A new model for p + ^{9}Be reaction as BNCT neutron source

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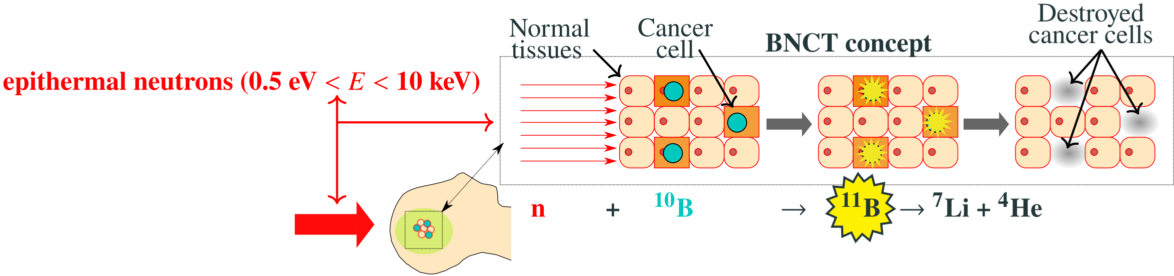
Accelerator-based BNCT neutron sources



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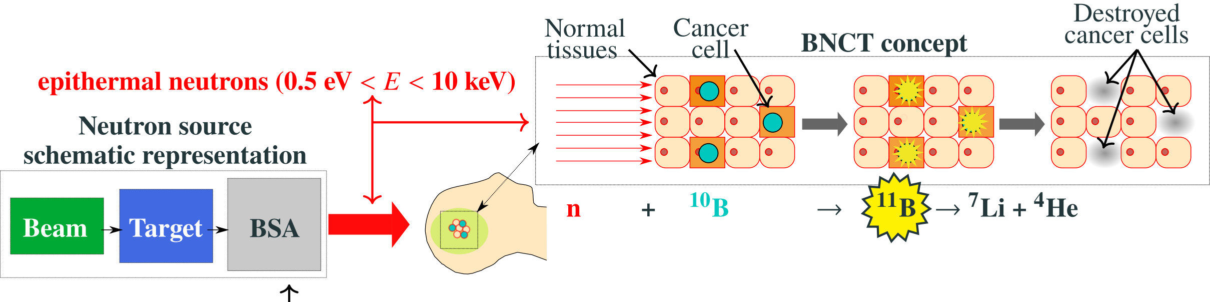

Beam Shaping Assembly (moderator, reflectors, filters, shielding, collimator, . . .) optimized for beam quality and patient safety

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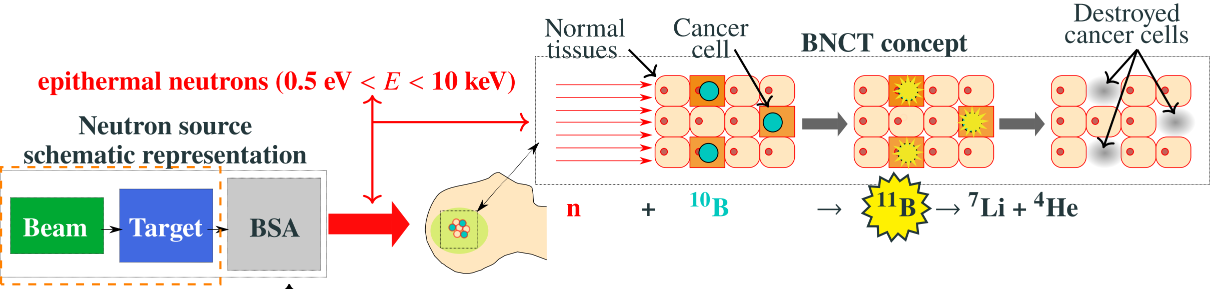

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particle beam from accelerator (usually protons) + **Target (usually ^{7}Li or ^{9}Be)**

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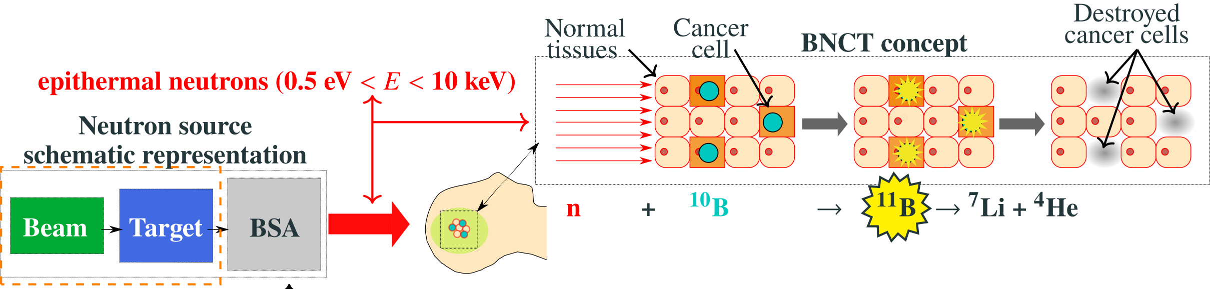

