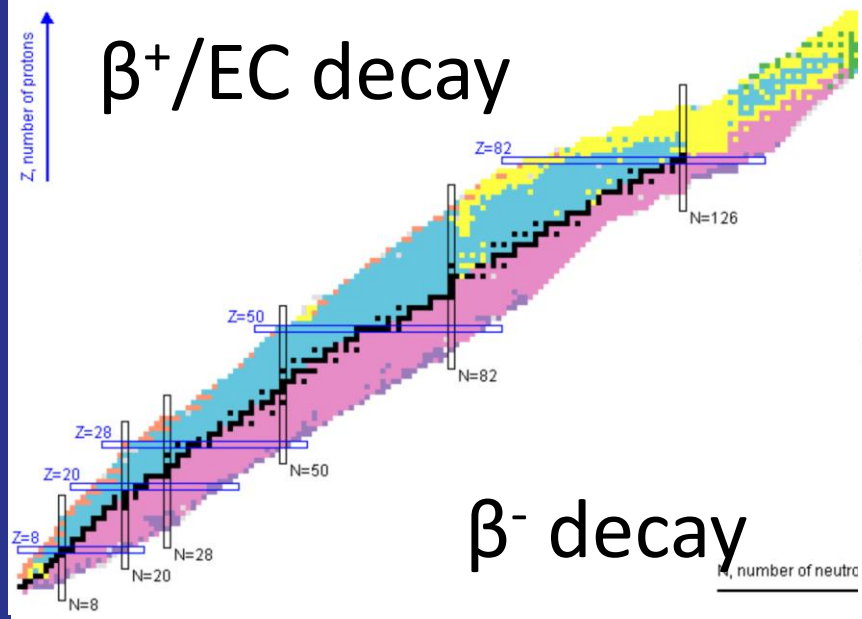
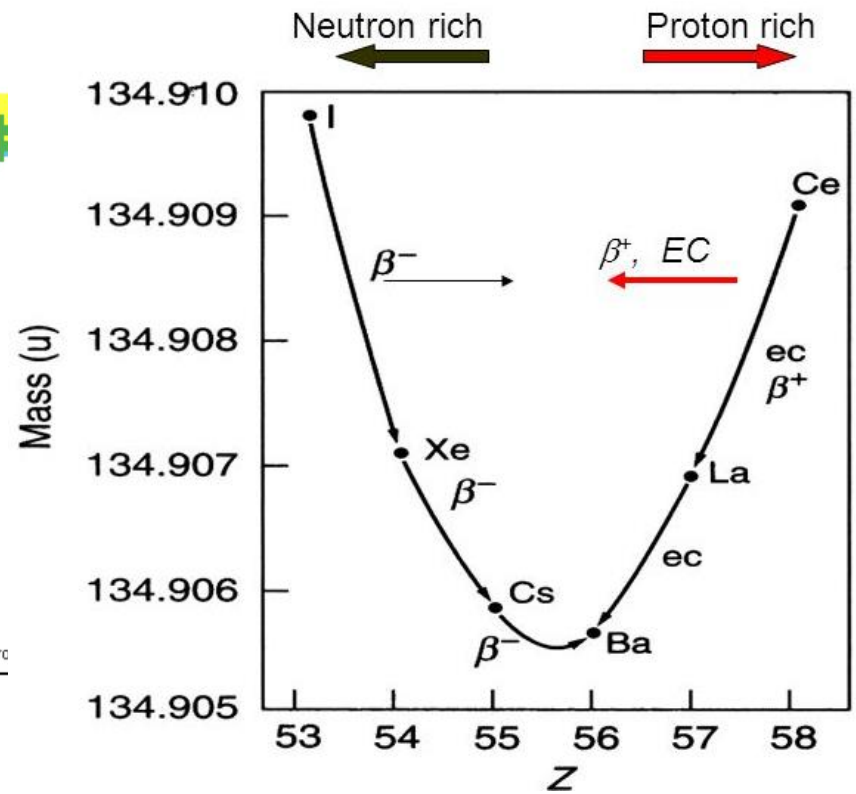
^{11}Be: the neutron-rich nucleus that could emit protons

Bruno Olaizola
CERN

ISOLDE Seminar – 2 August 2022

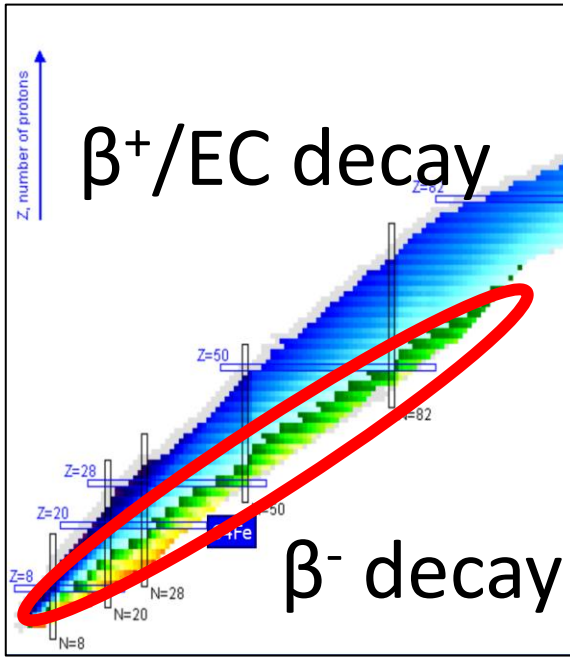
Nuclear mass parabola

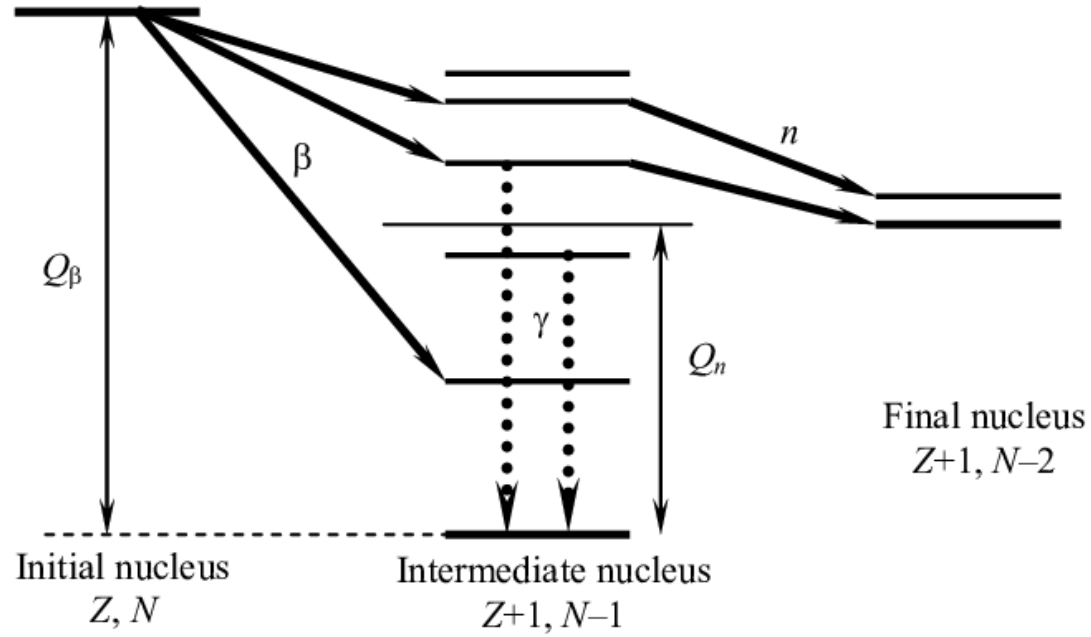




Particle emission

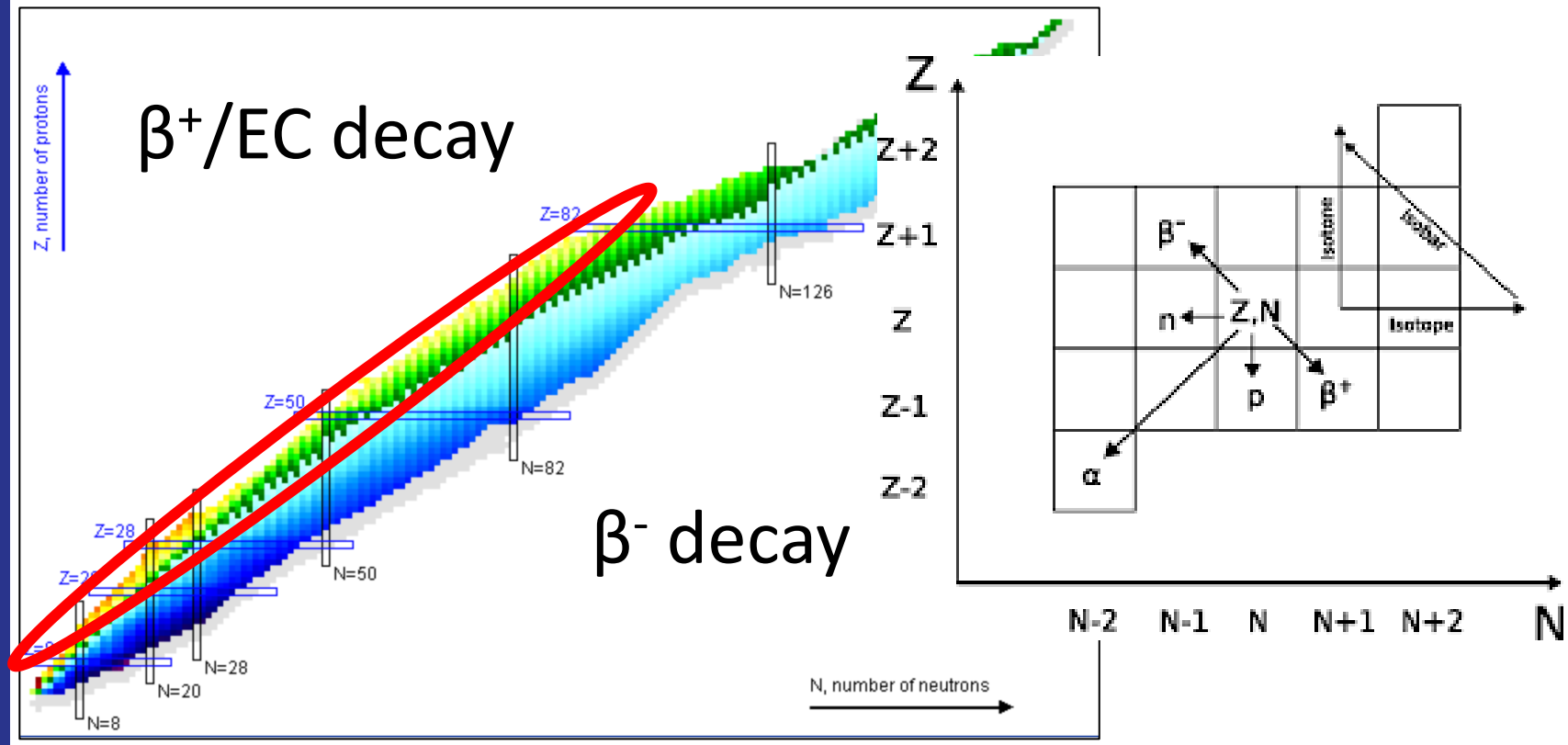
Neutron emission





Particle emission

Proton emission

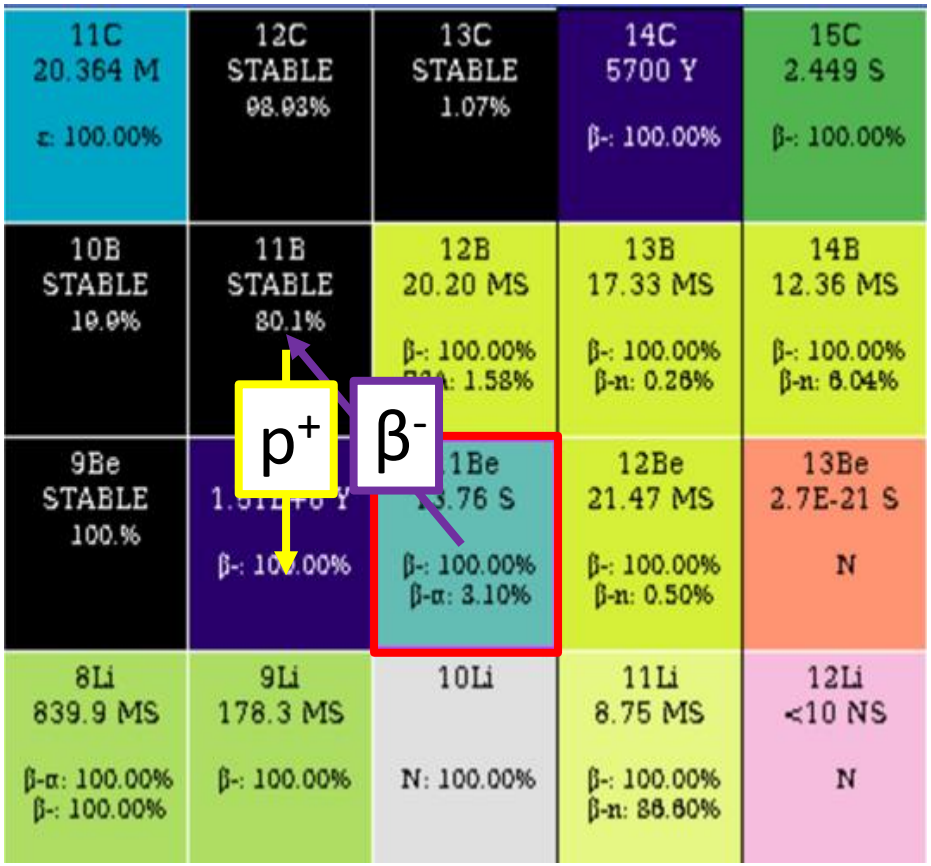


β⁻ delayed proton emission

- Proton emission and β⁻ decay seem opposite processes
- If neutron binding energy of the nucleus satisfies:

