

# Neutron and photon yields for the $^{51}\text{V}(\text{p},\text{n})^{51}\text{Cr}$ reaction near threshold

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Accelerator and Research reactor Infrastructures for  
Education and Learning

**ARIEL**



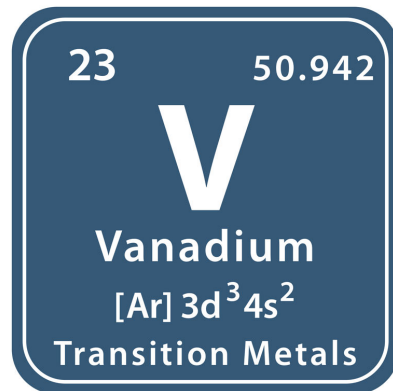
# Introduction

## Natural Vanadium

V-51 99.75%  
Stable

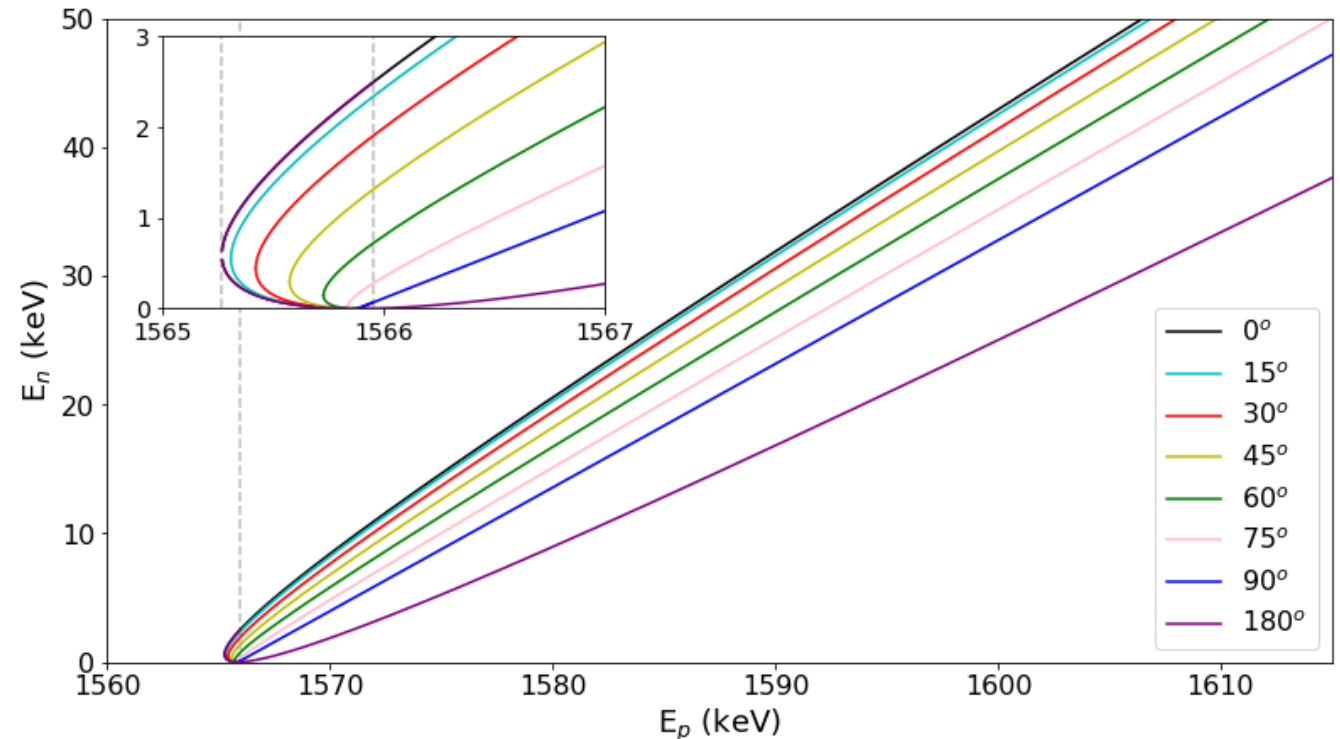
V-50 0.25%  
 $t_{1/2} = 1.5 \cdot 10^{17} \text{ y}$

