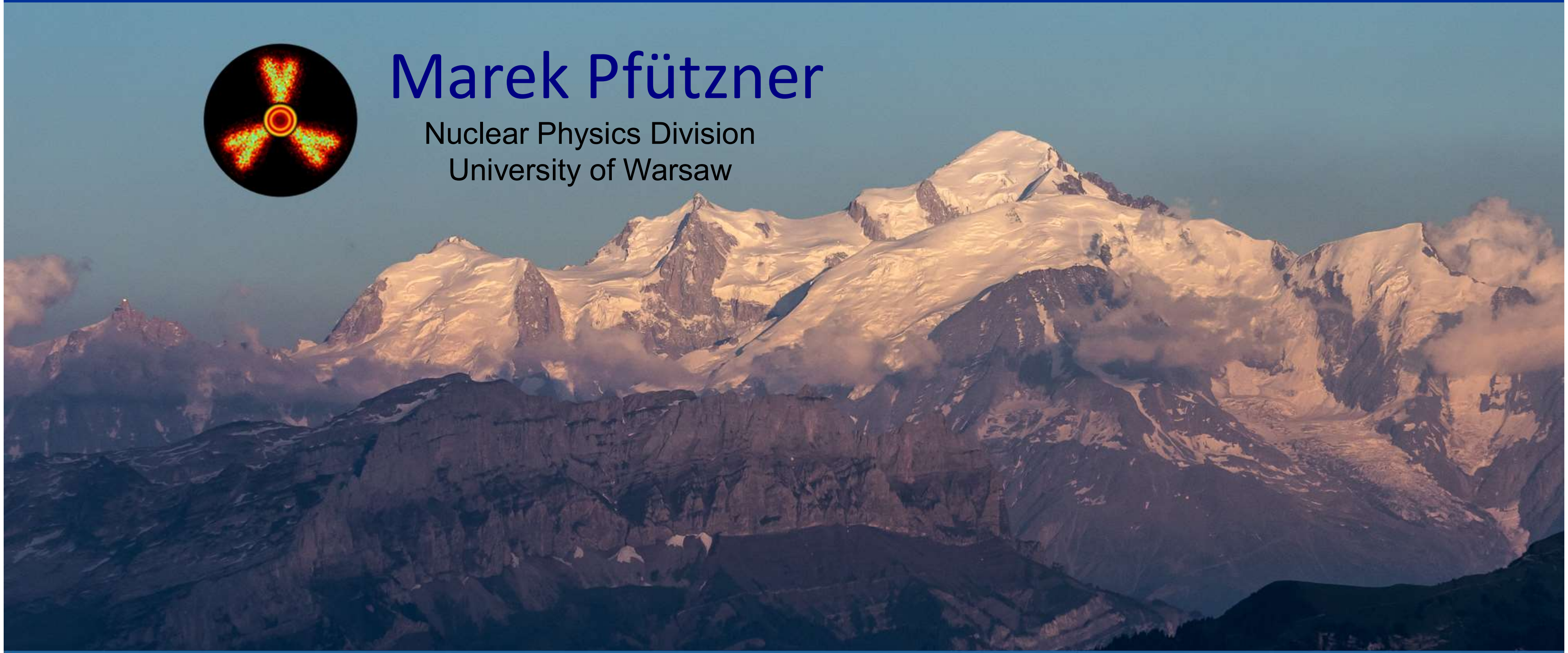
Looking for β-Delayed Protons in the Decay of ^{11}Be



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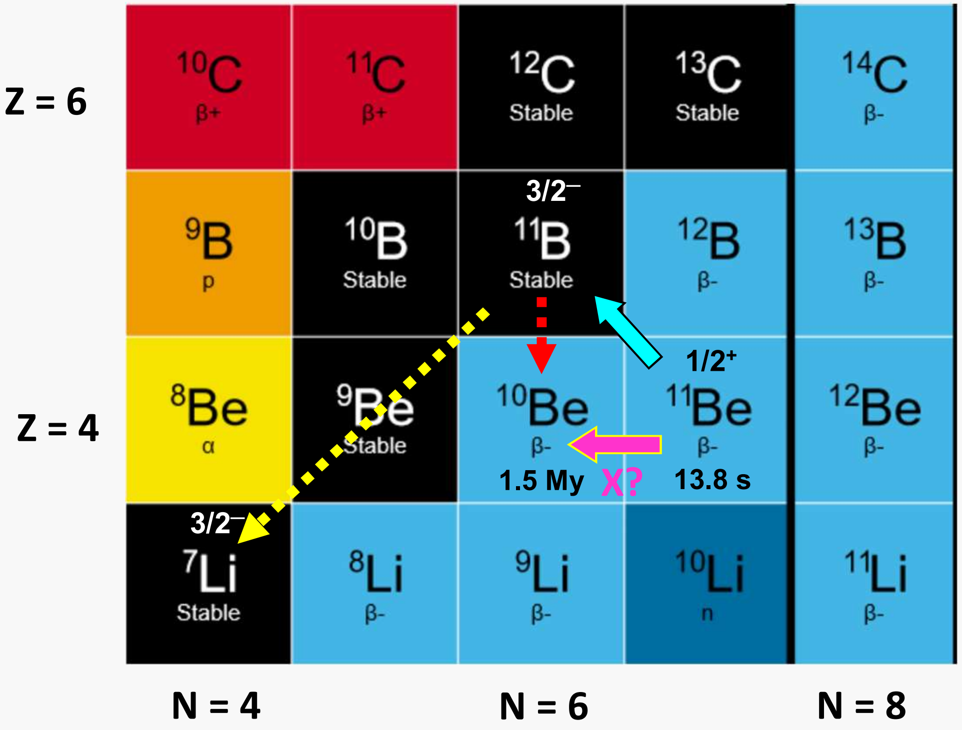
ISOLDE Workshop and Users meeting 2024

Case of ^{11}Be



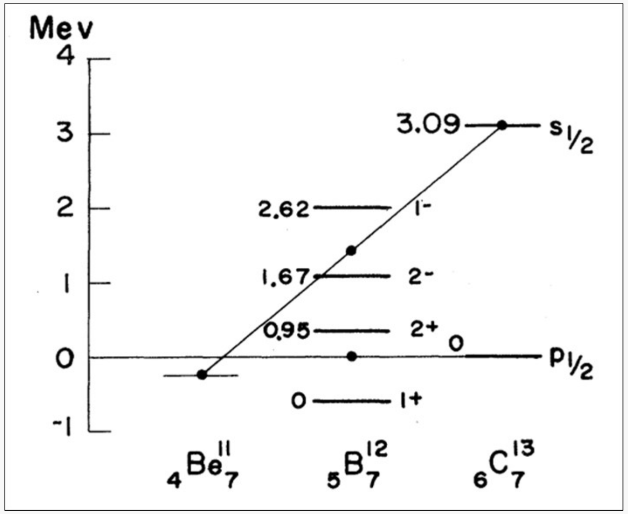
Z = 6	^{10}C β+	^{11}C β+	^{12}C Stable	^{13}C Stable	^{14}C β-
	^{9}B p	^{10}B Stable	3/2⁻ ^{11}B Stable	^{12}B β-	^{13}B β-
Z = 4	^{8}Be α	^{9}Be Stable	^{10}Be β- 1.5 My	1/2⁺ ^{11}Be β- 13.8 s	^{12}Be β-
	3/2⁻ ^{7}Li Stable	^{8}Li β-	^{9}Li β-	^{10}Li n	^{11}Li β-
	N = 4		N = 6		N = 8

- In 2018 a dark neutron decay was proposed as a solution to the n half-life puzzle

  Fornal & Grinstein PRL 120 (2018)

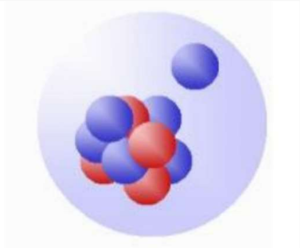
  → new decay channel: ^{11}Be → ^{10}Be + X

  → same final nucleus as after ^{11}Be βp !

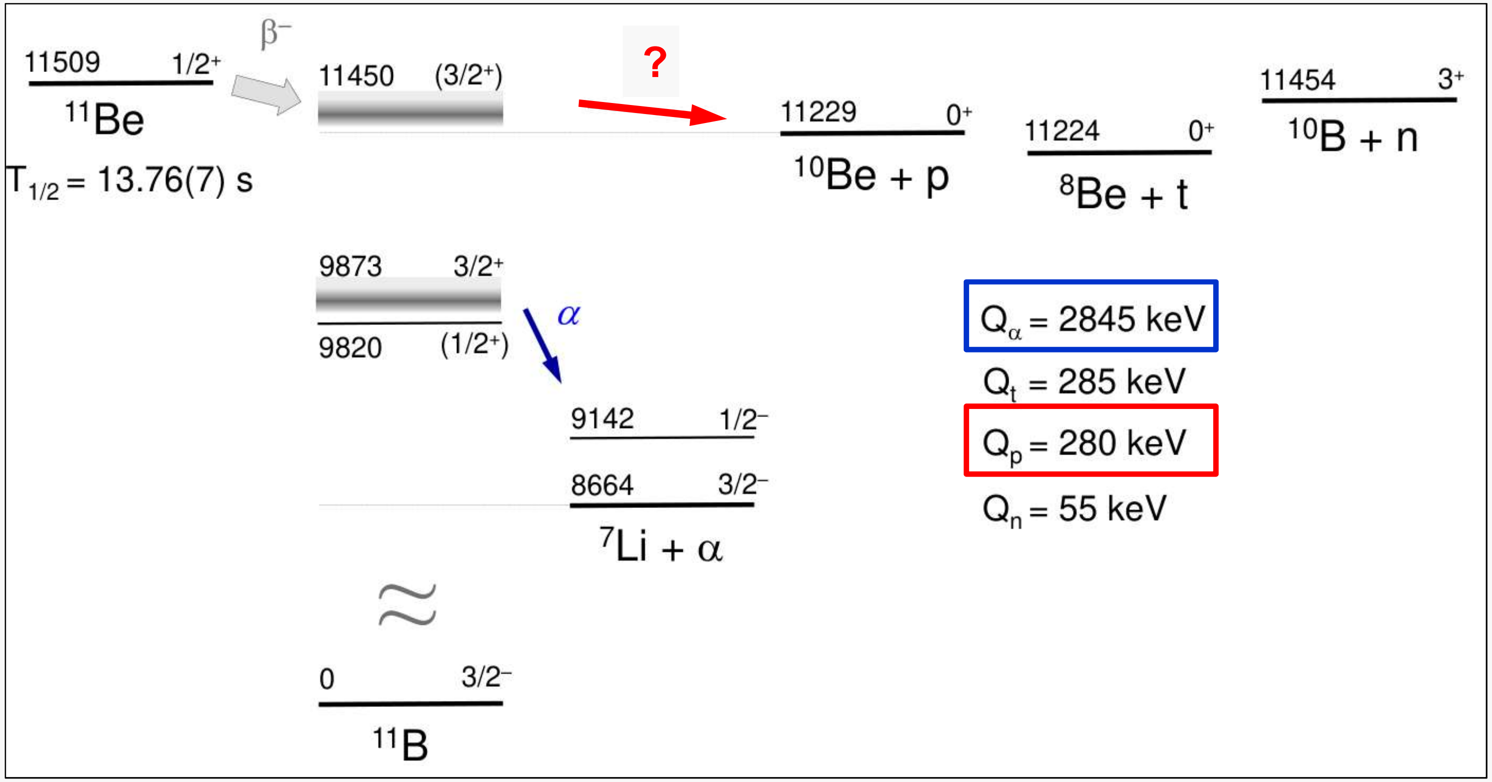


Talmi & Unna (1960)

- spin inversion → $1/2^+$ → long half-life
- $s_{1/2}$ g.s. and S(n) = 502 keV → **1n halo**
- The β^-p channel open → probe the halo



^{11}Be decay scheme



- The $\beta^-\alpha$ emission is known, $b_\alpha = 3.3(1)\%$
- The **β^-p** decay possible, the predicted branching: $b_p < 10^{-6}$

^{11}Be $\beta\alpha$ spectrum

- First observation by Alburger and Wilkinson (1971)
- Improved measurement: Alburger et al (1981)

  b_α = 2.9(4)%, transition through $3/2^+$ at 9.87 MeV

- Most recent result: Refsgaard et al. (2019)

  DSSD detectors @ ISOLDE

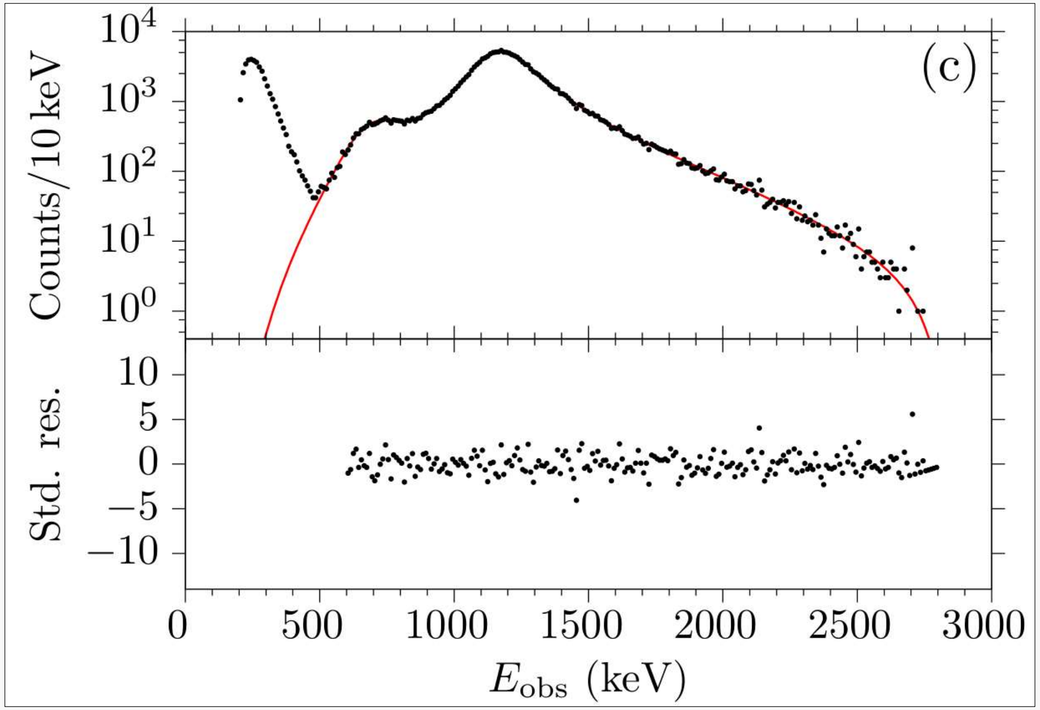
  b_α = 3.3(1)%,

  transition through:

  $3/2^+$ at 9.87 MeV

  and 3/2+ at 11.49 MeV

- Note a large background below 500 keV due to β particles – protons are hidden there!



