Plans for direct measurement of ^{10}Be destruction reaction

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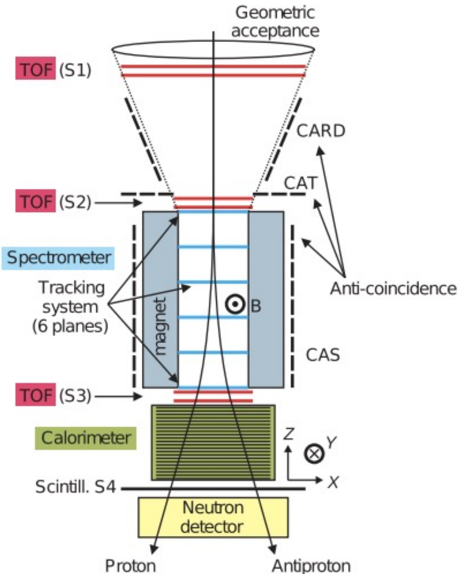
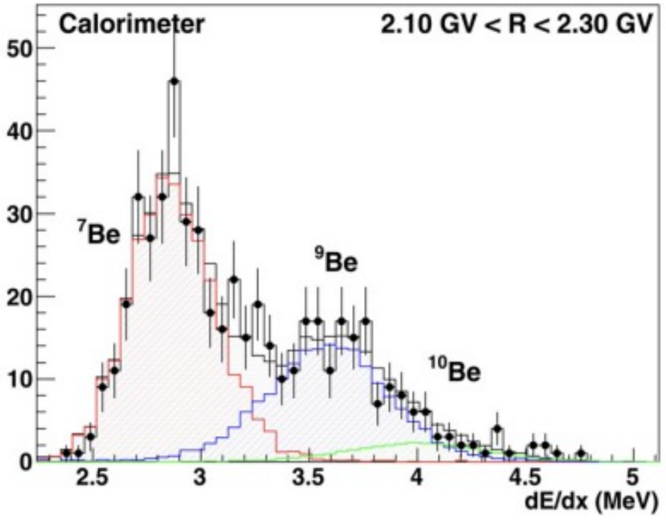
Importance of ^{10}Be

W. Menn et al, ApJ. 862:141 (2018)





P. Banerjee et al, Nature Com. 7:13639 (2016)

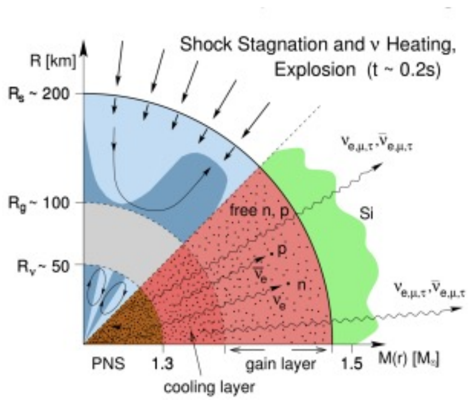
Table 1 | Yields of short-lived radionuclides from an 11.8-solar-mass core-collapse supernova.

R/I	τ_R (Myr)	Y_R ($M_\odot$)	$X_I^\odot$	$(N_R/N_I)_{ESS}$ Data	Case 1	Case 2	Case 3
$^{10}Be/^{9}Be$	2.00	3.26(−10)	1.40(−10)	(7.5 ± 2.5)(−4)	6.35(−4)	6.35(−4)	5.20(−4)
$^{26}Al/^{27}Al$	1.03	2.91(−6)	5.65(−5)	(5.23 ± 0.13)(−5)	1.02(−5)	9.90(−6)	5.77(−6)
$^{36}Cl/^{35}Cl$	0.434	1.44(−7)	3.50(−6)	~(3-20)(−6)	2.00(−6)	1.45(−6)	6.15(−7)
$^{41}Ca/^{40}Ca$	0.147	3.66(−7)	5.88(−5)	(4.1 ± 2.0)(−9)	3.40(−9)	2.74(−9)	2.26(−9)
$^{53}Mn/^{55}Mn$	5.40	1.22(−5)	1.29(−5)	(6.28 ± 0.66)(−6)	4.04(−4)	6.39(−6)	6.16(−6)
$^{60}Fe/^{56}Fe$	3.78	3.08(−6)	1.12(−3)	~1(−8);(5-10)(−7)	9.80(−7)	9.80(−7)	1.10(−7)
$^{107}Pd/^{108}Pd$	9.38	1.37(−10)	9.92(−10)	(5.9 ± 2.2)(−5)	6.27(−5)	6.27(−5)	5.72(−5)
$^{135}Cs/^{133}Cs$	3.32	2.56(−10)	1.24(−9)	~5(−4)	7.51(−5)	7.51(−5)	3.18(−5)
$^{182}Hf/^{180}Hf$	12.84	4.04(−11)	2.52(−10)	(9.72 ± 0.44)(−5)	7.36(−5)	7.36(−5)	6.34(−6)
		8.84(−12)			1.60(−5)	1.60(−5)	2.37(−6)
$^{205}Pb/^{204}Pb$	24.96	9.20(−11)	3.47(−10)	~1(−4);1(−3)	1.27(−4)	1.27(−4)	7.78(−5)

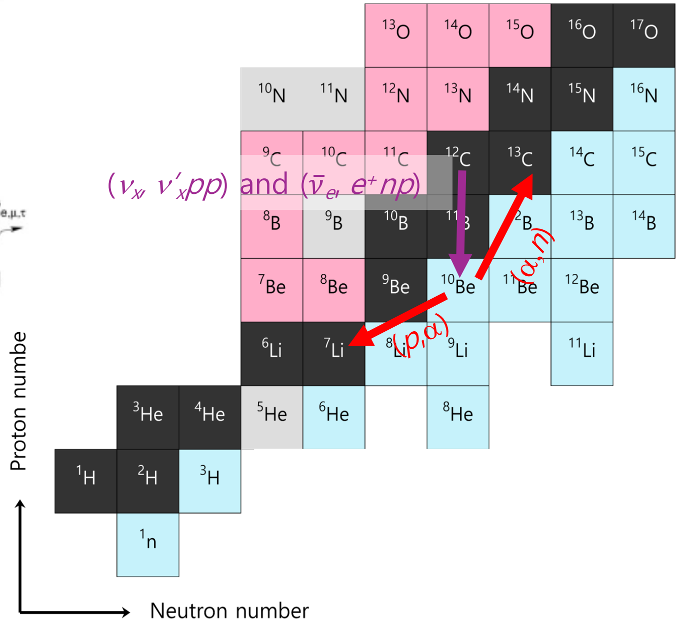
Comparisons are made to the corresponding isotopic ratios deduced from meteoritic data. Case 1 estimates are calculated from equation (1) using the approximate best-fit f and Δ of Fig. 2, assuming no fallback. The higher and lower yields for ^{182}Hf are obtained from the laboratory and estimated stellar decay rates[47] of ^{181}Hf, respectively. Case 2 (3) is a fallback scenario in which only 1.5% of the innermost 1.02×10^{-2} solar mass (0.116 solar mass) of shocked material is ejected. With guidance from refs 22,31, well-determined data are quoted with 2σ errors, while data with large uncertainties are preceded by '~'. Note that $x(-y)$ denotes $x \times 10^{-y}$. Data references are: ^{10}Be (refs 14,16,18,19), ^{26}Al (refs 2,32), ^{36}Cl (refs 33-35), ^{41}Ca (refs 36,37), ^{53}Mn (ref. 38), ^{60}Fe (refs 39,40), ^{107}Pd (ref. 41), ^{135}Cs (ref. 42), ^{182}Hf (ref. 43) and ^{205}Pb (refs 44,45).

- ^{10}Be ($T_{1/2}$ ~ 1.4 Myrs) has been detected with the satellite-borne experiment PAMELA
  - Ratio between radioactive nuclides and stable isotopes gives evidence of the Early Solar system
- Solar system formation was triggered by gravitational collapse.
  - Low-in mass and explosion energy Supernova is one of the candidates.

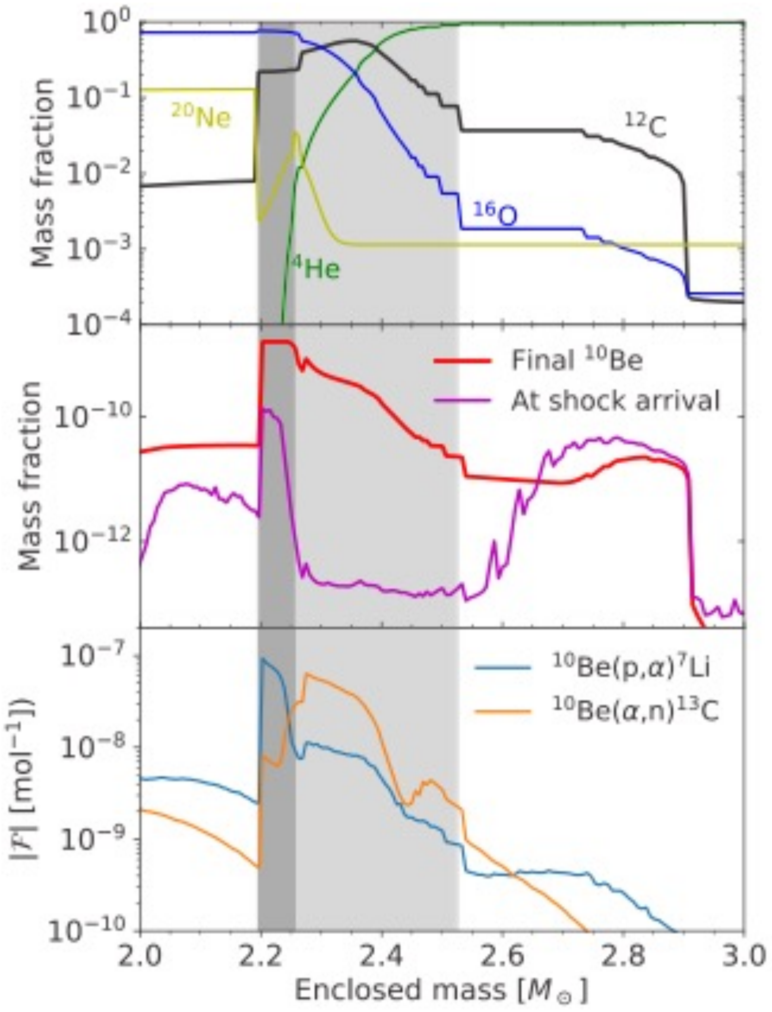
Production and destruction ^{10}Be



H. T. Janka et al., Phys. Rep. 442,38 (2007)



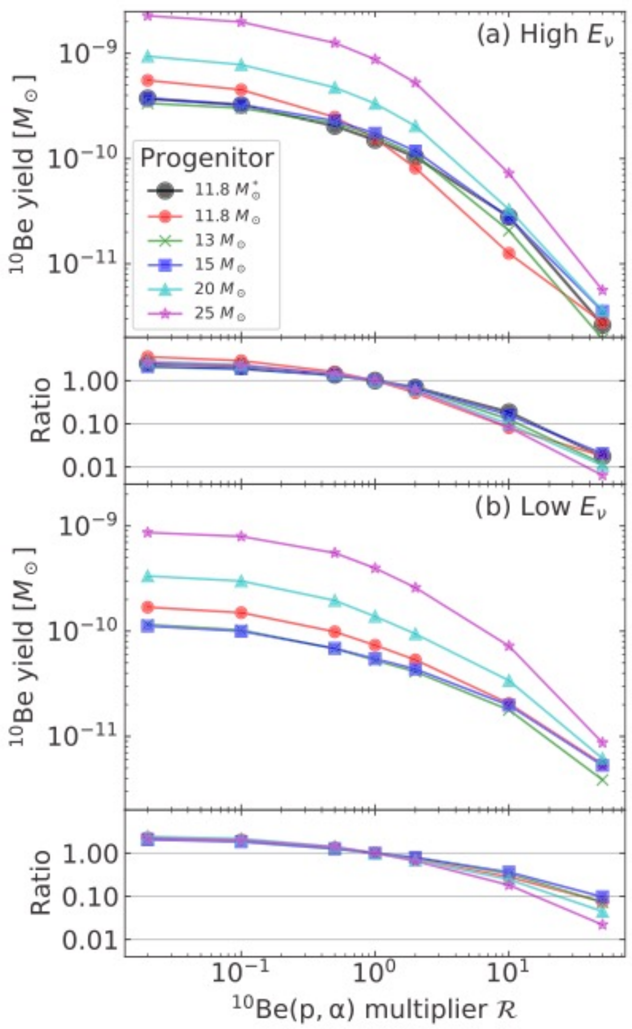
A. Sieverding, et al., Phys. Rev. C 106, 015803 (2022)



