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

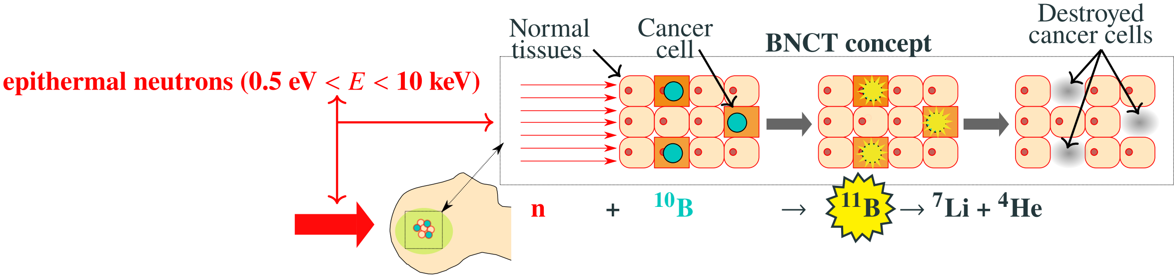
Alessandro Colombi[1]*, Ian Postuma[1], Silva Bortolussi[1,2], Valerio Vercesi[1], Andrea Fontana[1]

[1]INFN – Sezione di Pavia
[2]University of Pavia – Physics Department
alessandro.colombi@pv.infn.it

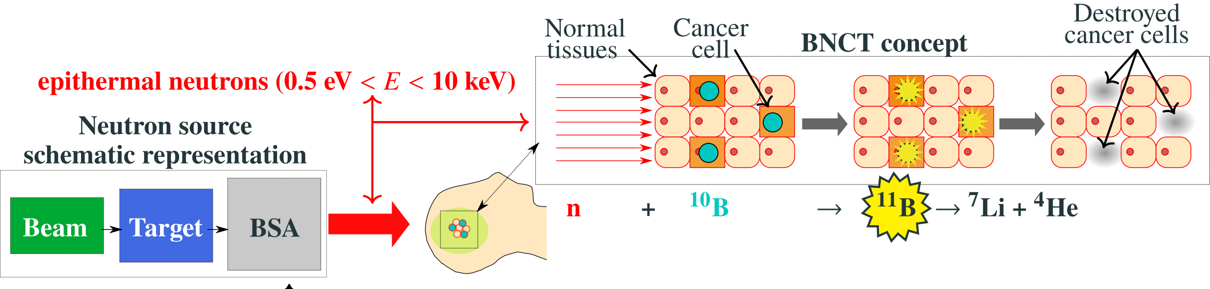
Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