High melting point and conductivity

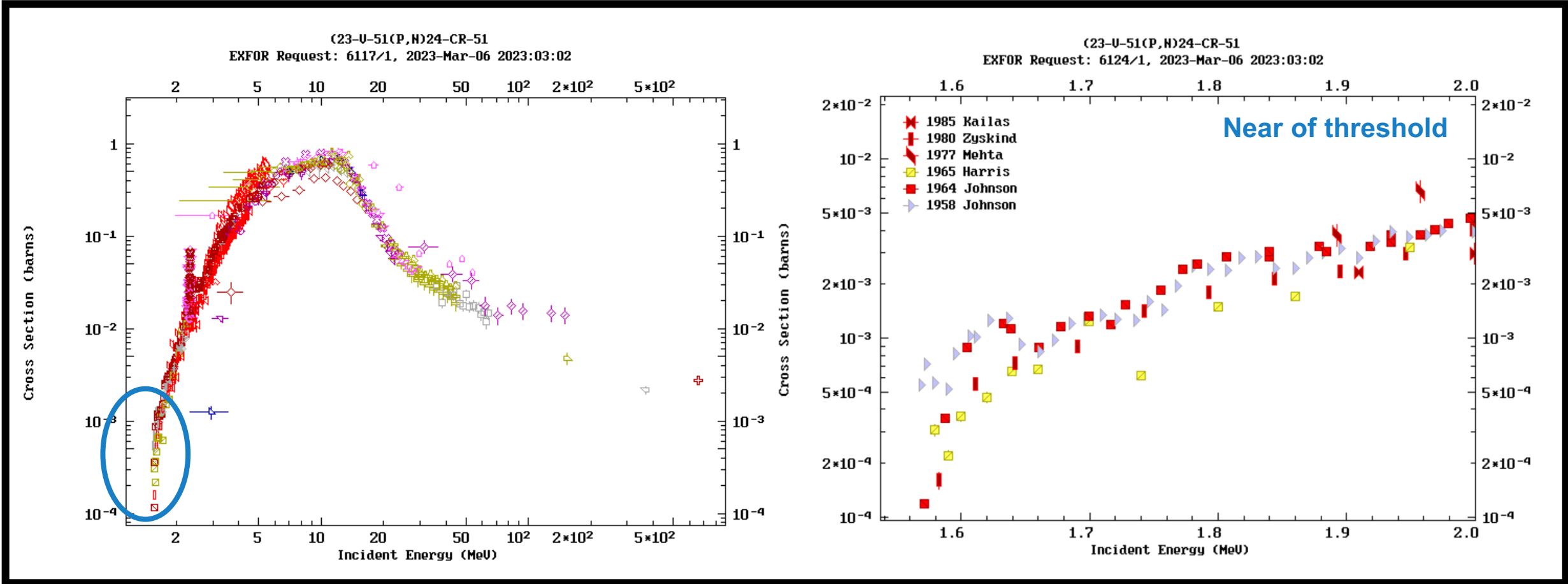


$$Q = -1534.92 \text{ keV}$$
$$E_{th} = 1565.28 \text{ keV}$$

Monoenergetic source for various applications, keV region



# Background: Cross section data



# Background: Main motivations



- ☐ Lack of data.
- ☐ Possible application to nuclear astrophysics: to be studied.
- ☐ The employment of the reaction as a useful monoenergetic neutron source at low energies.
- ☐ Use for medical applications. **We propose to study the near-threshold  $^{51}\text{V}(\text{p},\text{n})^{51}\text{Cr}$  reaction as a neutron source for Boron Neutron Capture Therapy.**