- ^{10}Be produced by ν process during Core-collapse supernova
  - ^{12}C$(\nu_x, \nu'_x pp)^{10}$Be and ^{12}C$(\bar{\nu}_e, e^+ np)^{10}$Be
- ^{10}Be destruction mechanism
  - ^{10}Be$(p,\alpha)^{7}$Li and ^{10}Be$(\alpha,n)^{13}$C reaction

Importance of ^{10}Be(p,α)^{7}Li reaction

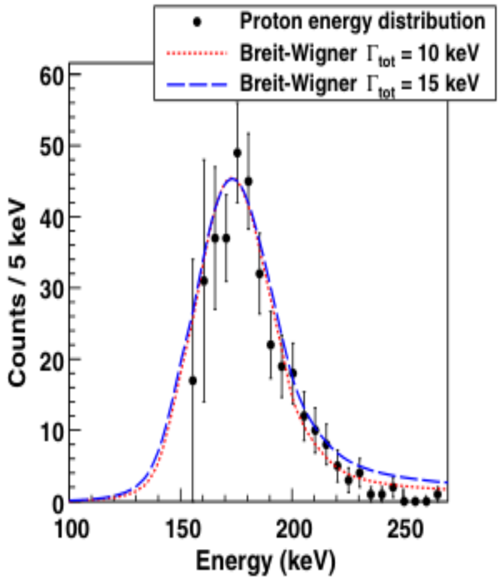
A. Sieverding, et al., Phys. Rev. C 106, 015803 (2022)



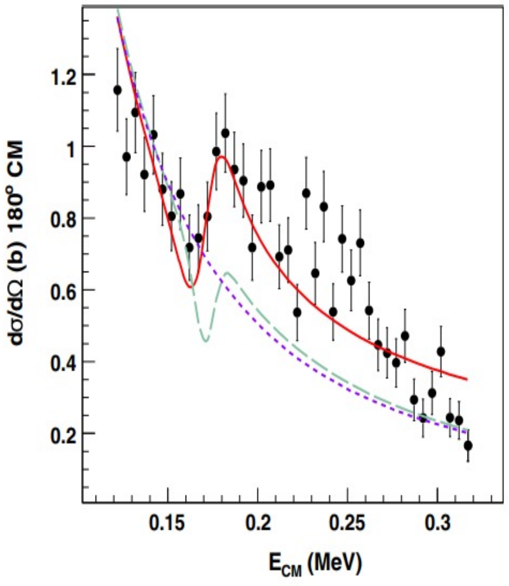
- Sensitivity study was performed to investigate ^{10}Be abundance
  - In different mass model and neutrino energy case
- ^{10}Be(p,α)^{7}Li is main destruction mechanism of ^{10}Be

Previous ^{11}B energy level studies

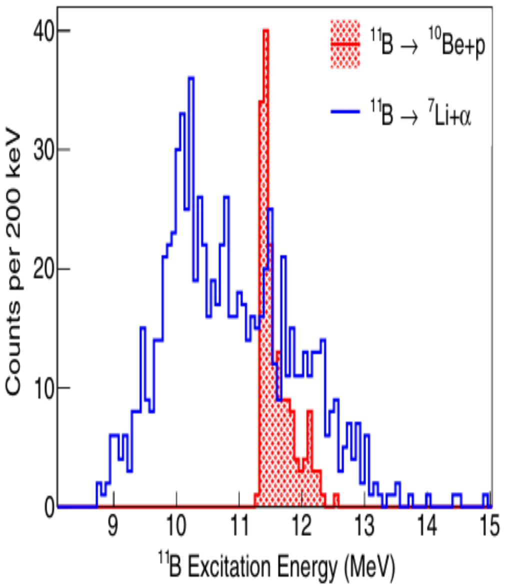
Y. Ayyad et al., Phys. Rev. Lett. 123, 082501 **(2019)**



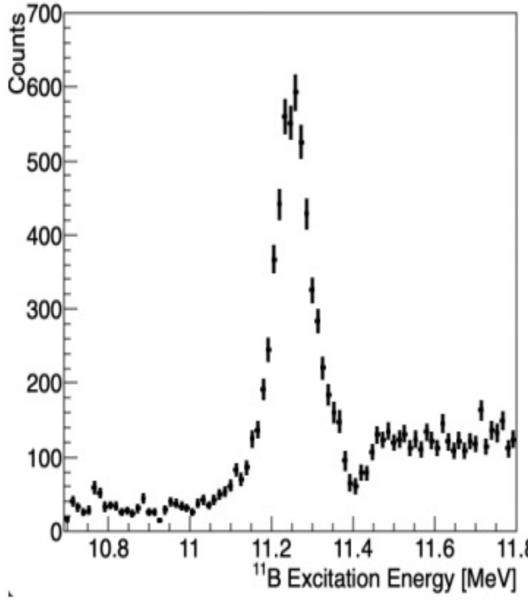
Y. Ayyad et al., Phys. Rev. Lett. 129, 012501 (**2022**)



E. Lopez-Saavedra et al., Phys. Rev. Lett. 129, 012502 **(2022)**



A. N. Kuchera et al., Phys. Rev. C 110, 054319 (2024)



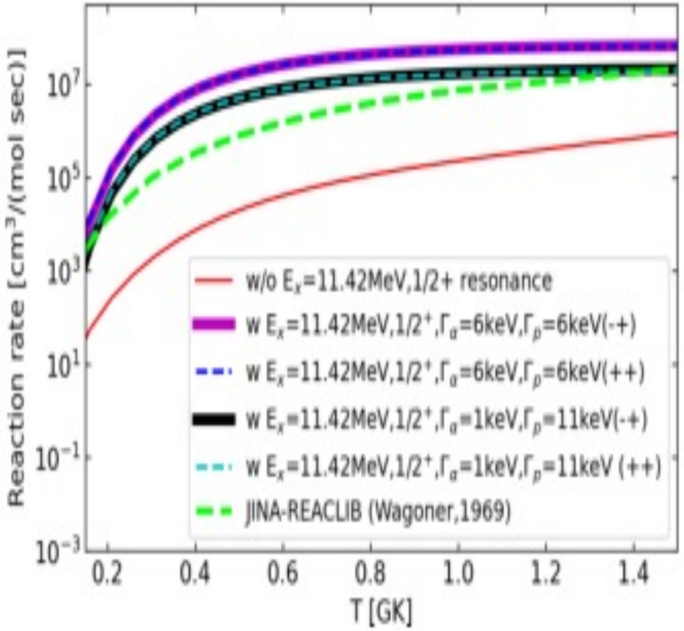
- Four different experiment with different method
  - ^{11}Be(β^-p) decay
  - ^{10}Be(*p,p*)^{10}Be scattering
  - ^{10}Be(*d,n*)^{11}B* transfer reaction and decay measurement
  - ^{10}B(*d,p*)^{11}B* transfer reaction

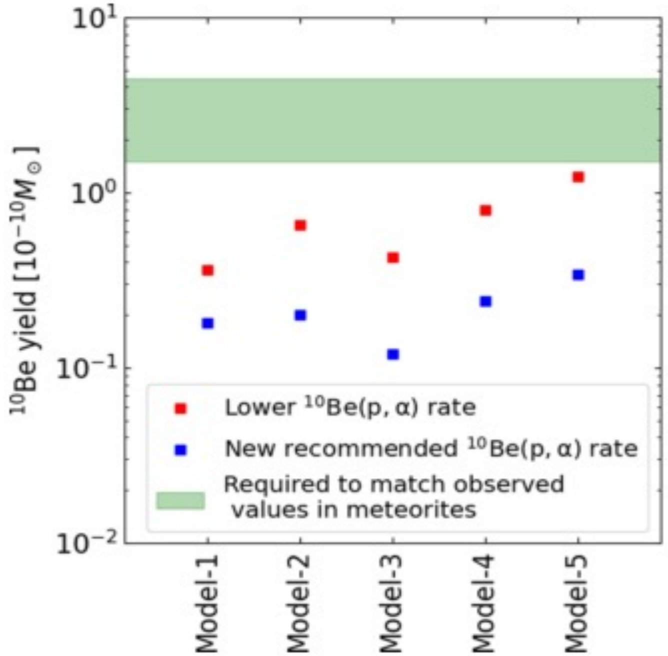
- Energy level was identified near the proton threshold (p_{th} = 11.23 MeV)
  - E_x = 11.42 ± 0.02 MeV (E_r = 0.19 MeV)
  - Large proton width

- Gamow Window at T = 1 GK
  - E_r = 0.11 – 0.48 MeV
  - E_x = 11.34 – 11.71 MeV

Previous $^{10}Be(p,\alpha)^{7}Li$ reaction rate

A. Sieverding, et al., Phys. Rev. C 106, 015803 (2022)

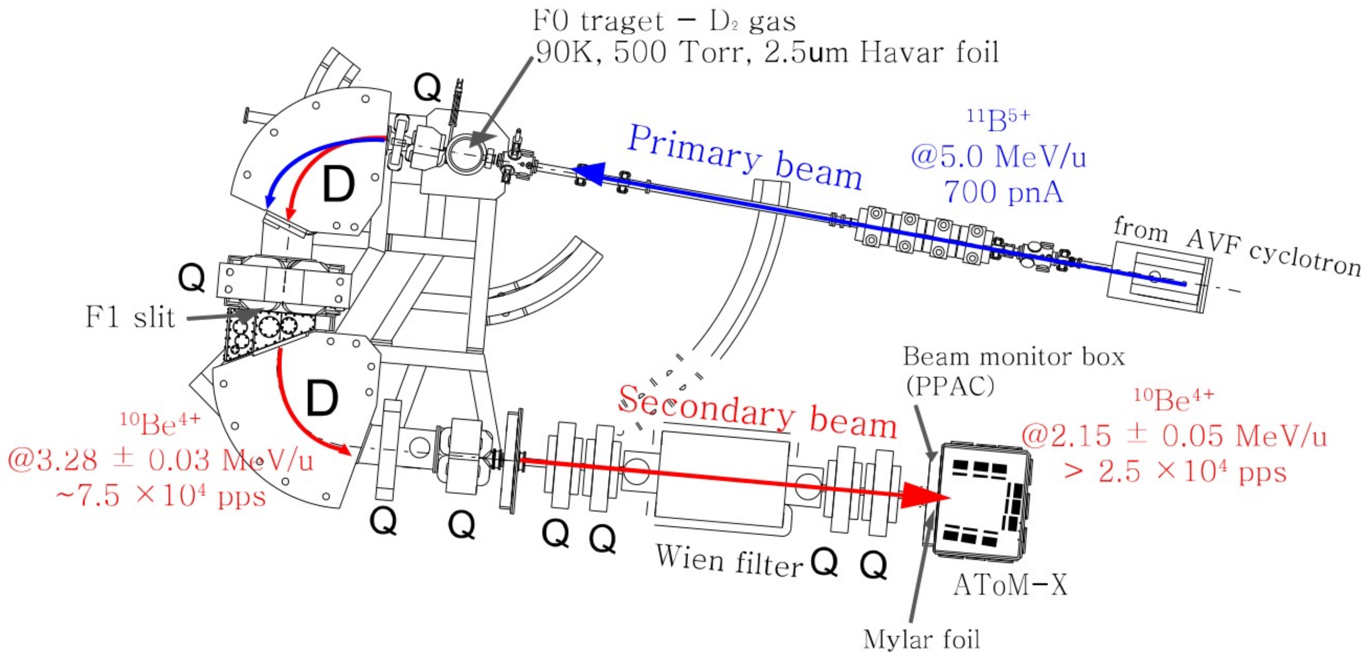




Ex [MeV]	J^{π}	Γ_p[KeV]	Γ_α[KeV]
11.27	9/2+	1.0E-15	110
11.42	**1/2+**	**6,11**	**6,1**
11.49	3/2+	1.0E-4	93
11.60	5/2+	1.0E-5	90
11.89	5/2-	1.0E-4	100
12.04	7/2+	1.0E-3	500
12.55	1/2+	100	105