Refsgaard at al., PRC 99, 044316 (2019)

Search for delayed protons

- **Indirect method**:

  collect ^{11}Be (ISOLDE), then look for ^{10}Be in the sample with AMS (Uppsala, Vienna)

  1st approach: → $b_p = (2.5 \pm 2.5) \times 10^{-6}$ Borge at al., J. Phys. G 40, 035109 (2013)

  2nd approach: → $\boldsymbol{b_p = (8.3 \pm 0.9) \times 10^{-6}}$ Riisager at al., Phys. Lett. B 732 (2014) 305

  3rd approach: → $\boldsymbol{b_p < 2.2 \times 10^{-6}}$ Riisager at al., EPJ A 56 (2020) 100

  → a source for ^{10}Be contamination found (^{10}Be^{1}H$^+$)

- **Direct search:**

  implant ^{11}Be in a TPC and see tracks of protons (TRIUMF)

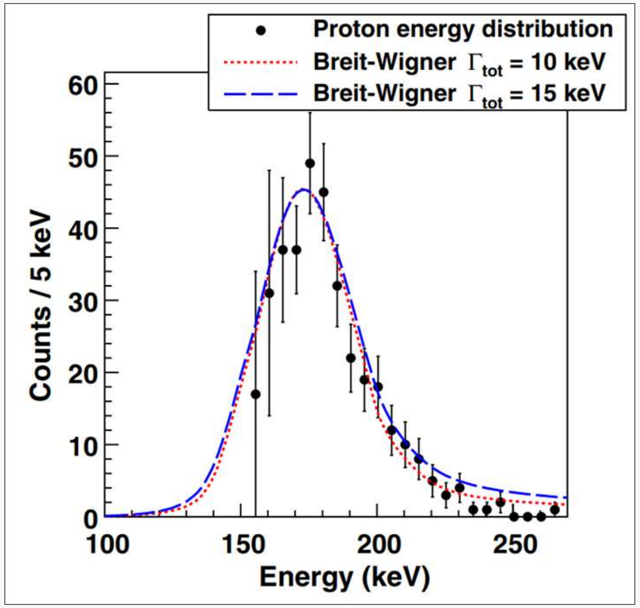
  → $\boldsymbol{b_p = (13 \pm 3) \times 10^{-6}}$

  Ayyad at al., PRL 123 (2019) 082501

  Gas mixture: 90% He + 10% CO_2 @ 60 torr

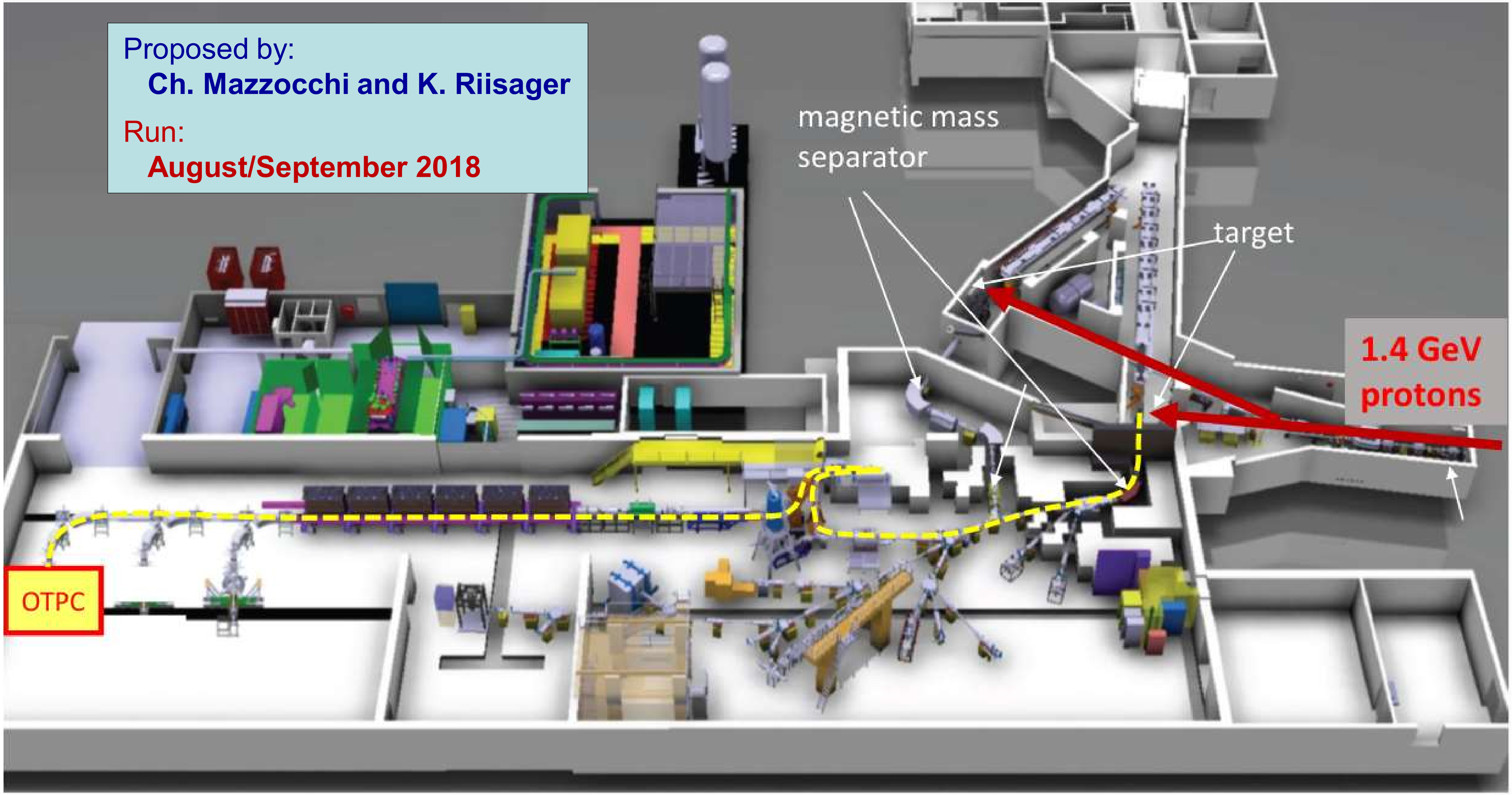
  → 200 keV proton ≈ 10 cm track

  no spectrum of α particles



Experiment IS629

- 1.4 GeV p beam on UC_x target → bunches of ^{11}Be @ 7.5 MeV/u sent to OTPC every 60 s



Proposed by:
Ch. Mazzocchi and K. Riisager

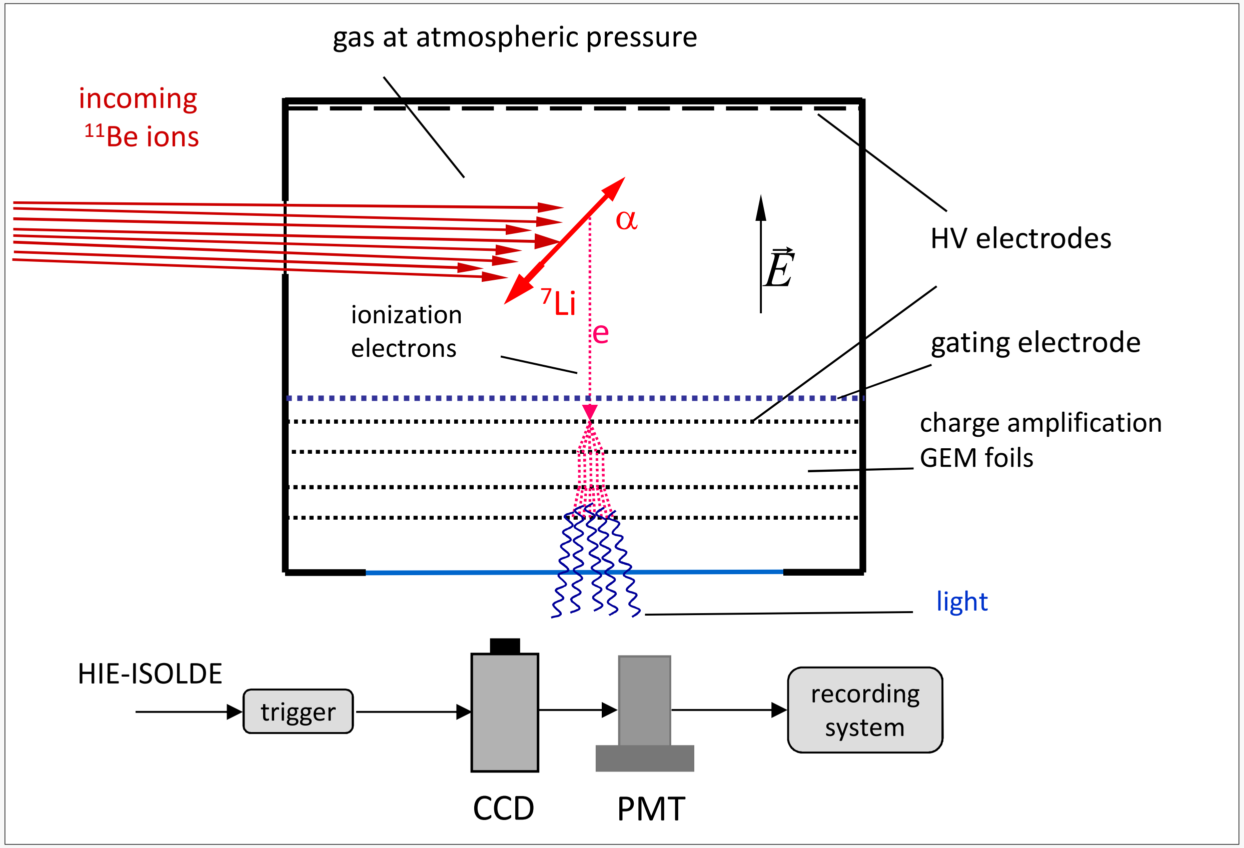
Run:
August/September 2018

María J G Borge and Klaus Blaum *J. Phys. G: Nucl. Part. Phys.* **45** 010301 (2018)

The Warsaw OTPC @ ISOLDE

Time projection chamber with optical readout (OTPC)