# Background: BNCT

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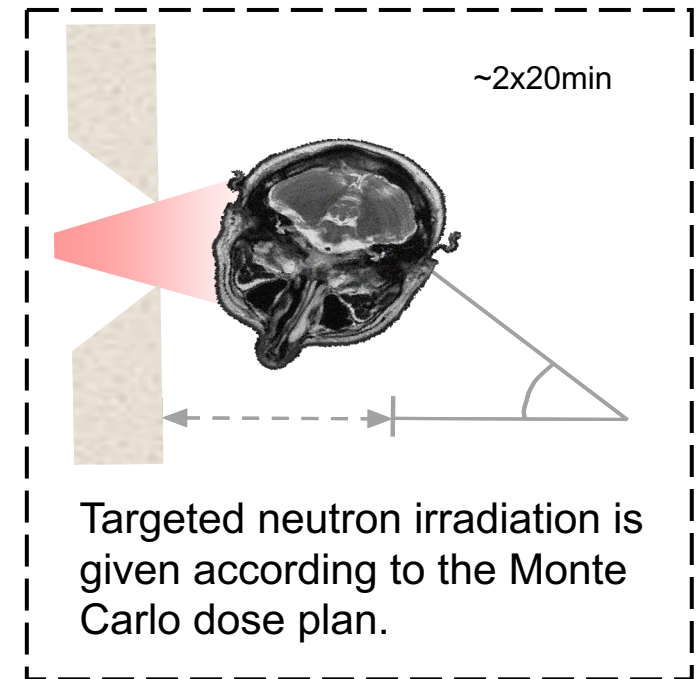
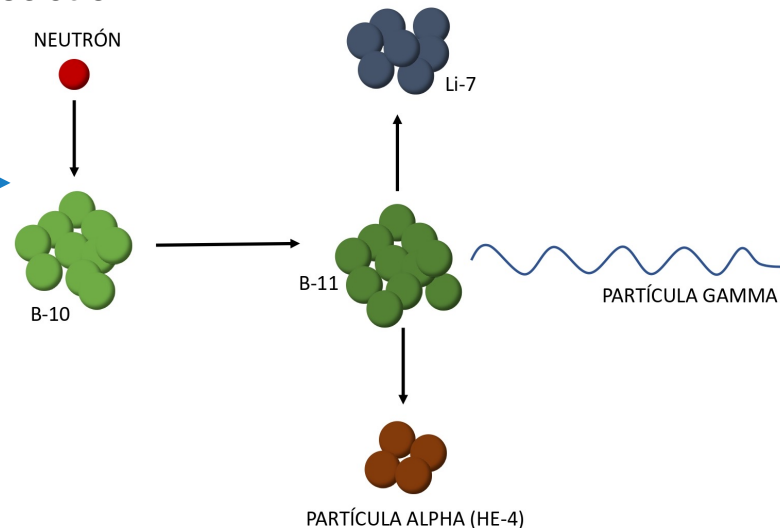


**Boron Neutron Capture Therapy (BNCT)** is an experimental binary radiation therapy design for treating highly resistant tumors. **One day of treatment.**

