Halo nuclei as open quantum systems

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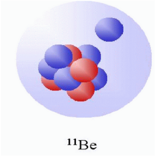
Peculiarity of ^{11}Be and motivation to study ^{11}B

Halo Nucleus

A nuclear system where the core nucleons are tightly bound and one or more valence nucleons are weakly bound, forming a diffuse cloud around the core.



Halo nucleus configuration.

Key properties:

- Neutron separation energy: $S_n = 501.6$ keV.
- Exotic decay: $\beta^- p^+$ decay occurs in nuclei with $S_n < 782$ keV.

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

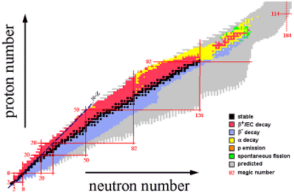


Chart of nuclei.

Motivation

Physics Motivation

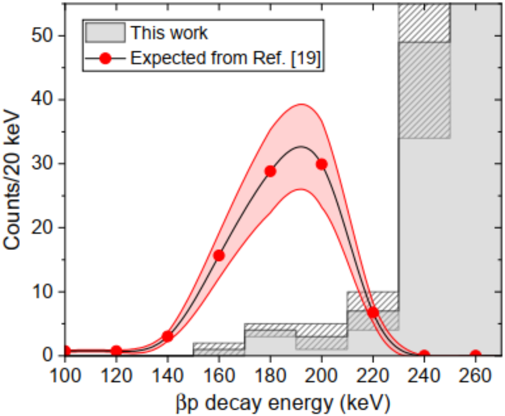
- Weak binding of ^{11}Be halo neutron near proton emission threshold $\rightarrow$ neutron wave function extends into the continuum.
- Enhanced decay channel via narrow resonant state closer to S_p in daughter nucleus ^{11}B.
- Fano resonance phenomenon: asymmetric line shapes in nuclear spectroscopy.

Theory vs Experimental Motivation

- Theoretical models assuming directly proton emission into the continuum reflected $b_p \simeq 10^{-10}$ [4].
- Assuming sequential decay $b_p \simeq 10^{-6}$ in [4] and [2].
- Beta decay experiments: [2] obtained $b_p \simeq 1.3(3) \cdot 10^{-5}$, [8] inferred an upper limit $b_p < 2.2 \cdot 10^{-6}$.

[4] Elkamawy, W. et al. *Phys. Rev. B, 821, 136610 (2021)*; [2] Ayyad, Y. et al. *Phys. Rev. L. 123, 082501 (2019)*; [8] Riisager, K. et al. *Phys. Lett. B 805, 135451 (2020)*

Motivation



Discussed ^{11}B resonant state enhanced in $\beta^- p^+$ decay in ^{11}Be. Grey tpc approach [5] and Red [2]

[5] Sokołowska, N. et al. *Phys. Rev. C. 110, 034328 (2024)*; [2] Ayyad, Y. et al. *Phys. Rev. L. 123, 082501 (2019)*

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Neutron Capture Reaction

^{10}B(d,p) Reaction

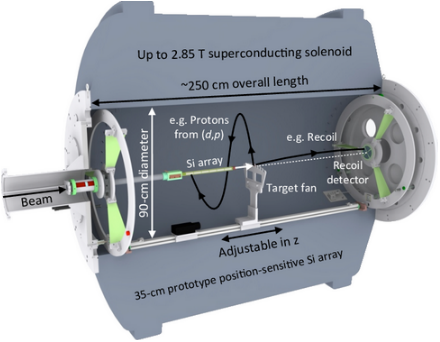
- Objective: Obtain clarifying information of light particle emission in estates closer to drip lines in ^{11}B.
- Populate directly ^{11}B continuum coupled states via neutron capture reaction in inverse kinematics.
- States forbidden by beta decay reaction are allowed by neutron transfer reaction. ¡Neutron penetrability effect!

$$^{11}\mathrm{B}^* \rightarrow {}^{10}\mathrm{Be} + \mathrm{p}, \quad {}^{11}\mathrm{B}^* \rightarrow {}^{10}\mathrm{B} + \mathrm{n}, \quad {}^{11}\mathrm{B}^* \rightarrow {}^{7}\mathrm{Li} + \alpha,$$

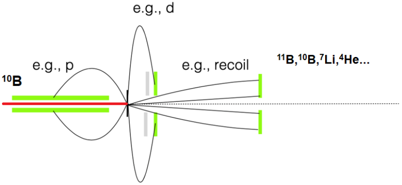
S_n (MeV)	S_p (MeV)	S_α (MeV)
11.454	11.228	8.664

Separation energies of ^{11}B on different light particles.