$$S_n < (m_n - m_p - m_e)c^2 \approx 782\ keV$$

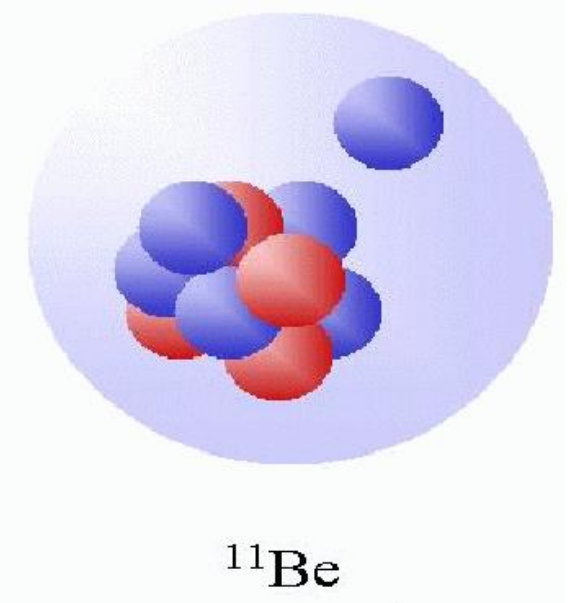
- β⁻-delayed proton emission (β⁻p) is energetically allowed

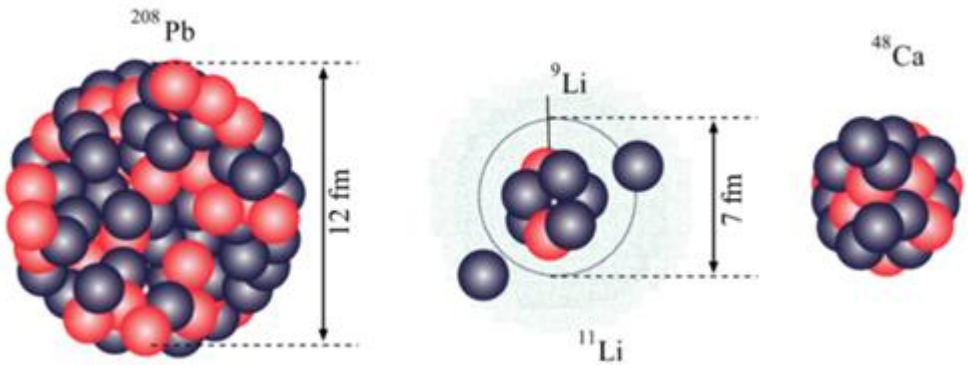


Pfutzner, Rev. Mod. Phy. **84**, (2012)

β⁻-delayed proton emission

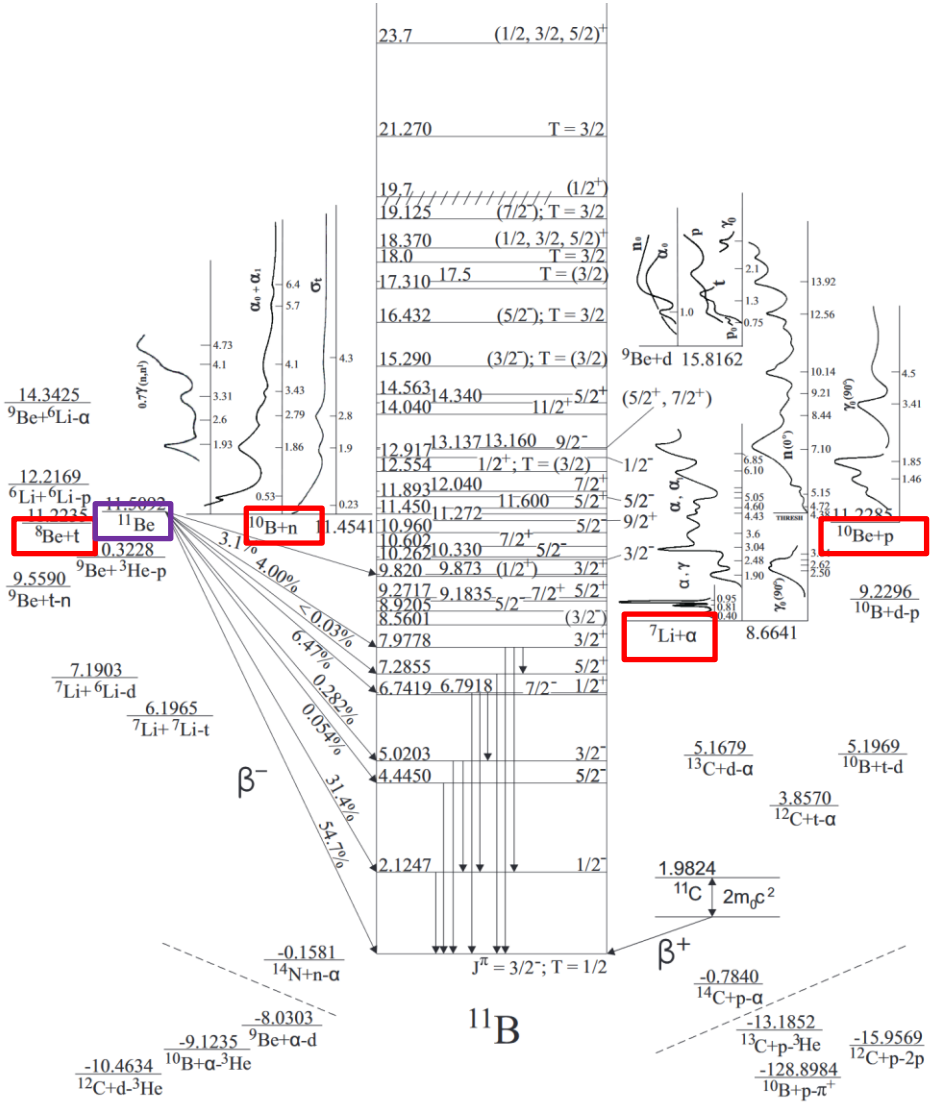
- Only ^{11}Be and ^{19}C (and maybe ^{31}Ne) satisfy this condition
- Such loosely bound neutrons are only found in halo nuclei
- Wave functions of the halo neutron and core can be treated independently



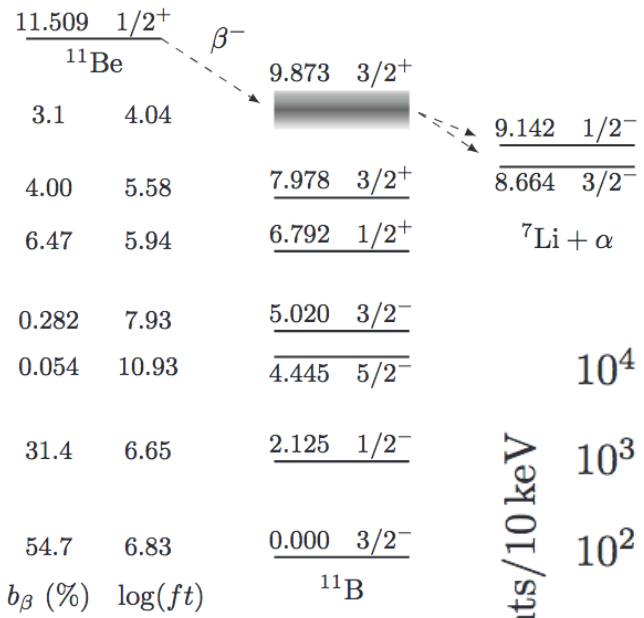


Riisager, Phys. Scr. **T152,** 014001 (2013)

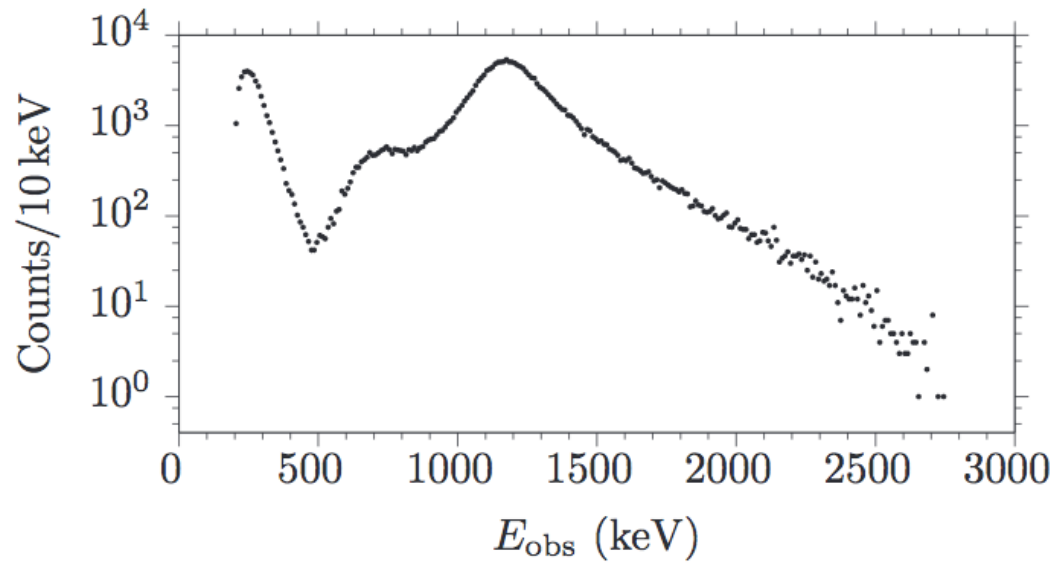
^{11}Be beta decay



β⁻ delayed alpha emission



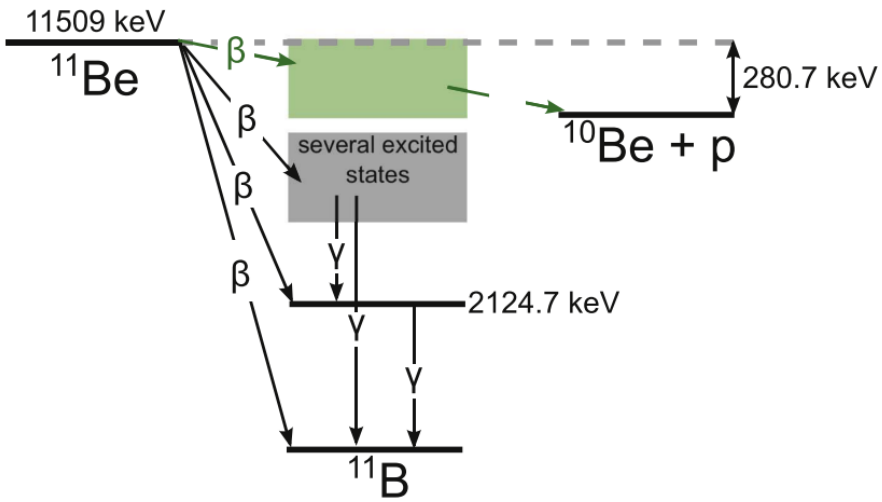
b_α=3.3(1)%

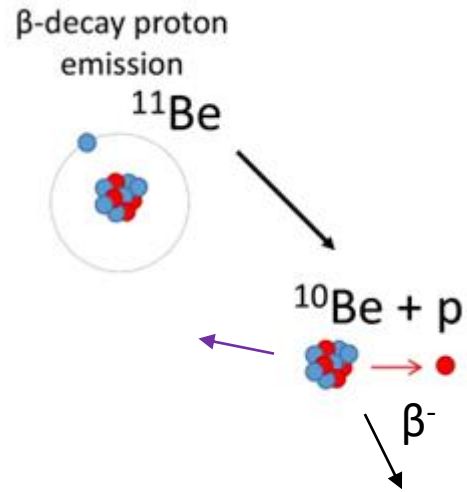


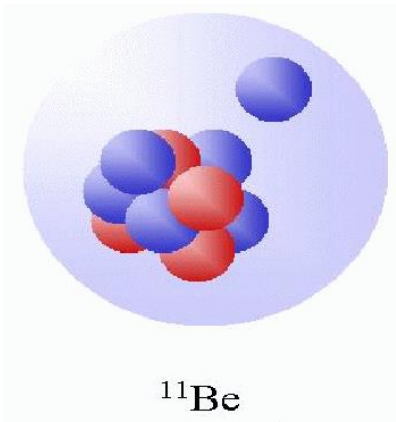
J. Refsgaard, J. Büscher, A. Arokiaraj, H. O. U. Fynbo, R. Raabe, and K. Riisager

