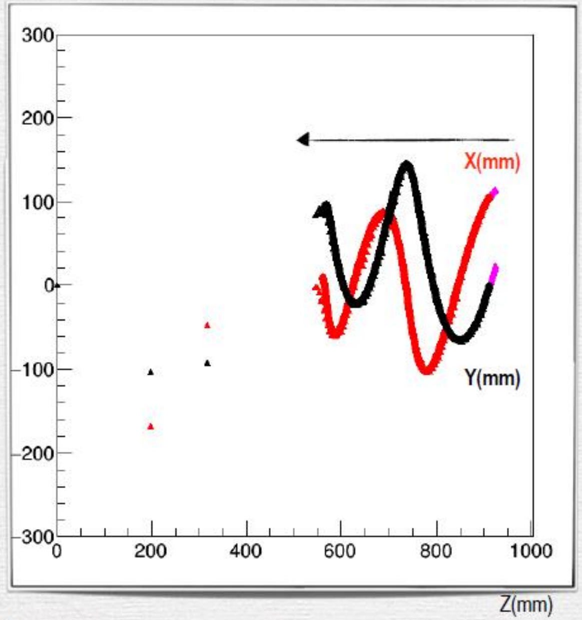
[a] O: operational, C: under construction, P: Project, T: test device.
[b] Two GEM versions: GEM-MSTPC (CNS) [19,20] GEM-MSTPC (KEK) [21,22].
[c] GEM-MSTPC (CNS): $23.5 \cdot 29.5 \cdot 10.0$, GEM-MSTPC (KEK): $10.0 \cdot 10.0 \cdot 10.0$.

S. Beceiro-Novo et al. / Progress in Particle and Nuclear Physics 84 (2015) 124–165

AT-TPC: Monte Carlo minimization

- Hough transformation defines initial conditions: scattering and azimutal angles, vertex and magnetic rigidity.
- A MC minimization is performed starting a propagation of the particle from the vertex and calculating the χ^2 for each point along the Z coordinate. The energy loss is calculated by using SRIM code.
- The real vertex and energy is found by extrapolating back the spiral until the minimum distance of approach (with respect the expected vertex position)