- $^{10}Be(p,\alpha)^{7}Li$ reaction rate was calculated
  - **Sensitive to the energy level at E_x = 11.42 MeV**
- Could not explain observed values in meteorites
- For unknown partial width, the reduced widths are adopted as ~$0.01\gamma_w^2$ Wigner limit

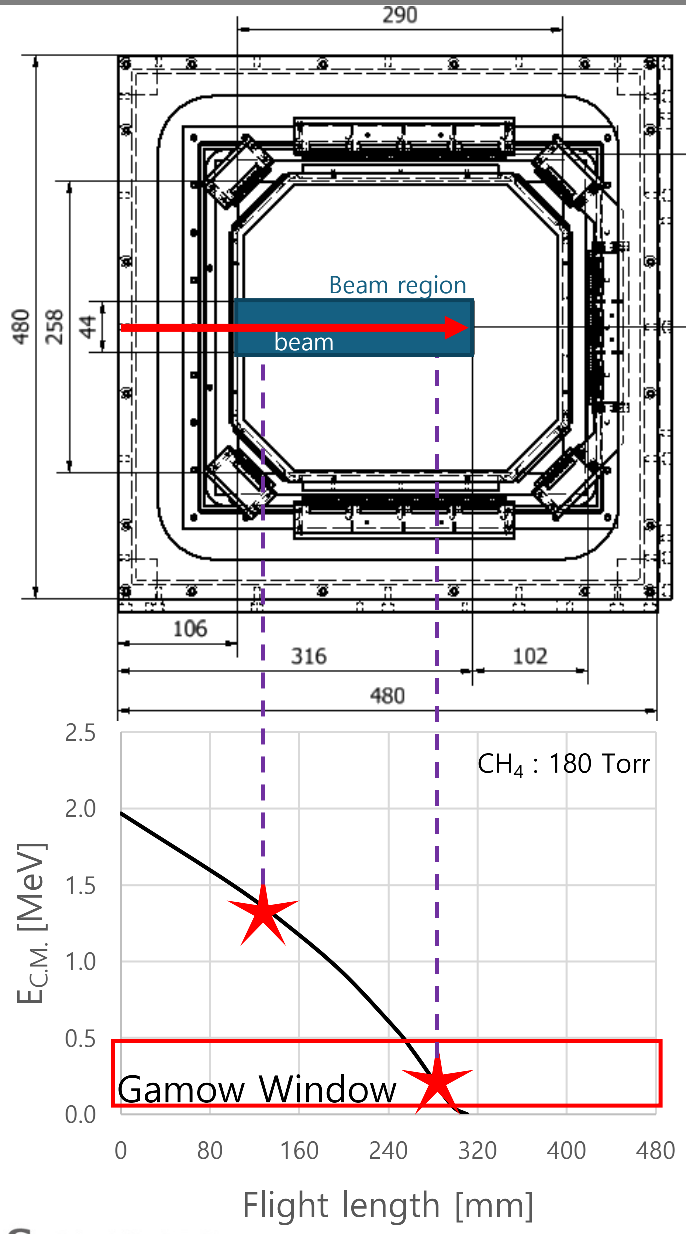
Experimental method and secondary beam production at CRIB

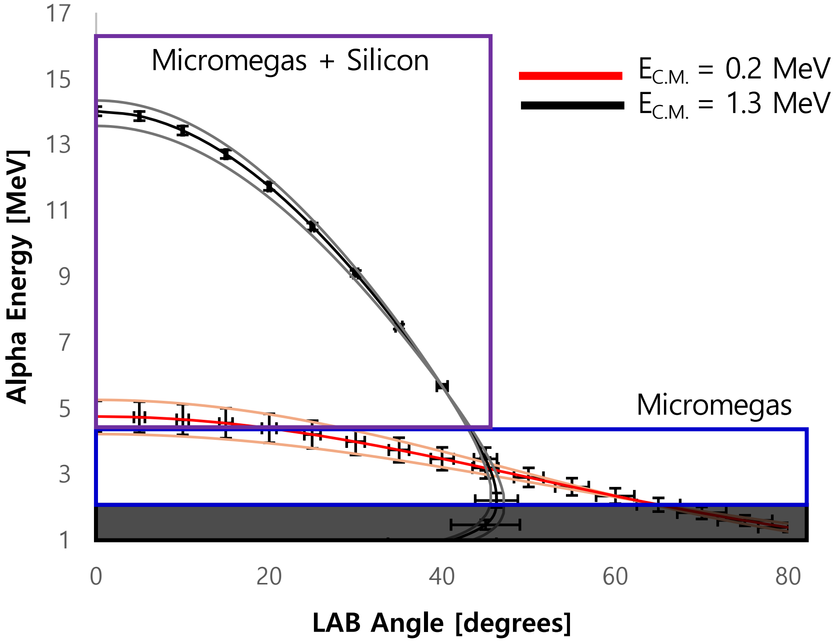


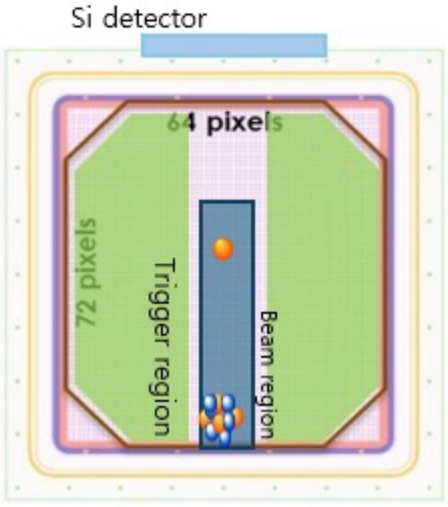
Primary beam	E (MeV/u)	Intensity (pnA)	D_2 target
^{11}B (q = 5$^+$) (previous)	5.0 (5.0)	700 (700)	90 K, 500 Torr, 2.5 μm Havar (90 K, 400 Torr, 2.5 μm Havar)
Secondary beam	**E (MeV/u)**	**Intensity (pps)**	**Purity**
^{10}Be at F3 target (previous)	2.15 ± 0.05 (2.49 ± 0.03)	2.5 × 10^4 (2.0 × 10^4)	> 95% (~95%)

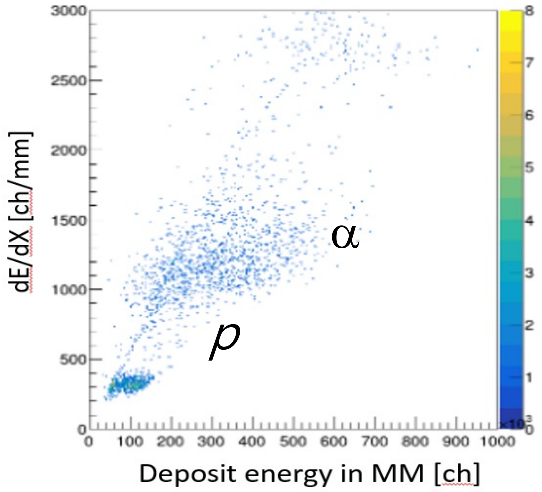
- ^{10}Be(p,α)^{7}Li direct reaction measurement
  - Thick target method
  - Inverse kinematics
- ^{10}Be RI beam produced at CRIB to measure ^{10}Be(α,α)^{10}Be reaction
- Expected ^{10}Be secondary RI beam
  - Energy : 2.15 MeV/u
  - Intensity : 2.5 × 10^4 pps
  - Purity : 95 %
- PPACs
- Active target TPC (AToM-X)
  - CH_4 at the pressure of 180 Torr

Experimental condition of AToM-X



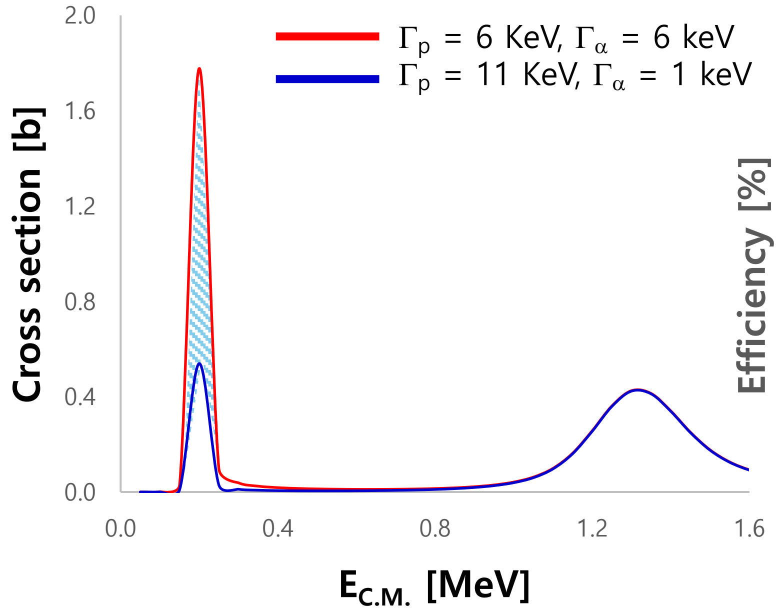


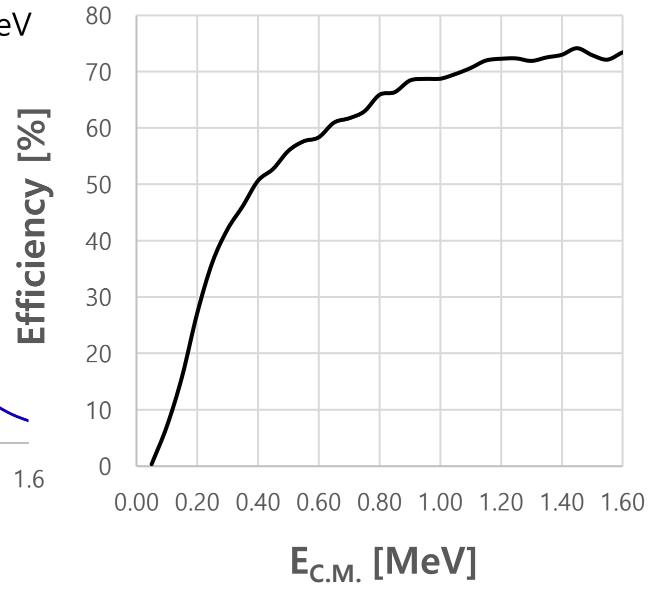




- ^{10}Be RI beam will be stopped in a beam region
- Cover the energy range below $E_{C.M.}$ = 1.5 MeV
  - Cover the two dominant resonance energy region
- Can measure the alpha particle using only Micromegas

Yield estimation and Beam time





Expected counts

	E_r = 0.2 MeV	E_r = 1.3 MeV
Γ_p = 6 KeV, Γ_α = 6 keV	230	1620
Γ_p = 11 KeV, Γ_α = 1 keV	70	1610

- Yield = $\boldsymbol{\sigma \cdot I \cdot N \cdot \epsilon \cdot t}$
  - $\boldsymbol{\sigma}$ = cross section
  - $\boldsymbol{\epsilon}$ = Efficiency
  - $\boldsymbol{t}$ = Times
  - $\boldsymbol{I}$ = Beam Intensity
  - $\boldsymbol{N}$ = Number of target
- Reaction cross section calculated by AZURE
- Efficiency based on simulation
- **Beam time on target : 10 days for ~ 10 % statistical uncertainty**

NP2412-AVF81

Title: **The first direct measurement of $^{10}Be(p,\alpha)^{7}Li$ reaction cross section**