1. A stable isotope,  $^{10}\text{B}$ , is **injected into the patient**, accumulating in cancer cells.



2. Tumor region is irradiated with epithermal neutrons, inducing (n, $\alpha$ ) reaction in  $^{10}\text{B}$ .

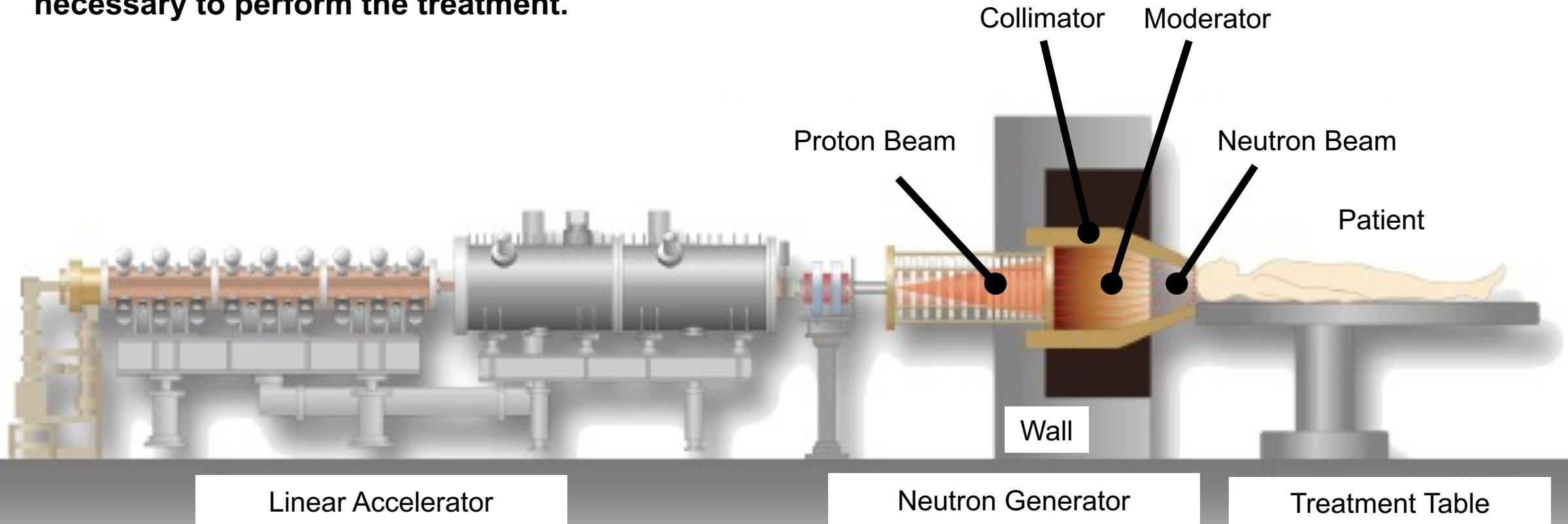


# Background: BNCT

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An epithermal neutron source is necessary to perform the treatment.



# Background: BNCT

## BNCT Neutron Sources Criteria

✓  $^{51}\text{V}(\text{p},\text{n})^{51}\text{Cr}$   
around 1596 keV

Reference magnitude	Limit	Neutrons	Energy range
$\Phi_{\text{epi}} (\text{cm}^{-2}\text{s}^{-1})$	$\geq 10^9$	Thermal	0.025-500 eV
$\Phi_{\text{epi}} / \Phi_{\text{th}}$	$\geq 100$	Epithermal	0.5-10 keV
$\Phi_{\text{epi}} / \Phi_{\text{fast}}$	$\geq 20$	Fast	>10 keV
$D'_{\text{n(fast)}} / \Phi_{\text{epi}} (\text{Gy cm}^2)$	$\leq 2 \cdot 10^{-3}$		
$D'_{\text{gamma}} / \Phi_{\text{epi}} (\text{Gy cm}^2)$	$\leq 2 \cdot 10^{-3}$		

In discussion:  
0.5 - 20 keV

- What is the most accurate cross-section value of the  $^{51}\text{V}(\text{p},\text{n})^{51}\text{Cr}$  reaction at  $E_p$  near the threshold?
- Is the neutron yield enough to use existing accelerators as a neutron source? And if so, what does the neutron spectra look like?
- Is the neutron field adequate for BNCT?
- What is the photon yield at a given  $E_p$  ?