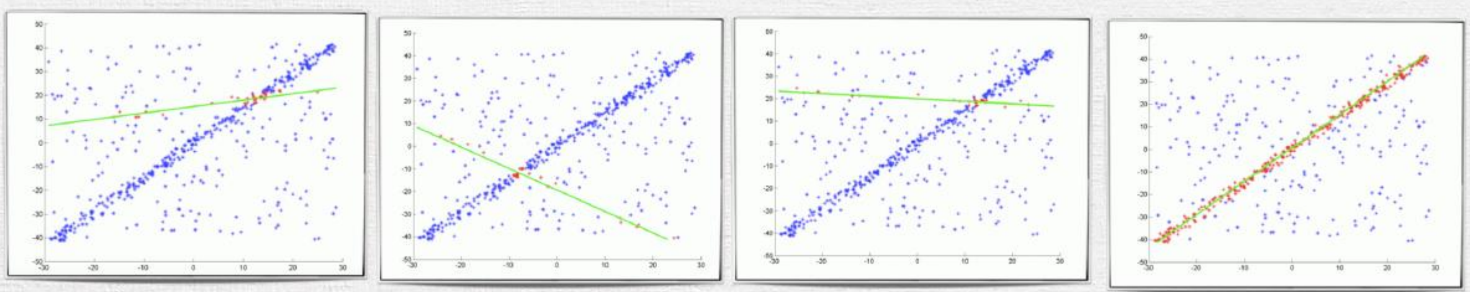


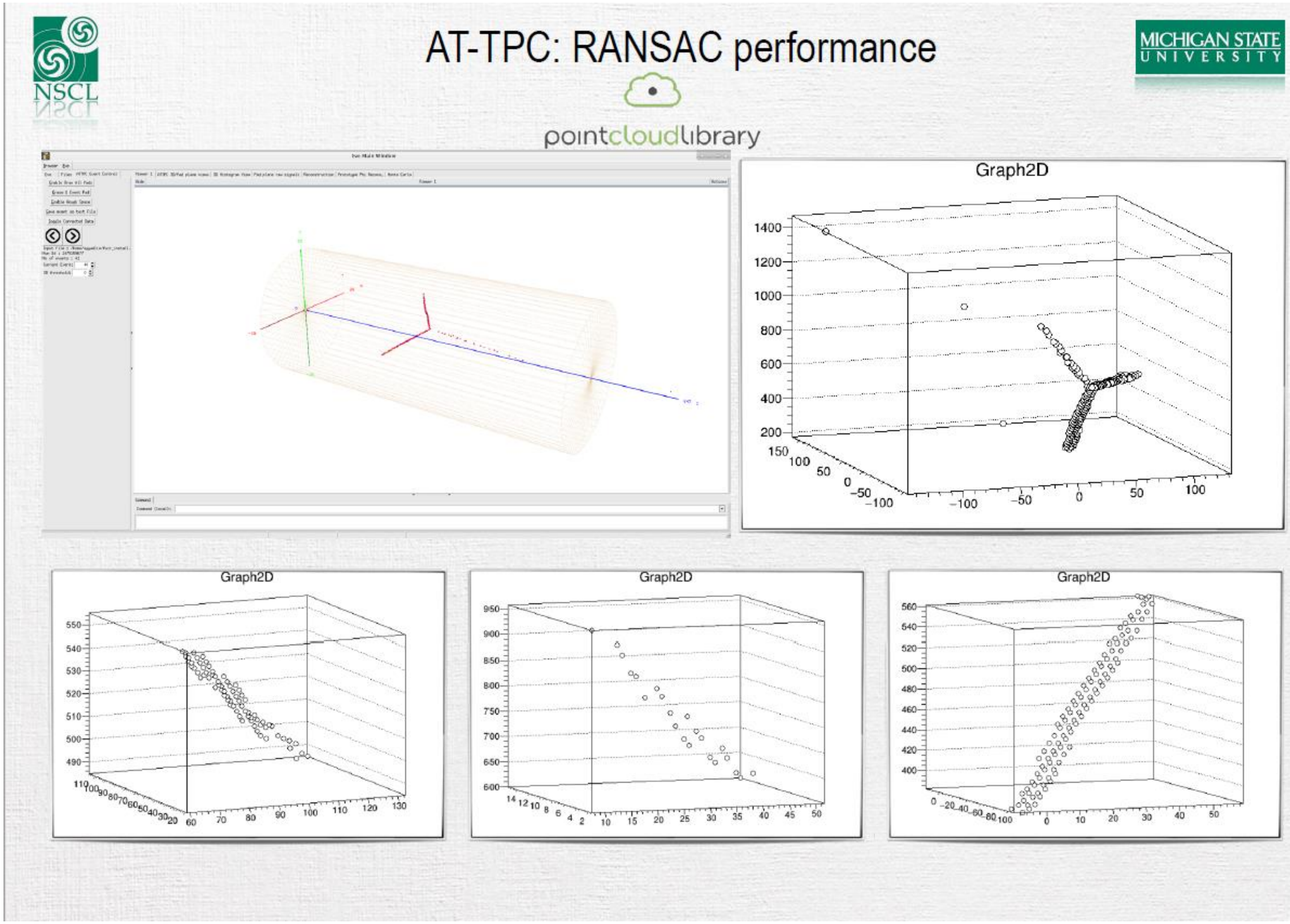
AT-TPC: RANSAC algorithm

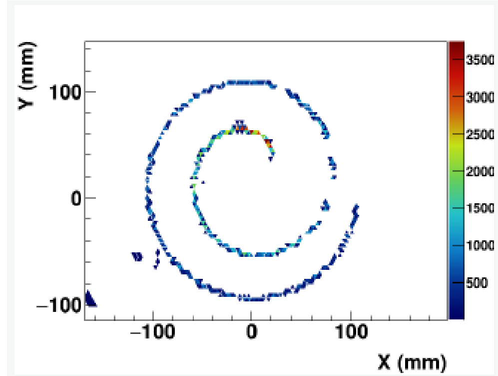
pointcloudlibrary

RANSAC (Random Sample Consensus) is a randomized algorithm for robust model fitting.