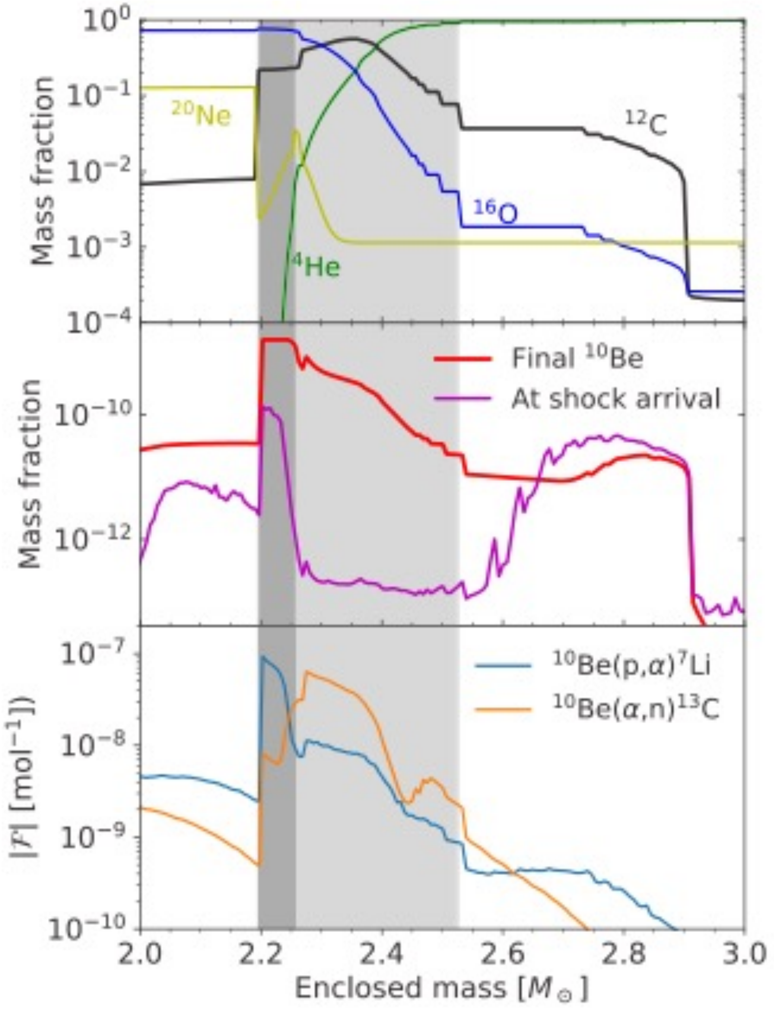
Spokesperson(s): **Minju Kim**

Approved — Grade **A**
13.5 days

Plan to perform in 2026

Previous $^{10}Be(\alpha,n)^{13}C$ reaction study

A. Sieverding, et al., Phys. Rev. C 106, 015803 (2022)



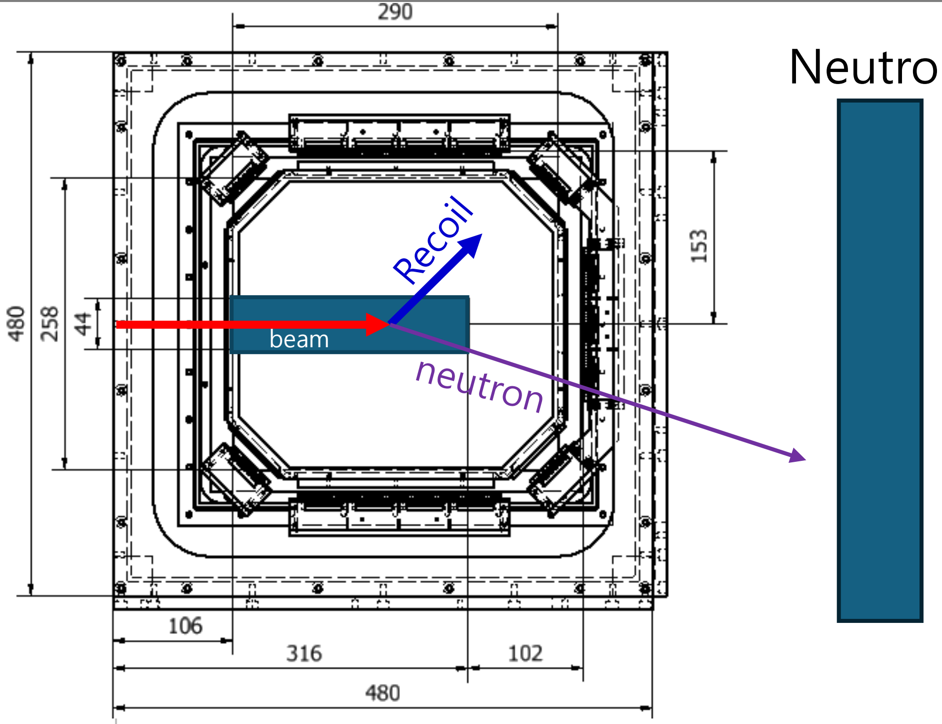
P.J. Haigh et al., Phys. Rev. C 78, 014319 **(2008)**

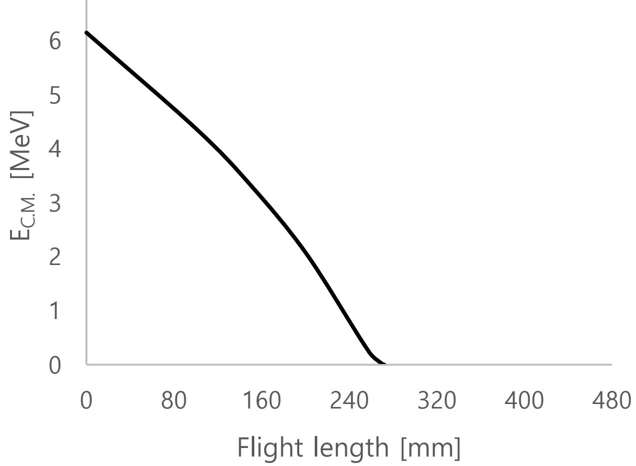
TABLE VII. Proposed energy levels of ^{14}C for $E_x > 11.66$ MeV. The second panel shows the indicated levels taken from the $^{13}C(n,n)$ measurement of Ref. [23] and the latest compilation [24]. The fifth panel shows a compilation of the ^{14}C states which are observed to decay via α-emission. Evidence for the α-decay of these states is from $^{7}Li(^{9}Be,^{10}Be+\alpha)$ [25], $^{14}C(^{13}C,^{10}Be+\alpha)$ [26] and $^{14}C(^{14}C,^{10}Be+\alpha)$ [27] measurements.

This work		[23,24]			2n transfer [18]		$^{13}C(\vec{p},\pi^+)$ [28]		$^{9}Be(^{7}Li,d)$ [18]		States which α-decay [25–27]	
E_x (MeV)	J^π	E_x (MeV)	J^π	Ref.	E_x (MeV)	J^π	E_x (MeV)	J^π	E_x (MeV)	J^π	E_x (MeV)	Ref.
		11.666	4^-	[24]	11.66	4^-	11.7	4^-	11.66	4^-		
11.73	$0^-, 1^-, 2^-$	11.73	5^-	[24]	11.73(3)	4^+			11.73	4^+		
		11.9(3)	(1^-)	[23]								
		12.20	1^-	[23]								
		12.61	2^-	[23]					12.58	(3^-)		
		12.863		[24]					12.86			
12.96	$0^-, 2^-, 3^-$	12.963	(3^-)	[24]	12.96(4)	3^-	12.96		12.96			
		(13.50)		[24]								
		13.7	2^-	[23]	13.7(1)		13.56					
14.1					14.0(1)				14.03		14.3(1)	[27]

- Several energy levels in ^{14}C have been studied
- Spins-Parities and partial widths of levels were not constrained.
- Gamow Window at T = 1 GK
  - E_r = 0.41 – 0.97 MeV
  - E_x = 12.42 – 12.98 MeV

^{10}Be(α,n)^{13}C reaction measurement : neutron measurement



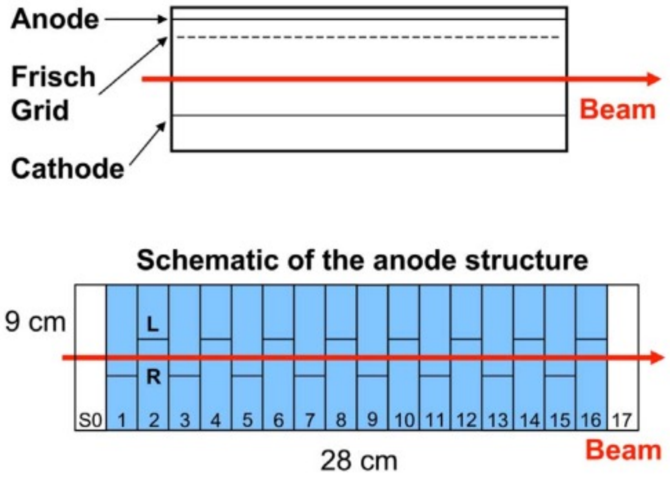


- AToM-X + neutron detector array
  - Benchmarked TexAT + TexNeut
- Neutron will be measured by neutron detector
- Beam and Heavy recoil will be measured by AToM-X
- ^{4}He:CO_2 (9:1) mixture gas at the pressure of 60 Torr

^{10}Be(α,*n*)^{13}C reaction measurement : recoil measurement

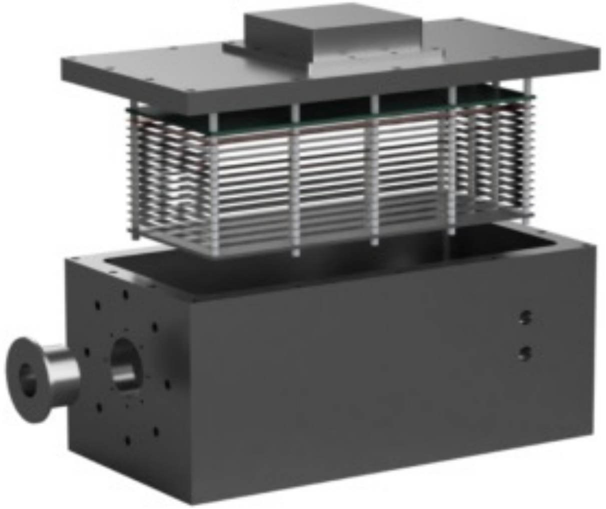
Nucl. Instrum. Meths. A 799, 197-202 (2015)

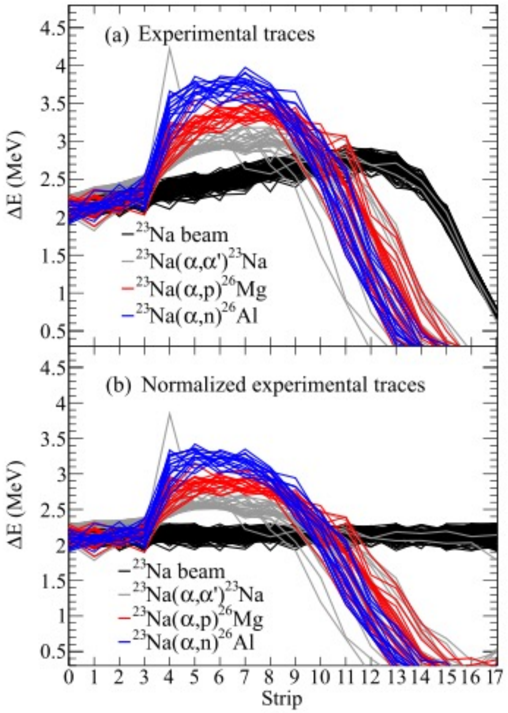
ANL MUSIC

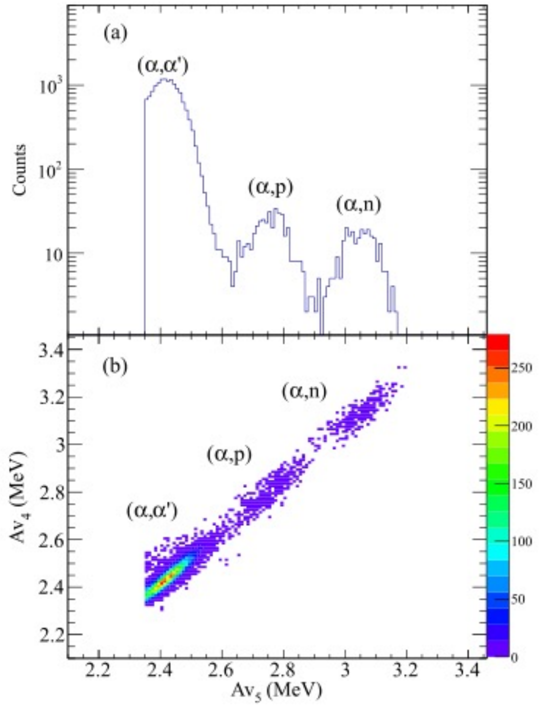


Nucl. Instrum. Meths. A 1047, 167777 (2023)