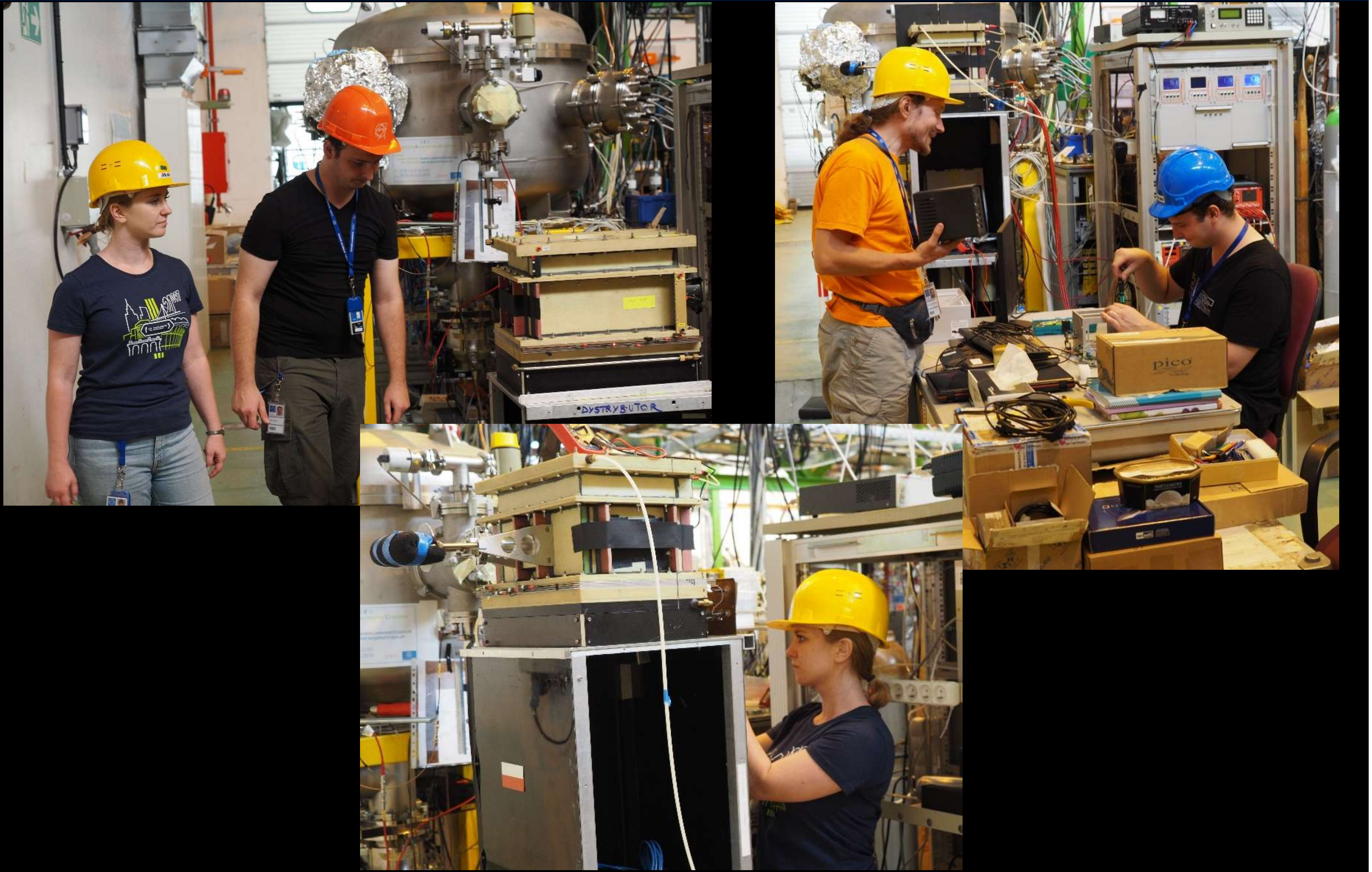
- Gas mixture: 97% He + 1.6% CF_4 + 1.4% N_2 @ atmospheric pressure



- No sensitivity to β electrons!

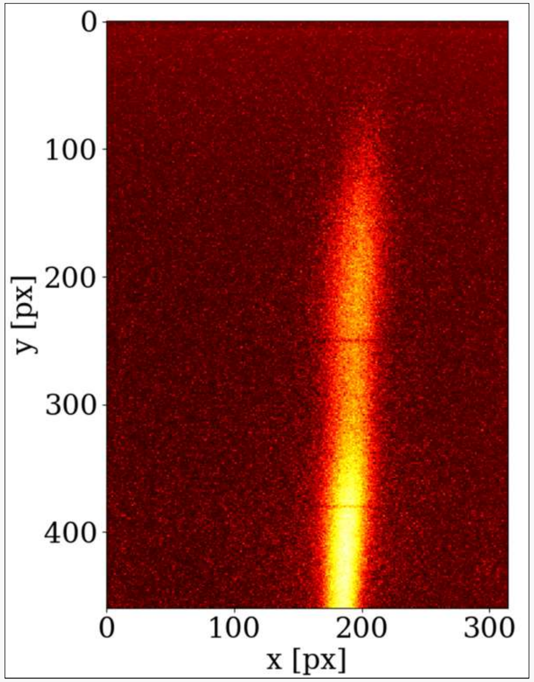
- Combination of the CCD image with the PMT waveform allows to reconstruct the event in three dimensions fully

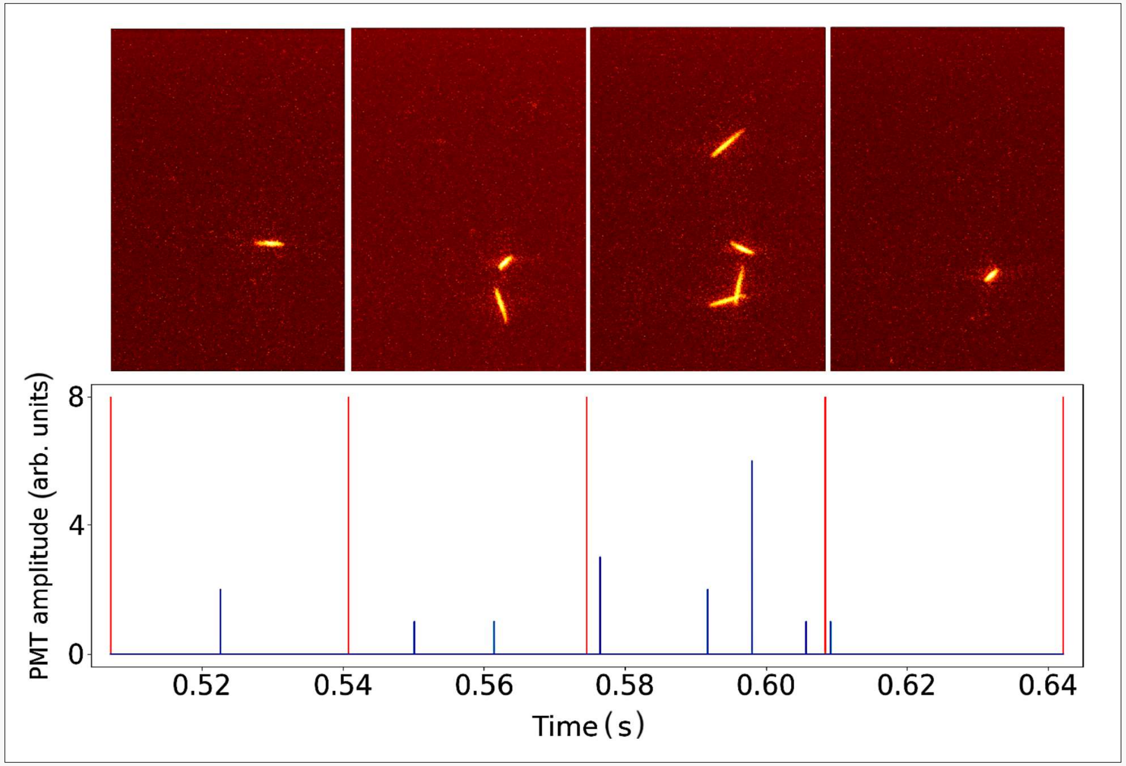
OTPC @ ISOLDE



Decay events

- Running OTPC mode: bunch plus „movie”
  - Bunches of about 10^4 ions of accelerated ^{11}Be implanted every 1 min.
  - After implantation: 252 frames of 33 ms (13 s) + 47 s break
- In total, about 1.4 M frames recorded, featuring about 1.5 M $\beta\alpha$ events





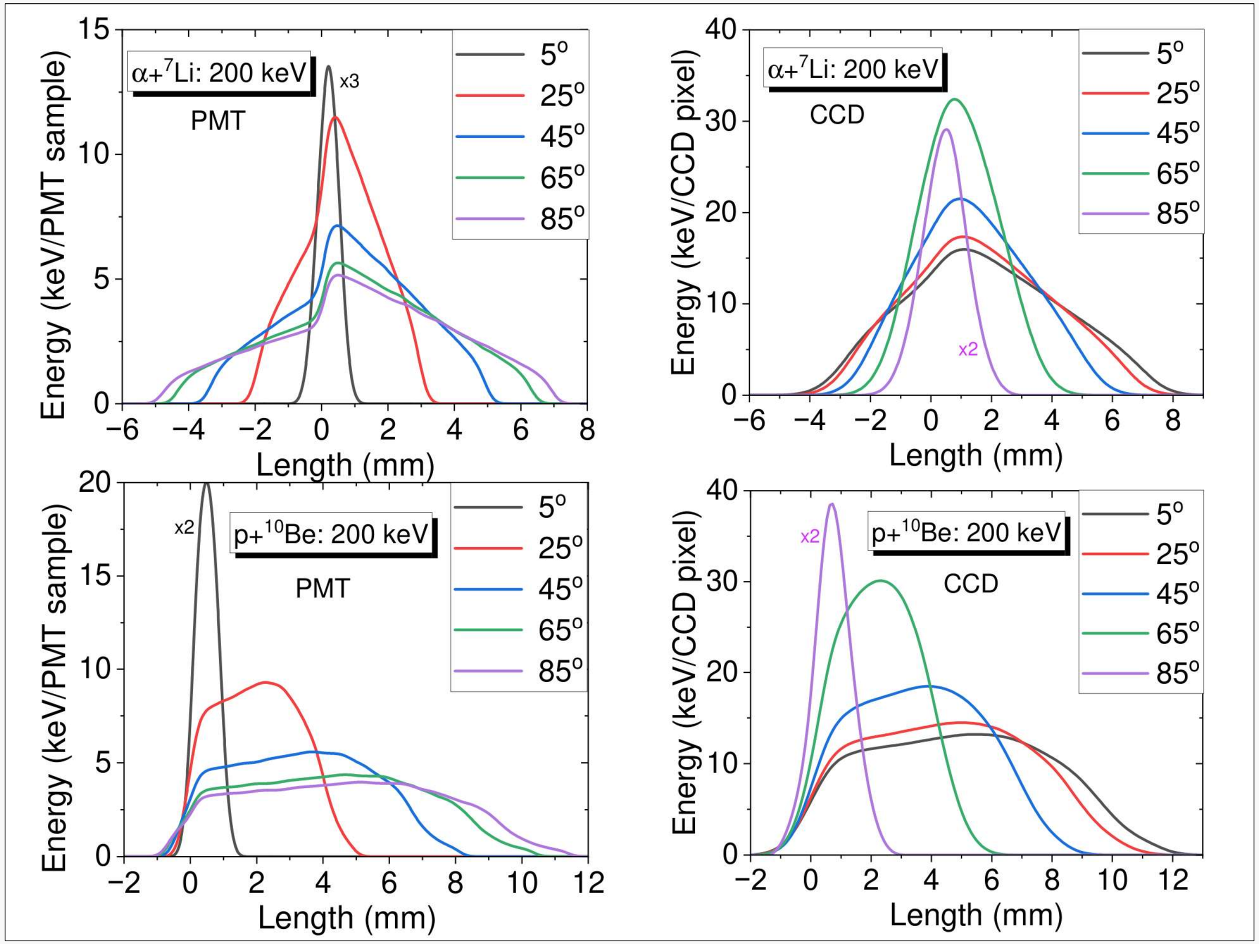
- For further analysis, we selected **only frames with a single decay event** (≈ 230 000)

SRIM predictions

- SRIM package used to predict expected profiles of energy deposit
- Two decay scenarios considered:

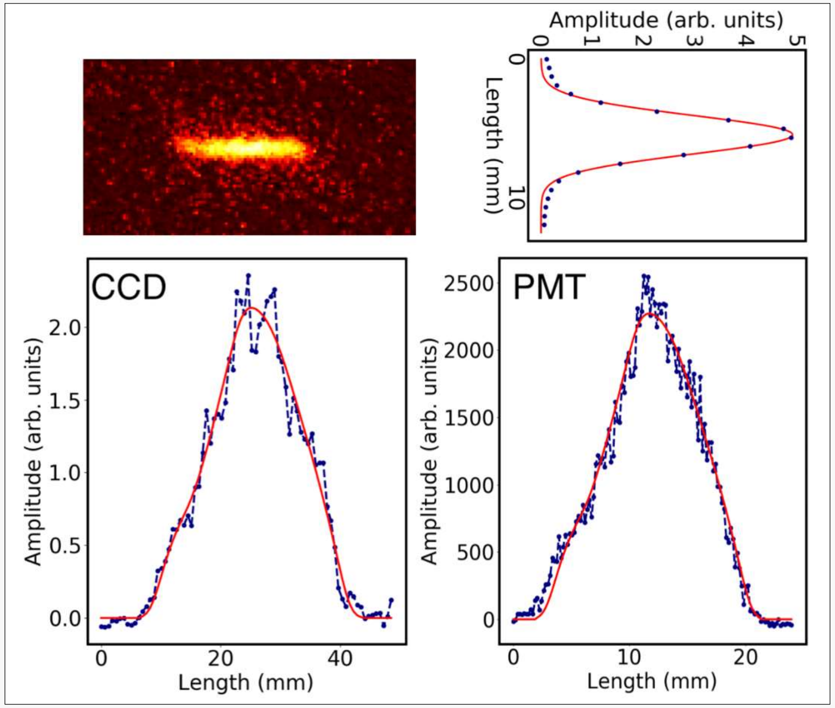
$^{11}\mathrm{B}^* \rightarrow {}^{7}\mathrm{Li} + \alpha$