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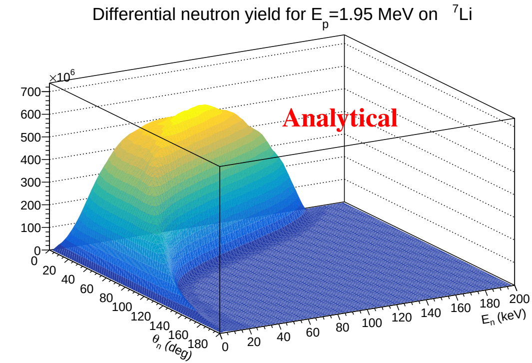
Reaction	Energy (MeV)	Max E_n	Melting Point (°C)	Residual ($T_{1/2}$)
^{7}Li(p,n)^{7}Be	2.3–2.5	∼ hundreds keV	180	^{7}Be (53.2 d)
^{9}Be(p,x)^{9}B	4/5–30	MeV → tens MeV	1210	^{9}B (8×10^{-19} s)

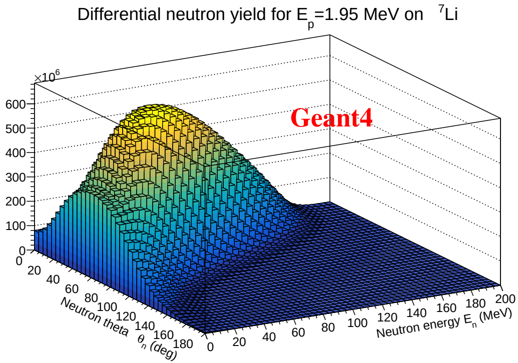
p + ^{7}Li reaction

- Solved analytically and with Geant4 (QGSP_BIC_AllHP physics-list).
- Only 1 reaction channel: p + ^{7}Li $\rightarrow$ ^{7}Be + n

C.L. Lee, X.-L. Zhou, NIMB 152 (1999)

Energy (MeV)	Analytic yield (n/mC)	MC yield (n/mC)
1.95	6.29×10^{10}	5.94×10^{10}
2.00	1.10×10^{11}	1.08×10^{11}
2.30	5.86×10^{11}	5.67×10^{11}

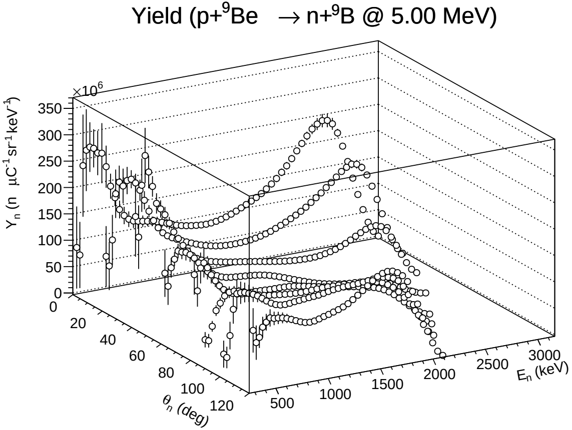




p +^{9}Be, yield data

- Data from Agosteo et al. (2011)

S. Agosteo et al., Characterization of the energy distribution of neutrons generated by 5 MeV protons on a thick beryllium target at different emission angles., Applied Radiation and Isotopes 69.12 (2011): 1664-1667.



Data only up to 120°.

How to reproduce the spectra up to 120°?

How to extrapolate up to 180°?

p + ^{9}Be reaction channels

- Reaction channels at 5 MeV:

channel	products	Q-value (keV)	Threshold (keV)
(p, n)	^{9}B + n_0	-1850.4	2057.4
	^{9}B* + n_1	-3529.96	3924.62
	^{9}B* + n_2	-4194.96	4663.97
(p, p′n)	^{8}Be + p + n	-1664.54	1850.77
(p, αn)	^{5}Li + α + n	-3540	3930
(p, p′αn)	2α + p + n	-1572.70	1748.65

Many open channels!