ATHENA



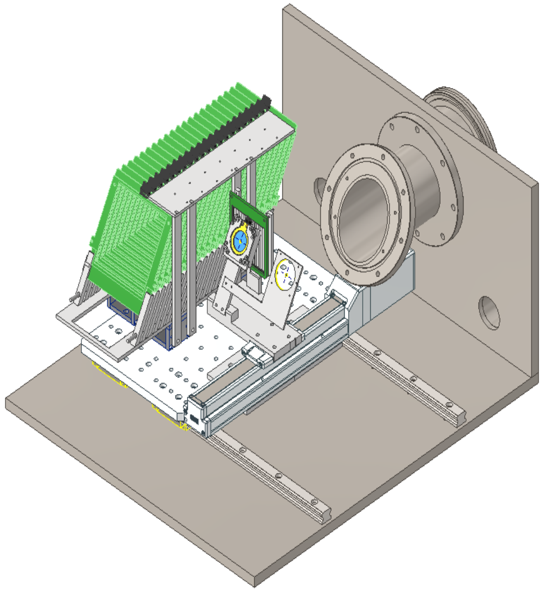


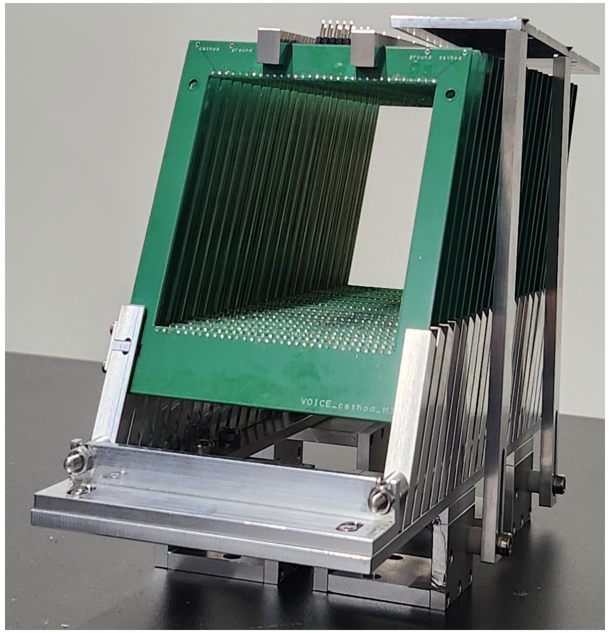


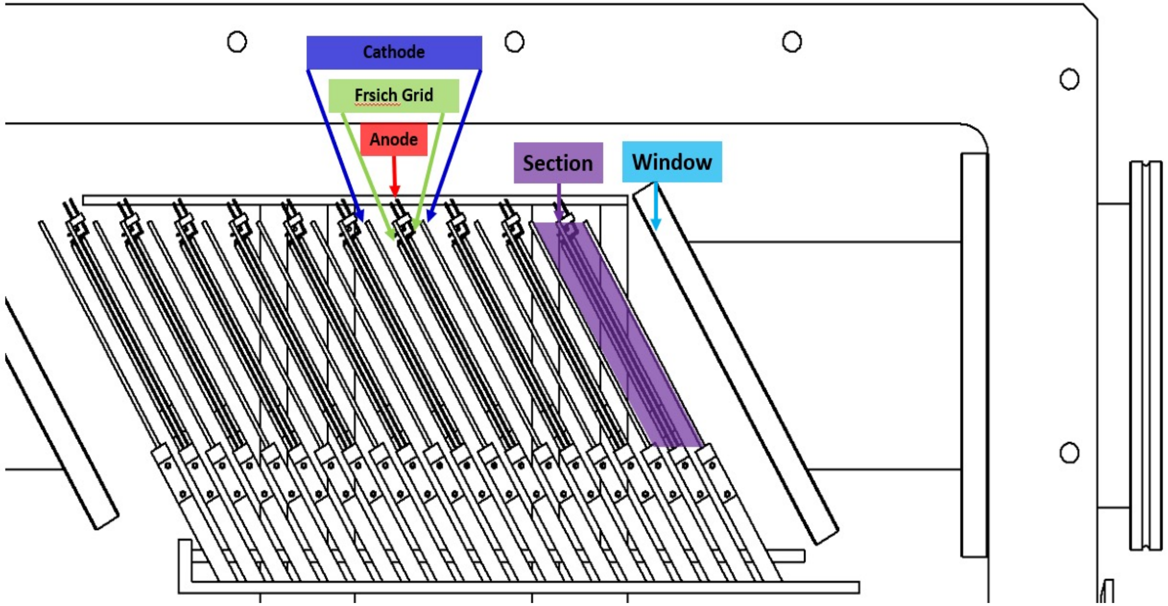
- Multi Sampling Ionization Chamber (MuSIC)
  - ^{4}He active gas target have been used
  - Measure α-particle induced reactions
  - When the nuclear reaction occurs, Z-number changes and slowed down.

    → Distinctive Bragg curves

VOICE (Vertically Oriented-wire Ionization Chamber with sEgmentation)

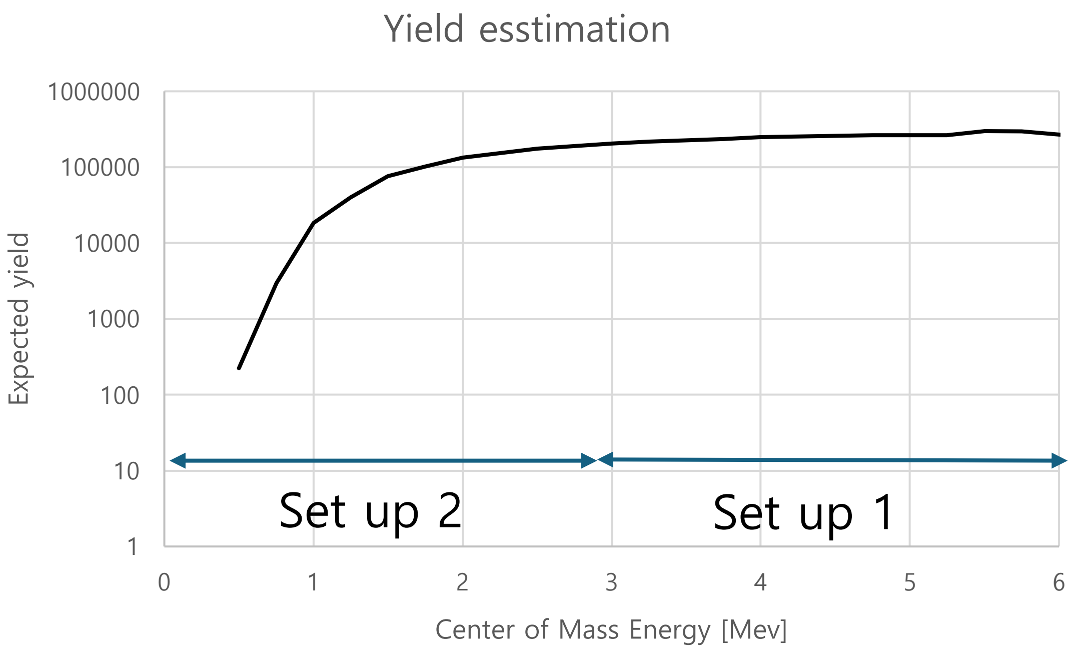






- VOICE
  - Newly developed MUSIC at CENS
  - Vertical (tilted) wire electrodes
  - 10 um thick gold coating tungsten wire
- **Commissioning experiment of $^{40}Ar + \alpha$ reaction will be performed at RAON**

Yield estimation for $^{10}Be(\alpha,n)^{13}C$



- Reaction cross section calculated by TALYS
- Yield = $\boldsymbol{\sigma} \cdot \boldsymbol{I} \cdot \boldsymbol{N} \cdot \boldsymbol{\epsilon} \cdot \boldsymbol{t}$
  - $\boldsymbol{\sigma}$ = cross section
  - $\boldsymbol{\epsilon}$ = Efficiency
  - $\boldsymbol{t}$ = Times (5 days for each setup)
  - $\boldsymbol{I}$ = Beam Intensity
  - $\boldsymbol{N}$ = Number of target (660 Torr and 20 mm for each setup)
- It is possible to measure down to the 0.5 MeV region
- **Plan to submit proposal for $^{10}Be(\alpha,n)^{13}C$ reaction measurement using the VOICE**

Summary

- ^{10}Be abundance is important to understand the Solar system.

- ^{10}Be(p,α)^{7}Li reaction
  - Main destruction mechanism
  - We propose ^{10}Be(p,α)^{7}Li direct measurement at CRIB.
    - **AToM-X** will be used to measure ^{10}Be(p,α)^{7}Li reaction.
  - A total of 13.5 days of beam time was approved (NP2412 – AVF 81)
    - Plan to perform in 2026

- ^{10}Be(α,n)^{13}C reaction
  - One of important destruction mechanism
  - Combine neutron detector and ATTPC can be used for measurement.
  - **VOICE** is under developed to measure (α,n) reaction.
  - Will submit the proposal using VOICE at CRIB in RIKEN