$^{11}\mathrm{B}^* \rightarrow {}^{10}\mathrm{Be} + \mathrm{p}$



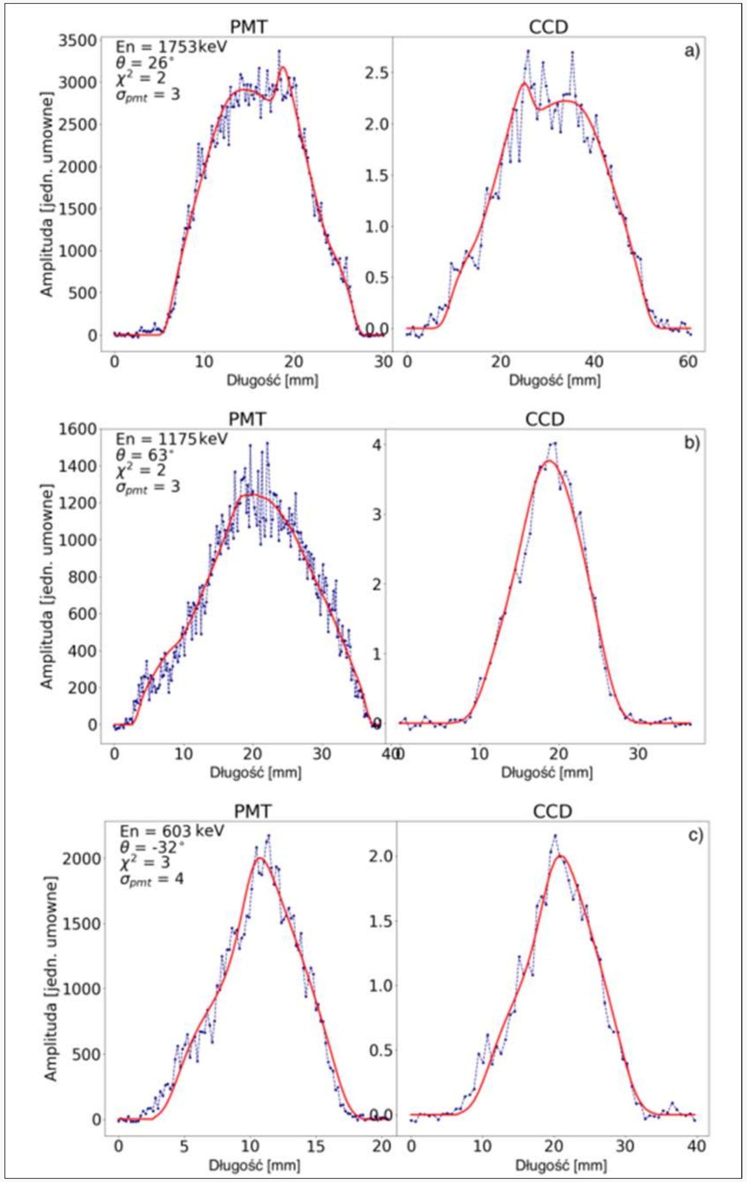
Event reconstruction

- Example reconstruction of $\beta\alpha$ events



$E_{\beta\alpha}$ = 1140 keV, θ = 28°

- SRIM package used to predict expected profiles of energy deposit

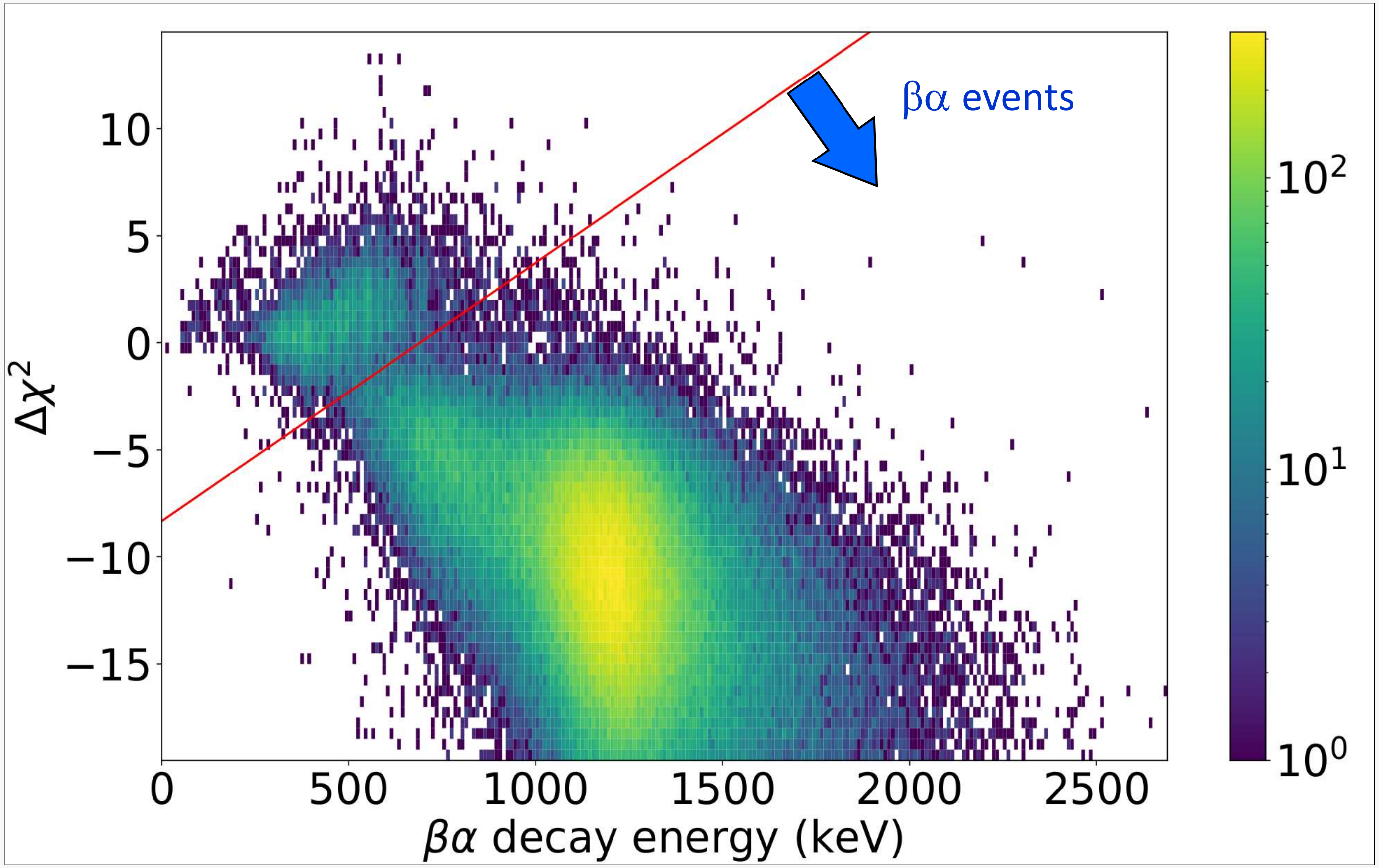


Event selection

- Each event was reconstructed using both βα and βp scenarios (→ min χ^2)
  - → $\Delta\chi^2 = \chi^2_\alpha - \chi^2_p$

$\Delta\chi^2 < 0$
looks more
like βp

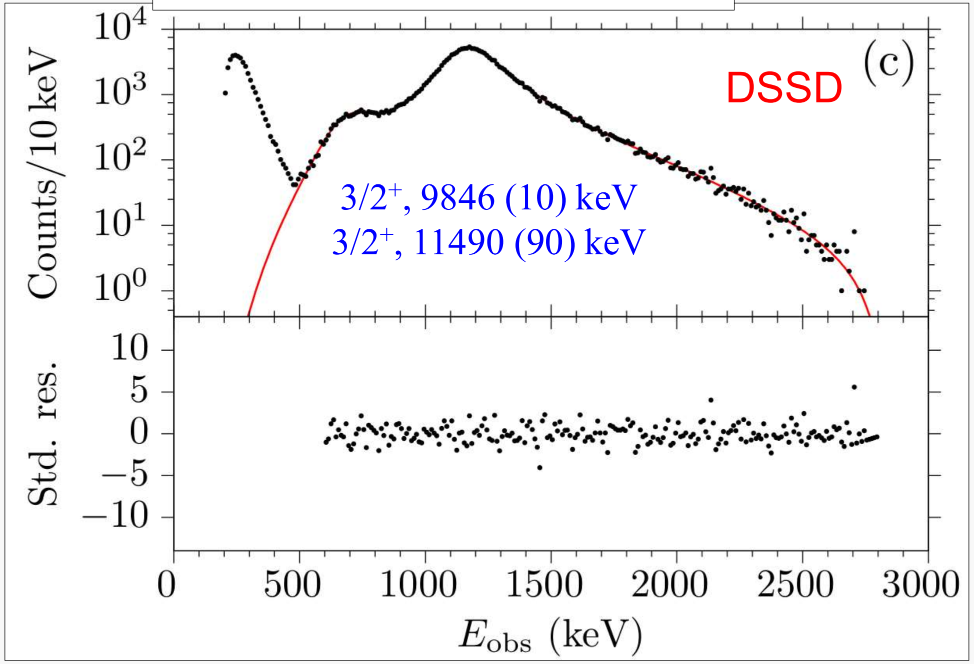
$\Delta\chi^2 < 0$
looks more
like βα



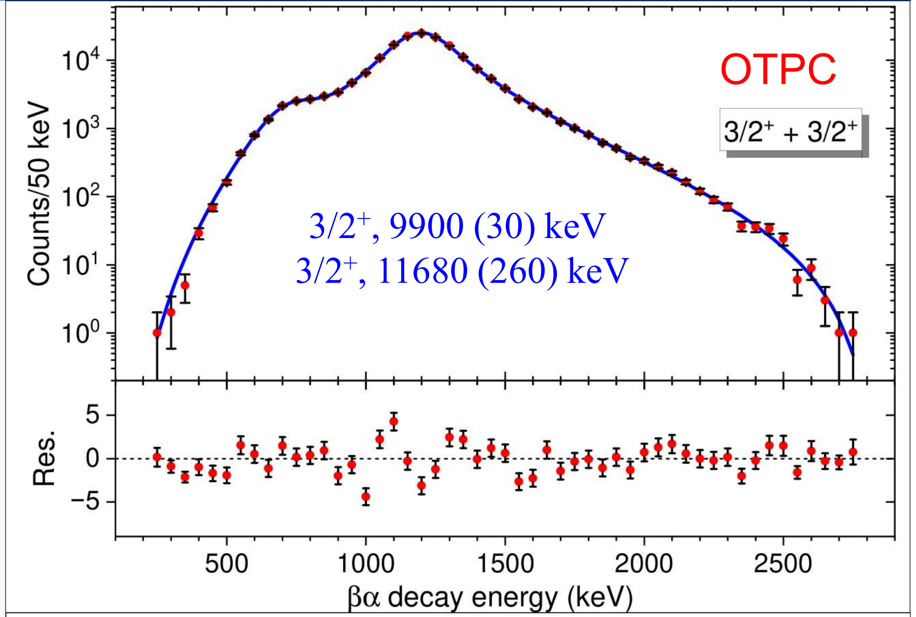
$\beta\alpha$ decay of ^{11}Be

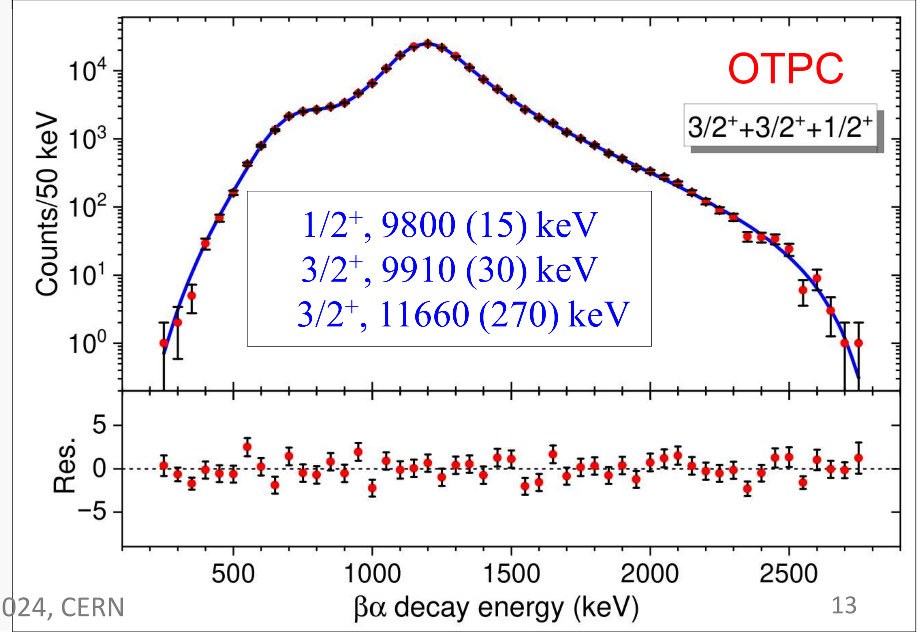
- Experimental energy spectrum of 181 k $\beta\alpha$ events with best-fitted **R-matrix** description