- HELIOS (Helical Orbit Spectrometer) in Argonne, USA.



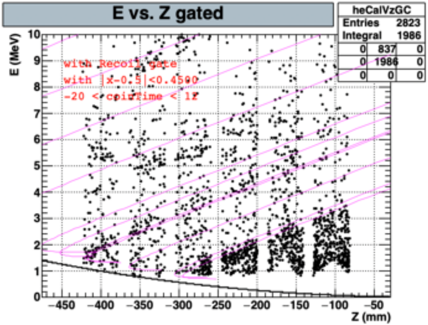
Detector scheme.



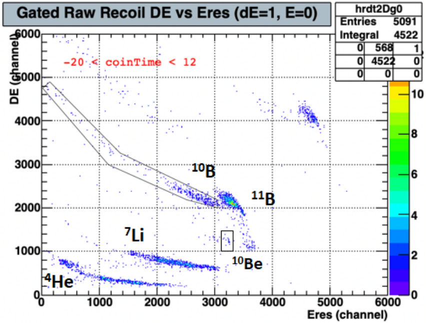
Experiment performed.

Silicon arrays: position–sensitive (longitudinal) + TOF from cyclotron period.
Telescope detectors at solenoid end → identification of heavy nuclei.
Reconstruction of proton emission angle.
Focusing → extended dynamic range and no recoil escape.
Elimination of kinematic compression → Better CM resolution.

^{11}B Excitation Energies

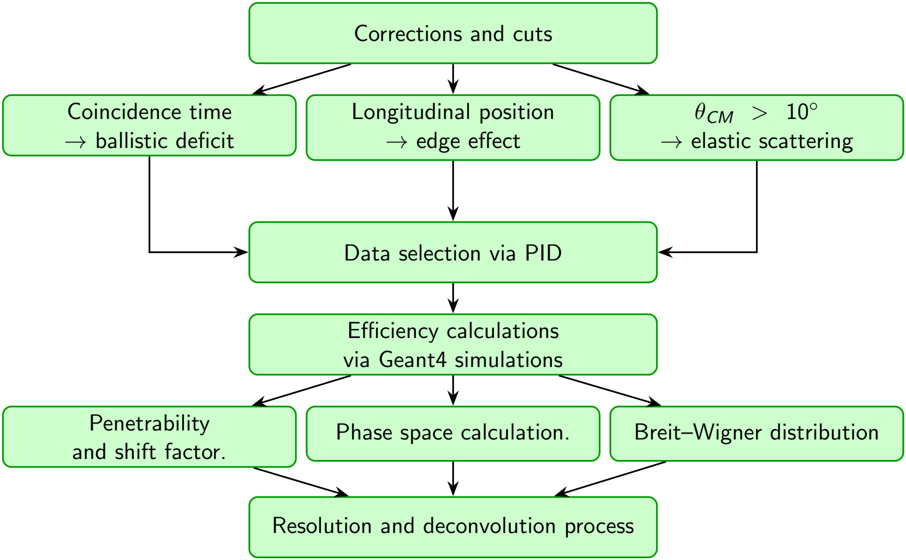


Proton energy vs Si array position.



Telescope detector PID plot.

Analysis Workflow



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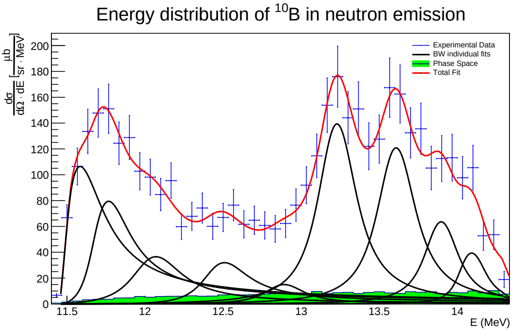
Neutron channel

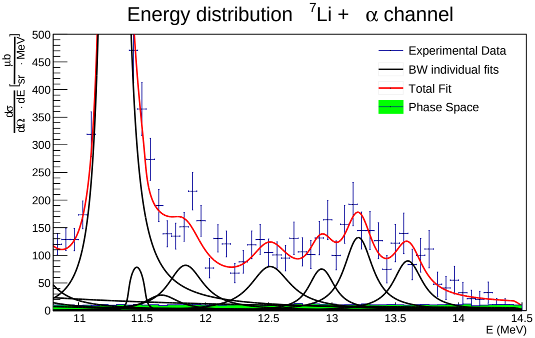


Fit for neutron channel emission.