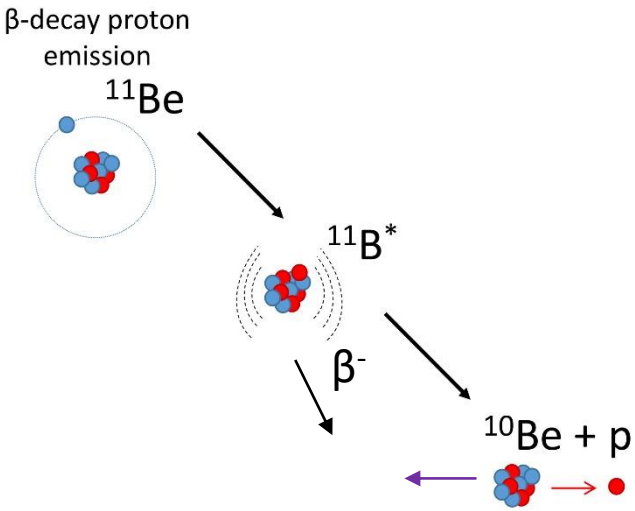
Phys. Rev. C 99, 044316 – Published 25 April 2019

β⁻ delayed proton emission







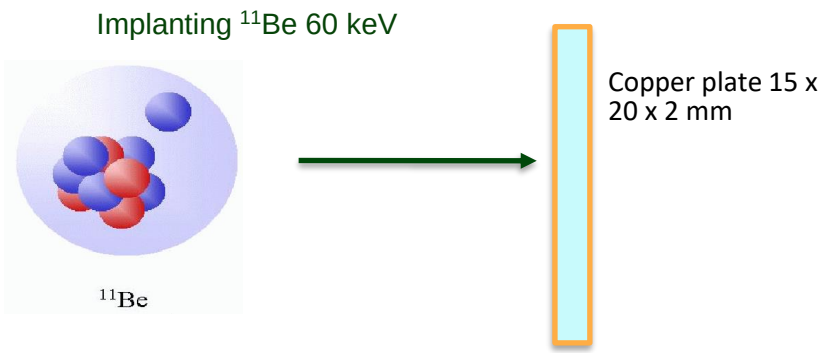


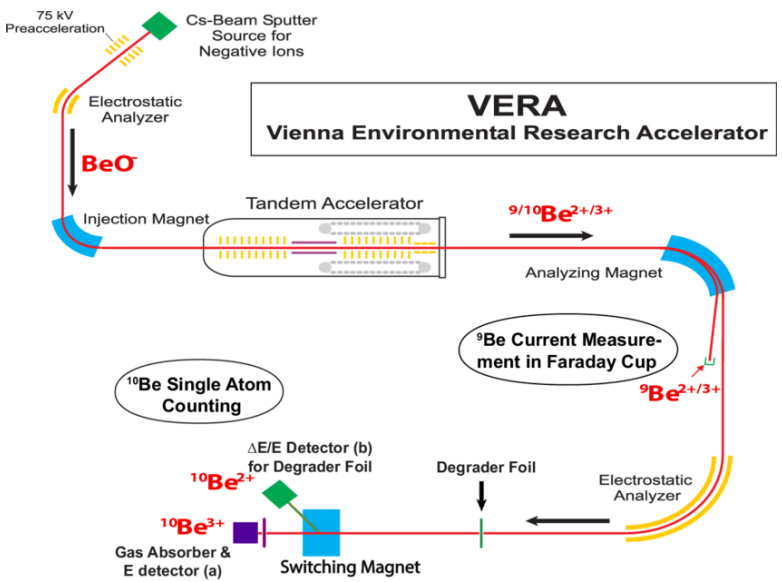
Borge and B Jonson J. Phys. G: Nucl. Part. Phys. 44 (2017) 044011

https://msutoday.msu.edu/news/2022/halos-and-dark-matter

First attempt

- Riisager et al. implanted ^{11}Be in a catcher and let it decay
- Then analyzed the ratio of ^{10}Be/ ^{11}B in the catcher with the accelerator mass spectrometry technique
- ^{11}Be -> ^{10}Be branching ratio was $8.3(9)\cdot10^{-6}$
- This value is orders of magnitude higher than theoretical predictions



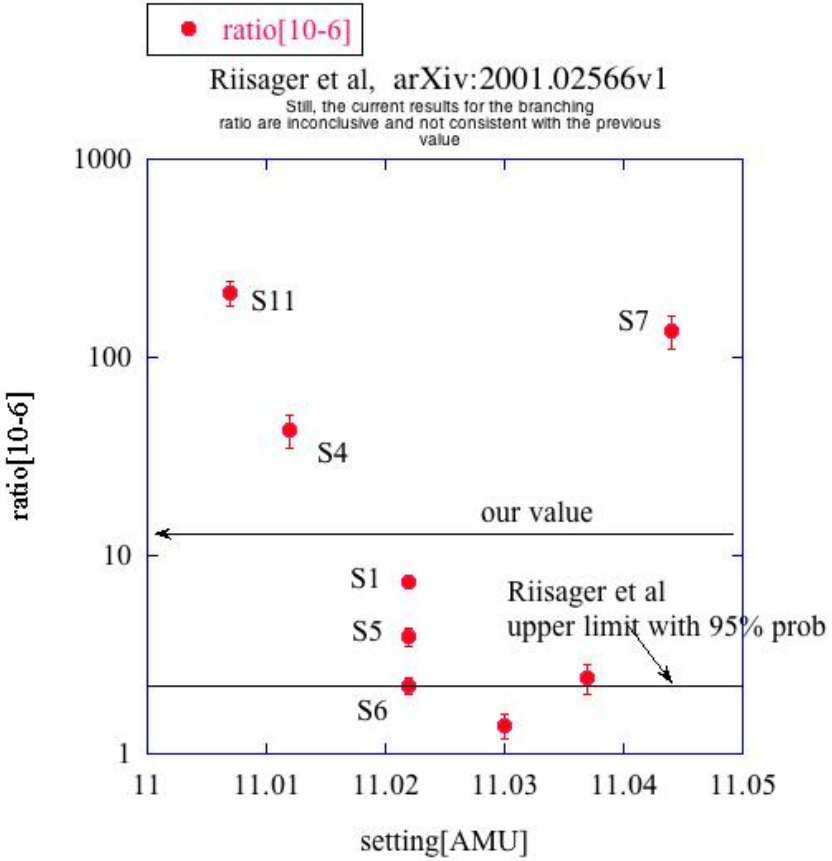


Riisager, PLB **732** 305 (2014)

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

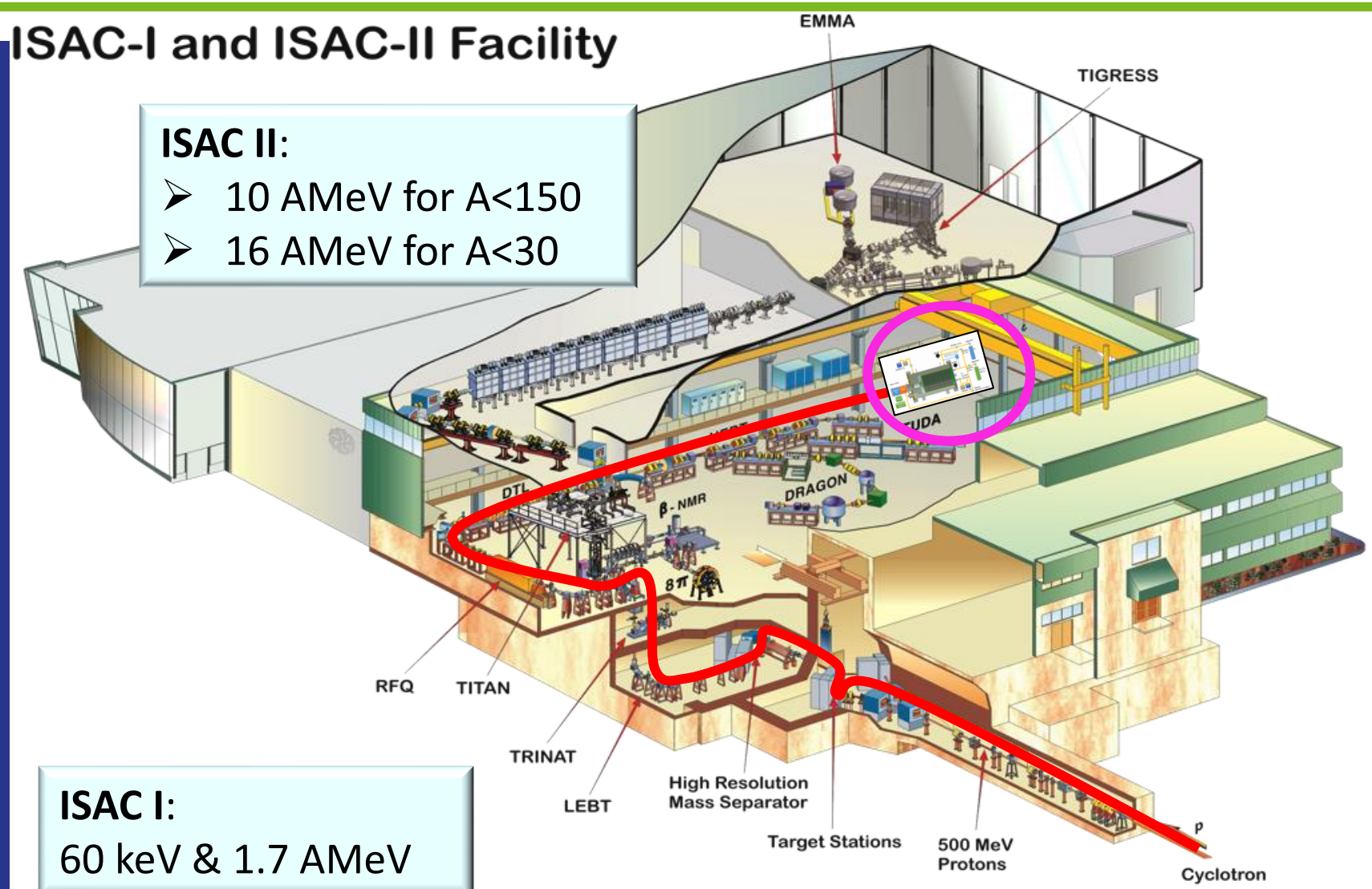
Second attempt

- Riisager et al repeated the experiment with a much larger number of samples
- No agreement
- Hypothesized the presence of ^{10}Be in catcher is from molecular ^{10}BeH
- Give a much lower upper limit of $<2.2\cdot10^{-6}$



Riisager Eur. Phys. J. A (2020) 56 :100

Experiment at TRIUMF



ISAC II:

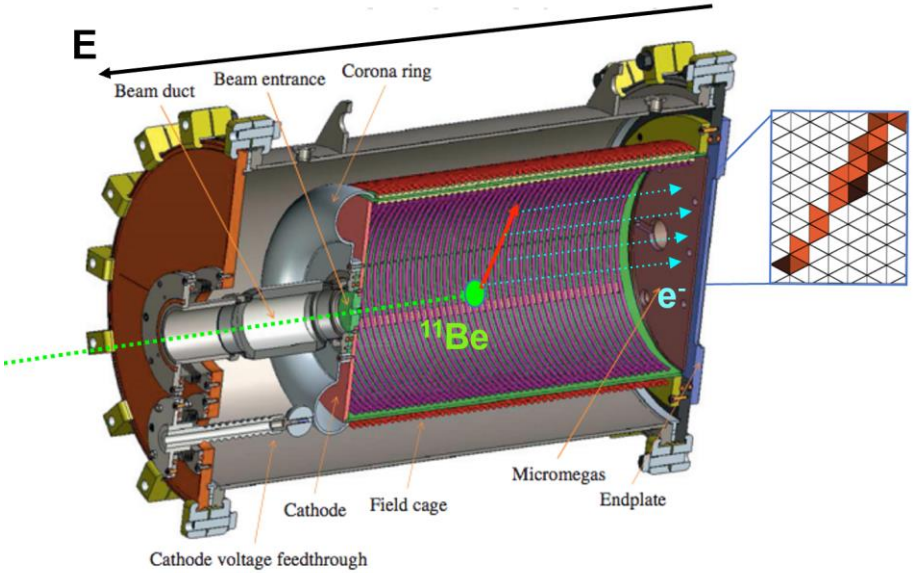
- 10 AMeV for A<150
- 16 AMeV for A<30

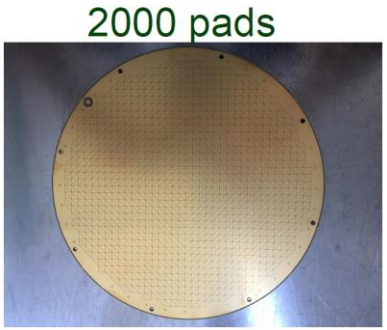
ISAC I:

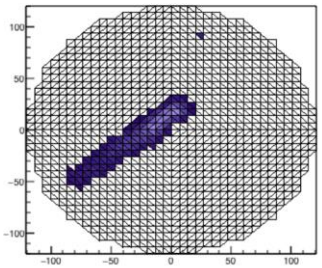
60 keV & 1.7 AMeV

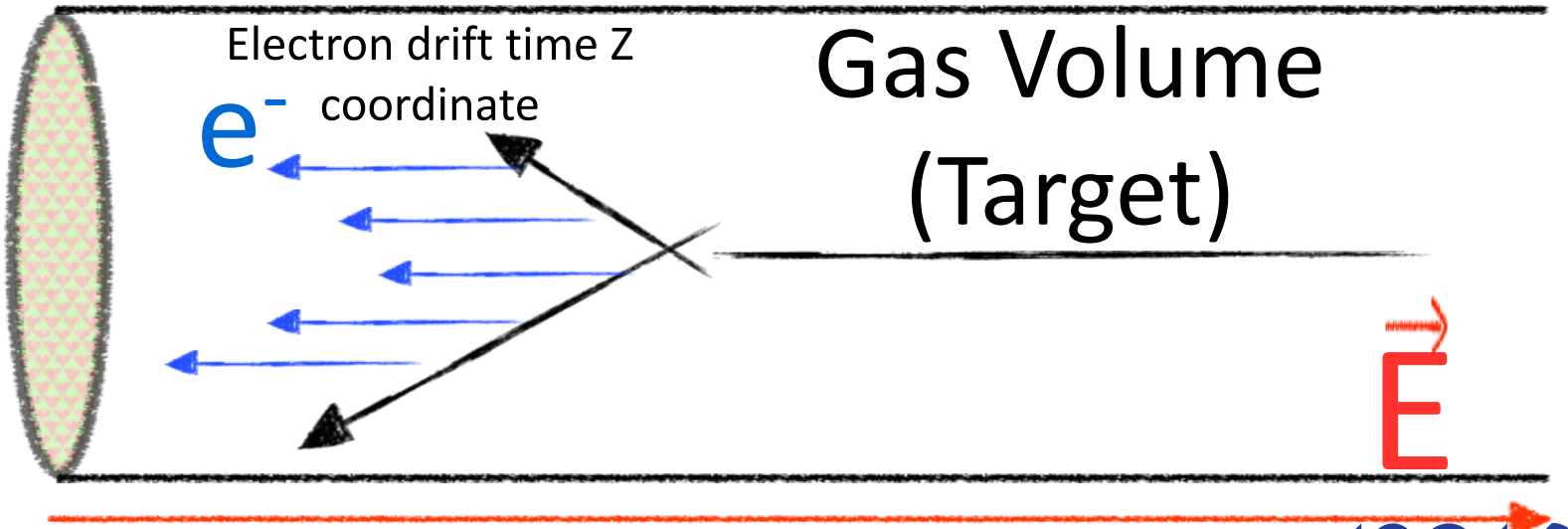
TRIUMF

pAT-TPC

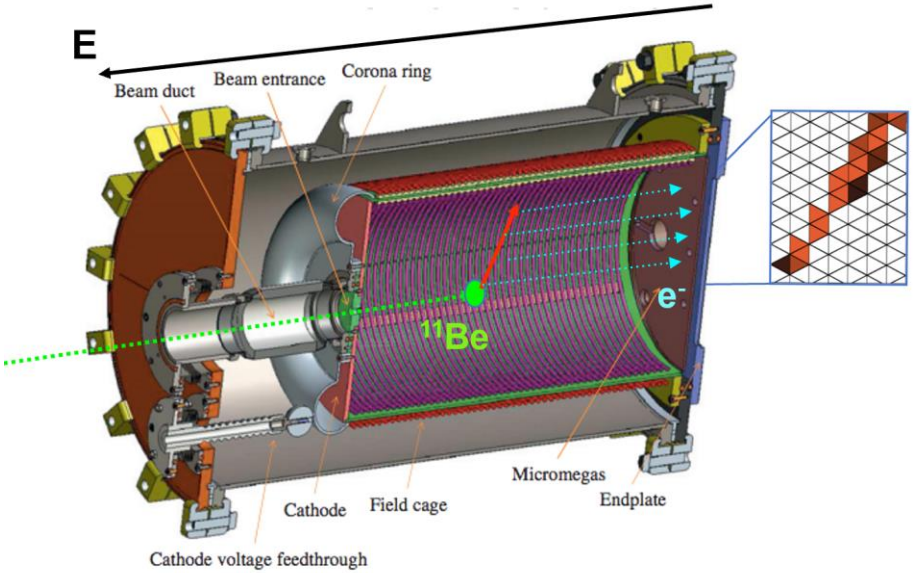

E
Beam duct
Beam entrance
Corona ring
^{11}Be
e-
Micromegas
Endplate
Cathode
Field cage
Cathode voltage feedthrough


2000 pads




Electron drift time Z coordinate
e-
Gas Volume (Target)
E

~~pAT~~-TPC


E
Beam duct
Beam entrance
Corona ring
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Micromegas
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Field cage
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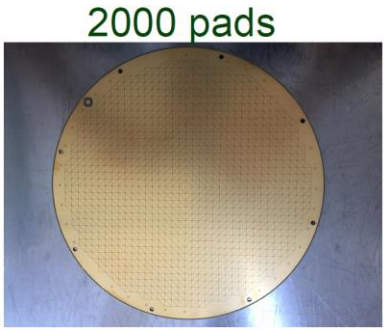
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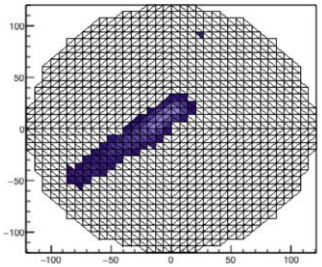
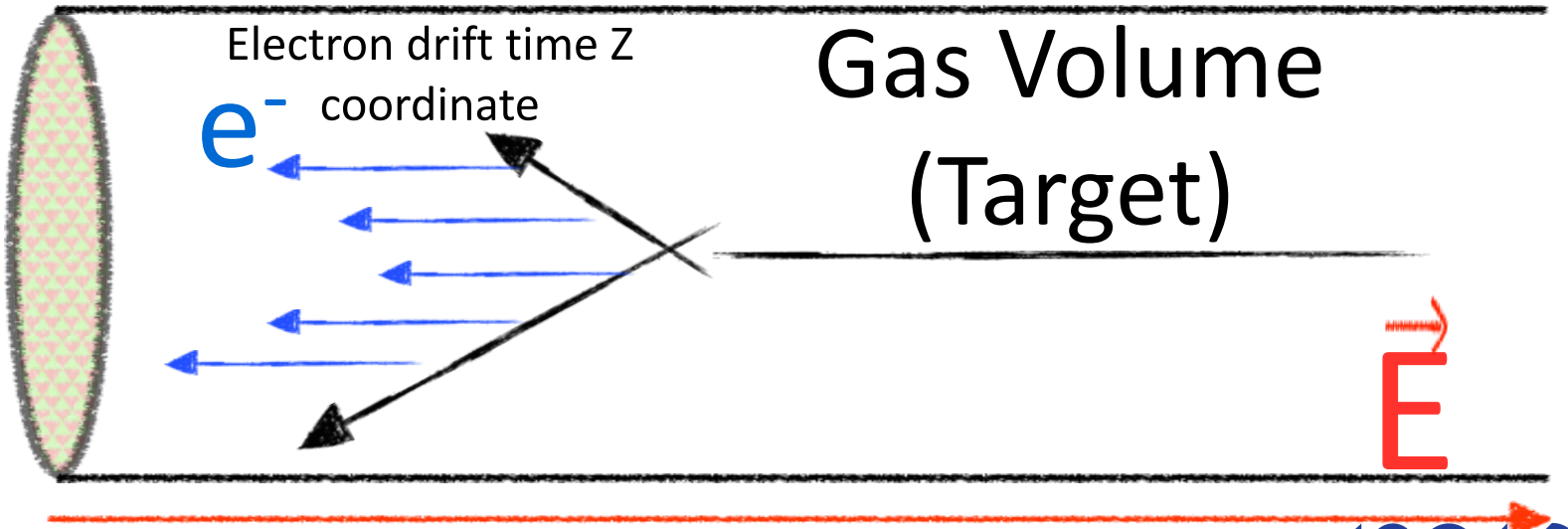
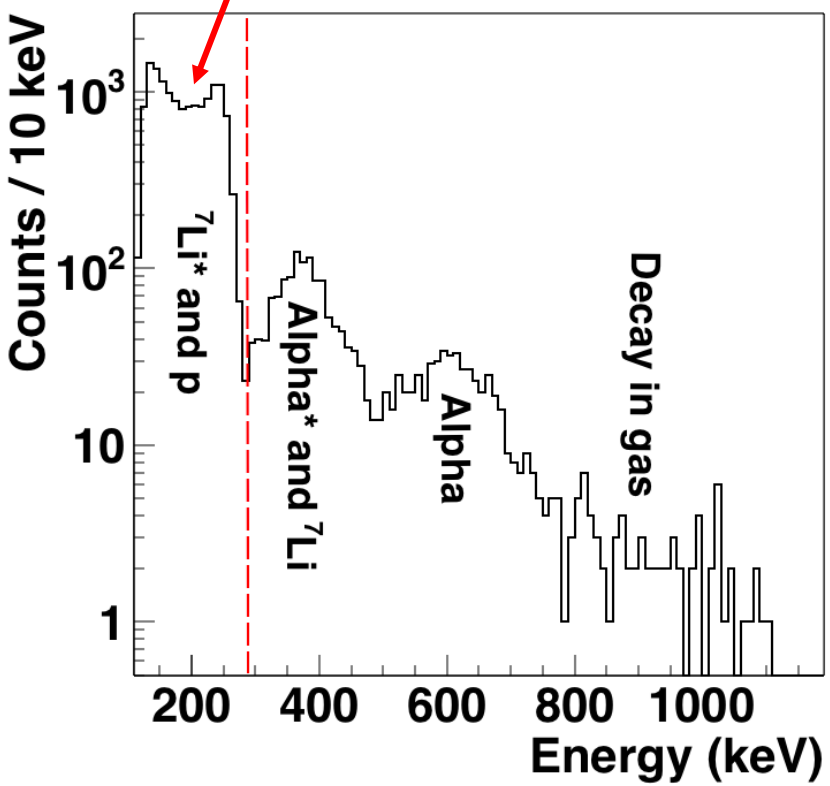


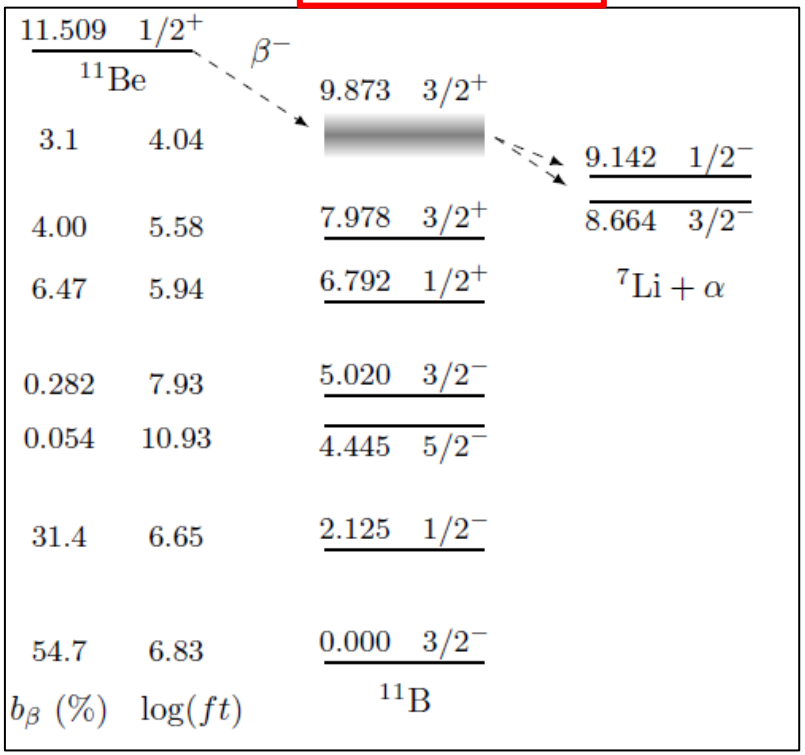

Electron drift time Z coordinate
e-
Gas Volume (Target)
E

Results

Protons?