They all involve the same final state:

2α + p + n

$$p + {}^{9}\text{Be} \rightarrow \begin{cases} {}^{9}\text{B} + \text{n} \rightarrow {}^{8}\text{Be} + \text{p} + \text{n} \\ {}^{8}\text{Be} + \text{p} + \text{n} \rightarrow 2\alpha + \text{p} + \text{n} \\ {}^{5}\text{Li} + \alpha + \text{n} \rightarrow \alpha + \text{p} + \alpha + \text{n} \\ \alpha + \text{p} + \alpha + \text{n} \end{cases}$$

^{9}B $T_{1/2}$ = 0.8 as = 0.8×10^{-18} s

^{8}Be $T_{1/2}$ = 81.9 as = 81.9×10^{-18} s

^{5}Li $T_{1/2}$ = 0.37 zs = 0.37×10^{-21} s

Analytical approach

The basis is the Lee and Zhou formalism:

$$\frac{d^2N}{dE_n d\Omega} = \frac{f_{Be} N_0 \rho}{eA} \cdot \frac{\frac{d\sigma}{d\Omega_{cm}} \cdot \frac{d\Omega_{cm}}{d\Omega} \frac{dE_p}{dE_n}}{-\frac{dE_p}{dx}} \iff Y'' = k \cdot \frac{X' \cdot J}{S}$$

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With the four channels $\longrightarrow$ $Y''_{tot} = Y''_{p,n} + Y''_{p,p'n} + Y''_{p,p'\alpha n} + Y''_{p,\alpha n}$

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The differential cross sections are not known for each individual reaction channel.

The differential and total cross sections are available only for (p,n_0) and (p,xn).

Hybrid model

Idea: hypothesis of 2 dominant channels, (p,n_0) and (p,p′n) as in [1].

We used TENDL-2023 cross section for the (p, n_0) channel. How to calculate the yield of (p,p’n)?

[1] C. Wang and B. Moore, *Thick beryllium target as an epithermal neutron source for neutron capture therapy*, Medical Physics 21(1994)1633.

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Cross section of (p, p′n) can be derived from the cross sections of (p, xn) and (p,n_0).

$$\boxed{X_{p,p'n} = X_{tot} - X_{p,n}}$$

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$$Y''_{tot} \approx Y''_{p,n} + \hat{Y}''_{p,p'n} = Y''_{p,n} + Y''_{p,p'n} f_{p,p'n}(\theta_n, E_n).$$

Correction factor to reproduce the realistic angular distribution of (p, p'n): parameters from yield data fitting

$$f_{p,p'n}(\theta_n, E_n) = p_0 + \frac{p_1}{1 + \exp(p_2\,\theta_n)} \exp\left[- \frac{(E_n - p_3 - p_4 \sin(\theta_n/2))^2}{p_5} \right].$$

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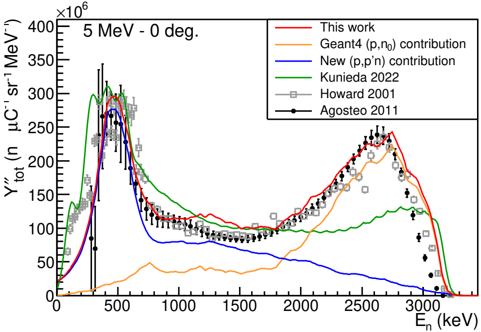
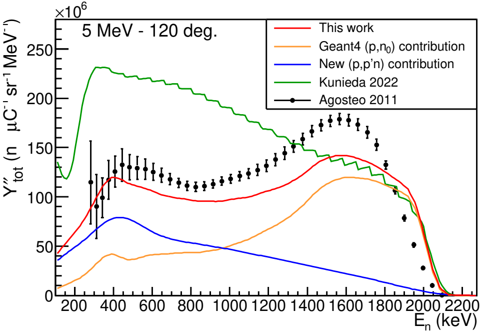
Results



×10^6
5 MeV - 0 deg.
This work
Geant4 (p,n0) contribution
New (p,p'n) contribution
Kunieda 2022
Howard 2001
Agosteo 2011
Y''tot (n μC-1 sr-1 MeV-1)
0
50
100
150
200
250
300
350
400
0
500
1000
1500
2000
2500
3000
En (keV)



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1200
1400
1600
1800
2000
2200
En (keV)

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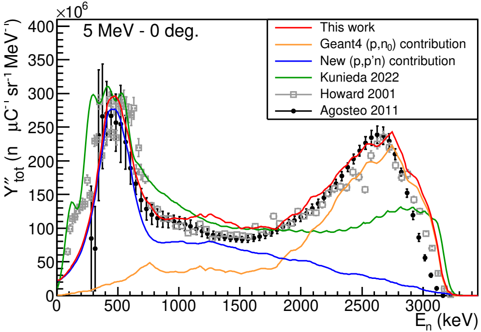