Literature data for comparison



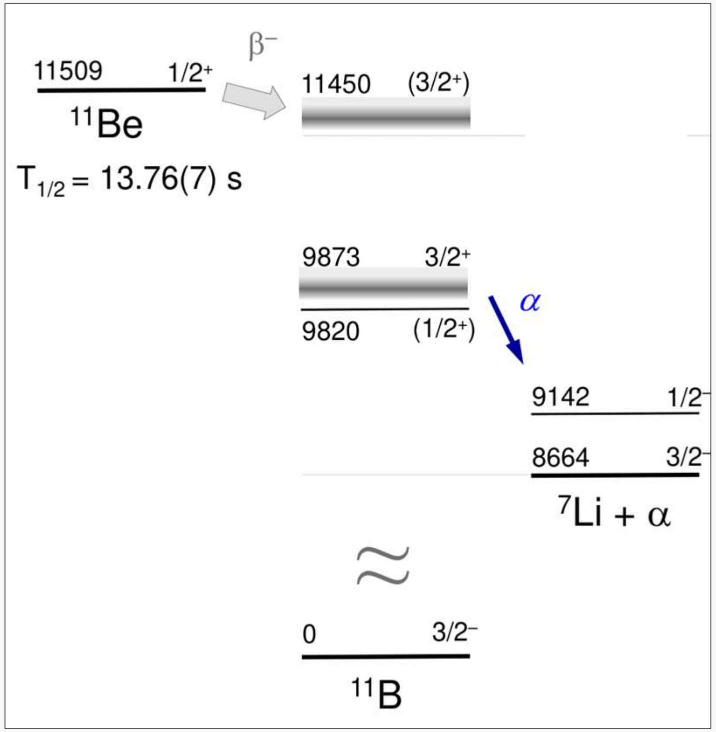
Refsgaard at al., PR C99, 044316 (2019)

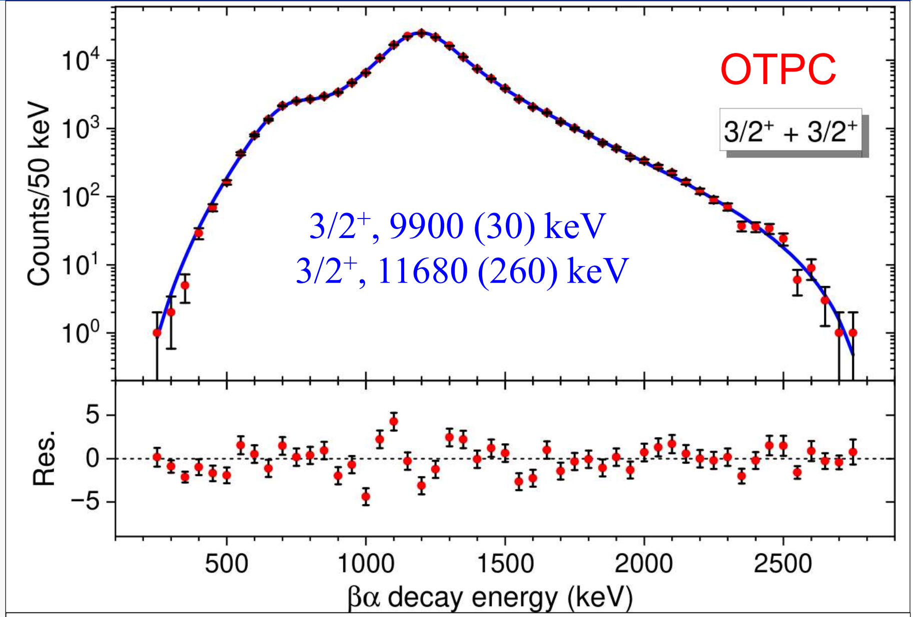


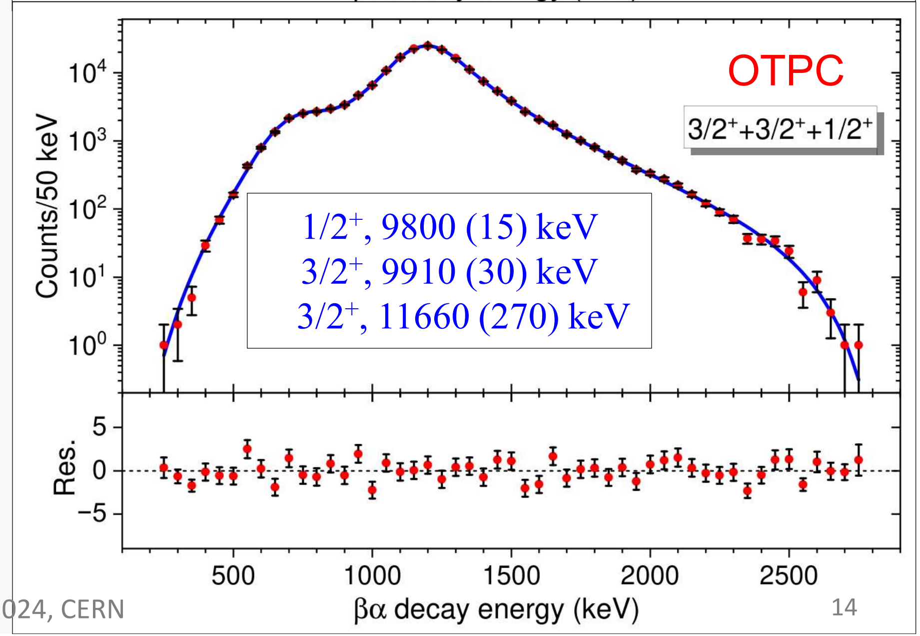


βα decay of ^{11}Be

- Experimental energy spectrum of 181 k βα events with best-fitted **R-matrix** description







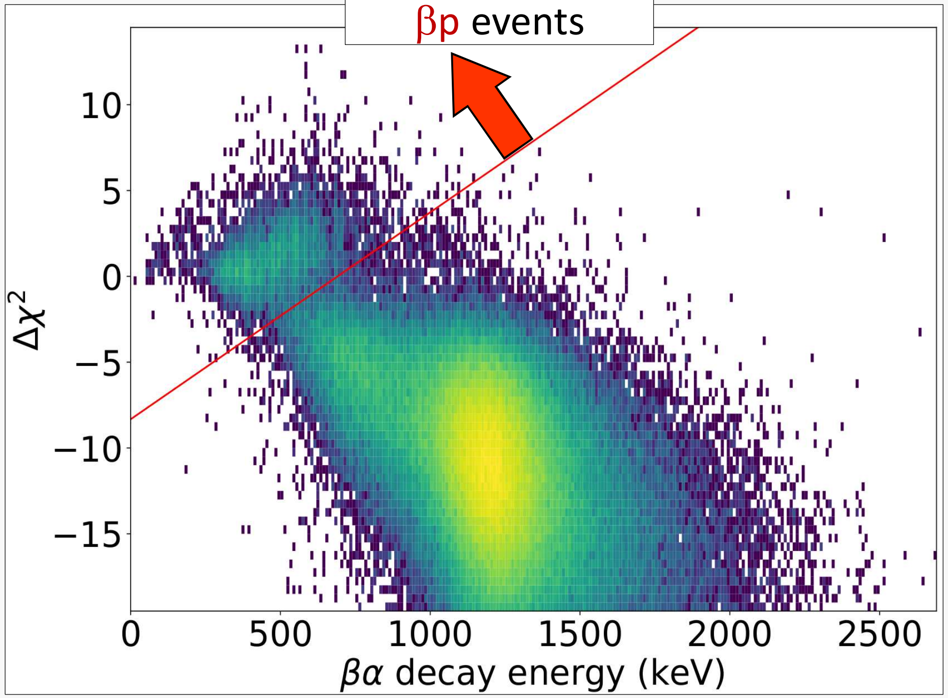
Search for βp emission

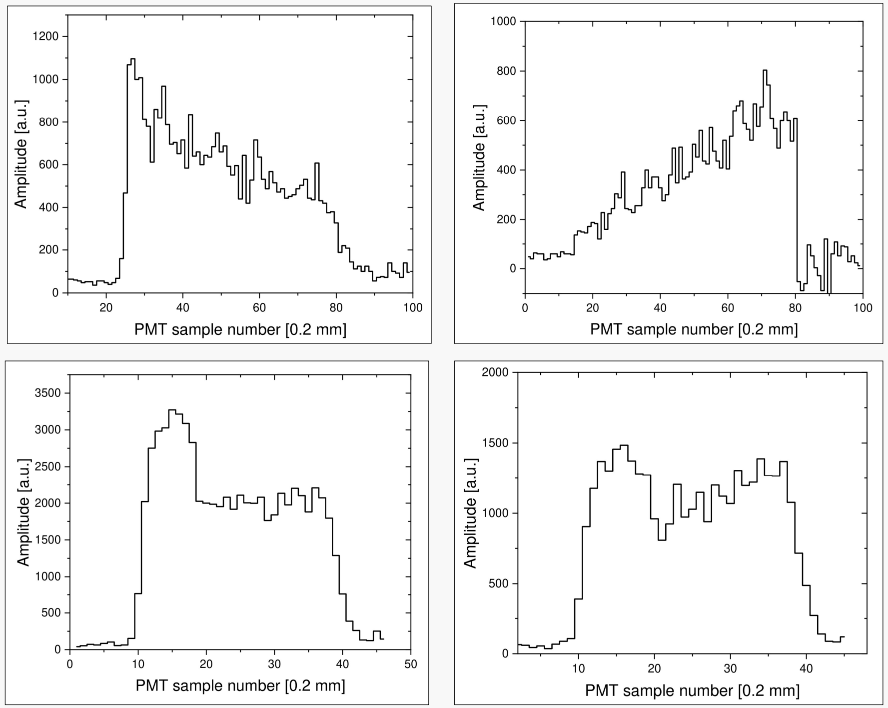
- Possible βp events are hidden in the *island* above the red line (≈3% of the total statistics)
- All these events were inspected visually

Most of them are clearly damaged

- particle hitting the cathode or GEM
- decay between GEMs
- drop of signal
- ...