Thank you for your attention

Backup

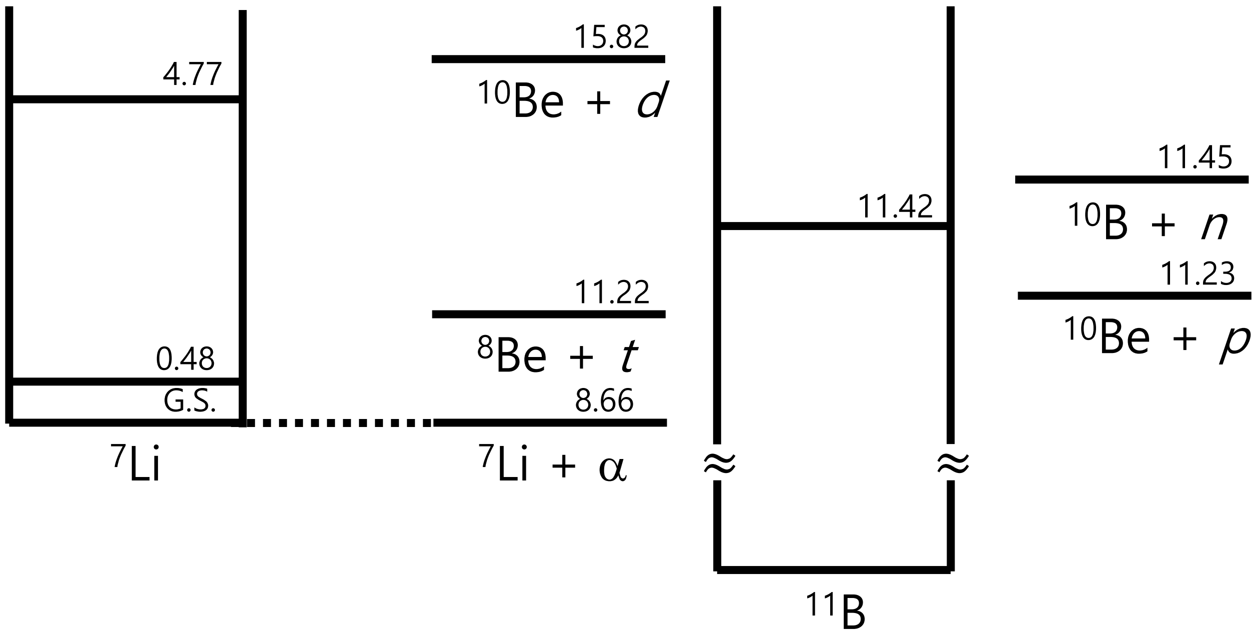
Reactions

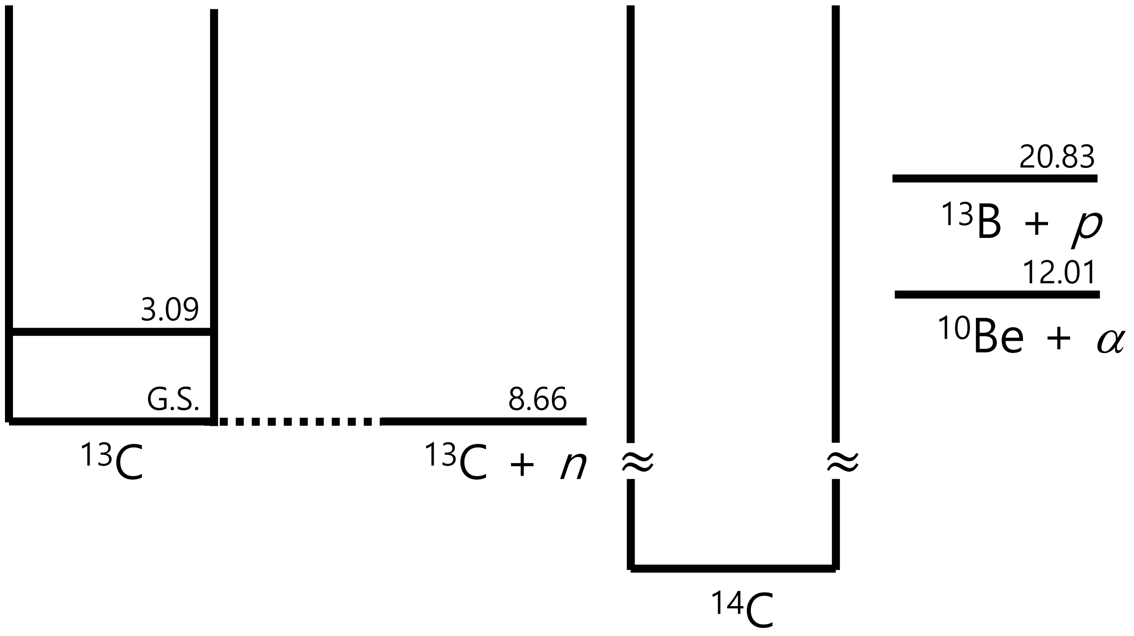
Gamow Window T = 1 GK

E_r = 0.11 – 0.48 MeV

E_x = 11.34 – 11.71 MeV

- Gamow Window at T = 1 GK
  - E_r = 0.41 – 0.97 MeV
  - E_x = 12.42 – 12.98 MeV

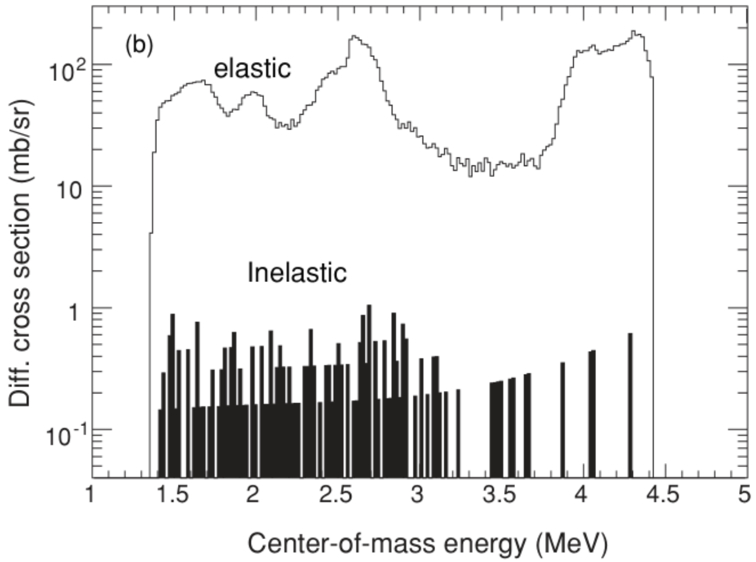


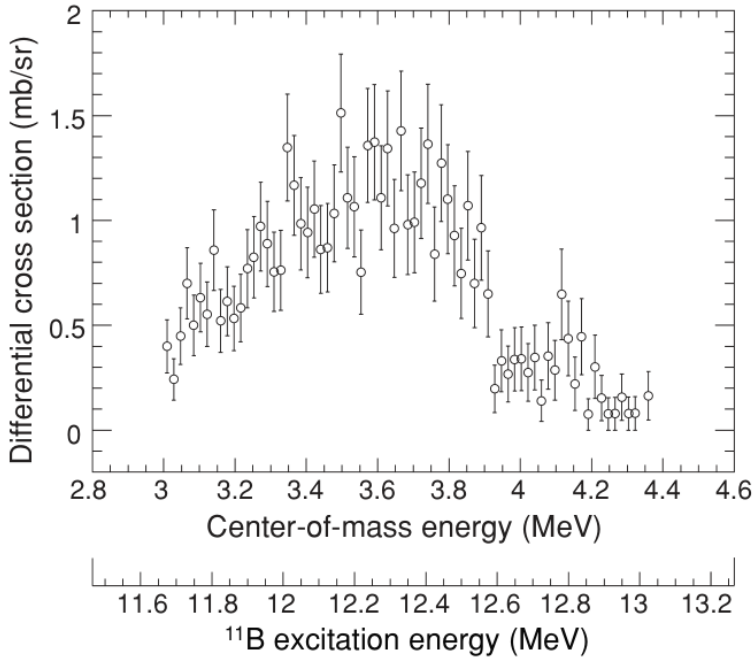


Reaction Q value

Previous study of $^{7}Li(\alpha,\alpha)^{7}Li$ experiments

H. Yamaguchi et al., Phys. Rev. C 83, 034306 (2011)





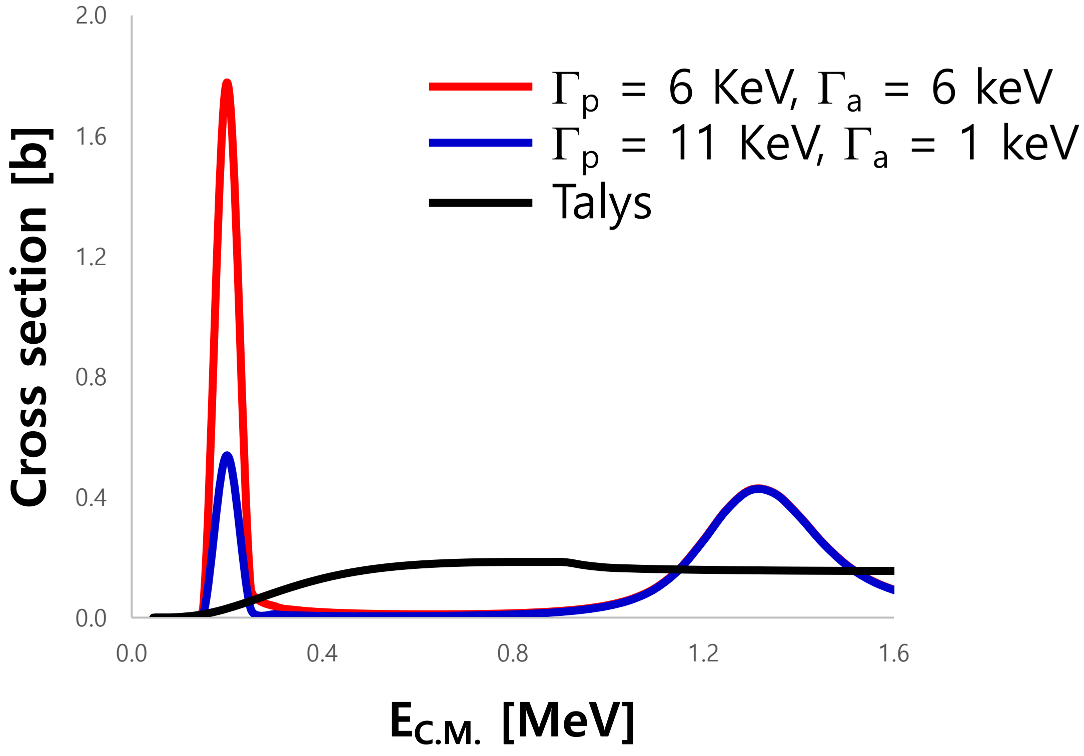
- In elastic channel should be negligible

Resonance parameters

A. Sieverding, et al., Phys. Rev. C 106, 015803 2022

Ex [MeV]	J^{π}	Γ_p[KeV]	Γ_{α}[KeV]
11.272	9/2+	1.0E-15	110
11.425	1/2+	6,11	6,1
11.490	3/2+	1.0E-4	93
11.600	5/2+	1.0E-5	90
11.893	5/2-	1.0E-4	100
12.040	7/2+	1.0E-3	500
12.550	1/2+	100	105

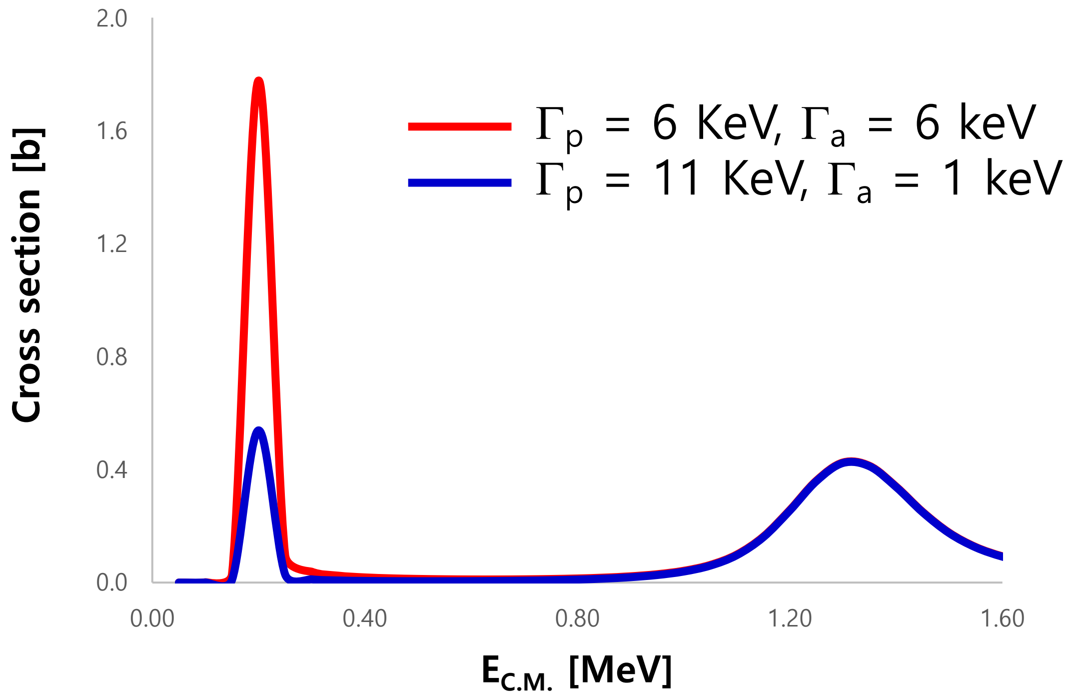
For unknown partial width, the reduced widths are adopted as ~$0.01\gamma_w^2$ Wigner limit



Background from Carbon

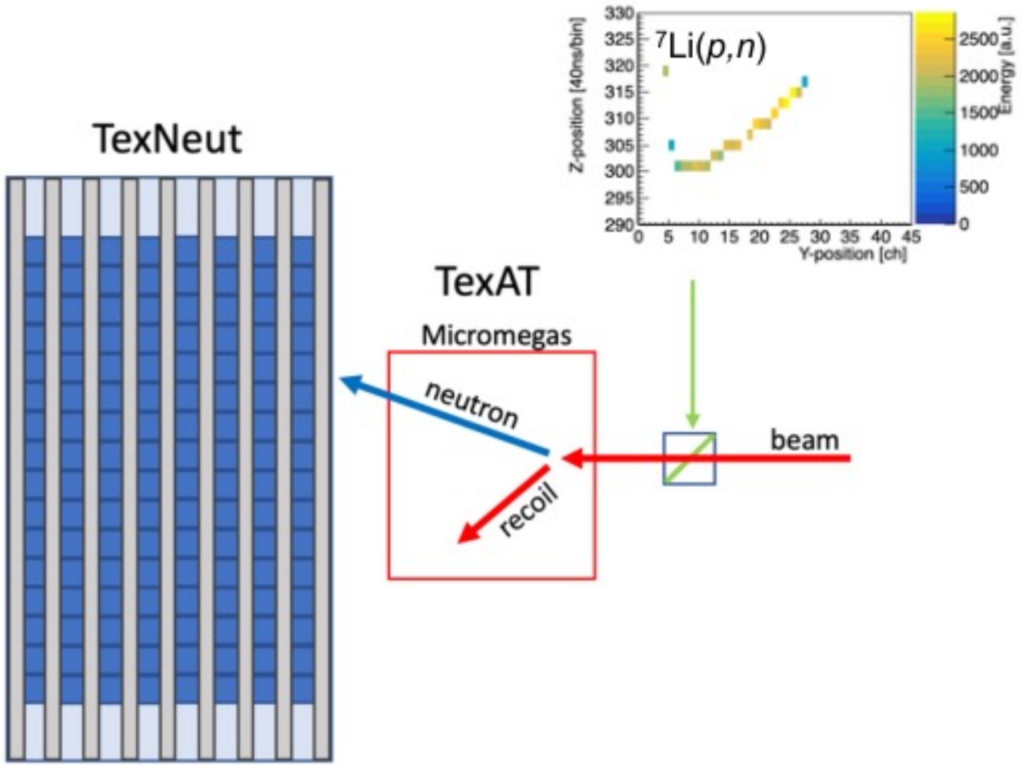
1. Yields of residual nuclei

Z	N	A	events	percent	x-section(mb)
10	11	**21 Ne**	771	77.1%	1.8
9	12	**21 F**	14	1.4%	0.0326
8	10	**18 O**	210	21%	0.489
8	9	**17 O**	5	0.5%	0.0117
TOTAL			1000	100	2.33062