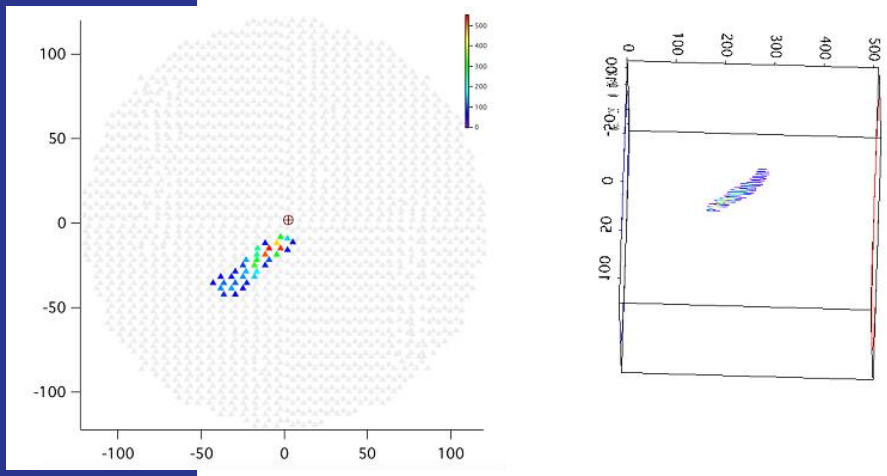


βα= 3.3(1)%

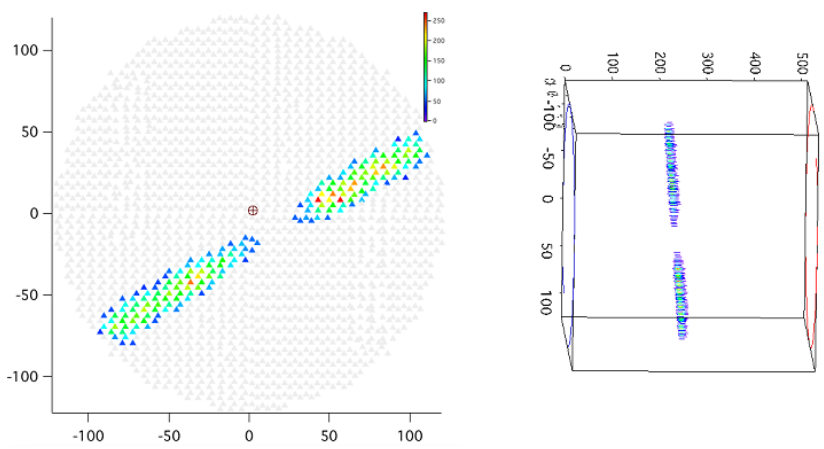


Particle traces

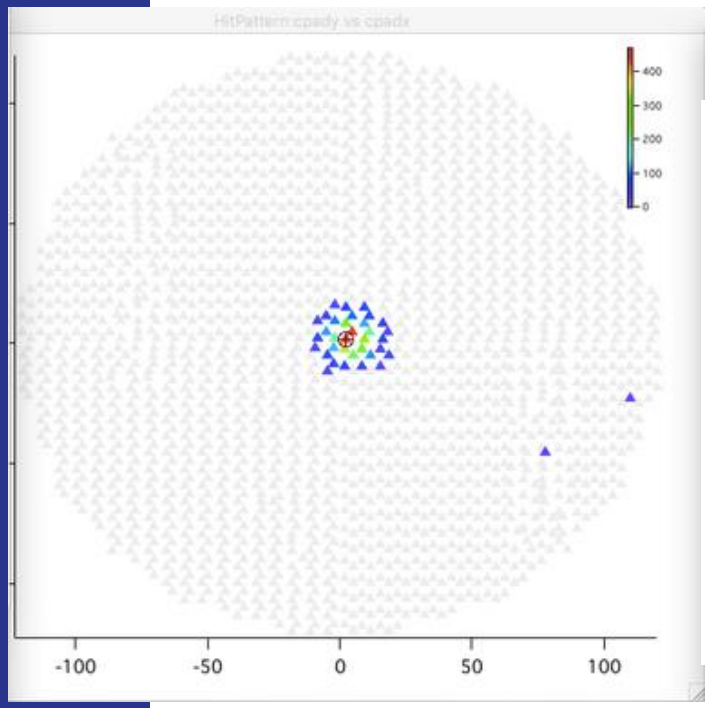
Proton?

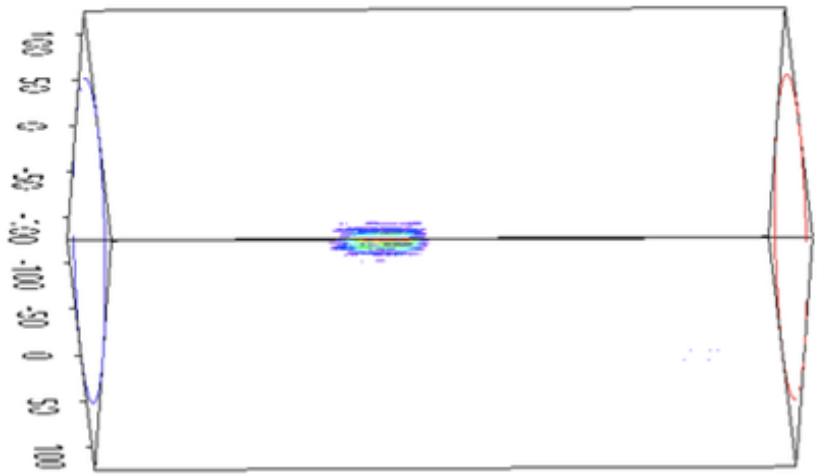


^{7}Li + α event



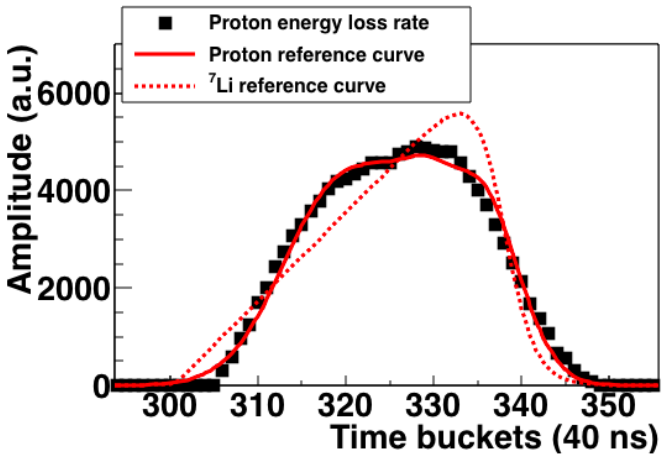
Proton beam calibration

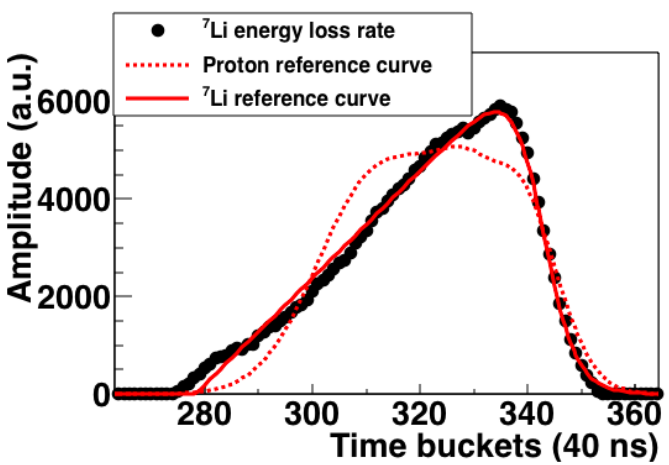




OH^+ beam from OLIS-TRIUMF produced protons of 180 keV for calibration

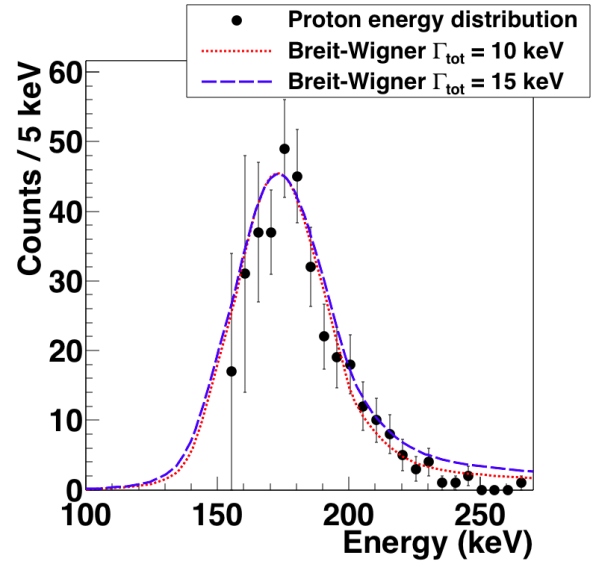
Observation





Y. Ayyad *et al.*

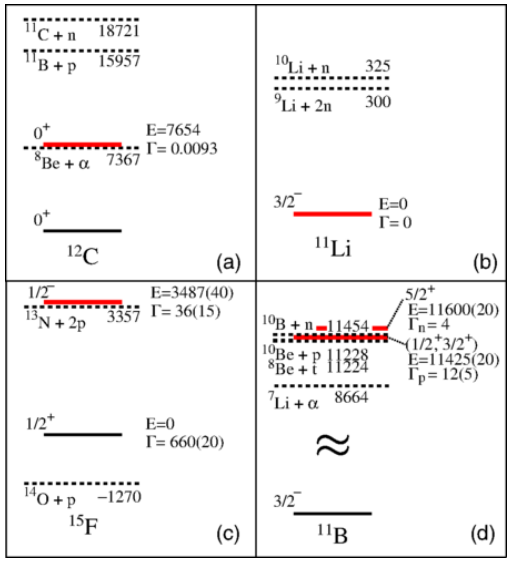
Phys. Rev. Lett. 123, 082501 – Published 22 August 2019; Erratum Phys. Rev. Lett. 124, 129902 (2020)

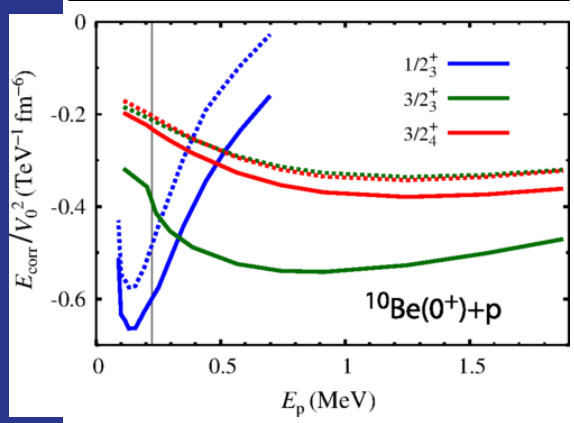


- First direct observation of $\beta^{-}p$ in a neutron-rich nuclei.
- Branching ratio is $1.3(3)\times10^{-5}$, with 30% uncertainty… Theoretical calculations yield 8.0×10^{-6}.
- A narrow resonance in ^{11}B was inferred. E = 11425(20) keV, Γ=12(5) keV, $J^{\pi} = 1/2^{+}$

Theory tries to reproduce the result

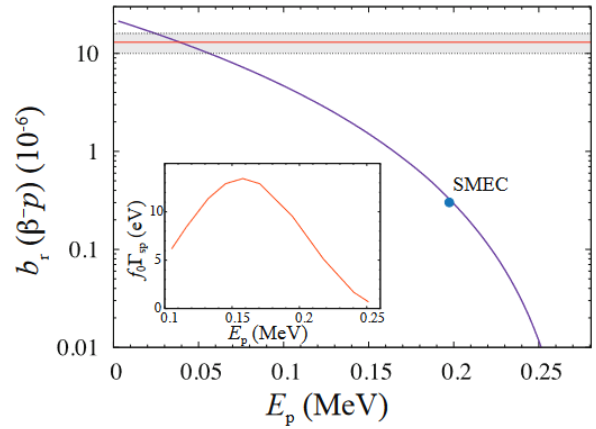
Phys Rev Lett. 124, 042502 (2020)



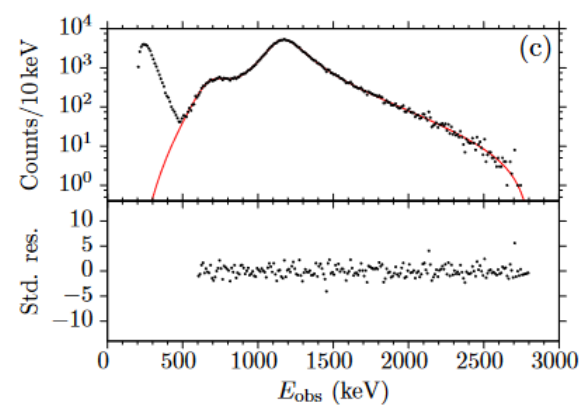


- Shell model embedded in the continuum (SMEC).
- Near-threshold collectivity driven by the interplay between nuclear interactions and decay channels.
- Strongest collectivization is predicted at $E_p \simeq 142$ keV.
- Core-coupled proton state [^{10}Be ⊗ p] with the negligible [^{7}Li ⊗ α] component.
- SMEC finds a consistent description of the beta-delayed alpha branching ratio of ^{11}Be and the $\Gamma_p(1/2_3^+)$.

arXiv:2112.05622



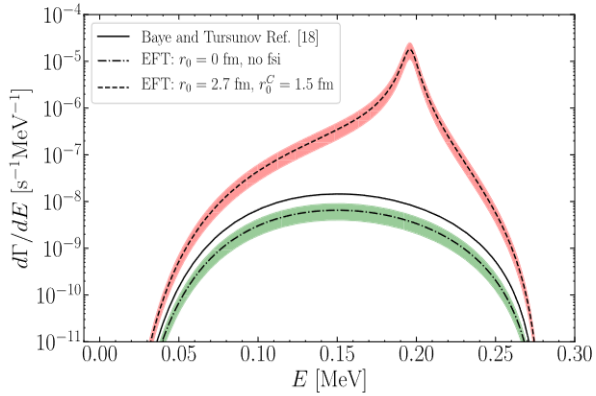
Model	I	II	III
States	$3/2^+$	$3/2^+ + 1/2^+$	$3/2^+ + 3/2^+$
χ^2_ℓ/ndf	21.7	3.11	1.26

