Advances in neutron source modeling for BNCT applications

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BNCT basic concept

Boron Neutron Capture Therapy (BNCT) targets non-operable or therapy-resistant tumors. A boron drug accumulates in cancer cells, which are then irradiated with **epithermal neutrons.** Neutron capture by boron-10 releases particles (α and ^{7}Li) that destroy the cell while sparing nearby tissue[1]. This requires a neutron beam with a **precise energy spectrum.** Common reactions: **proton beams with ^{7}Li or ^{9}Be as targets. Beryllium** is our choice and will be used in the **upcoming Italy BNCT facility (ANTHEM project)**[2].
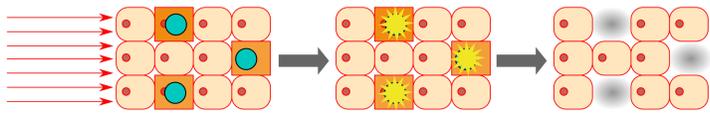
Reaction	Energy (MeV)	Max E_n	Target Melting Point (°C)	Residual ($T_{1/2}$)
^{7}Li(p,n)^{7}Be	2.3–2.5	$\sim$ hundreds keV	180	^{7}Be (53.2 d)
^{9}Be(p,x)^{9}B	4/5–30	MeV → tens MeV	1278	^{9}B (8×10^{-19} s)

Neutrons from p + ^{9}Be reaction @ 5 MeV: a *hybrid model*

A 5 MeV pencil proton beam is directed onto a thick Be target (3 mm radius, 3 mm thickness) to maximize neutron-producing reactions down to threshold. The quantity to consider is the **double differential neutron yield** that depends mainly on: **differential cross sections**, the **phase-space** and **stopping power**.

$$\frac{d^2N}{dE_n d\Omega} = \frac{f_{Be}N_0\rho}{eA} \cdot \frac{\frac{d\sigma}{d\Omega_{cm}} \cdot \frac{d\Omega_{cm}}{d\Omega}\frac{dE_p}{dE_n}}{-\frac{dE_p}{dx}} \equiv Y'' = k \cdot \frac{X' \cdot J}{S}$$
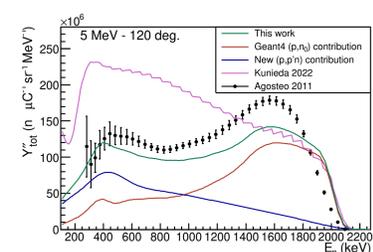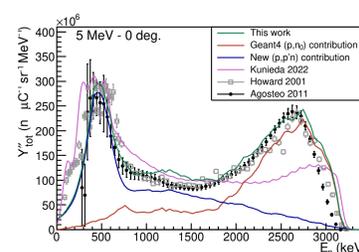
At 5 MeV **several reaction channels** are open, producing different residual nuclei that lead to the same final state: p + n + 2α. Therefore, we have to evaluate the following sum:

$$Y''_{tot} = Y''_{p,n} + Y''_{p,p'n} + Y''_{p,p'\alpha n} + Y''_{p,\alpha n}$$

The differential and total cross sections are available only for (p,n$_0$) and (p,xn). ⇒ **hypothesis of 2 dominant channels**[3]: (p,n$_0$) and (p,p'n). We use TENDL-2023 cross section for (p, n$_0$) and derive the (p, p'n) cross section as follows:

$$X_{p,p'n} = X_{tot} - X_{p,n} \quad \rightarrow \quad X'_{p,p'n} = \frac{X_{p,p'n}}{4\pi} \quad \rightarrow \quad Y''_{p,p'n} = k \cdot \frac{X'_{p,p'n} \cdot J_{p,p'n}}{S}$$

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

Integrating over solid angle and energy we obtain the **total neutron yield**, as **reported in the table.**

Reference paper

| 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}

Conclusions: the proposed hybrid model gives a **significant improvement** with respect to the other currently available models ⇒ **new reference**[4]. In this study we also validated the efficacy of a Beam Shaping Assembly proposed in a previous study[5].