- Fusion reaction cross section calculation using PACE4
  - Quantum-mechanical model
  - Bombarding energy: 2.2 MeV
  - $^{10}Be(^{12}C,\alpha)^{18}O$

$^{10}Be(\alpha,n)^{13}C$ reaction measurement : neutron measurement

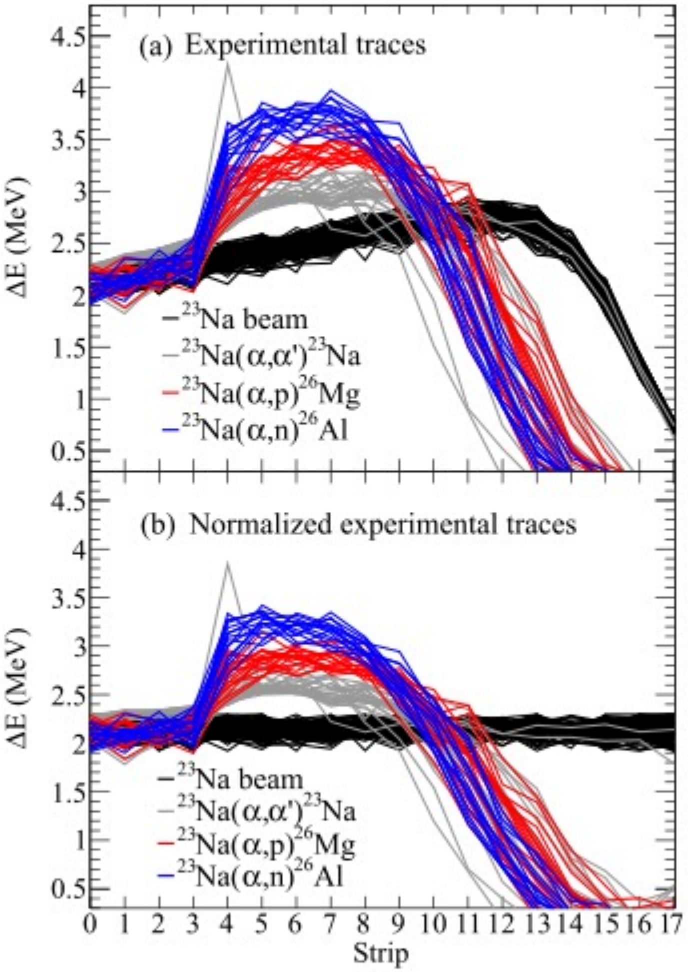


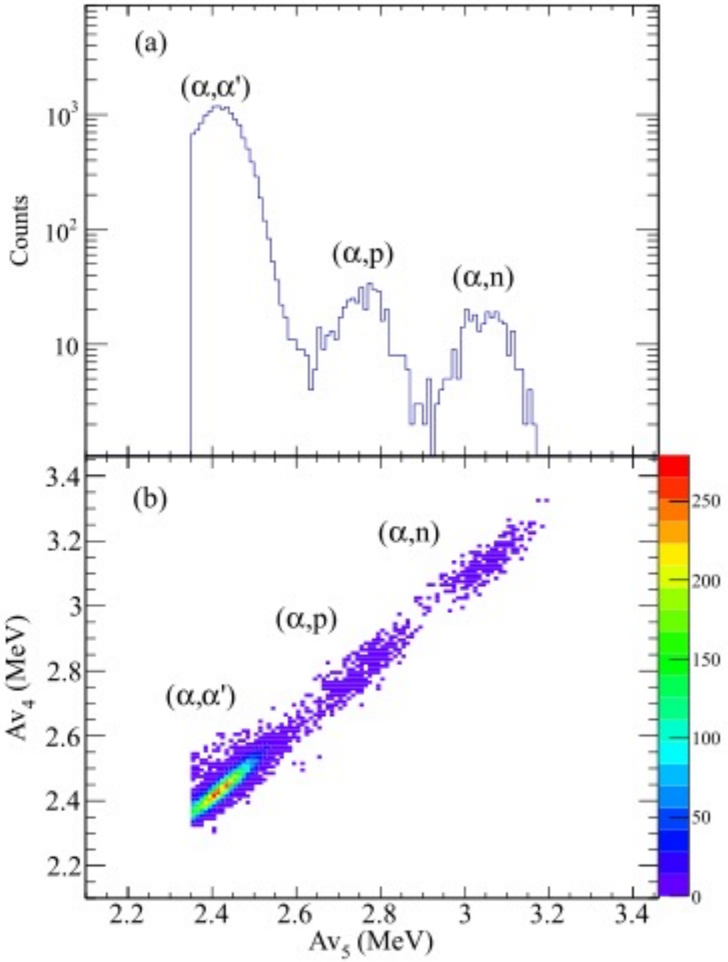
Adopted from Dustin P. Scriven presentation
"TexAT-TPC and a Neutron Detector Array. TexNeut

- AToM-X + neutron detector array
  - Benchmarked TexAT + TexNeut

Previous MUSIC results

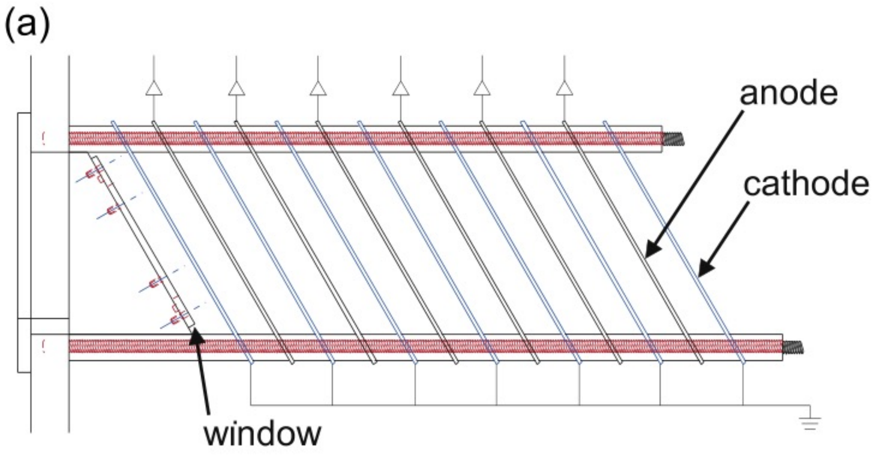
Nucl. Instrum. Meths. A 799, 197-202 (2015)



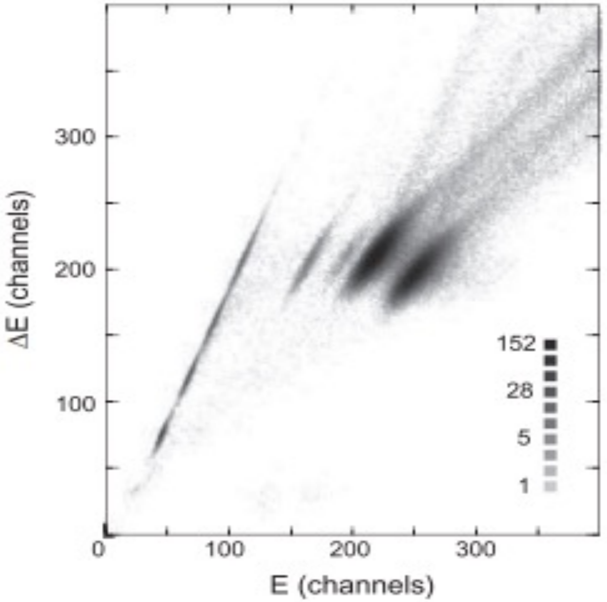


Vertical Ionization chamber

Nucl. Instrum. Meths. A 751, 6 (2014)

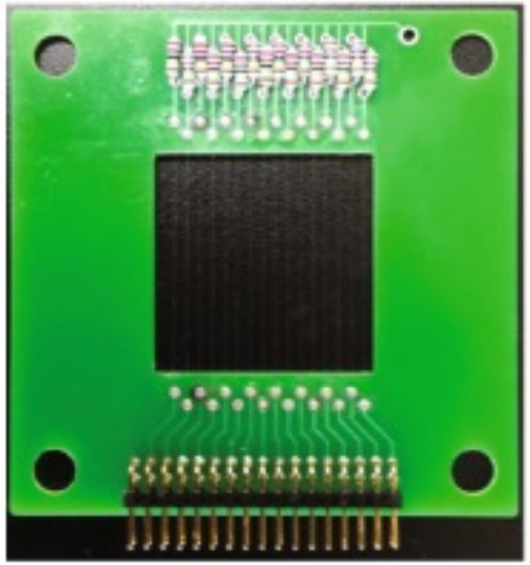


Fast Ionization Chamber



Beam Identification plot

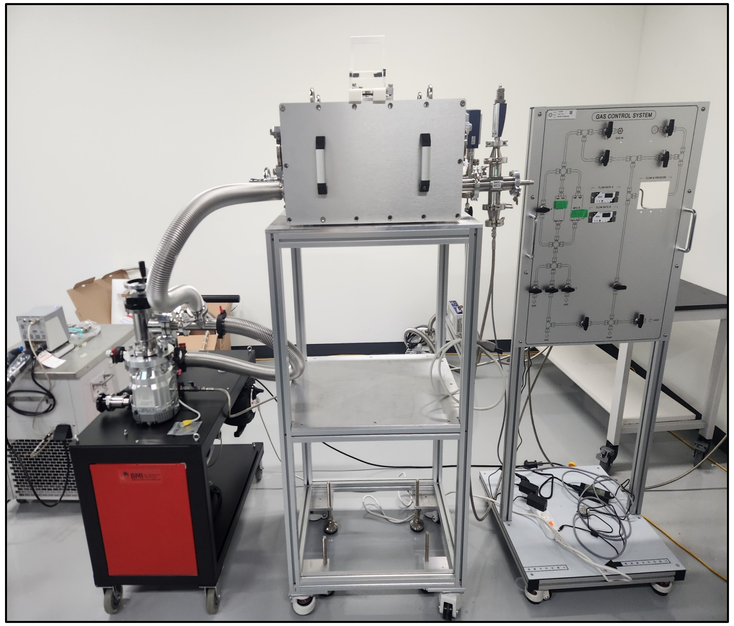
Jou. Kor. Phys. Soc. 68, 10 (2016)