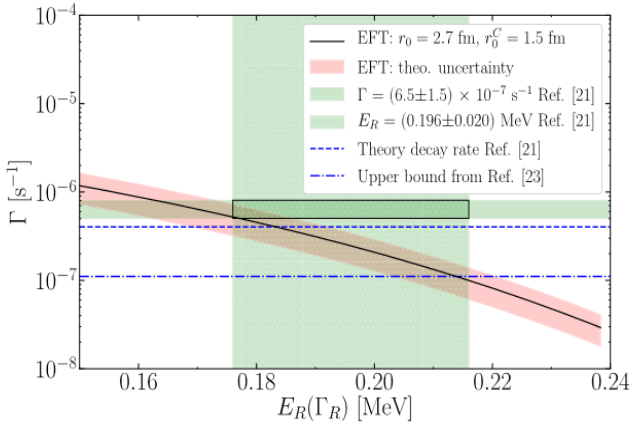


PRC 99, 044316 (2019)

Theory tries to reproduce the result

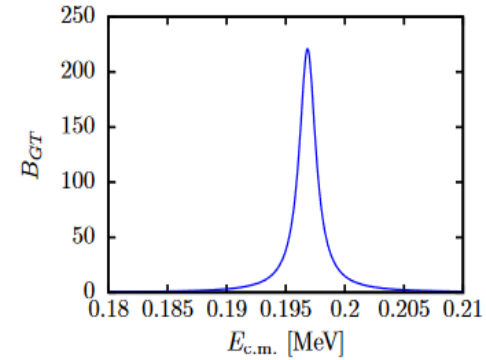
Physics Letters B 821 (2021) 136610





- Halo Effective Field theory (EFT) yields results consistent with the experiment. b_p =4.9 +5.6-2.9(exp) +4.0-0.8(theo.) and Γ=9.0+4.8-3.3(exp)+5.3-2.2(theo.) keV.
- No resonance: Γ=(6.6+-2.6) 10^{-10} s
- From ab-initio calculations with no-core shell model with continuum (NCSMC) b_p= (1.3+-0.5) 10^{-6} s
- Alpha decay spectroscopic factor is consistent with our estimate inferred from the decay width.
- From shell model calculations (A. Volya EPL 130, 1, 2020) the decay proceeds via the isobaric analog state with a lifetime of 2.6 10^{10} s SFp = 0.23. Small alpha width does not explain the experimental branching ratio.

Phys. Rev. C 105, 054316 (2022)

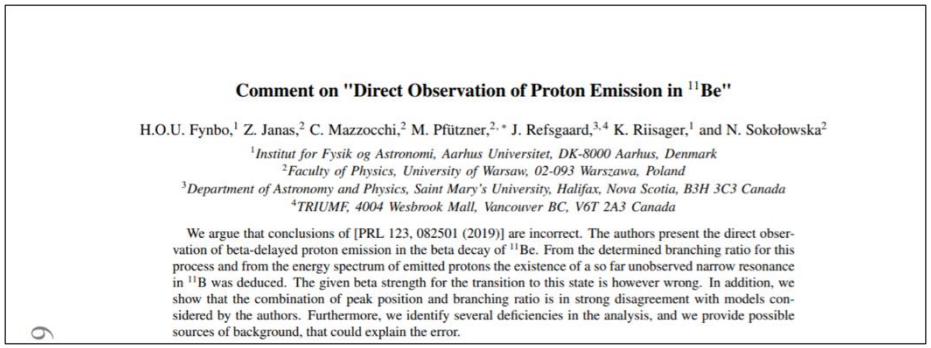


J^π	$S(^{11}B \to {}^{10}Be)$ $(0^+, 1)$	$S(^{11}B \to {}^{10}B)$ $(1_1^+, 0)$	$(1_2^+, 0)$	$S(^{11}B \to {}^{7}Li)$ $(3/2^+, 1/2)$
$1/2_1^+$	0.276	0.250	2×10^{-4}	0.218
$1/2_2^+$	0.0525	0.171	0.562	0.002
$1/2_3^+$	0.067	0.231	0.188	0.011
$3/2_1^+$	0.079	6×10^{-4}	0.215	0.009
$3/2_2^+$	4×10^{-4}	0.581	0.002	0.012
$3/2_3^+$	6×10^{-4}	0.011	0.006	0.021
$3/2_4^+$	0.067	0.034	0.35	0.006

J_i^π	E (EXP)	$E(psdu)$	$E(fsu)$	$B(GT)$	$\log_{10}(ft)$	SF_p	SF_α
$1/2_1^+$	6.7918	7.1743	6.5998	0.009	5.625	0.078	0.198
$3/2_1^+$	7.9779	8.0855	8.6337	0.000	8.286	0.040	0.034
$1/2_2^+$	(9.820)	9.9360	10.9678	0.191	4.301	0.175	0.170
$3/2_2^+$	9.873	10.6324	10.6968	0.001	6.737	0.057	0.002
$3/2_3^+$	(11.450)	11.5736	10.8534	0.615	3.792	0.008	0.038
$3/2_4^+$		11.9769	11.9453	1.731	3.343	0.012	0.008
$1/2_3^+$		12.7309	12.4382	0.659	3.762	0.019	0.012
$3/2_5^+$		12.9830	12.2265	0.035	5.046	0.003	0.023
$3/2_6^+$		13.1816	12.9324	0.222	4.235	0.001	0.007
$1/2_4^+$		13.1963	13.5568	0.959	3.599	0.057	0.004
$3/2_7^+$		14.4333	13.3750	0.037	5.011	0.003	0.001
$3/2_8^+$		14.9305	14.4300	0.008	5.674	0.013	0.001
$1/2^+, 3/2$	12.554	14.7199	12.6631	0.571	3.195	0.230	0.000

EPL 130, 1, 2020

Criticism



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]

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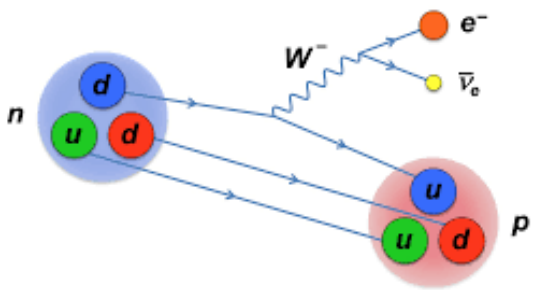
We argue that conclusions of [PRL 123, 082501 (2019)] are incorrect. The authors present the direct observation of beta-delayed proton emission in the beta decay of ^{11}Be. From the determined branching ratio for this process and from the energy spectrum of emitted protons the existence of a so far unobserved narrow resonance in ^{11}B was deduced. The given beta strength for the transition to this state is however wrong. In addition, we show that the combination of peak position and branching ratio is in strong disagreement with models considered by the authors. Furthermore, we identify several deficiencies in the analysis, and we provide possible sources of background, that could explain the error.

- No reliable particle identification.
- B(GT)>3



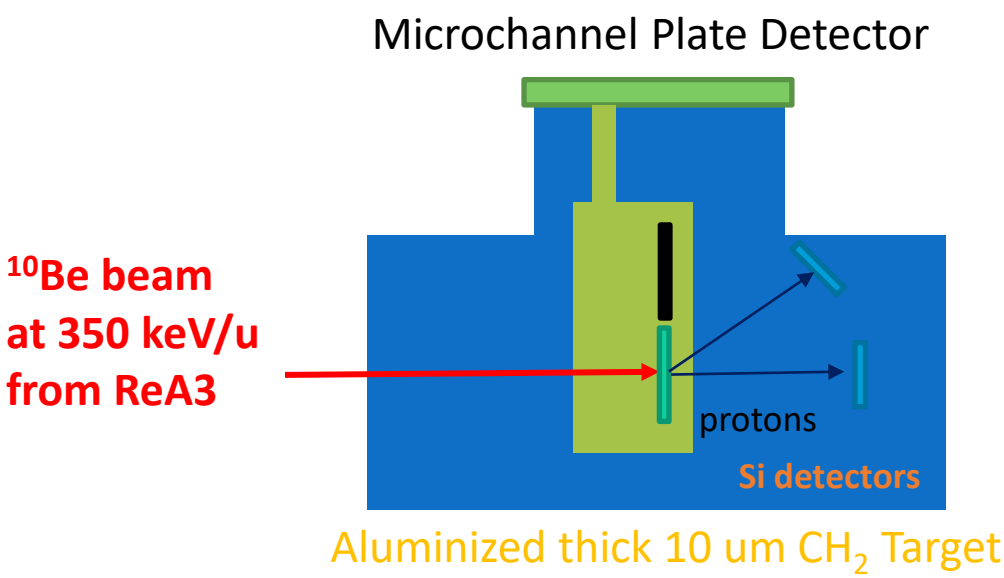
$$B(GT; i \rightarrow f) = \frac{6177}{f_A \cdot t_{i \rightarrow f}}$$

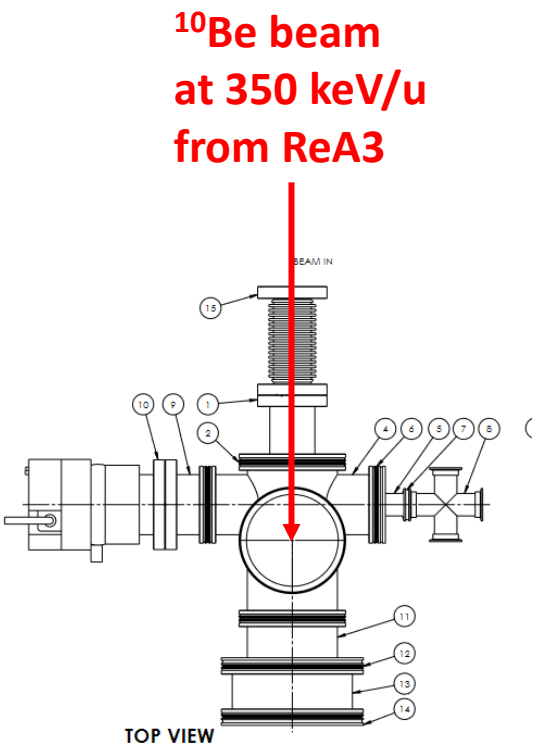
- B(GT)=3 free neutron decay
- Strict limit

- Our result B(GT)=$5.5^{+8.3}_{-3.3}$
- Within value at the 1σ limit
- B(GT) more sensitive to resonance energy than to branching ratio (for this case)

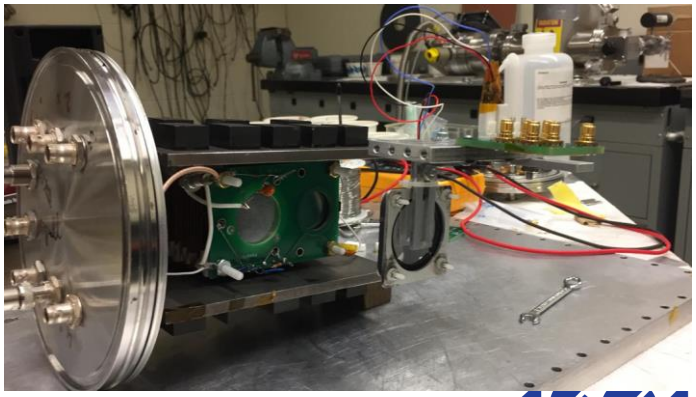
https://arxiv.org/abs/1912.06064

^{10}Be+p resonant scattering at ReA3 (FRIB)