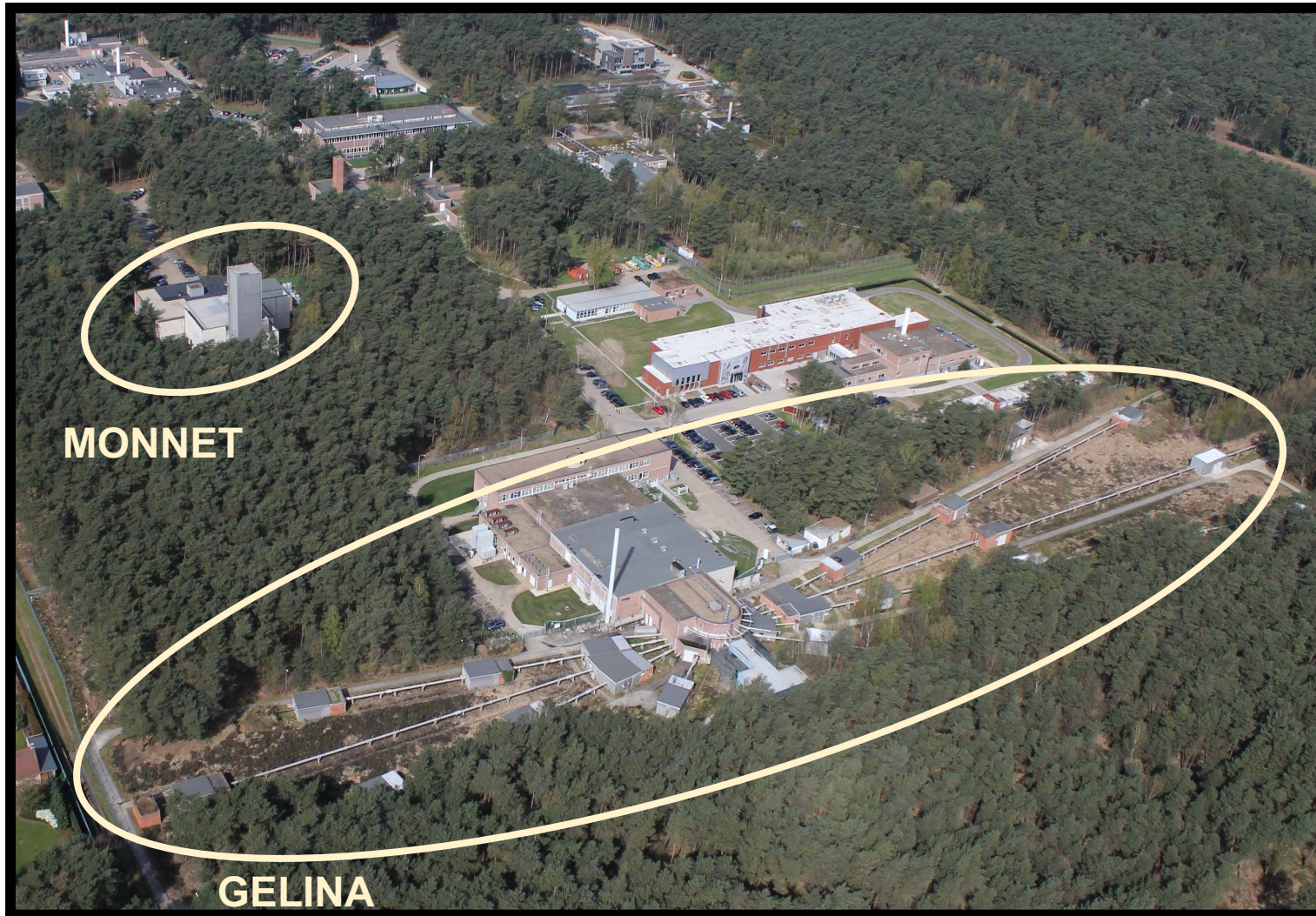
# Goals of the proposal



- ☐ To measure the well-known  ${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$  reaction at 1912 keV:
  - ☐ To check the setup.
  - ☐ To check the analysis.
  - ☐ To use it as additional **reference** for the neutron yield of the  ${}^{51}\text{V}(\text{p},\text{n}){}^{51}\text{Cr}$  reaction.
- ☐ To measure and determine via time-of-flight technique the most adequate proton energy beam for the  ${}^{51}\text{V}(\text{p},\text{n}){}^{51}\text{Cr}$  reaction. It should be at **AROUND 1596 keV**.
- ☐ To measure the  ${}^{51}\text{V}(\text{p},\text{n}){}^{51}\text{Cr}$  reaction near threshold via activation method of gold samples, to know the forward neutron yield, and to measure the Chromium-51 decay itself.
- ☐ To measure the forward **photon yield** and the selected proton energy.