Centroid (MeV)	J^{π} State	Width Γ (keV)
11.682(15)	$5/2^+$	250(25)
11.828(25)	$5/2^-$	232(60)
12.099(30)	$7/2^+$	300(75)
12.546(30)	$1/2\ (3/2)^+$	280(75)
12.900(60)	$1/2^-$	250(50)
13.235(30)	$7/2\ (5/2)^+$	250(50)
13.613(20)	$7/2\ (5/2)^+$	254(60)
13.900(40)	$7/2\ (5/2)^+$	216(65)
14.100(30)	$11/2^+$	140(30)

Resonant states of ^{11}B.

Alpha channel

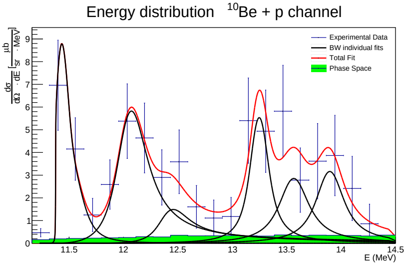


Fit above 11.5 MeV for α emission.

Centroid (MeV)	J^{π} State	Width Γ (keV)
11.280(20)	$9/2^+$	110(20)
11.460(20)	$1/2^+$	30(15)
11.66(30)	$5/2^+$	275(50)
11.85(20–50)	$5/2^-$	292(100)
12.52(30)	$1/2\ (3/2)^+$	335(75)
12.92(50)	$1/2^-$	200(75)
13.210(50)	$7/2\ (5/2)^+$	231(60)
13.6(50)	$7/2\ (5/2)^+$	237(80)

Resonant states of ^{11}B.

Proton channel



Fit for proton channel emission.

Centroid (MeV)	J^π State	Width Γ (keV)
11.452(15)	$1/2^+$	24(15–25)
12.100(30)	$7/2^+$	261(80)
12.510(100)	$1/2\ (3/2)^+$	288(100)
13.250(50)	$7/2\ (5/2)^+$	230(70)
13.570(50)	$7/2\ (5/2)^+$	240(50)
13.900(80)	$7/2\ (5/2)^+$	193(80)

Resonant states of ^{11}B.

	[2]	[3]	New Results
J^π	$(1/2^+, 3/2^+)$	$(1/2^+)$	$(1/2^+)$
E_R	11.425(20) MeV	11.40(20) MeV	$11.45 - 0.05_{syst} \pm 0.15_{stat}$ MeV
Γ	12(5) keV	16(3) keV	24^{+25}_{-15} keV
Γ_p	–	4.5(11) keV	3^{+3}_{-1} keV
Γ_α	–	11(3) keV	21^{+22}_{-13} keV

Comparison of the 11.4 MeV state in ^{11}B.

[2] Ayyad, Y. et al. *Phys. Rev. L. 123, 082501 (2019)*; [3] Ayyad, Y. et al. *Phys. Lett. L. 129 (2020)*

Branching Ratios

State (MeV)	J^π State	Neutron	Alpha	Proton
11.45	$1/2^+$	0	0.876(37)	0.124(37)
11.65	$5/2^+$	0.839(15)	0.161(15)	0
11.85	$5/2^-$	0.549(110)	0.451(110)	0
12.10	$7/2^+$	0.888(10)	0	0.112(10)
12.50	$1/2\ (3/2)^+$	0.336(10)	0.653(10)	0.011(3)
12.90	$1/2^-$	0.218(5)	0.782(5)	0
13.20	$7/2\ (5/2)^+$	0.543(7)	0.440(7)	0.017(1)
13.60	$7/2\ (5/2)^+$	0.632(7)	0.355(7)	0.012(1)
13.80	$7/2\ (5/2)^+$	0.952(2)	0	0.048(2)
14.10	$11/2^+$	1	0	0

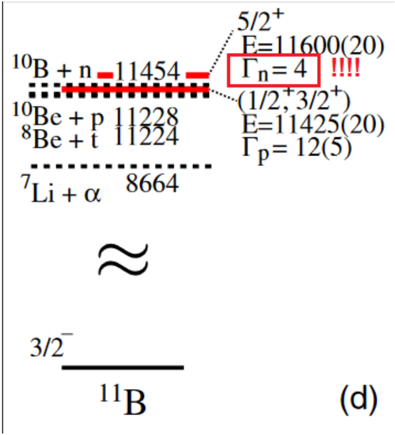
Branching ratios for the resonant states of ^{11}B through neutron, alpha and proton emission channels.