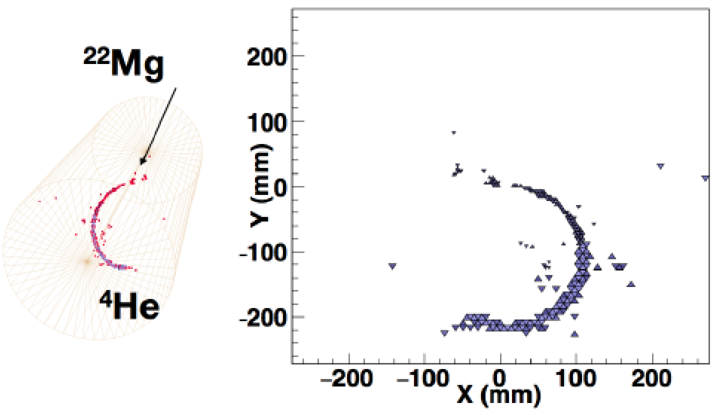
Its basic operation:
1. select sample set
2. compute model
3. compute and count inliers
4. repeat until sufficiently confident



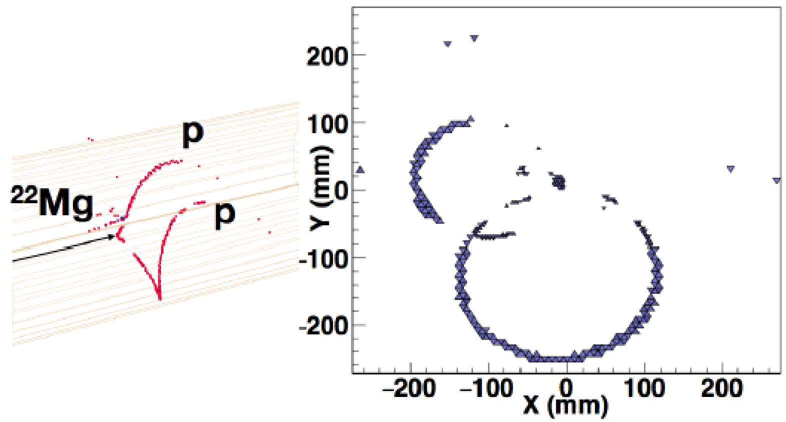

AT-TPC: RANSAC performance
NSCL
MICHIGAN STATE UNIVERSITY
pointcloudlibrary
Graph2D
Graph2D
Graph2D
Graph2D



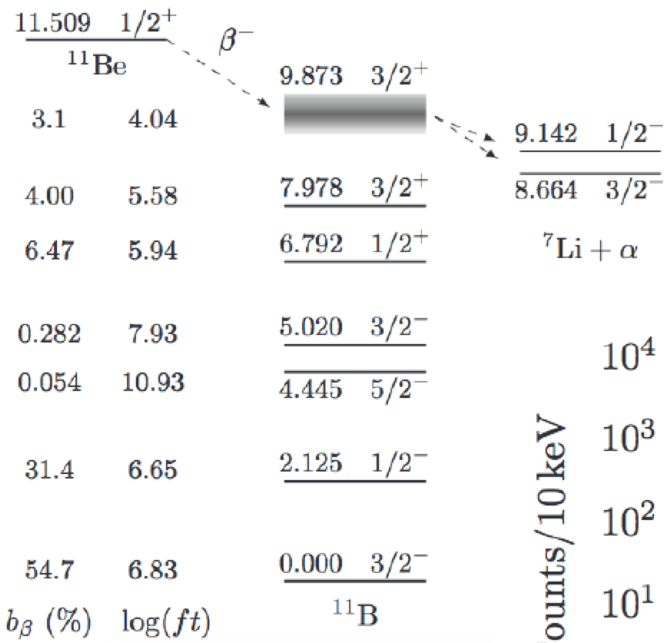
Y (mm)
X (mm)
100
0
−100
−100
0
100
3500
3000
2500
2000
1500
1000
500