# The perfect facility: MONNET

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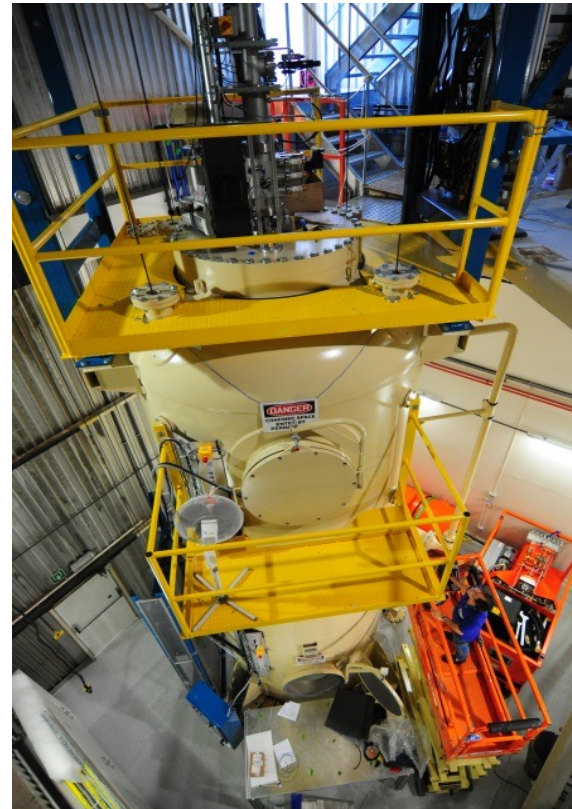


## Neutron facilities at JRC-GEEL

MONNET  
(MONo energetic Neutron Tower)

The tandem accelerator based fast neutron source (MONNET) is a 3.5 MV electrostatic accelerator for the production of continuous and pulsed proton-, deuteron- and helium ion beams

- Protons, deuterons and alpha particles
- DC ( $I_{p,d} < 50 \mu\text{A}$ )
- Pulsed beam available (1 – 2 ns)
- Energy range: 200 keV – 7 MeV