Theoretical study of p + ^{9}Be–^{7}Li reaction @ 5 MeV

- A **150 μm** ^{9}Be target leaves protons still above threshold. **Concept: exiting protons** enter Li → **extra neutrons. Straggling considered** at Be exit and Li entrance[6]:

$$\left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^9Be(p,xn)} = \left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^9Be} \left(\frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left(\frac{E_p - \langle E_{out}\rangle}{\sqrt{2}\,\sigma}\right)\right)$$

$$\left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^7Li(p,xn)} = \left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^7Li} \left(\frac{1}{2} - \frac{1}{2}\,\mathrm{erf}\left(\frac{E_p - \langle E_{out}\rangle}{\sqrt{2}\,\sigma}\right)\right).$$
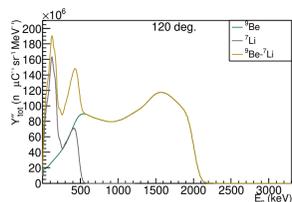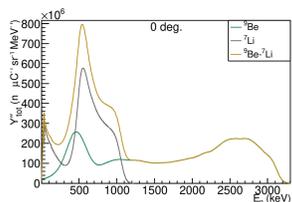
Total neutron yield from $d\Omega$ and dE_n integration.

Target	Y_{tot} (n/mC)
Be	2.82×10^{12}
Li	1.23×10^{12}
Be–Li	4.05×10^{12}

- **Be thickness varied** around 150 μm (circled point) to reflect realistic fabrication fluctuations (in range **120—180 μm**)
- Study done to assess this impact on Be––Li target performance, keeping **Li thick enough** to exploit protons to threshold.
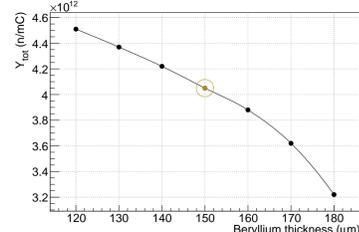

Evaluation of Be–Li Target Performance: Assessed using a previously published BSA[5]; Compared IAEA FOMs in air and dosimetric FOMs in a Snyder phantom.

Key Findings:
- ► **Total neutron flux increase of $\sim$50%** (bottom left for the 130 μm Be layer case).
- ► **Fast-neutron contribution remains stable** between 120 μm and 140 μm, the most relevant contribution for normal-tissue dosimetry (bottom right, circled region).

A bilayer target enhances BNCT robustness against thickness variations while maintaining competitive clinical performances.
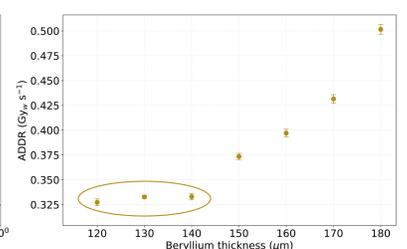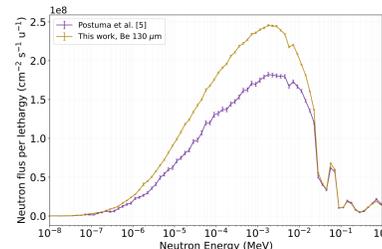

⇒ **Further work** on mechanical/thermal behaviour is required to **determine** the **maximum sustainable current** of the composite target.

⇒ **Additional Monte Carlo studies** are needed to model realistic beam profiles and **engineered target geometries.**

Neutron sources without Beam Shaping Assembly

We investigated the feasibility of BNCT-relevant neutron sources without a Beam Shaping Assembly by surveying different near-threshold reactions.

- We found critical error in a recent study on p+^{45}Sc reaction[7]: → **missing degree–to–radians conversion in the yield calculation.**
- impact visible below (different y-scale): the original distribution (left) versus the corrected one (right) → **yield overestimation by $180/\pi$** (1.4×10^6 vs 2.4×10^4).
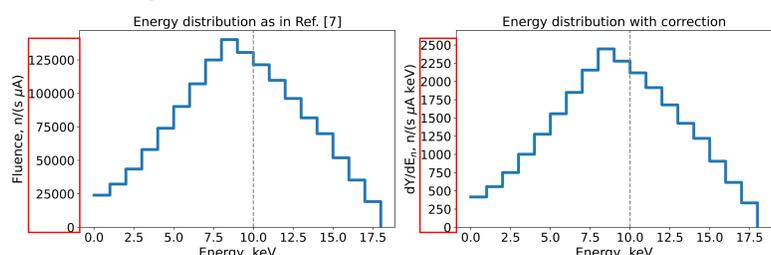
⇒ **new dosimetric calculations needed** starting with correct yield.

Computational developments in Geant4

We developed an **extension of General Particle Source (GPS):**

- ► new class `G4SPSAngEneDistribution`: sampling of 2D correlated angle–energy
- ► new macro command `/gps/hist2d <filename>` for importing externally generated spectra while preserving native correlations.

The tool has been **validated using our hybrid-model** neutron results and **cosmic-ray spectra** from EXPACS[8], and is planned for inclusion in a future Geant4 release.

Work carried out within the **Geant4INFN project**; testing and manuscript preparation are ongoing.

References

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