Main interest **New** **Unexpected** **Expected**

11.6 MeV State in ^{11}B

Partial widths on 11.6 MeV level.

From the results given, the partial widths obtained for this level are: $\Gamma_n = 210^{+20}_{-21}$ keV, $\Gamma_\alpha = 40^{+4}_{-4}$ keV.



Level scheme of neutron emission in level 11.6 MeV [7].

[7] Okołowicz, J. et al. *Phys. Rev. L. 124(4), (2020)*;

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Conclusions

What do we get from the results?

- New information to complete the ^{11}B structure that is relevant to shell model calculations $\rightarrow$ Nilsson model.
- Level validation in terms of energy and measurement of their widths.
- 11.6 MeV state completely different results on partial widths.
- 11.4 MeV state is been seen in alpha and proton emission, proton width in agreement with [2].
- 13 MeV states and above, have been discovered in the three channels.
- New experimental data $\rightarrow$ Recalculation of branching ratio of $\beta^- p^+$ decay in ^{11}Be.

[2] Ayyad, Y. et al. *Phys. Rev. L. 123, 082501 (2019)*;

Thank You!

I appreciate your attention.

Any Questions?

Penetrability and Shift factor

Coulomb Penetrability for Charged Particles

$$\frac{d^2 u_\ell}{d\rho^2} + \left[1 - \frac{\ell(\ell+1)}{\rho^2} - \frac{2\eta}{\rho}\right] u_\ell = 0$$

$$\rho = 0.218735 \cdot r \sqrt{\frac{M_t M_p}{M_t + M_p} E}$$

$$\eta = 0.1574854 \cdot Z_t Z_p \sqrt{\frac{M_t M_p}{(M_t + M_p) E}}$$

$$r = 1.3 \cdot (A_1^{1/3} + A_2^{1/3}) \text{ fm}$$

$$s_\ell = R \cdot \frac{k}{F_\ell^2(\eta, \rho) + G_\ell^2(\eta, \rho)}\bigg|_{r=R}$$

Coulomb wave functions F_ℓ and G_ℓ determine the penetrability for charged particle emission, including angular momentum ℓ and the Coulomb barrier [1].

[1] Nuclear Reactions, Chapter 2, Pages 73-138. John Wiley Sons, Ltd, (2015)

Penetrability and Shift factor

How can penetrability be implemented in neutron emission? [6]

$$\Gamma_l(E_0) = 2 s_l(E_0)\,\gamma^2 = \Gamma_0, \quad \frac{\Gamma_\ell(E)}{\Gamma_\ell(E_0)} = \frac{\Gamma_\ell(E)}{\Gamma_0} = \frac{s_\ell(E)}{s_\ell(E_0)} \tag{1}$$

$$s_\ell = \frac{2/\pi}{J^2_{\ell+1/2}(kR) + Y^2_{\ell+1/2}(kR)} \tag{2}$$

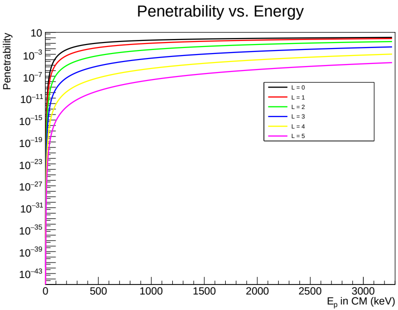
$$\Gamma_\ell(E) = \Gamma_0 \frac{k}{k_0} \frac{J^2_{\ell+1/2}(k_0 R) + Y^2_{\ell+1/2}(k_0 R)}{J^2_{\ell+1/2}(kR) + Y^2_{\ell+1/2}(kR)} \tag{3}$$

$$\Delta E = -\Gamma_0 \frac{s_\ell(E) - s_l(E_0)}{2 s_\ell(E_0)} \tag{4}$$

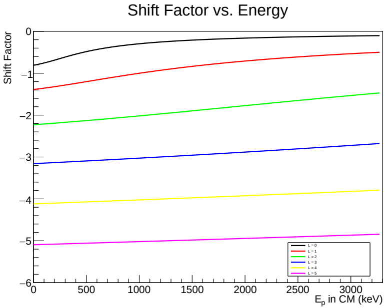
$$d\sigma \propto \frac{\Gamma_\ell(E)}{(E_0 - \Delta E - E)^2 + \frac{1}{4}\Gamma_\ell^2(E)} \tag{5}$$

[6] Gibelin, J. et al. *Few-Body Systems, 64(2), (2019)*;

Penetrability and Shift factor for Proton

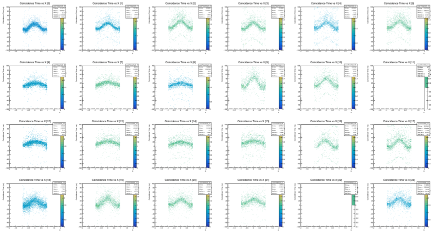


Penetrability for proton emission.