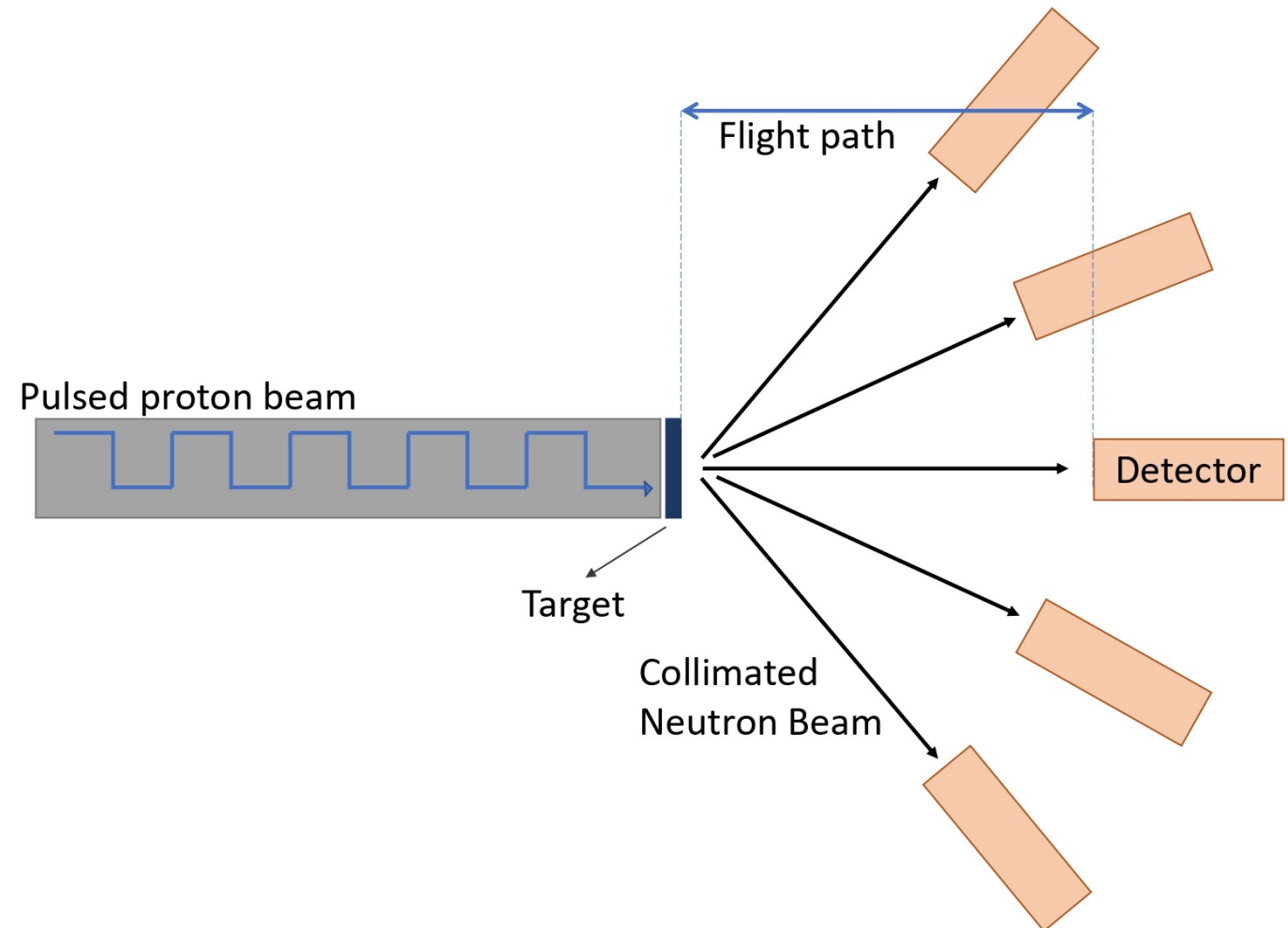


# Description of the work

## Time of flight measurement;

- Proton beam at ~1596 keV
- Pulse width 1 – 2 ns
- V thick target
- $^6\text{Li}$ -glass detectors
- Flight path 25 – 100 cm
- Measurement by TOF at 0 to 90 degrees
- Repetition Rate 312.5 or 625 kHz

$^7\text{Li}(p,n)^7\text{Be}$  at 1912 keV as reference



# Description of the work



## Measurement of the threshold;

- By irradiating vanadium targets over the proton energy of range of 1560 to 1600 keV, thick target yields will be measured using the generated Cr-51 activity.
- Gold foils will be activated with the neutron field generated by the  $^{51}\text{V}(\text{p},\text{n})^{51}\text{Cr}$  reaction at a proton energy of about half keV above the reaction threshold.

## Photon yield;

Photon yield will be obtained in a conventional setup for the activation technique.

- NaI or LaBr3 detector during the bombardment of V target with continuous proton beam.
- HPGe detector to measure the later decay of the produced Cr-51.

### Cr - 51

$t_{1/2} = 27 \text{ d}$

Gamma  
particle of  
320.1 Kev

# Conclusions



The characterization of the neutron and photon yields of the reaction  $^{51}\text{V}(p,n)^{51}\text{Cr}$  at energies close to the threshold will be performed in the JRC-MONNET facility this year.

The main objective of this characterization is the use of the vanadium neutron source due to the lack of data on angle-energy yields. Possible applications will be for monoenergetic neutron beams, validation of nuclear data and neutron capture therapy.

The complete experiment, with the time-of-flight and activation measurements, is intended to be part of my training as PhD student and early researcher. Since, the study of this reaction is the major part of my PhD Thesis. ARIEL has granted funding for the experiment and also for a 12-week stay in the JRC-Geel.

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## Thanks for your attention!