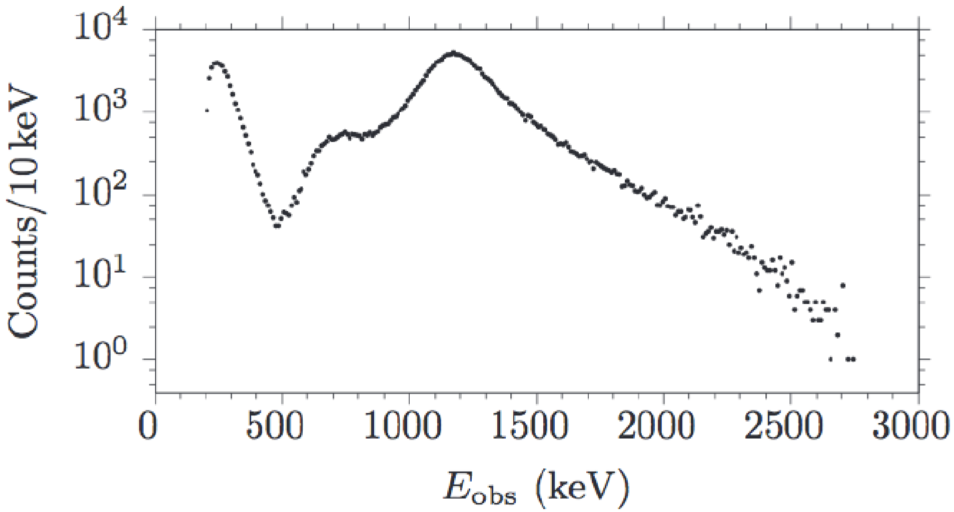


²²Mg
⁴He
Y (mm)
X (mm)
200
100
0
-100
-200
−200
−100
0
100
200



p
²²Mg
p
Y (mm)
X (mm)
200
100
0
-100
-200
−200
−100
0
100
200

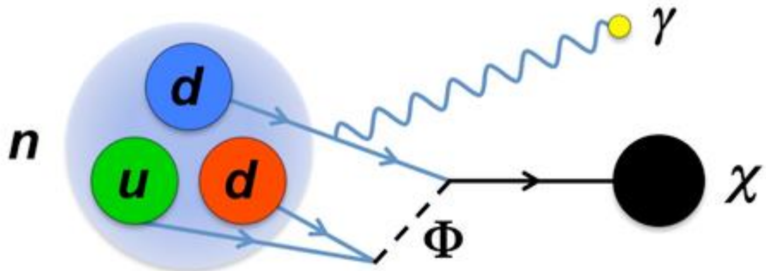

11.509 1/2+
11Be
β−
9.873 3/2+
9.142 1/2−
8.664 3/2−
7Li + α
3.1 4.04
4.00 5.58 7.978 3/2+
6.47 5.94 6.792 1/2+
0.282 7.93 5.020 3/2−
0.054 10.93 4.445 5/2−
31.4 6.65 2.125 1/2−
54.7 6.83 0.000 3/2−
bβ (%) log(ft)
11B

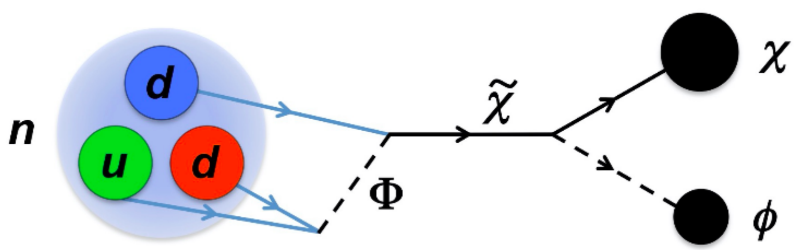

Counts/10 keV
10^4
10^3
10^2
10^1
10^0
0 500 1000 1500 2000 2500 3000
E_obs (keV)

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

Phys. Rev. Lett. 120, 191801 (2018).