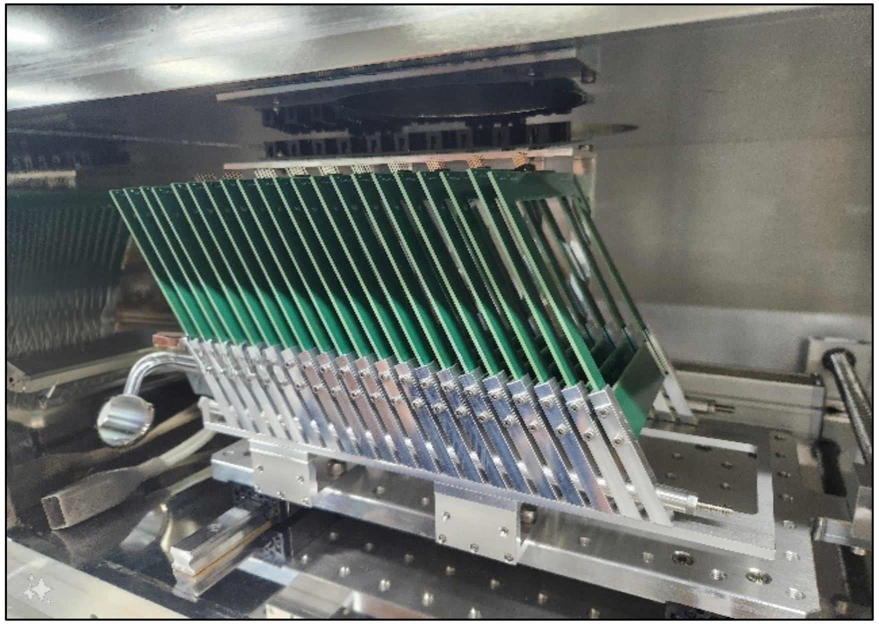


Position Sensitive Electrode

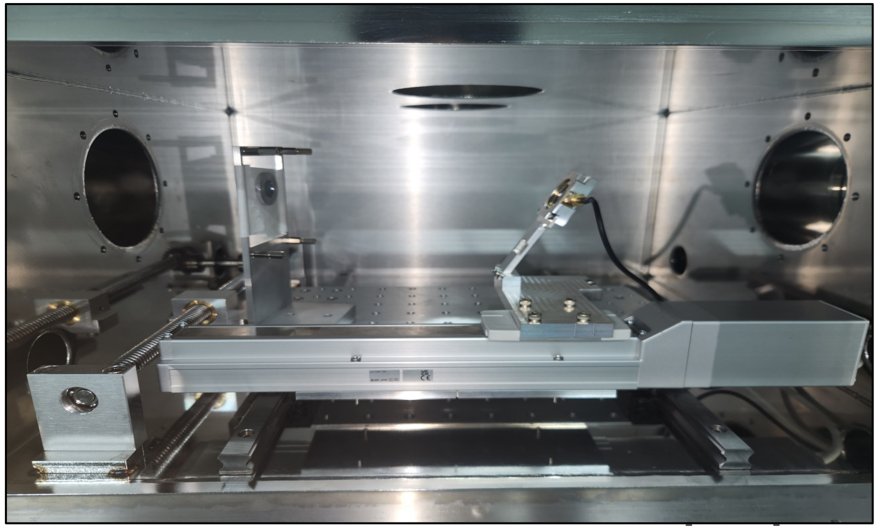
- Multiple active regions along with the beam trajectory
- Shorter drift length → Capability to manage high-rate beams (>10^6 pps)
- Some IC detectors are equipped with position-sensitive strips.

Construction of VOICE

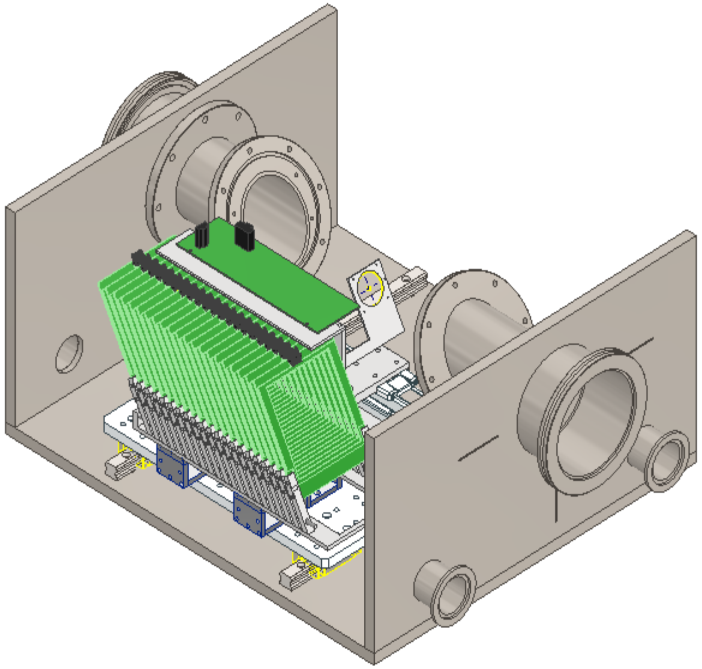


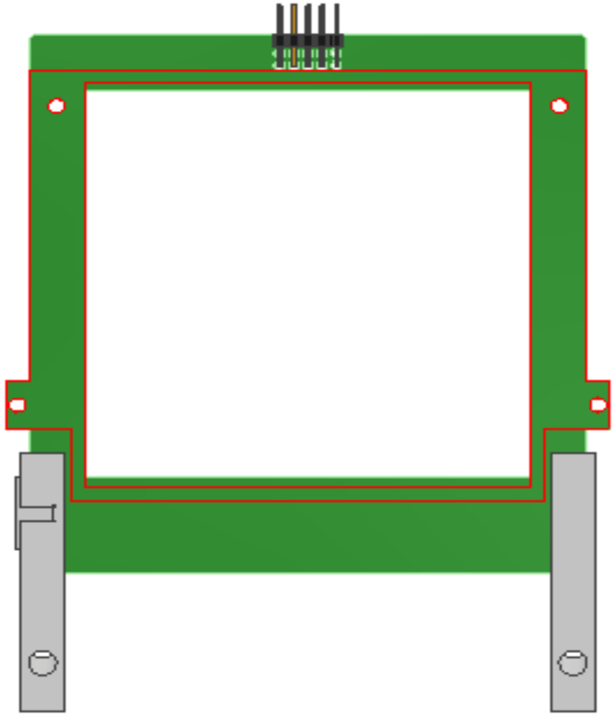


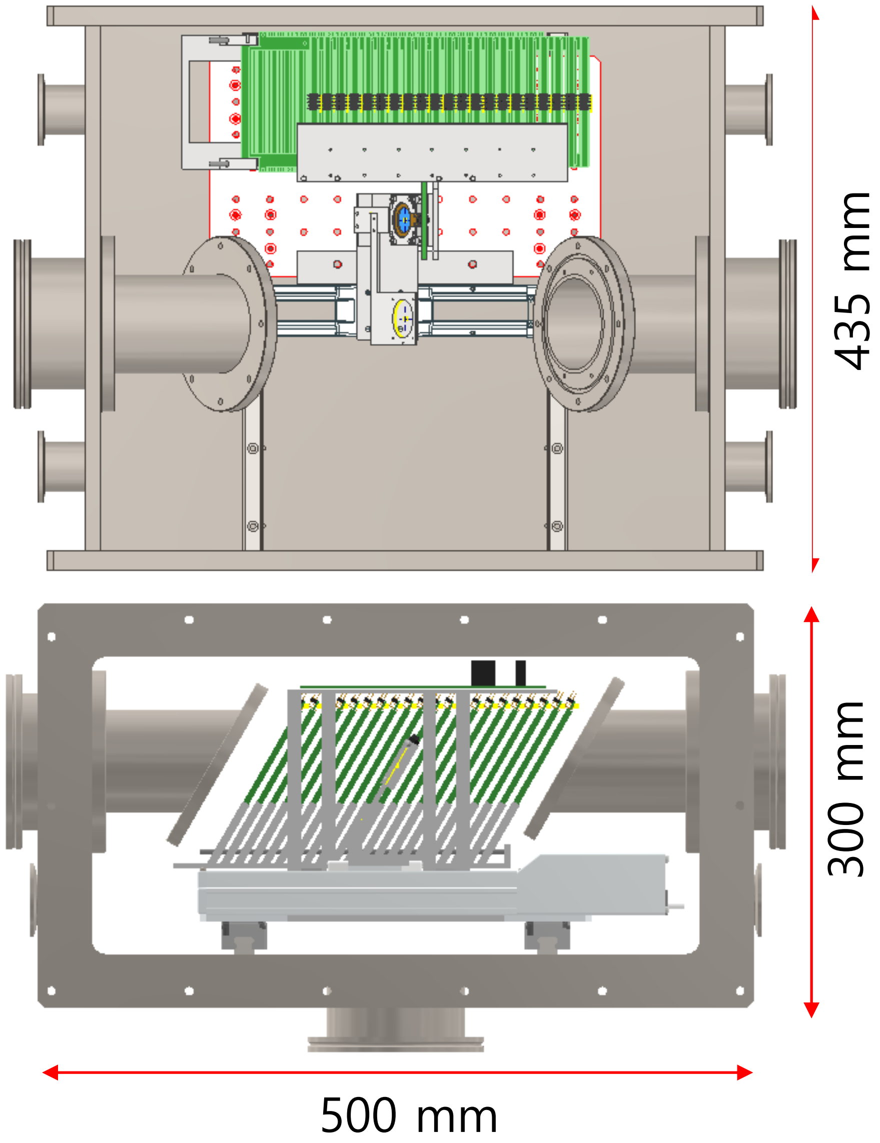
- Chamber
- Gas control system
- Pumping station
- Tilted-wire type electrodes
- Beam monitoring devices



Design of VOICE







- Ionization Chamber part
  - Vertical(tilted)-wire type electrode
  - Frisch Grid
- Beam monitoring
  - Silicon Surface Barrier detector
  - Beam Viewer

VOICE status

- A VOICE (Vertically Oriented-wire Ionization Chamber with sEgmentation) is under development
- VOICE can be used for beam particle identification and nuclear reaction measurement
  - Beamline detector for particle identification.
  - measure various (α,*p*) and (α,*n*) reactions
- In-house test is processing
- Simulation code based on NPTool is being developed
- Commissioning experiments and further physics experiments are expected in the following years.

2023 H2
2024 H1
2024 H2
2025 H1
2025 H2
2026

Chamber
Gas Handling system
Electrode Design
Beam Monitor Design
Manufacture
DAQ Preparation
System Commissioning (Using alpha source)
Commissioning Experiments (Using SI beam)
Physics Experiments (Using RI beam)

^{10}Be production at Catania tandem

Table 1
Characteristics of the present ^{10}Be beam compared with the ones of other ^{10}Be beams developed worldwide. NF means that the corresponding information has not been found in the considered reference. Intensities in [20,22] were intentionally reduced due to the use of an active target. The intensity of [35] was also intentionally reduced, being the available one a factor 10 larger than the one used.

Production method	Laboratory	Energy MeV	Purity %	Intensity ions × s^{-1}	Ref.
Fragmentation	GANIL	~300	95	1×10^4	[15,16]
Fragmentation	NSCL	800-1200	NF	1×10^5	[17]
Fragmentation	NSCL	680	NF	200-400	[20]
Fragmentation	RIKEN	600	95	3×10^4	[18]
Fragmentation	HIRFL	72	92	5×10^3	[19]
Transfer	Notre Dame	38-44	NF	3×10^4	[21]
Transfer	Notre Dame	35	42-93	1×10^2	[22]
Transfer	São Paulo	23	3	1×10^3-1×10^5 (× μA prim. beam)	[23,36]
Transfer	RIKEN	26	95	2×10^4	[24]
Transfer	ANU	40	25	1×10^4 (× μA prim. beam)	[37]
ISOL	ISOLDE CERN	29	100	1×10^6	[35]
ISOL	TRIUMF	41	100	1×10^7	[38]
OFF-LINE	INFN-LNS	47-54	99.8	2.5×10^9	Pres. work
OFF-LINE	HRIBF-ORNL	25-107	>99	1-5×10^6	[1,39]

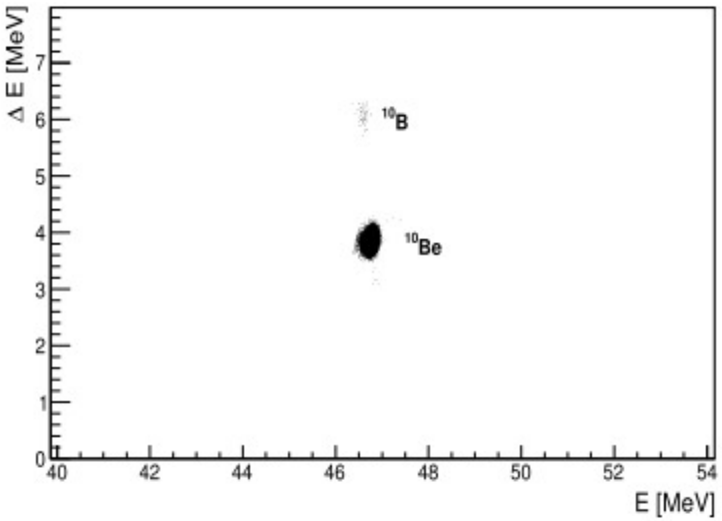


Fig. 4. DE-E spectrum measured, inside the CT2000 scattering chamber, with a telescope placed at zero degree hit by the ^{10}Be beam with an intensity reduced to about 100 pps. The spectrum shows a pure ^{10}Be beam with a minor ^{10}B contamination of the order of 0.15%.