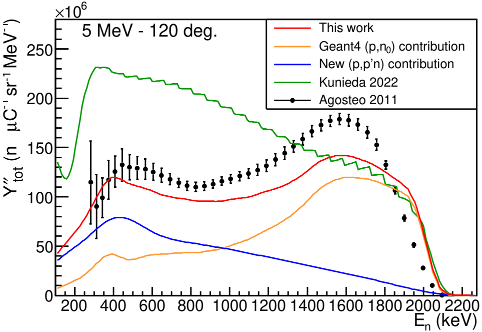

Based on (p,n_0) and $(p,p'n)$ →

Reference	Y_{tot} (n/mC)
This work	**2.96×10^{12}**
Data from Agosteo	**$3.3 - 3.5 \times 10^{12}$**
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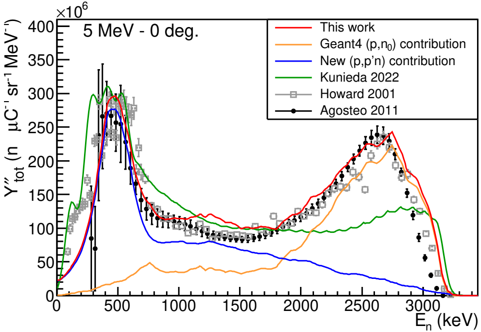

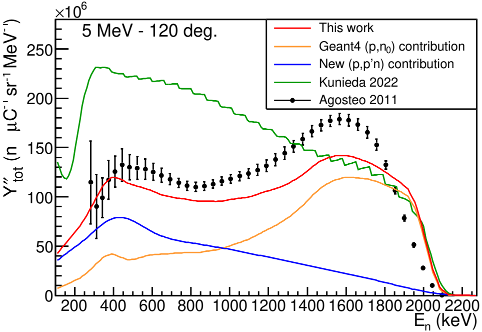

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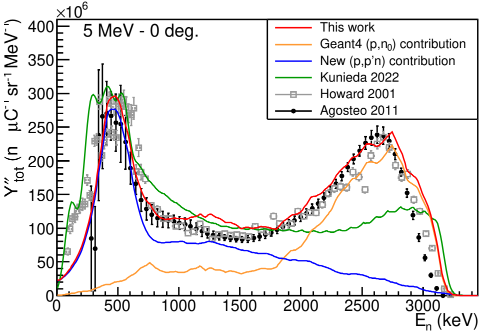

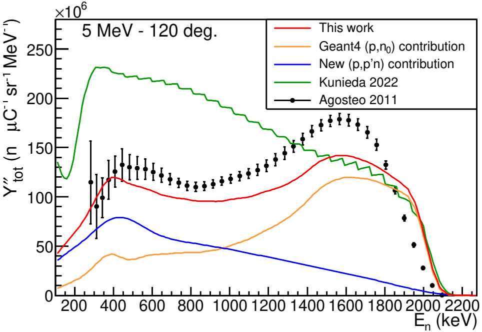

Based on (p,n_0) and $(p,p'n)$ → This work

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Implemented in JENDL5
Based on (p,n_0), (p,n_2) and (p,n_4) → Kunieda 2022

Conclusions

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- **Reassessment of BSA's efficacy proposed in [2].**

[2] I. Postuma et al., *A novel approach to design and evaluate BNCT neutron beams combining physical, radiobiological, and dosimetric figures of merit*, Biology 10, 174 (2021).

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Paper submitted!

Next step

▷ **Implementation of this source in a Geant4 example on BNCT.**

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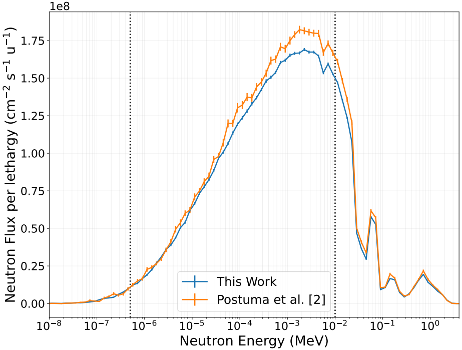
Backup slide

Reassessment of BSA's efficacy proposed in a **previous study [2]** with model valid at all angles.
Previous study based on experimental measurements and basic extrapolation from 120° to 180°.

	ϕ_{epi} 10^9 $(cm^{-2}s^{-1})$	$\frac{\phi_{th}}{\phi_{epi}}$	$\frac{\dot{D}_{Fast}}{\phi_{epi}}$ 10^{-13} (cm^2Gy)	$\frac{\dot{D}_{\gamma}}{\phi_{epi}}$ 10^{-13} (cm^2Gy)	$\frac{J}{\phi_{epi}}$
IAEA	> 0.5	< 0.05	< 7	< 2	> 0.7
Postuma et al. [2]	1.08 ± 0.004%	0.009 ± 6.12%	9.50 ± 1.07%	4.17 ± 1.79%	0.74 ± 0.62%
This work	1.02 ± 0.001%	0.010 ± 2.38%	9.32 ± 0.49%	4.18 ± 0.78%	0.73 ± 0.20%



Absence of significant deviations reinforces the robustness and **potential applicability** of the **BSA** proposed in [2].

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