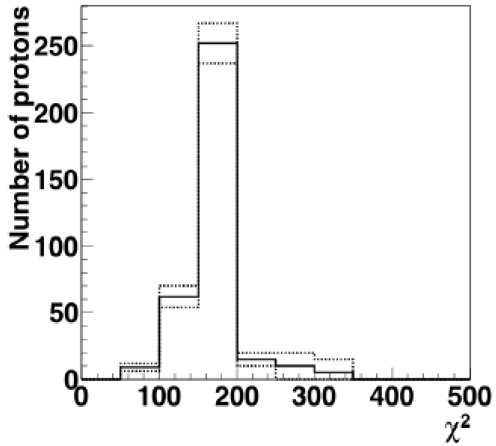
1) Neutron→dark particle + photon. In this case 937.900 MeV< m_χ< 939.565 MeV and 0.782 MeV< E_γ<1.664 MeV. No evidence was found (Z. Tang et al., Phys. Rev. Lett. 121, 022505 2018).

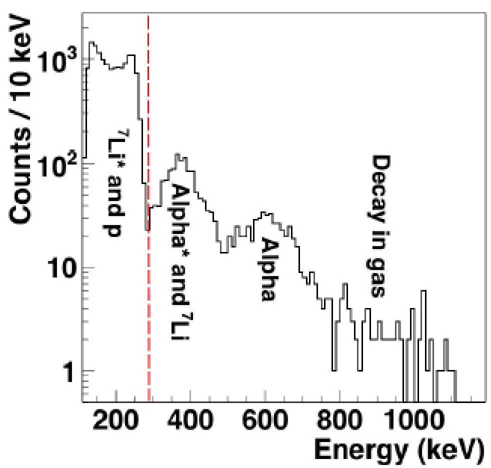
2) Neutron→two dark particles. 937.900 MeV< $m_\chi+m_\varphi$<939.565 MeV.

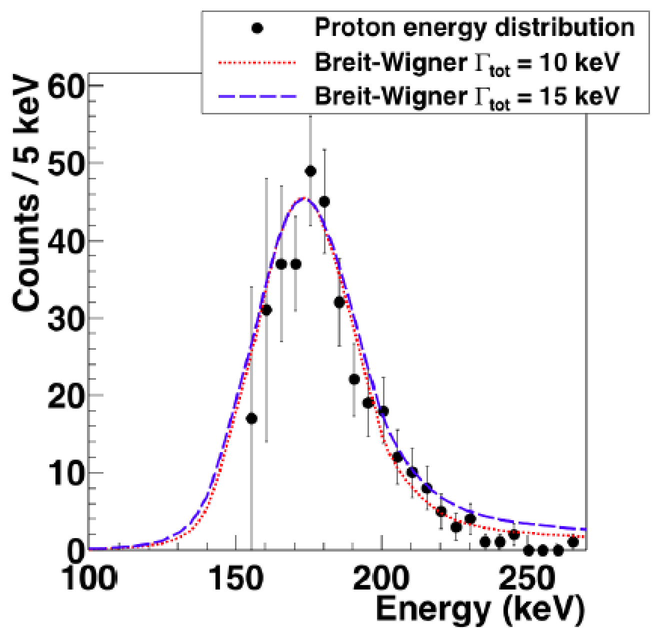
3) Neutron→dark particle + e^+e^-. Excluded $Br(n\to\chi e^+e^-)\approx1\%$ for e^+e^-pairs with energies $E_{e+e-}>2m_e+$ 100 keV. (X. Sun et al., .Phys. Rev., C97(5):052501, 2018).

4) Nuclear dark decays: 937.9 MeV< $m_\chi< m_n-S_n$… Fulfilled in neutron

- First direct observation of β-p in a neutron-rich nuclei.
- Branching ratio is 1.2×10^{-5}, with 30% uncertainty… Theoretical calculations yield 8.0×10^{-6}.
- A narrow resonance (12 keV) in ^{11}B was inferred. E = 11425(20)keV, Γ=12(5) keV, Jπ = 1/2;3/2+
- Decay into the continuum would be characterized by a much shorter branching ratio (10^{-10}).