UNIVERSITÀ DI PAVIA

Accelerator-based BNCT neutron sources

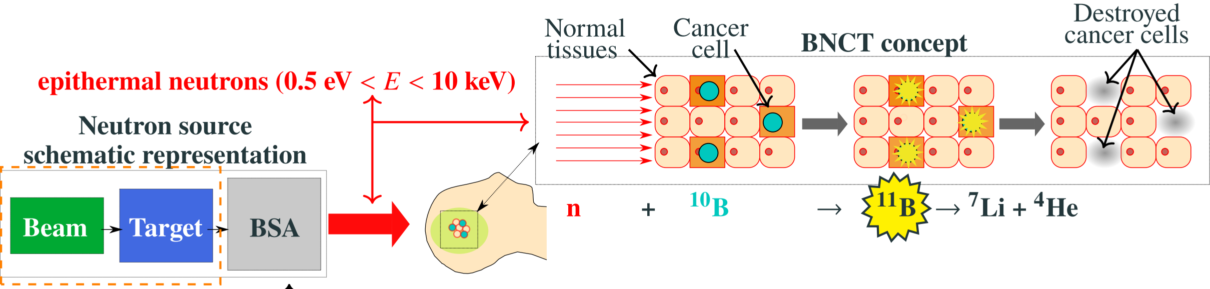


Accelerator-based BNCT neutron sources



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

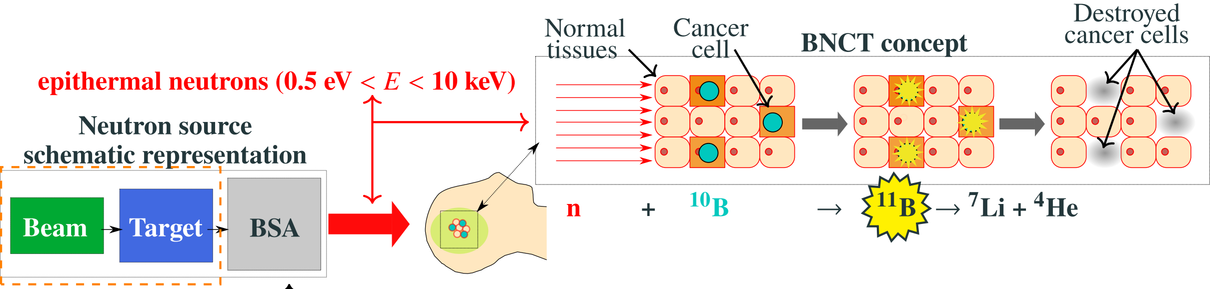
Accelerator-based BNCT neutron sources



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

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

Accelerator-based BNCT neutron sources



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

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

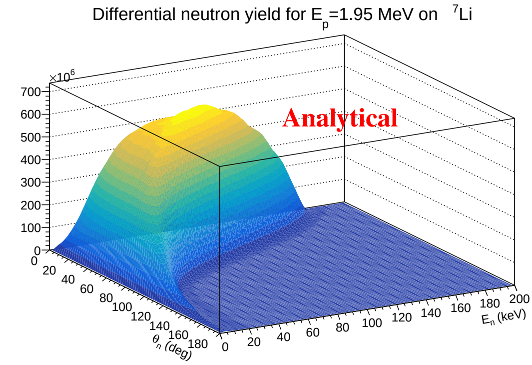
Reaction	Energy (MeV)	Max E_n	Melting Point (°C)	Residual ($T_{1/2}$)
^{7}Li(p,n)^{7}Be	2.3–2.5	∼ hundreds keV	180	^{7}Be (53.2 d)
^{9}Be(p,x)^{9}B	4/5–30	MeV → tens MeV	1210	^{9}B (8×10^{-19} s)

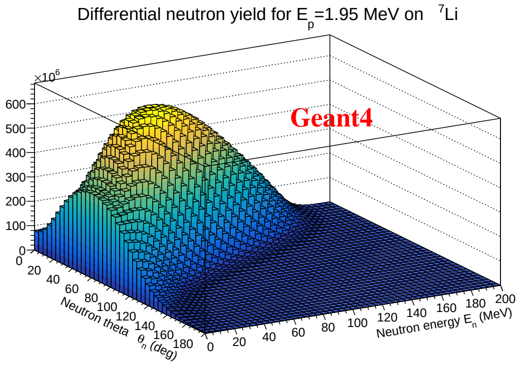
p + ^{7}Li reaction

- 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}

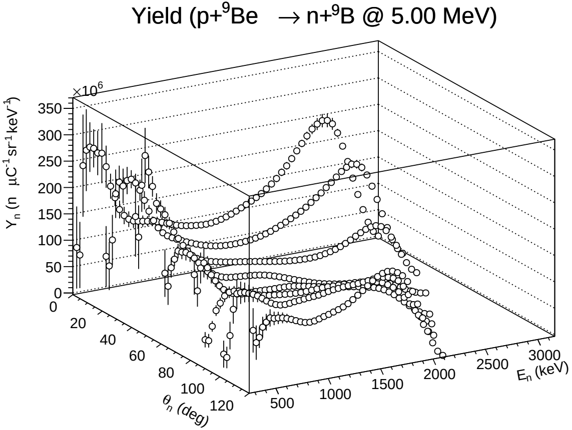




p +^{9}Be, yield data

- 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)	$^{9}\mathbf{B} + \mathbf{n_0}$	-1850.4	2057.4
	$^{9}\mathbf{B}^{*} + \mathbf{n_1}$	-3529.96	3924.62
	$^{9}\mathbf{B}^{*} + \mathbf{n_2}$	-4194.96	4663.97
(p, p′n)	$^{8}\mathbf{Be} + \mathbf{p} + \mathbf{n}$	-1664.54	1850.77
(p, αn)	$^{5}\mathbf{Li} + \alpha + \mathbf{n}$	-3540	3930
(p, p′αn)	$2\alpha + \mathbf{p} + \mathbf{n}$	-1572.70	1748.65

Many open channels!

They all involve the same final state:

$2\alpha + \mathbf{p} + \mathbf{n}$

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

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

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

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

Analytical approach

The basis is the Lee and Zhou formalism:

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

Analytical approach

The basis is the Lee and Zhou formalism:

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

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

Analytical approach

The basis is the Lee and Zhou formalism:

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

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

***k*, *J* and *S* can be evaluated** (J with MC methods for many particles final states).

Analytical approach

The basis is the Lee and Zhou formalism:

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

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

***k*, *J* and *S* can be evaluated** (J with MC methods for many particles final states).

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

Analytical approach

The basis is the Lee and Zhou formalism:

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

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

***k*, *J* and *S* can be evaluated** (J with MC methods for many particles final states).

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.

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)?

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

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

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

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)?