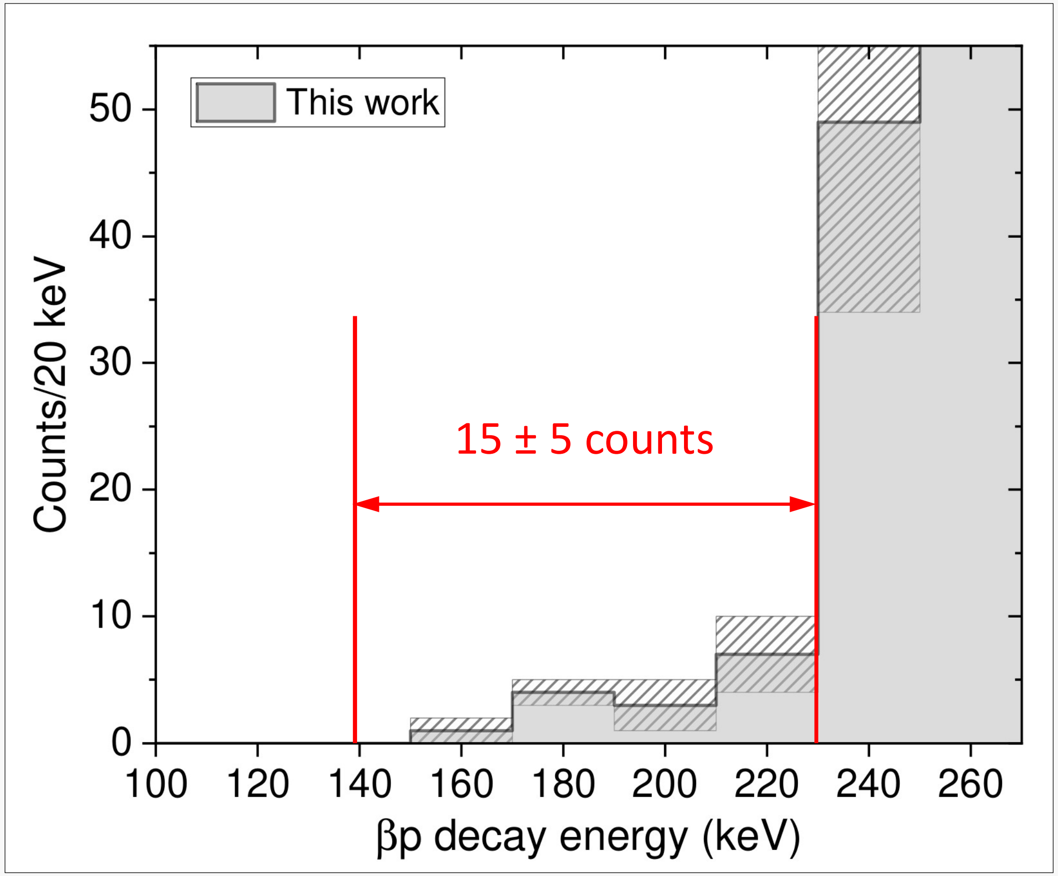
Here we look for βp events



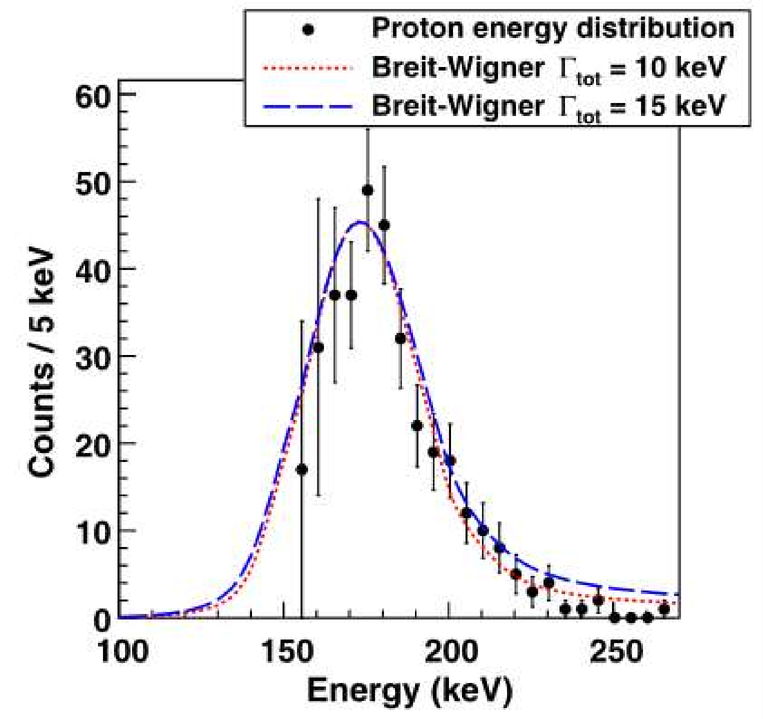


Spectrum of βp candidates

- From not discarded events, a spectrum of βp candidates was made
- The doubtful cases → systematical error



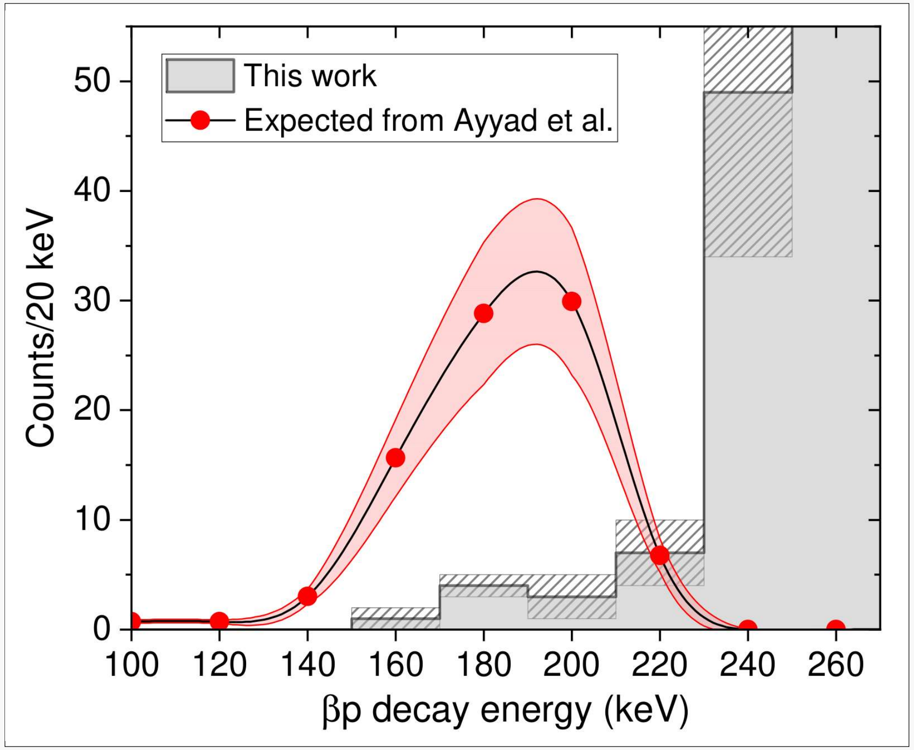
The βp branching limit



Ayyad at al., PRL 123, 082501 (2019)

$$E = 11425\ (20)\ \text{keV},$$
$$\Gamma = 12(5)\ \text{keV}, (1/2^{+}, 3/2^{+})$$

$$b_{\beta p} = 1.3\ (3) \cdot 10^{-5}$$



→ Branching limit for E < 230 keV:

$$\boldsymbol{b_{\beta p} < 2.2(6) \cdot 10^{-6}}$$

Further measurements are needed!

Summary

- $\beta\alpha$ spectrum, measured in the full energy range consistent with Refsgaard et al.

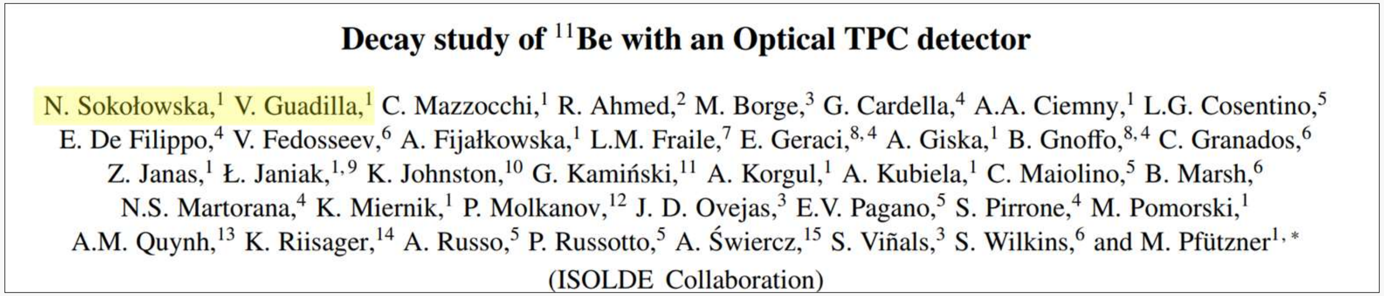
- R-matrix fit of $\beta\alpha$ spectrum improved by including $1/2^+$ state at 9.8 MeV in ^{11}B

- Limit for the βp decay of ^{11}Be for $E < 230$ keV :

  $$b_{\beta p} < (2.2 \pm 0.6_{sys} \pm 0.6_{stat})\ 10^{-6}$$

  → agrees with Riisager et al. (2020)
  contradicts Ayyad et al. (2019)

- We remeasured the branching ratio for $\beta\alpha$ decay of ^{11}Be at LNS Catania → $b_\alpha = 3.3(5)\%$



Decay study of ^{11}Be with an Optical TPC detector

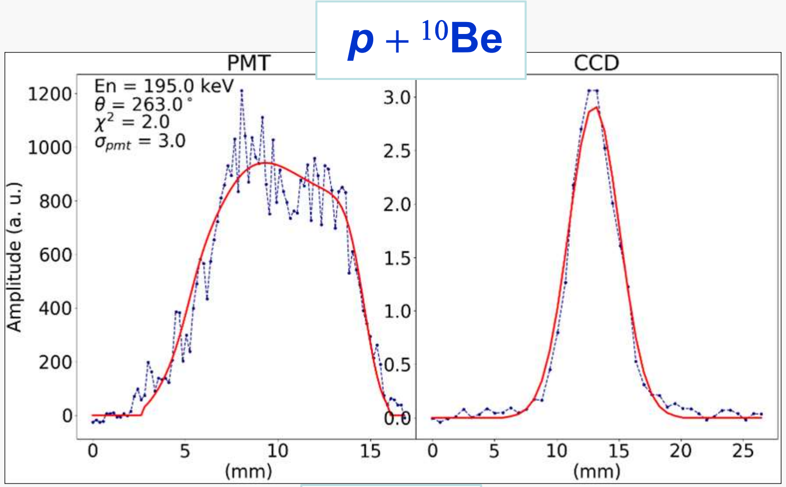
N. Sokołowska,[1] V. Guadilla,[1] C. Mazzocchi,[1] R. Ahmed,[2] M. Borge,[3] G. Cardella,[4] A.A. Ciemny,[1] L.G. Cosentino,[5] E. De Filippo,[4] V. Fedosseev,[6] A. Fijałkowska,[1] L.M. Fraile,[7] E. Geraci,[8,4] A. Giska,[1] B. Gnoffo,[8,4] C. Granados,[6] Z. Janas,[1] Ł. Janiak,[1,9] K. Johnston,[10] G. Kamiński,[11] A. Korgul,[1] A. Kubiela,[1] C. Maiolino,[5] B. Marsh,[6] N.S. Martorana,[4] K. Miernik,[1] P. Molkanov,[12] J. D. Ovejas,[3] E.V. Pagano,[5] S. Pirrone,[4] M. Pomorski,[1] A.M. Quynh,[13] K. Riisager,[14] A. Russo,[5] P. Russotto,[5] A. Świercz,[15] S. Viñals,[3] S. Wilkins,[6] and M. Pfützner[1,*]
(ISOLDE Collaboration)

N. Sokołowska et al., Phys. Rev. C 110, 034328 (2024)

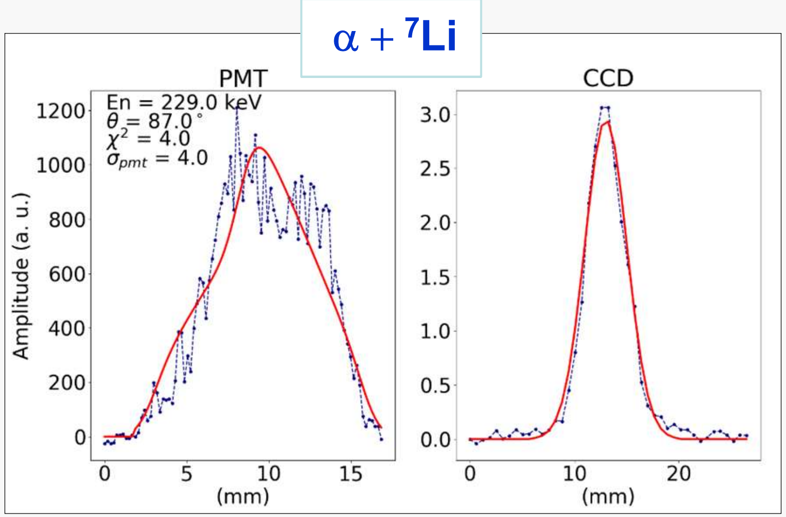
Thank you!

Two βp candidates

- Here βp scenario fits better than βα

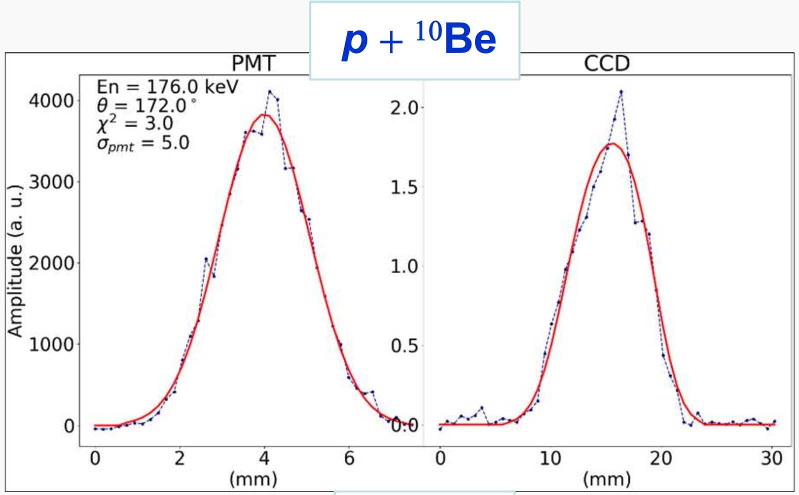


$p + {}^{10}$Be

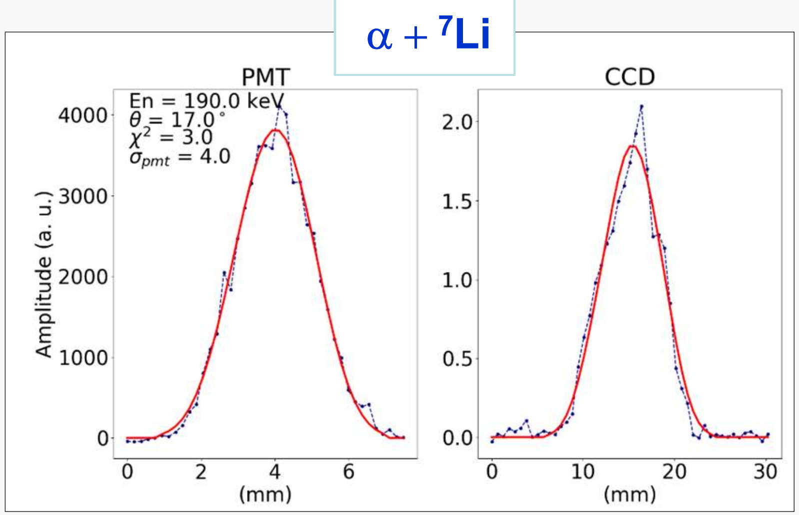


$\alpha + {}^{7}$Li

- Here two scenarios fit equally well



$p + {}^{10}$Be



$\alpha + {}^{7}$Li

Experiment @ LNS (Catania)