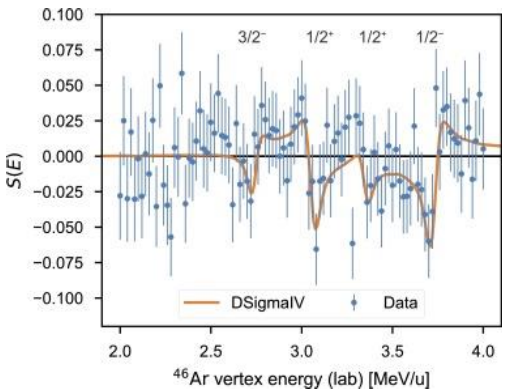


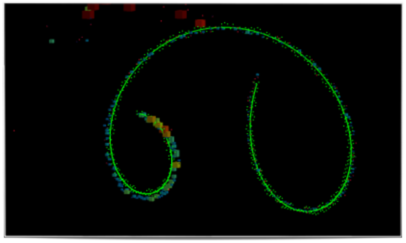




AT-TPC: Recent highlights

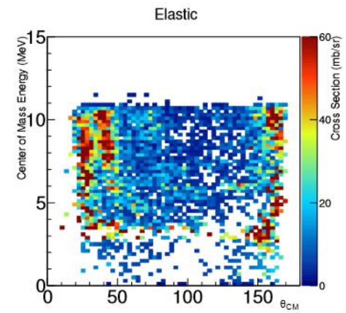
Resonant scattering of ^{46}Ar (4.5A MeV) on p (isobutane)
First ReA3 experiment with a radioactive beam (September 2015)
Study of spectroscopic factors at *N* = 29 using isobaric analogue resonances in inverse kinematics
J. Bradt, Y. Ayyad, D.Bazin et al., PLB 778, 2018155-160, 2018

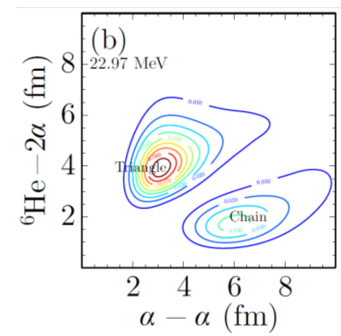




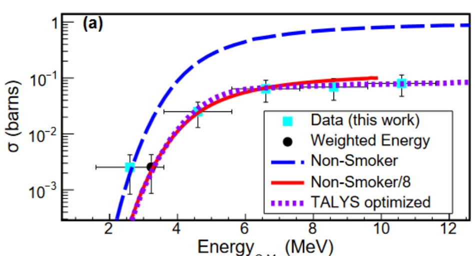
Same probe as (d,p)!

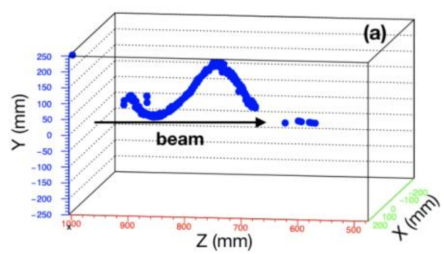
New negative-parity cluster states in ^{14}C with a mixed triangular – linear chain configuration.
L. Carpenter, Y. Ayyad, W. Mittig, T. Ahn et al.,
In preparation (PLB)





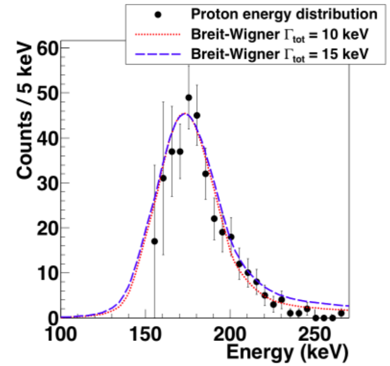
First direct measurement of 22Mg(α,p)25Al and implications for X-ray burst model-observation comparisons
J.S. Randhawa, Y. Ayyad, W. Mittig, Z. Meisel et al.
Accepted in Phys. Rev. Lett. (2020) https://arxiv.org/pdf/2001.06087.pdf