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

assuming isotropic distribution

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

$$X'_{p,p'n} = \frac{X_{p,p'n}}{4\pi}$$

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

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)?

Cross section of (p, p′n) can be derived from the cross sections of (p, xn) and (p,n$_0$).

assuming isotropic distribution

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

$$X'_{p,p'n} = \frac{X_{p,p'n}}{4\pi}$$

$$Y''_{p,p'n} = k \cdot \frac{X'_{p,p'n} \cdot J_{p,p'n}}{S}$$

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

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)?

Cross section of (p, p′n) can be derived from the cross sections of (p, xn) and (p,n$_0$).

assuming isotropic distribution

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

$$X'_{p,p'n} = \frac{X_{p,p'n}}{4\pi}$$

$$Y''_{p,p'n} = k \cdot \frac{X'_{p,p'n} \cdot J_{p,p'n}}{S}$$

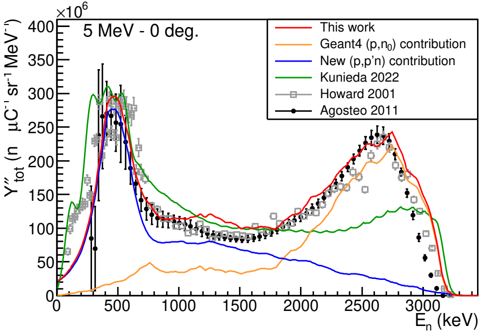
$$Y''_{tot} \approx Y''_{p,n} + \hat{Y}''_{p,p'n} = Y''_{p,n} + Y''_{p,p'n} f_{p,p'n}(\theta_n, E_n).$$

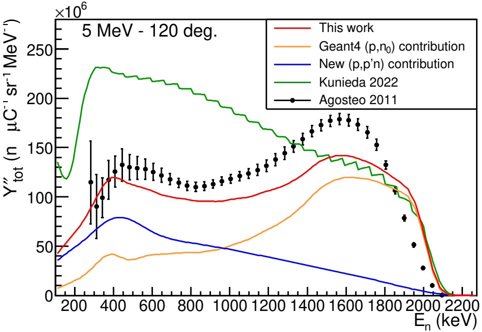
Correction factor to reproduce the realistic angular distribution of (p, p'n): parameters from yield data fitting

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

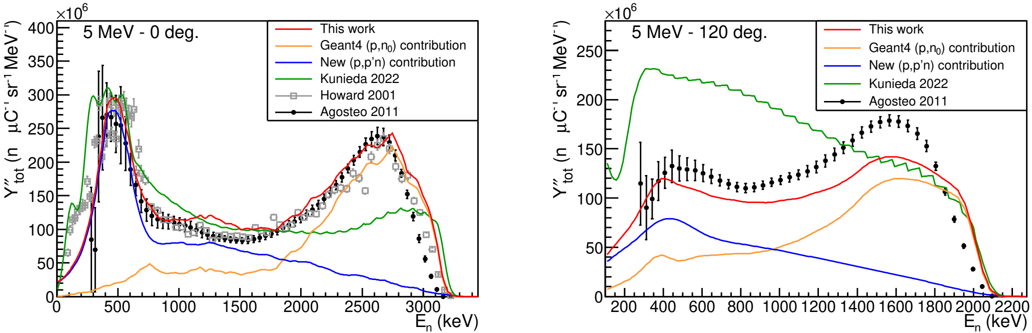
[1] C. Wang and B. Moore, *Thick beryllium target as an epithermal neutron source for neutron capture therapy*, Medical Physics 21(1994)1633.

Results


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


5 MeV - 120 deg.
×10^6
Y''tot (n µC⁻¹ sr⁻¹ MeV⁻¹)
En (keV)
This work
Geant4 (p,n0) contribution
New (p,p'n) contribution
Kunieda 2022
Agosteo 2011
0
50
100
150
200
250
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

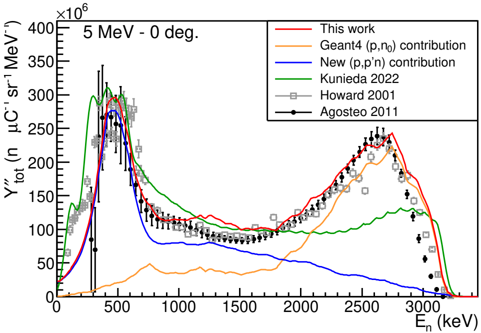
Results

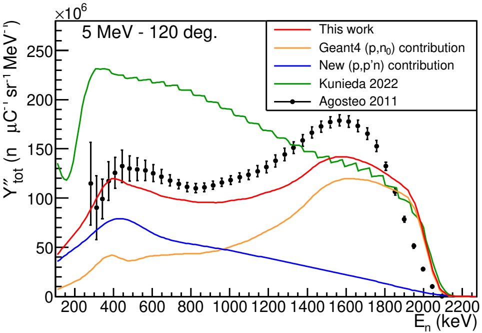


Based on (p,n_0) and $(p,p'n)$ →

Reference	Y_{tot} (n/mC)
This work	$\mathbf{2.96 \times 10^{12}}$
Data from Agosteo	$\mathbf{3.3 - 3.5 \times 10^{12}}$
DROSG2000	1.55×10^{12}
Kunieda 2022	$\mathbf{4.21 \times 10^{12}}$

