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

Bruno Olaizola
CERN
ISOLDE Seminar – 2 August 2022
Nuclear mass parabola

$\beta^+$/EC decay

$\beta^-$ decay
Particle emission

Neutron emission

$\beta^+/\text{EC decay}$

$\beta^-$ decay
Particle emission

Proton emission

$\beta^+/EC$ decay

$\beta^-$ decay
β⁻ delayed proton emission

- Proton emission and β⁻ decay seem opposite processes
- If neutron binding energy of the nucleus satisfies:
  \[ S_n < (m_n - m_p - m_e)c^2 \]
  \[ \approx 782 \text{ keV} \]
- β⁻-delayed proton emission (β⁻-p) is energetically allowed

Pfutzner, Rev. Mod. Phy. 84, (2012)
\(\beta^-\)-delayed proton emission

- Only \(^{11}\text{Be}\) and \(^{19}\text{C}\) (and maybe \(^{31}\text{Ne}\)) 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.

$^{11}\text{Be}$ beta decay
\( \beta^- \) delayed alpha emission

\[ b_\alpha = 3.3(1)\% \]

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

Phys. Rev. C 99, 044316 – Published 25 April 2019
$\beta^-$ delayed proton emission


First attempt

- Riisager et al. implanted $^{11}\text{Be}$ in a catcher and let it decay
- Then analyzed the ratio of $^{10}\text{Be}/^{11}\text{B}$ in the catcher with the accelerator mass spectrometry technique
- $^{11}\text{Be} \rightarrow ^{10}\text{Be}$ branching ratio was $8.3(9) \cdot 10^{-6}$
- This value is orders of magnitude higher than theoretical predictions
Riisager et al repeated the experiment with a much larger number of samples
No agreement
Hypothesized the presence of $^{10}\text{Be}$ in catcher is from molecular $^{10}\text{BeH}$
Give a much lower upper limit of $<2.2 \cdot 10^{-6}$
Experiment at TRIUMF

**ISAC-I and ISAC-II Facility**

**ISAC II:**
- 10 AMeV for $A<150$
- 16 AMeV for $A<30$

**ISAC I:**
- 60 keV & 1.7 AMeV
pAT-TPC

Electron drift time Z coordinate

Gas Volume (Target)

2000 pads
Electron drift time $Z$

Gas Volume (Target)
Results

Protons?

\[ \beta\alpha = 3.3(1)\% \]
Particle traces

Proton?

$^7\text{Li} + \alpha$ event
OH$^+$ beam from OLIS-TRIUMF produced protons of 180 keV for calibration
• First direct observation of $\beta^- p$ in a neutron-rich nuclei.
• Branching ratio is $1.3(3) \times 10^{-5}$, with 30% uncertainty… Theoretical calculations yield $8.0 \times 10^{-6}$.
• A narrow resonance in $^{11}$B was inferred. $E = 11425(20) \text{ keV}$, $\Gamma = 12(5) \text{ keV}$, $J^{\pi} = 1/2^+$
Theory tries to reproduce the result

• 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 $E_p \approx 142$ keV.
• Core-coupled proton state $[^{10}\text{Be} \otimes p]$ with the negligible $[^{7}\text{Li} \otimes \alpha]$ component.
• SMEC finds a consistent description of the beta-delayed alpha branching ratio of $^{11}\text{Be}$ and the $\Gamma_p(1/2_3^+)$.
Halo Effective Field theory (EFT) yields results consistent with the experiment. $b_p = 4.9 \pm 5.6 - 2.9 (\text{exp}) + 4.0 - 0.8 (\text{theo.})$ and $\Gamma = 9.0 + 4.8 - 3.3 (\text{exp}) + 5.3 - 2.2 (\text{theo.}) \text{ keV}$.

No resonance: $\Gamma = (6.6 - 2.6) \times 10^{-10} \text{ s}$

From ab-initio calculations with no-core shell model with continuum (NCSMC) $b_p = (1.3 - 0.5) \times 10^{-6} \text{ s}$

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 $2.6 \times 10^{-10} \text{ s}$. Small alpha width does not explain the experimental branching ratio.
Criticism

- 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)

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

- Dedicated experiment to locate the resonance
- Proton scattering

$^{10}\text{Be}$ beam at 350 keV/u from ReA3

Aluminized thick 10 um CH$_2$ Target
Results

Fit with code AZURE2

$E_{\text{res}} = (171 \pm 20)$ keV

$\Gamma_{\text{total}} = 16$ keV

$\Gamma_p = 4.5$ keV

$\Gamma_a = 11$ keV

CS$\sim 0.33$

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

Upper limit for alpha branch < 40%

C2S = 0.27(6)

$E_x=11.44\text{MeV} \rightarrow$ $E_{res}=11.44-11.228 = (212\pm 40)\text{keV}$
Problems persist

- New lower resonance energy $E_{\text{res}} = 196(20)$ keV $\rightarrow$ $E_{\text{res}} = 171(20)$ keV
  - $B(\text{GT}) = 2.3^{+0.7}_{-0.5} < 3$

- However, there could be an unaccounted alpha emitting branch from the resonance $\sim 75\%$ (us) or $< 40\%$ (FSU)
  - $B(\text{GT}) = 8^{+8}_{-4} >> 3$
  - 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)

Magnetic field for enhanced particle identification
ISS + SpecMAT

Nuclear Recoils from DD neutron exposure:
30 Torr data

~2.25 mm

~4-5 mm

D. Umbash private communication
Hot of the presses

PHYSICAL REVIEW C 106, 015803 (2022)

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

A. Sieverding, J. S. Randhawa, D. Zetterberg, R. J. deBoer, T. Ahn, R. Mancino, and W. R. Hix

1 Physics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6354, USA
2 Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA
3 Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996-1200, USA
4 Institut für Kernphysik (Theoriezentrum), Fachbereich Physik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64298 Darmstadt, Germany
5 GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany

(Received 15 March 2022; accepted 13 June 2022; published 12 July 2022)

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

- Direct observation of the exotic proton emission by a neutron-rich nucleus
  \[ b_p = 1.3(3) \cdot 10^{-5} \]
- 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


**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 $\beta^{-}$ into a proton
- *In beam* method counts number of protons created
- *In bottle* method counts number of neutrons disappearing
- Both results are $\sim 4\sigma$ away
- Different observables measuring different decay modes?
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 Gristein already suggested that neutron dark decay could occur in nuclei with $S_n < 1.572$ MeV.

$^{11}\text{Be}$ is the best candidate

$^{11}\text{Be} \rightarrow ^{10}\text{Be} + \chi$

$^{11}\text{Be} \rightarrow ^{10}\text{Be} + p$

Branching ratio upper limit of $10^{-4}$, depending on the dark particle mass
Neutron dark decay in nuclei

Riisager *et al.*  

This work:

Difference:

\[
\begin{align*}
11\text{Be} & \rightarrow 10\text{Be} + p^+ \\
11\text{Be} & \rightarrow 10\text{Be} + \chi \\
- & \\
11\text{Be} & \rightarrow 10\text{Be} + p^+ \\
11\text{Be} & \rightarrow 10\text{Be} + \chi
\end{align*}
\]
350A $^{11}$Be beam
- CH$_2$ target
- Thin Al layer
- Permanent magnet bends electrons from Al
- Detected by MCP
- Si detectors for p and α
- ToF between MCP and Si for particle identification
Bragg curves