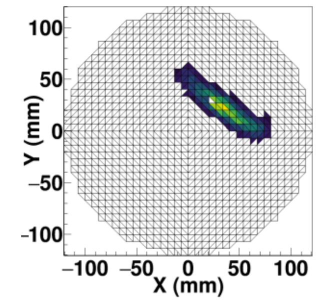




One single beam energy and very low rate (700 pps). Several reaction channels under study

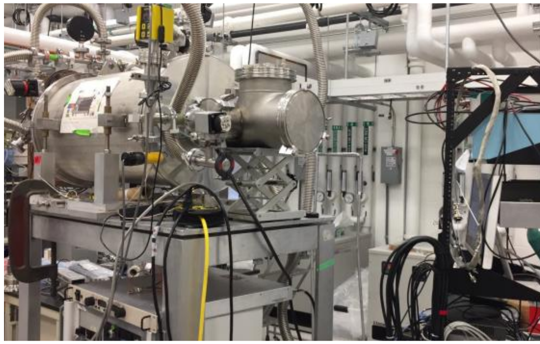
Direct Observation of Proton Emission in ^{11}Be
Y. Ayyad *et al.* Phys. Rev. Lett. 123, 082501 (2019)

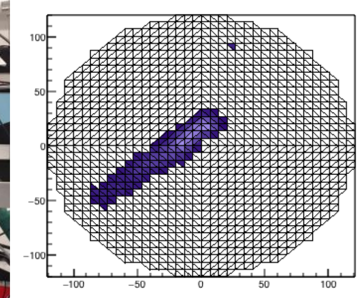




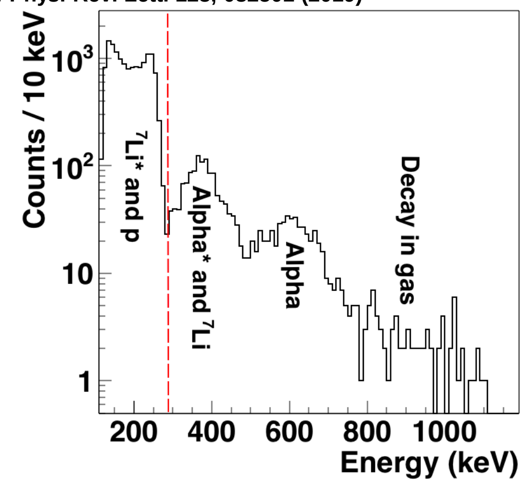
Very low detection thresholds! Energy Loss Particle ID

Experiment at TRIUMF-ISAC I



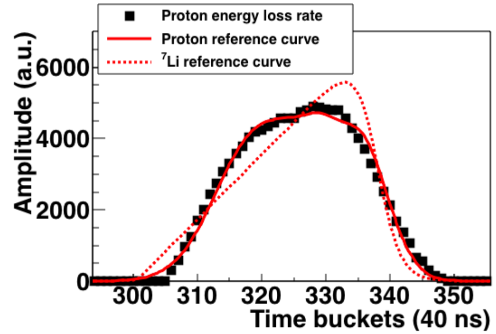


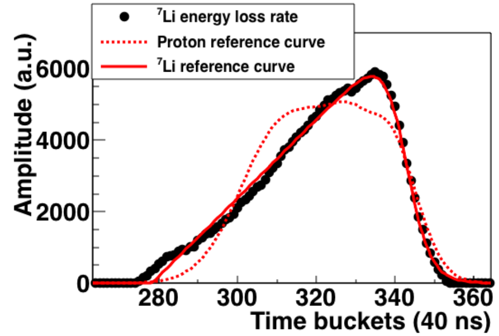
Direct Observation of Proton Emission in ^{11}Be
Y. Ayyad *et al.* Phys. Rev. Lett. 123, 082501 (2019)