- Fragmentation reaction:

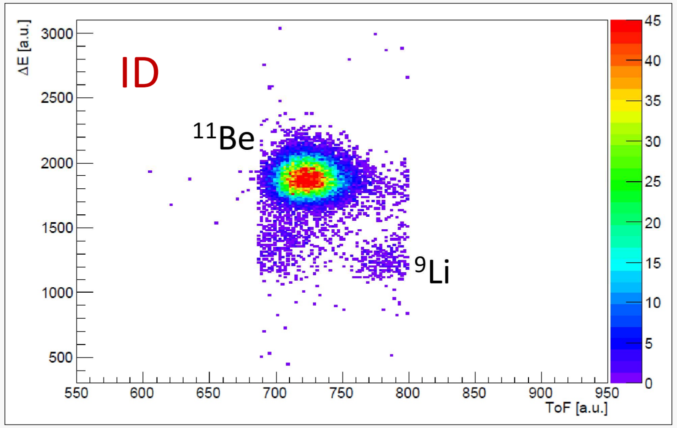
  ^{13}C @ 55 MeV/u + Be → ^{11}Be

  and in-flight identification of single ions

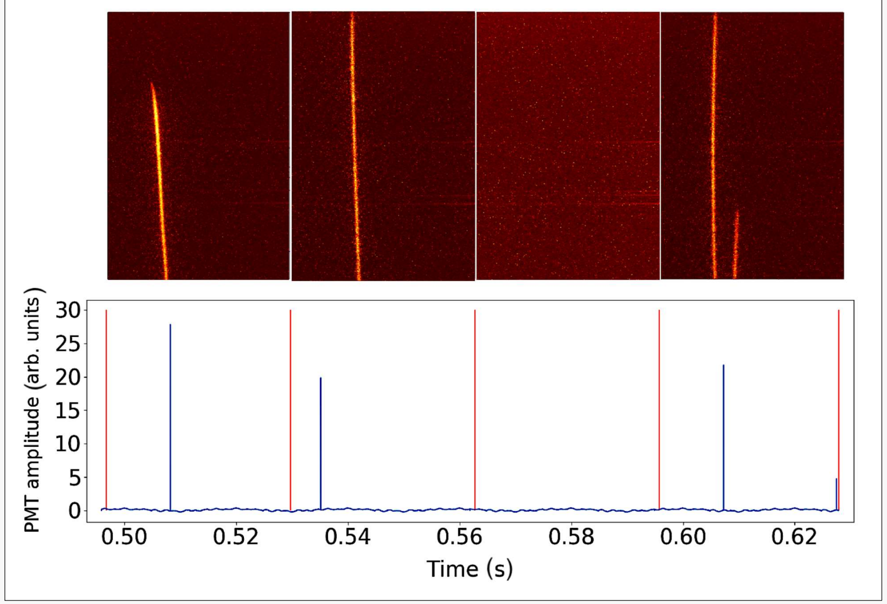
- Probability of stopping inside OTPC: 19(3)%

- ≈ 1800 βα events observed

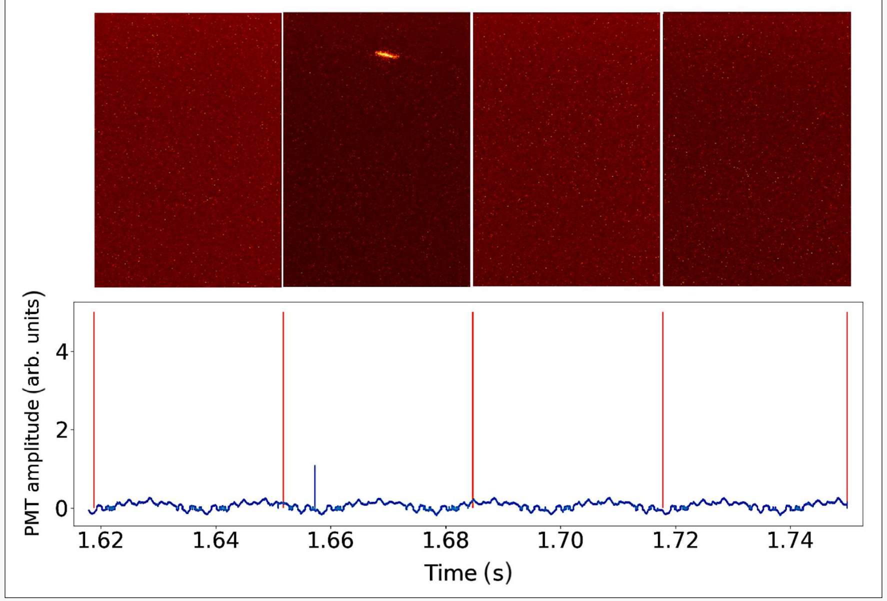
  → branching ratio: b_α = 3.3(5)%,



Counting stopped ions



Counting decays



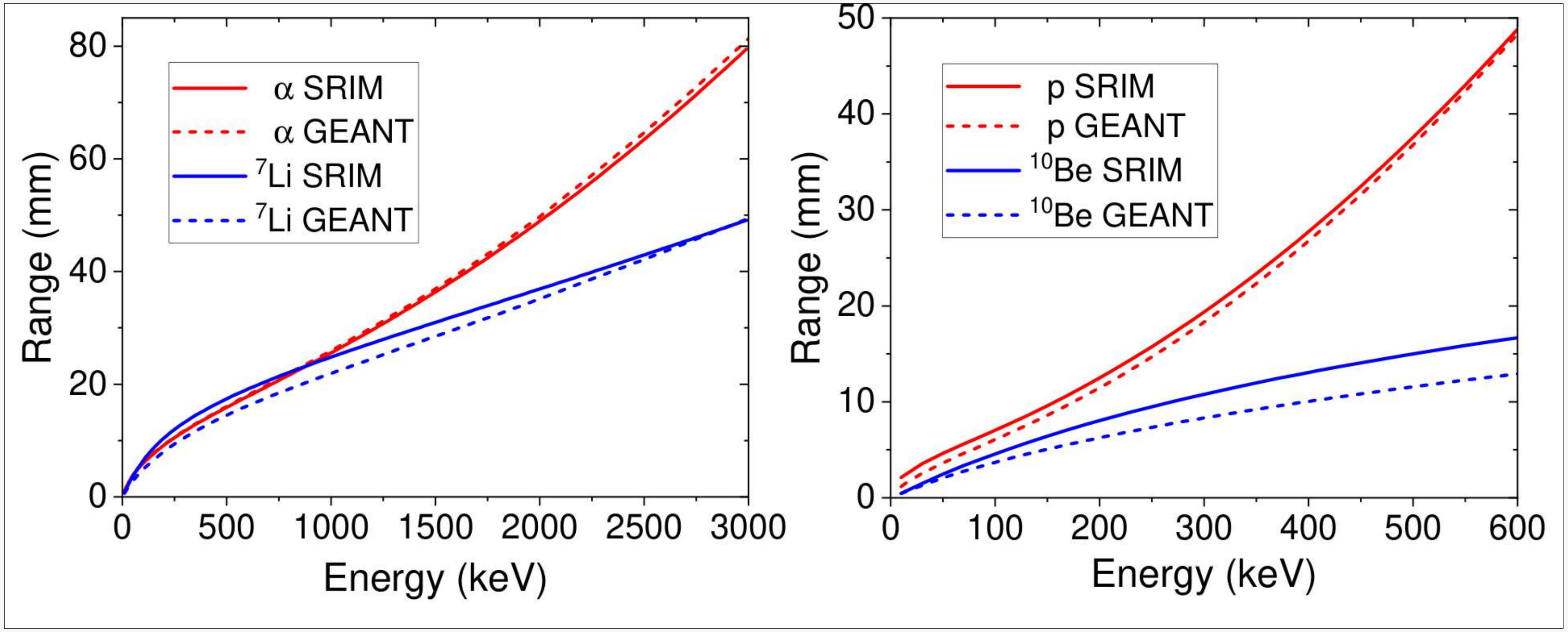
Two dE/dx models

- We used GEANT4 to simulate realistic decay events.

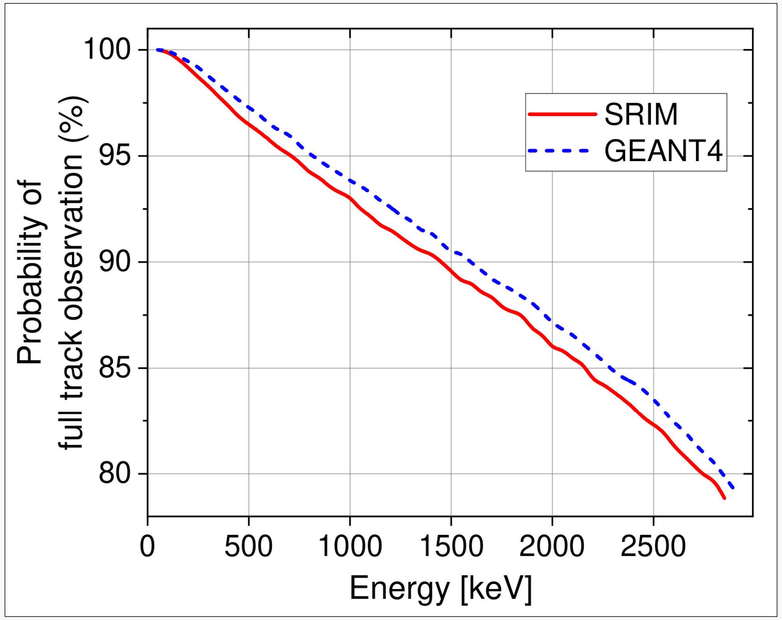
  However, GEANT used a different dE/dx model.

  → All event reconstruction was done with both of them

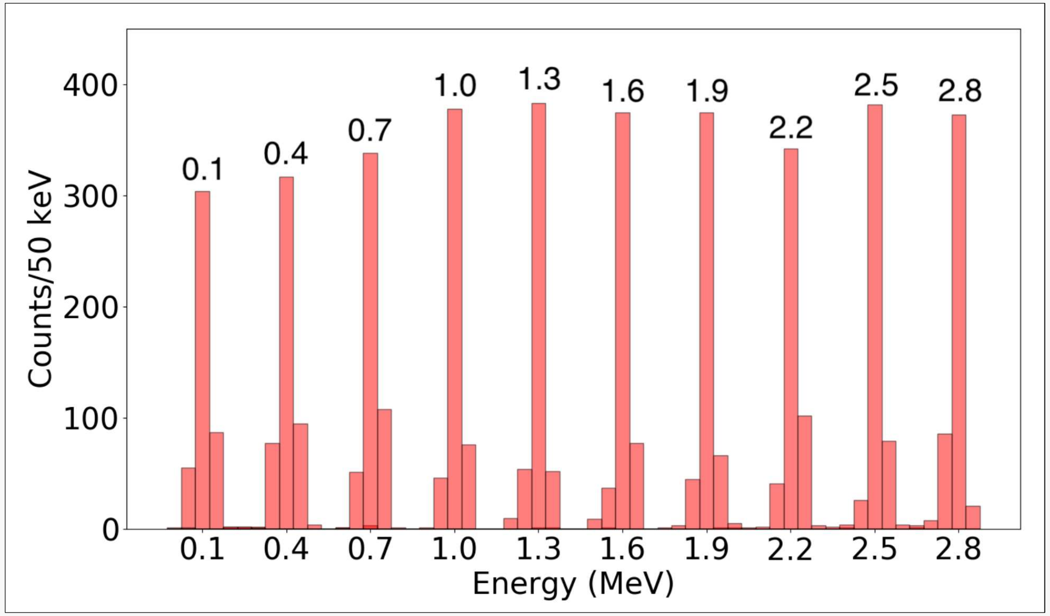
  → Results were consistent with each other but SRIM was found a bit better