Results





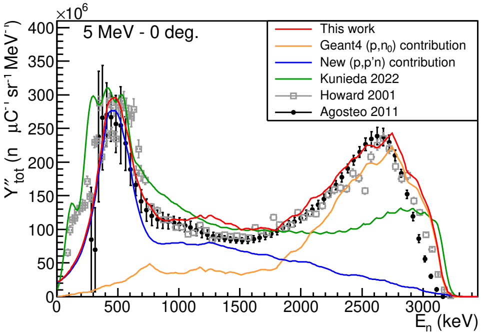
Based on (p,n_0) and (p,p′n) → This work

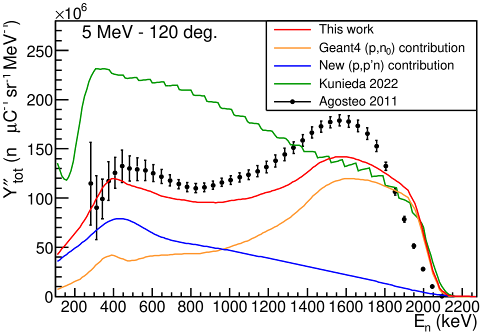
Distributed by IAEA

Based only on (p,n_0) → DROSG2000

Reference	Y_{tot} (n/mC)
This work	**2.96×10^{12}**
Data from Agosteo	**$3.3 – 3.5 \times 10^{12}$**
DROSG2000	1.55×10^{12}
Kunieda 2022	**4.21×10^{12}**

Results





Based on (p,n_0) and $(p,p'n)$

Distributed by IAEA

Based only on (p,n_0)

Reference	Y_{tot} (n/mC)
This work	**2.96×10^{12}**
Data from Agosteo	**$3.3 – 3.5 \times 10^{12}$**
DROSG2000	1.55×10^{12}
Kunieda 2022	**4.21×10^{12}**

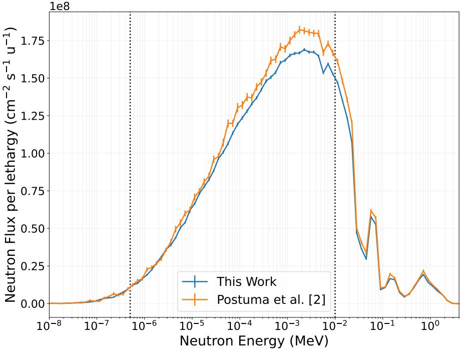
Implemented in JENDL5

Based on (p,n_0), (p,n_2) and (p,n_4)

Beam Shaping Assembly efficacy

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].

[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).

Conclusions

- **Hybrid model:** **inclusion of (p,p′n) channel missing in state-of-art models.**

Conclusions

- **Hybrid model:** **inclusion of (p,p′n) channel missing in state-of-art models.**
- **Neutron source for MC simulation for BCNT applications.**

Conclusions

- **Hybrid model: inclusion of (p,p′n) channel missing in state-of-art models.**
- **Neutron source for MC simulation for BCNT applications.**
- **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).

Conclusions

- **Hybrid model:** **inclusion of (p,p′n) channel missing in state-of-art models.**
- **Neutron source for MC simulation for BCNT applications.**
- **Reassessment of BSA's efficacy proposed in [2].**

Paper submitted!

Next step

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

[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).

Finanziato dall'Unione europea
NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN

Università degli Studi della Campania *Luigi Vanvitelli*

Anthem
AdvaNced Technologies for Human-centEred Medicine

Correction factor parameters

The best values of the parameters have been obtained with a maximum-likelihood fit performed with Minuit in ROOT. The results, including associated uncertainties and units, are reported in Table 2. Parameters listed without uncertainties correspond to values held constant during the fit to ensure convergence.

Parameter	**5 MeV**
p_0 (adim)	0.340 (fixed)
p_1 (adim)	2.018 ± 0.095
p_2 (rad^{-1})	1.228 ± 0.056
p_3 (MeV)	0.450 ± 0.006
p_4 (MeV)	-0.016 (fixed)
p_5 (MeV^2)	0.031 ± 0.002

BSA scheme

From [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).