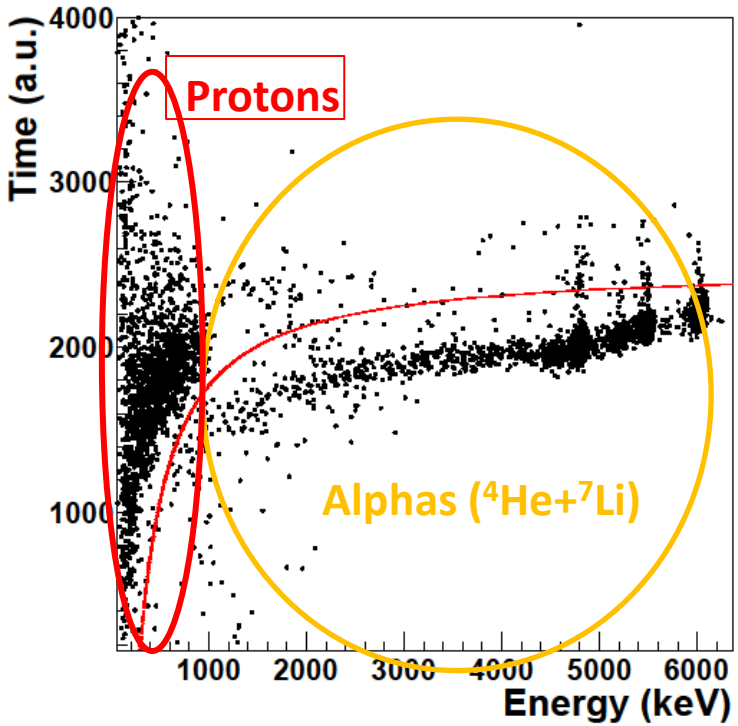


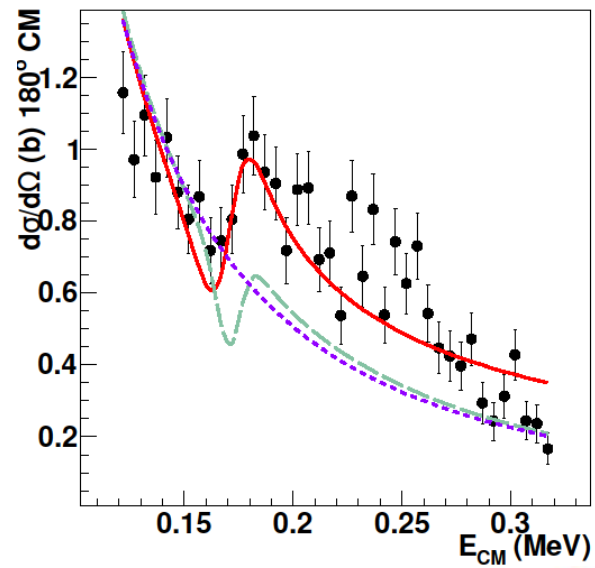


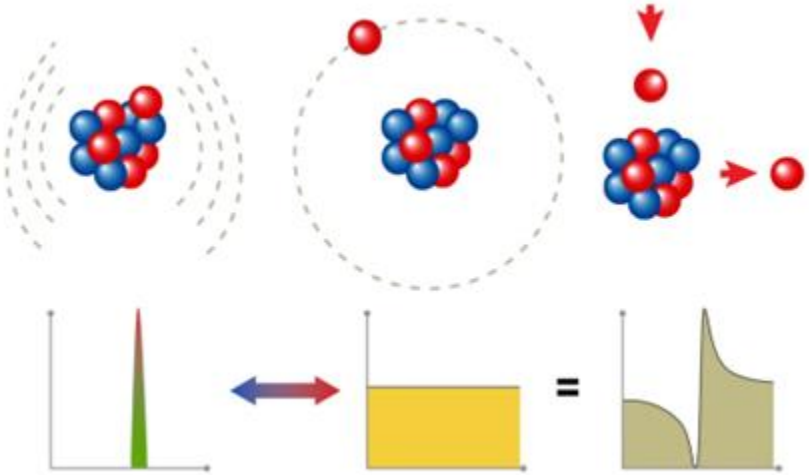
- Dedicated experiment to locate the resonance
- Proton scattering



Results







Fit with code AZURE2

E_{res}=(171 +-20) keV

Γ_{total} = 16 keV

Γ_p= 4.5 keV

Γ_a= 11 keV

CS~0.33

Phys. Rev. Lett. 129, 012501 (2022)

Confirmed by ^{10}Be(d,n) at FSU

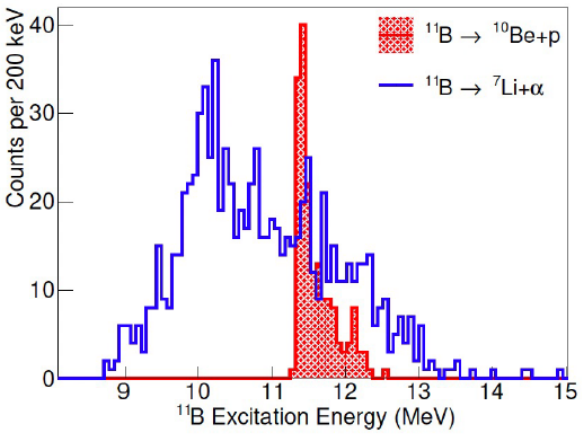


FIG. 3: Excitation energy spectrum in ^{11}B reconstructed from the $^{11}B^* \rightarrow {}^{10}Be + p$ (red) and $^{11}B^* \rightarrow {}^{7}Li + \alpha$ (blue). A prominent near-threshold peak at $E_{ex} = 11.44 \pm 0.04$ MeV is visible in the proton spectrum.

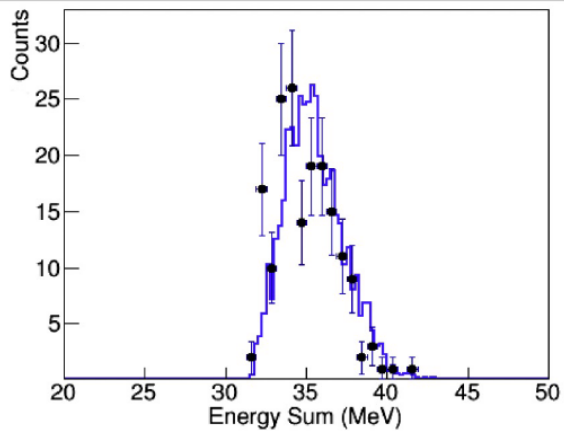


FIG. 4: Energy-sum signals of ^{10}Be + p events for the 11.44 MeV state, compared with a Monte Carlo simulation (in blue) that takes into account the DWBA-calculated angular distribution of the ^{10}Be(d,n)^{11}B* reaction. A value of $\ell = 0$ fits well the experimental data.

C2S = 0.27(6)

E_x=11.44MeV→
E_{res}=11.44-11.228=
(212+-40)keV

Upper limit for alpha branch < 40%

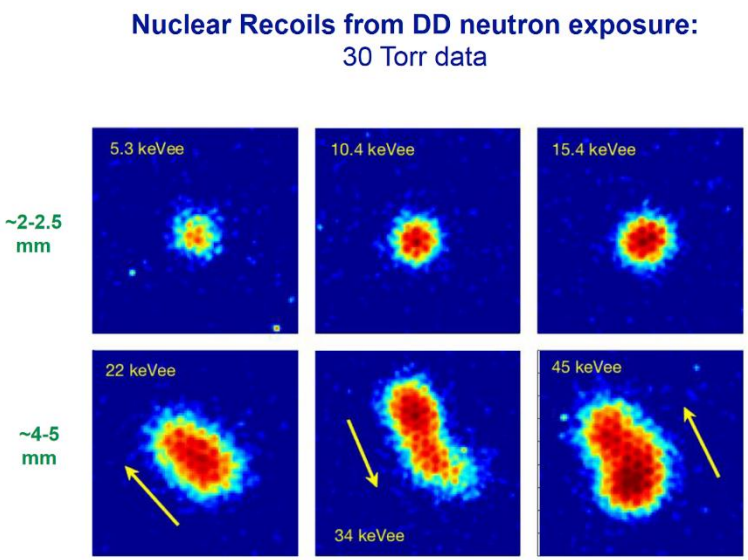
Phys. Rev. Lett. 129, 012502 (2022)

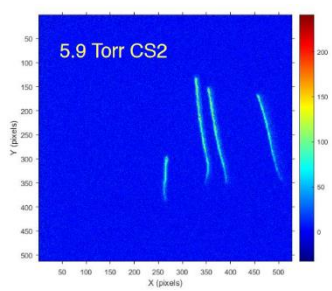
Problems persist

- New lower resonance energy E_{res}=196(20) keV → E_{res}=171(20) keV
  - B(GT)= $2.3^{+0.7}_{-0.5}$ < 3
- However, there could be an unaccounted alpha emitting branch from the resonance ~75% (us) or <40% (FSU)
  - B(GT)= 8^{+8}_{-4} >>3
  - INTC-P-632 approved to directly measure alpha branch
- Doubts about particle identification that affects the proton persists…

Remeasurement

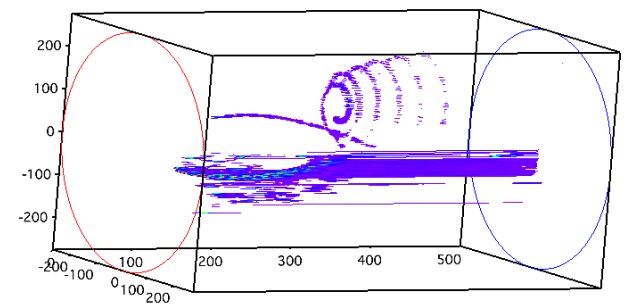
Negative Ion Drift Optical TPC
10 keV recoil
(experiment S2200 at TRIUMF)

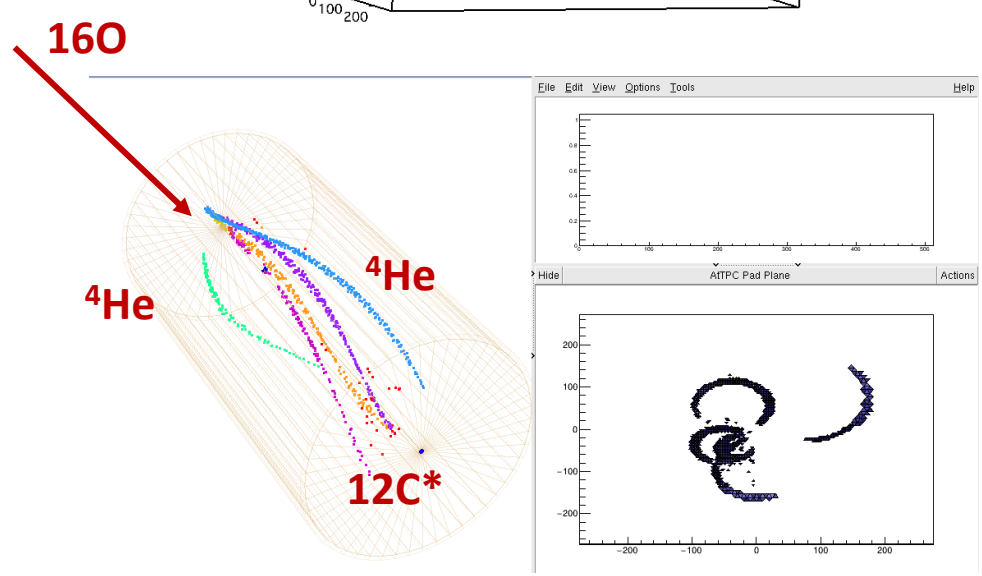




D. Umbash private communication

Magnetic field for enhanced particle identification
ISS + SpecMAT





Hot of the presses

PHYSICAL REVIEW C **106**, 015803 (2022)

Role of low-lying resonances for the ^{10}Be(p, α)^{7}Li reaction rate and implications for the formation of the Solar System

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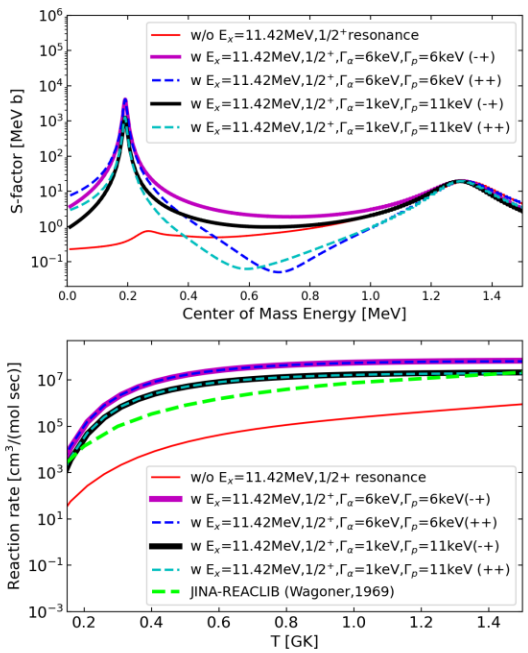


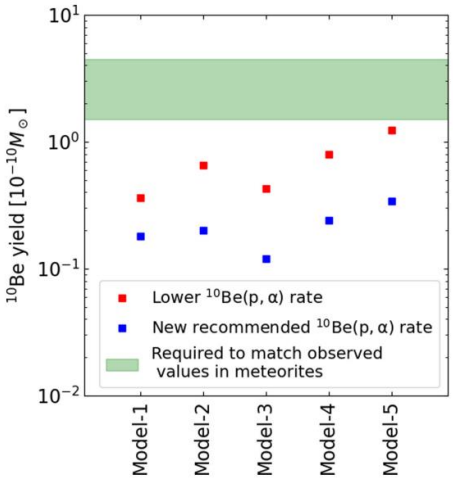


FIG. 8. ^{10}Be yield for the different models of the neutrino spectra listed in Table III for the recommended and lower ^{10}Be(p, α)^{7}Li reaction rate. The green band indicates the yield that is required to be in agreement with the observed ESS ^{10}Be / ^{9}Be ratio when assuming the scenario of Ref. [17].