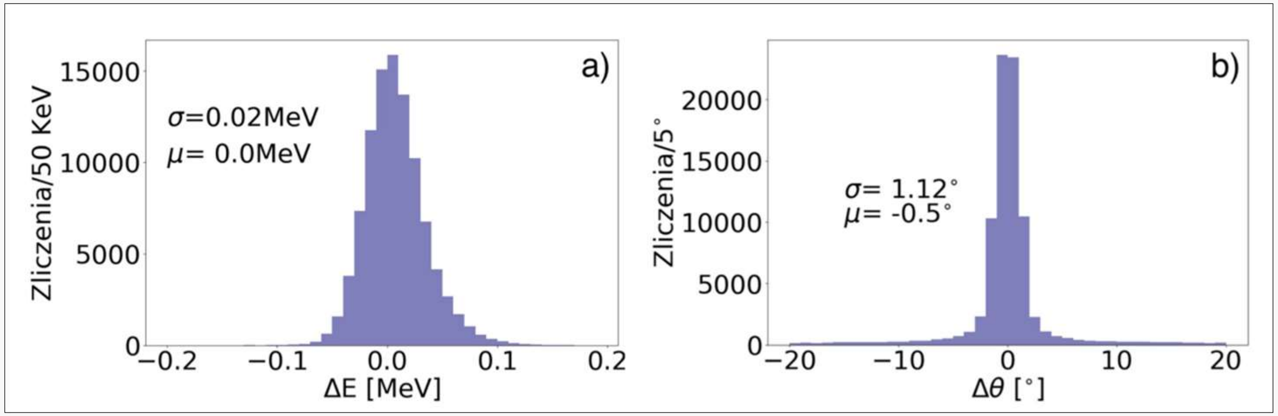


Efficiencies

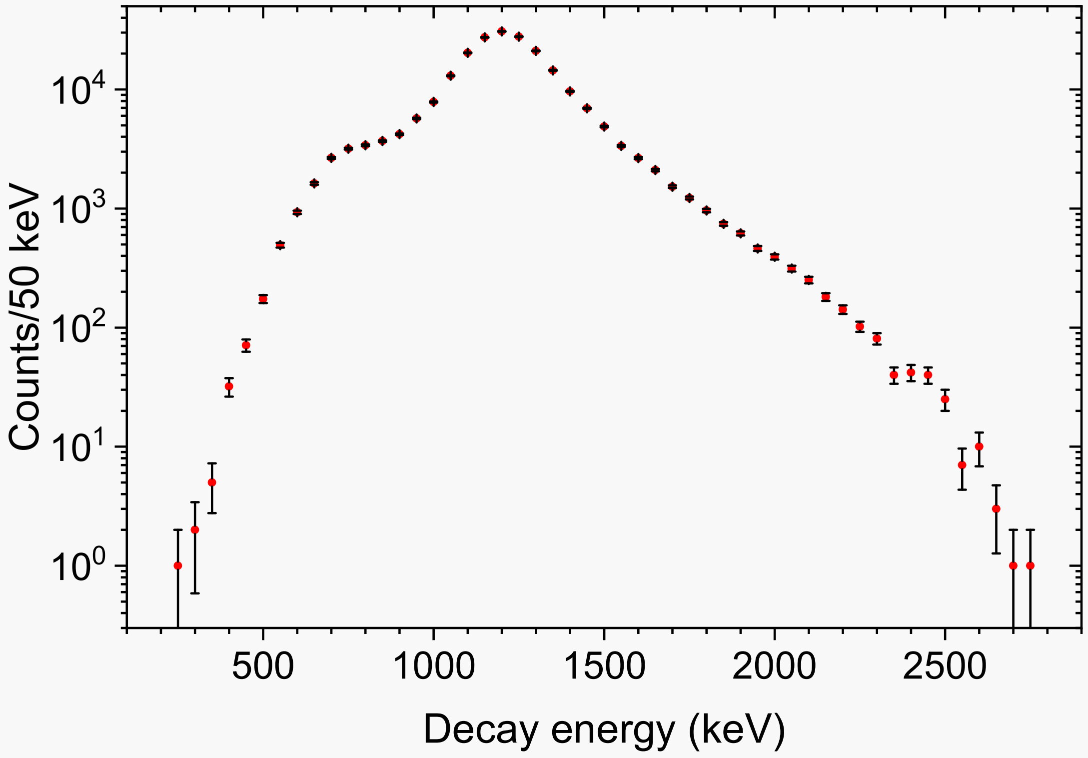


Reconstruction of simulated monoenergetic events

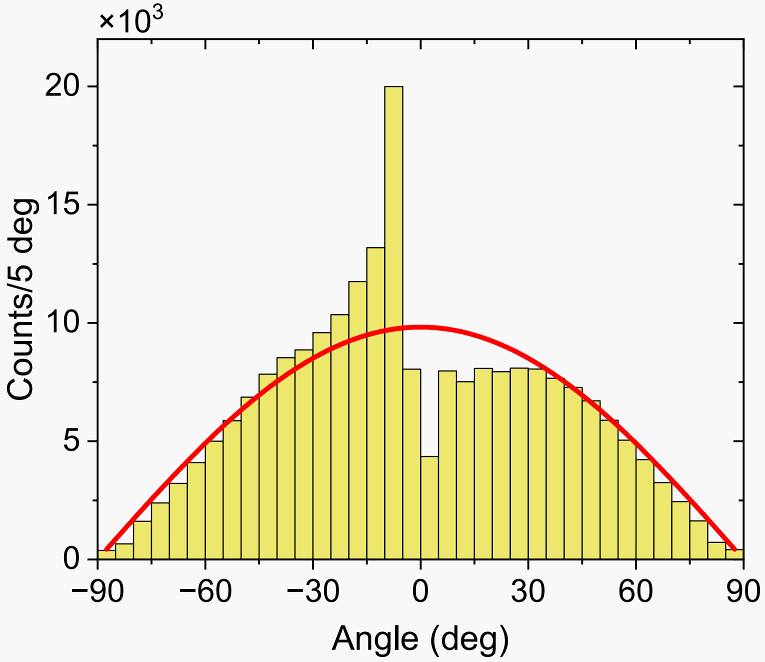




Experimental βα spectrum



Angle of α wrt horizontal plane



R-matrix

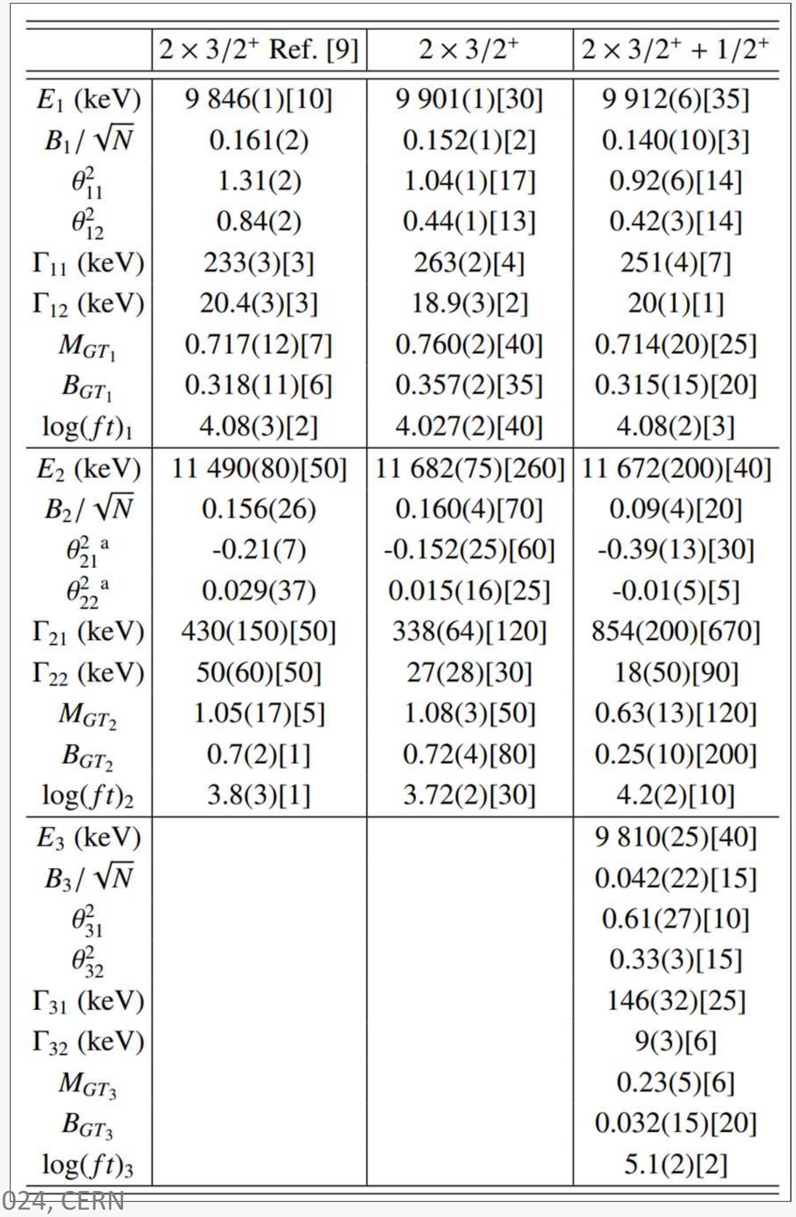
$$N(E) = \sum_c N_c(E),$$

$$N_c(E) = f_\beta P_c \left| \sum_{\lambda\mu} B_\lambda \gamma_{\lambda c} A_{\lambda\mu} \right|^2,$$

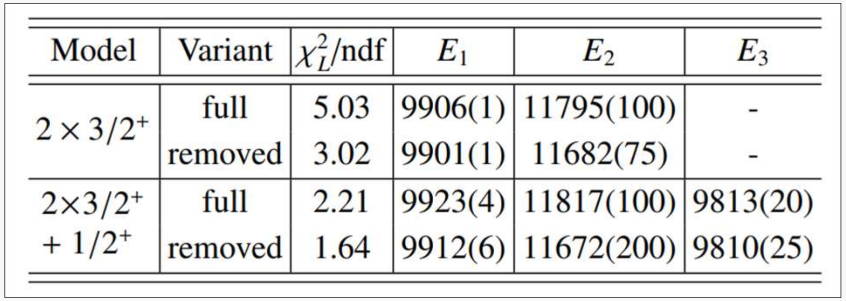
$$\Gamma_\lambda = \sum_c \Gamma_{\lambda c},$$

$$\Gamma_{\lambda c} = \frac{2P_c\gamma^2_{\lambda c}}{1 + \sum_c \gamma^2_{\lambda c} \frac{dS_c}{dE}\Big|_{E_\lambda}},$$

$$M_{GT,\lambda} = \left(\frac{\pi D}{N t_{1/2}}\right)^{\frac{1}{2}} \left(1 + \sum_c \gamma^2_{\lambda c} \frac{dS_c}{dE}\Big|_{E_\lambda}\right)^{-\frac{1}{2}} B_\lambda,$$



	$2 \times 3/2^+$ Ref. [9]	$2 \times 3/2^+$	$2 \times 3/2^+ + 1/2^+$
E_1 (keV)	9 846(1)[10]	9 901(1)[30]	9 912(6)[35]
$B_1/\sqrt{N}$	0.161(2)	0.152(1)[2]	0.140(10)[3]
θ^2_{11}	1.31(2)	1.04(1)[17]	0.92(6)[14]
θ^2_{12}	0.84(2)	0.44(1)[13]	0.42(3)[14]
Γ_{11} (keV)	233(3)[3]	263(2)[4]	251(4)[7]
Γ_{12} (keV)	20.4(3)[3]	18.9(3)[2]	20(1)[1]
M_{GT_1}	0.717(12)[7]	0.760(2)[40]	0.714(20)[25]
B_{GT_1}	0.318(11)[6]	0.357(2)[35]	0.315(15)[20]
$\log(ft)_1$	4.08(3)[2]	4.027(2)[40]	4.08(2)[3]
E_2 (keV)	11 490(80)[50]	11 682(75)[260]	11 672(200)[40]
$B_2/\sqrt{N}$	0.156(26)	0.160(4)[70]	0.09(4)[20]
θ^2_{21} ^{a}	-0.21(7)	-0.152(25)[60]	-0.39(13)[30]
θ^2_{22} ^{a}	0.029(37)	0.015(16)[25]	-0.01(5)[5]
Γ_{21} (keV)	430(150)[50]	338(64)[120]	854(200)[670]
Γ_{22} (keV)	50(60)[50]	27(28)[30]	18(50)[90]
M_{GT_2}	1.05(17)[5]	1.08(3)[50]	0.63(13)[120]
B_{GT_2}	0.7(2)[1]	0.72(4)[80]	0.25(10)[200]
$\log(ft)_2$	3.8(3)[1]	3.72(2)[30]	4.2(2)[10]
E_3 (keV)			9 810(25)[40]
$B_3/\sqrt{N}$			0.042(22)[15]
θ^2_{31}			0.61(27)[10]
θ^2_{32}			0.33(3)[15]
Γ_{31} (keV)			146(32)[25]
Γ_{32} (keV)			9(3)[6]
M_{GT_3}			0.23(5)[6]
B_{GT_3}			0.032(15)[20]
$\log(ft)_3$			5.1(2)[2]



Model	Variant	χ^2_L/ndf	E_1	E_2	E_3
$2 \times 3/2^+$	full	5.03	9906(1)	11795(100)	-
	removed	3.02	9901(1)	11682(75)	-
$2\times3/2^+ + 1/2^+$	full	2.21	9923(4)	11817(100)	9813(20)
	removed	1.64	9912(6)	11672(200)	9810(25)

SRIM predictions

- SRIM package used to predict expected profiles of energy deposit
- Two decay scenarios considered:

^{11}Be* → ^{7}Li + α

1200 keV, 30°

^{11}Be* → ^{10}Be + p

200 keV, 30°