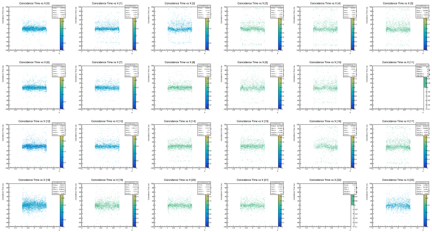


Shift factor calculation for proton emission.

Coincidence Time Corrections

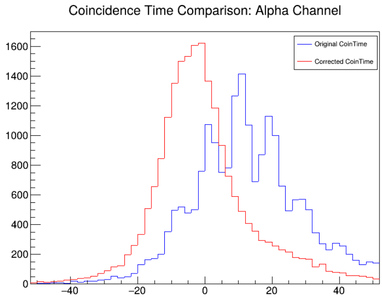


Coincidence time vs position without correction.

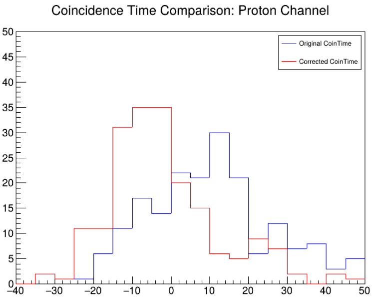


Coincidence time vs position with correction.

Coincidence Time Corrections

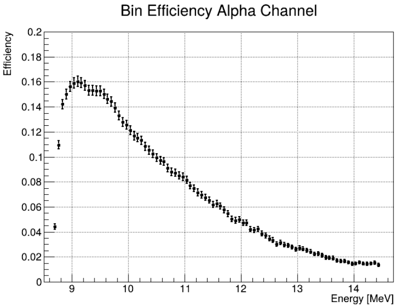


Coincidence time comparison after correction in alpha channel.

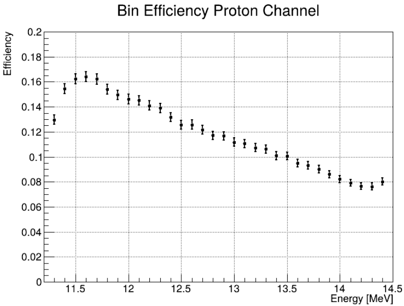


Coincidence time comparison after correction in proton channel.

Efficiency Simulations



Efficiency simulation of alpha channel.



Efficiency simulation of proton channel.

References

[1] *Nuclear Reactions*, chapter 2, pages 73–138. John Wiley Sons, Ltd, 2015.

[2] Y. Ayyad, B. Olaizola, W. Mittig, G. Potel, and Zelevinsky et al. Direct observation of proton emission in $^{11}\mathrm{Be}$. *Phys. Rev. Lett.*, 123:082501, Aug 2019.

[3] Yassid Ayyad, Wolfgang Mittig, Tianxudong Tang, and Olaizola et al. Evidence of a near-threshold resonance in $^{11}\mathrm{B}$ relevant to the β-delayed proton emission of $^{11}\mathrm{Be}$. *Physical Review Letters*, 129, 06 2022.

[4] Wael Elkamhawy, Zichao Yang, Hans-Werner Hammer, and Lucas Platter. β-delayed proton emission from ^{11}Be in effective field theory. *Physics Letters B*, 821:136610, 2021.

[5] Sokołowska et al. Decay study of $^{11}\mathrm{Be}$ with an optical time-projection chamber. *Phys. Rev. C*, 110:034328, Sep 2024.

[6] Julien Gibelin. On the experimental description of neutron resonances. *Few-Body Systems*, 64(2), March 2023.

[7] J. Okołowicz, M. Płoszajczak, and W. Nazarewicz. Convenient location of a near-threshold proton-emitting resonance in ^{11}B. *Physical Review Letters*, 124(4), January 2020.

[8] K. Riisager, M. J. G. Borge, and Briz et al. Search for β-delayed proton emission from ^{11}Be. *The European Physical Journal A*, 56(3), March 2020.