Summary

- Direct observation of the exotic proton emission by a neutron-rich nucleus
- $b_p=1.3(3)\cdot10^{-5}$
- Orders of magnitude larger than expected
- Some theory agrees with it
- Located the intermediate resonance in ^{11}B that enhances the decay
- Work is underway to improve precision and understand the process

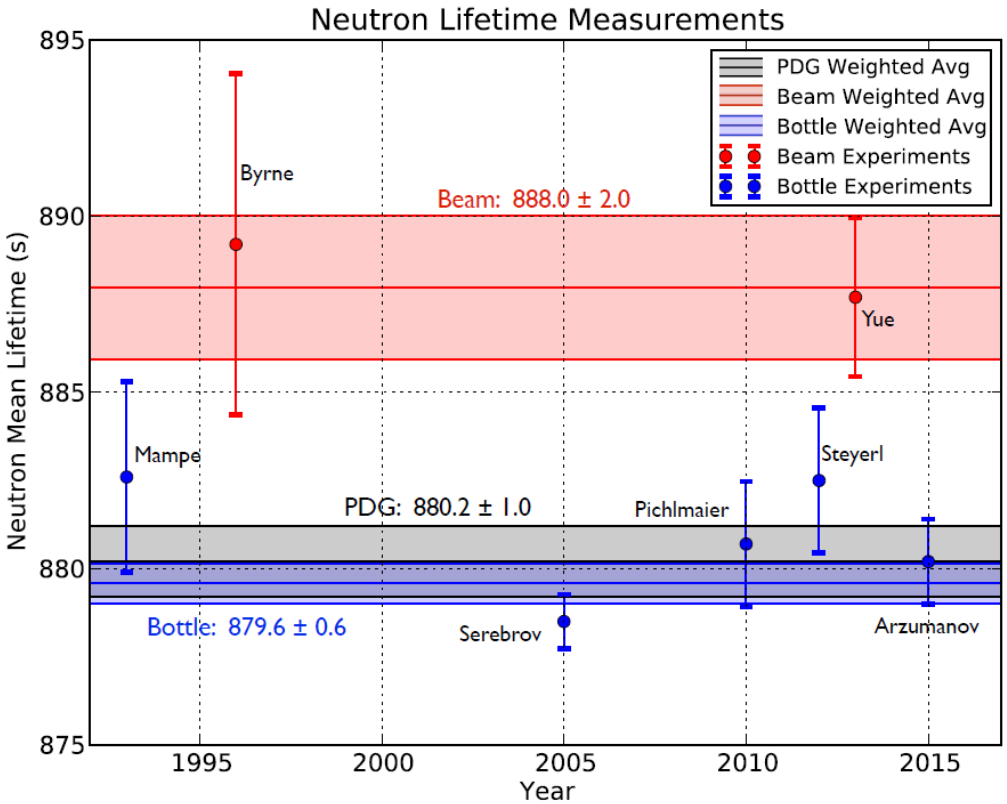
List of collaborators

- **TRIUMF:** **B. Olaizola**, M. Alcorta, M. Anholm, A. Babu, N. Bernier, S. Bhattacharjee, M. Bowry, R. Caballero Folch, I. Dillman, E. Dunling, G. Hackman, A. Garnsworthy, M. Holl, B. Koote, Y. Saito, P. Siyurte, R. Umashankar, D. Yates
- **NSCL:** **Y. Ayyad**, D. Bazin, S. Beceiro Novo, M. Cortesi, W. Mittig, J. S. Randhawa, N. Watwood
- **LBL:** C. Santamaria
- **Notre Dame:** T. Ahn
- **SFU:** C. Andreoiu
- **UoGuelph:** L. Atar, C.E. Svensson
- **Colorado:** K.G. Leach

THANK YOU!

Neutron lifetime puzzle

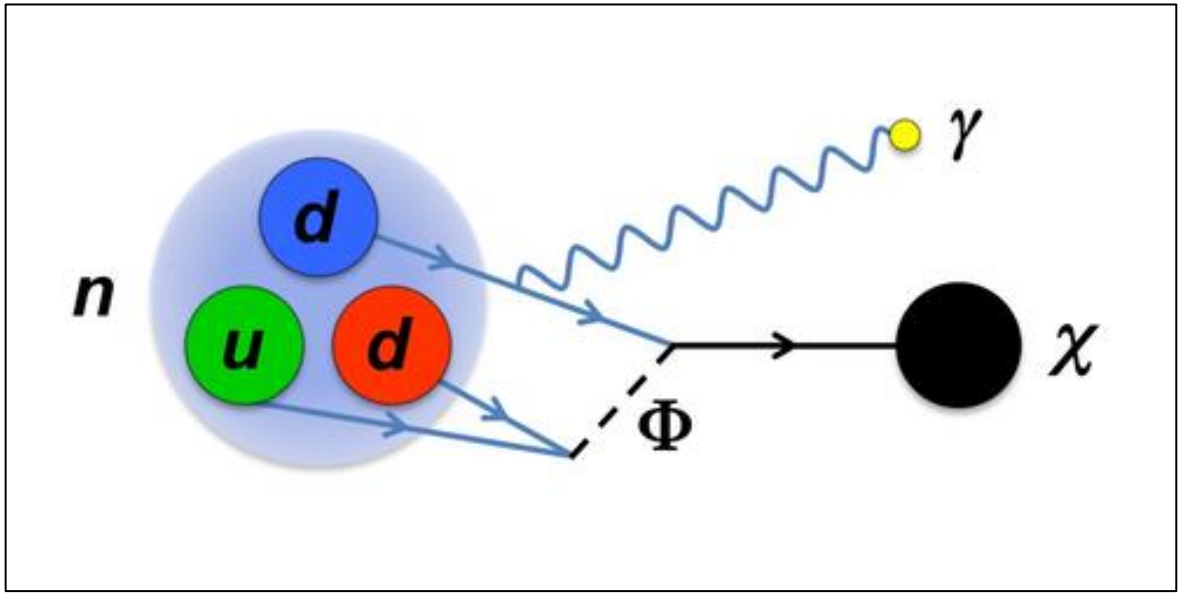
- Free neutron can β^- into a proton
- *In beam* method counts number of protons created
- *In bottle* method counts number of neutrons disappearing
- Both results are ~4σ away
- Different observables measuring different decay modes?



Bowman, arXiv:1410.5311 (2014)

Neutron dark decay

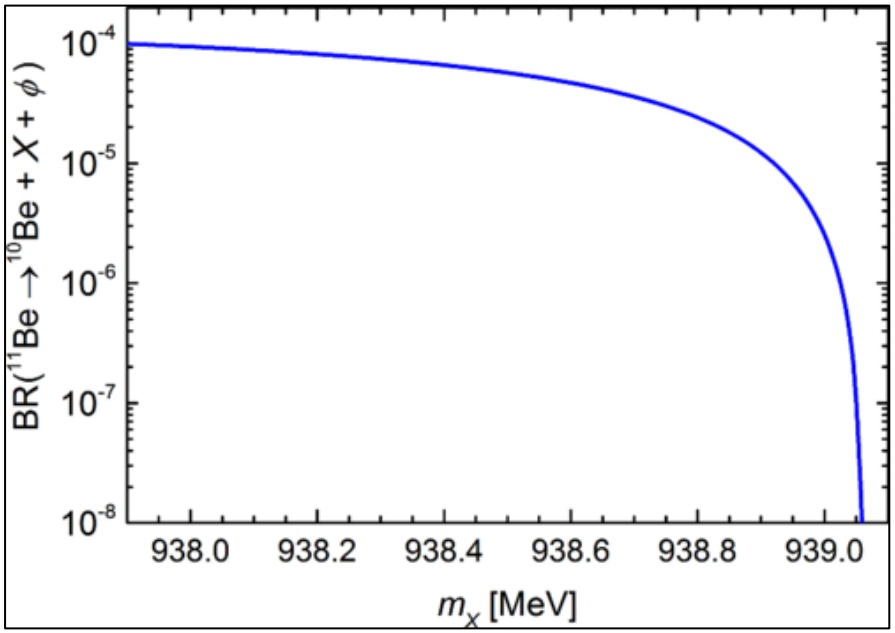
- Recently, Fornal and Grisntein suggested that the neutron could decay to a dark matter particle
- A branching ratio of ~1% would explain the neutron lifetime puzzle



Fornal and Grisntein PRL **120**, 191801(2018)

Neutron dark decay in nuclei

- Fornal and Gristein already suggested that neutron dark decay could occur in nuclei with S_n<1.572 MeV
- **^{11}Be is the best candidate**
- $^{11}Be \rightarrow {}^{10}Be + \chi$
- $^{11}Be \rightarrow {}^{10}Be + p$
- Branching ratio upper limit of 10^{-4}, depending on the dark particle mass

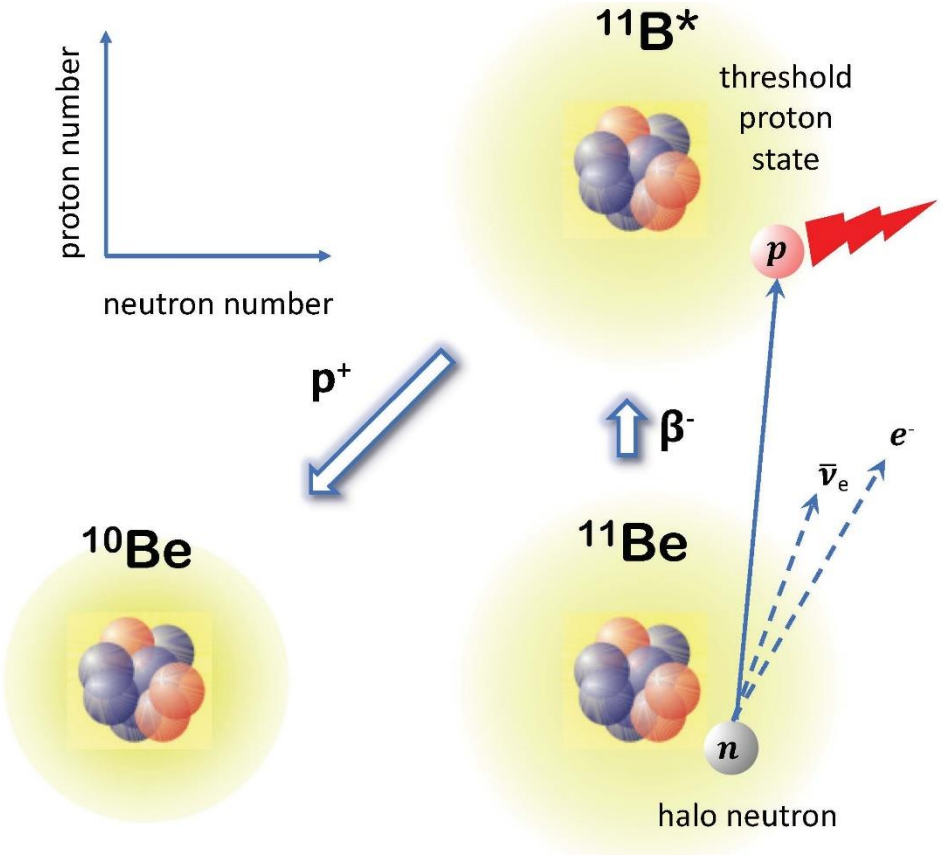


Pfutzner, PRC **97**, 042501 (2018)

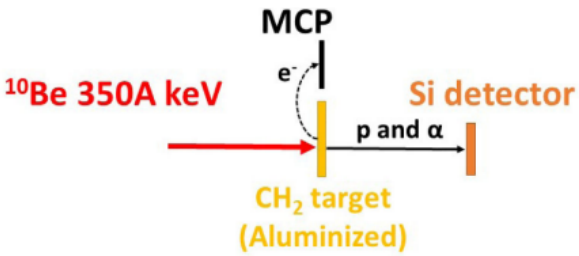
Neutron dark decay in nuclei

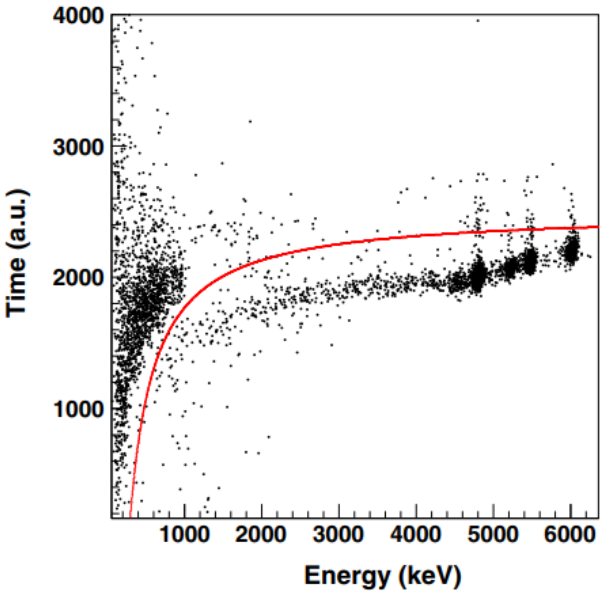
- Riisager *et al.* $\left\{ \begin{array}{l} {}^{11}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + p^{+} \\ {}^{11}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + \chi \end{array} \right.$
- This work : $-\quad {}^{11}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + p^{+}$

- Difference : ${}^{11}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + \chi$


proton number
neutron number
^{11}B*
threshold
proton
state
p
p+
β-
e-
$\bar{\nu}_e$
^{10}Be
^{11}Be
n
halo neutron

- 350A ^{11}Be beam
- CH_2 target
- Thin Al layer
- Permanent magnet bends electrons from Al
- Detectected by MCP
- Si detectors for p and α
- ToF between MCP and Si for particle identification





Bragg curves