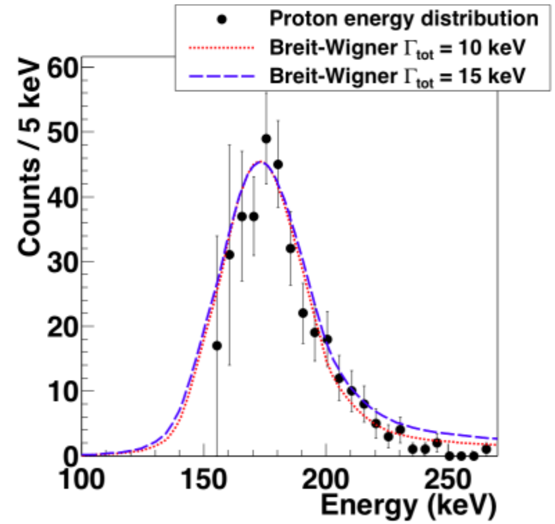


Implant-decay on the pAT-TPC: High detection efficiency (80%) and resolution (σ(E)~5%, (σ(θ)=1 deg)

- Full reconstruction and identification of p+ and α.
- He(+10% CO2) as thin tracking medium: low straggling and β-blind.
- The pAT-TPC was filled with 60 torr of He(+10% CO2)
- Beam energy of 390 keV/u deposited 11Be.
- First direct observation of β-p in a neutron-rich nuclei.
- Branching ratio is 1.2x10-5 , with 30% uncertainty… Theoretical calculations yield 8.0 × 10−6.
- A narrow resonance (12 keV) in 11B was inferred. E = 11425(20)keV, Γ=12(5) keV, Jπ = 1/2;3/2+







Criticism

PHYSICAL REVIEW LETTERS **123**, 082501 (2019)

Editors' Suggestion

Direct Observation of Proton Emission in ^{11}Be

PHYSICAL REVIEW LETTERS **124**, 042502 (2020)

Convenient Location of a Near-Threshold Proton-Emitting Resonance in ^{11}B

J. Okołowicz,[1] M. Płoszajczak,[2] and W. Nazarewicz[3]
[1]*Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31342 Kraków, Poland*
[2]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM—CNRS/IN2P3, BP 55027, F-14076 Caen Cedex, France*
[3]*Department of Physics and Astronomy and FRIB Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

Comment on "Direct Observation of Proton Emission in ^{11}Be"

H.O.U. Fynbo,[1] Z. Janas,[2] C. Mazzocchi,[2] M. Pfützner,[2,*] J. Refsgaard,[3,4] K. Riisager,[1] and N. Sokołowska[2]
[1]*Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus, Denmark*
[2]*Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland*
[3]*Department of Astronomy and Physics, Saint Mary's University, Halifax, Nova Scotia, B3H 3C3 Canada*
[4]*TRIUMF, 4004 Wesbrook Mall, Vancouver BC, V6T 2A3 Canada*

Eur. Phys. J. A (2020) 56:100
https://doi.org/10.1140/epja/s10050-020-00110-2

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Regular Article - Experimental Physics

Search for beta-delayed proton emission from ^{11}Be

K. Riisager[1,a], M. J. G. Borge[2,3], J. A. Briz[3], M. Carmona-Gallardo[4], O. Forstner[5], L. M. Fraile[4], H. O. U. Fynbo[1], A. Garzon Camacho[3], J. G. Johansen[1], B. Jonson[6], M. V. Lund[1], J. Lachner[5], M. Madurga[2], S. Merchel[7], E. Nacher[3], T. Nilsson[6], P. Steier[5], O. Tengblad[3], V. Vedia[4]

Not reliable results mostly because of wrong PID

But we have reanalyzed the data with an improved framework to refute these conclusions. To be published very soon…

Analysis of Bragg curves

- Reference curves were obtained for ^{7}Li and protons.
- The shape of the Bragg curve depends on the angle of emission.
- A Monte Carlo fit based on an objective function that minimizes the energy loss per time was developed.
- Curves are rotated, stretched, shifted and renormalized.
- Then the energy loss per unit time is compared between both, the experimental and the reference curve.