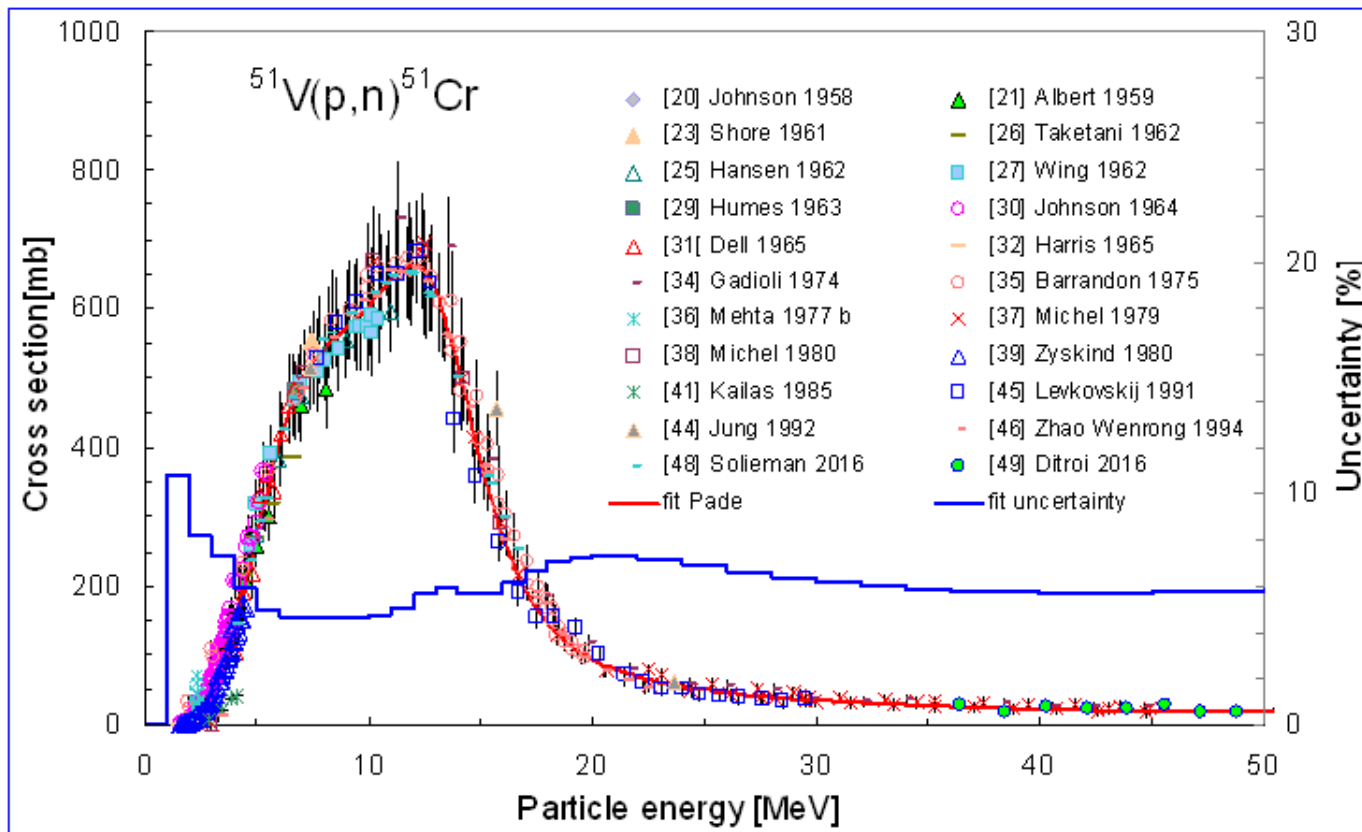
[averdera@ugr.es](mailto:averdera@ugr.es)

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# New cross section data

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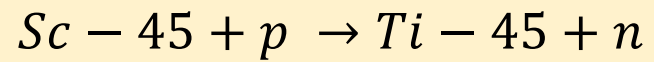


<https://www-nds.iaea.org/medical/v1p51cr0.html>

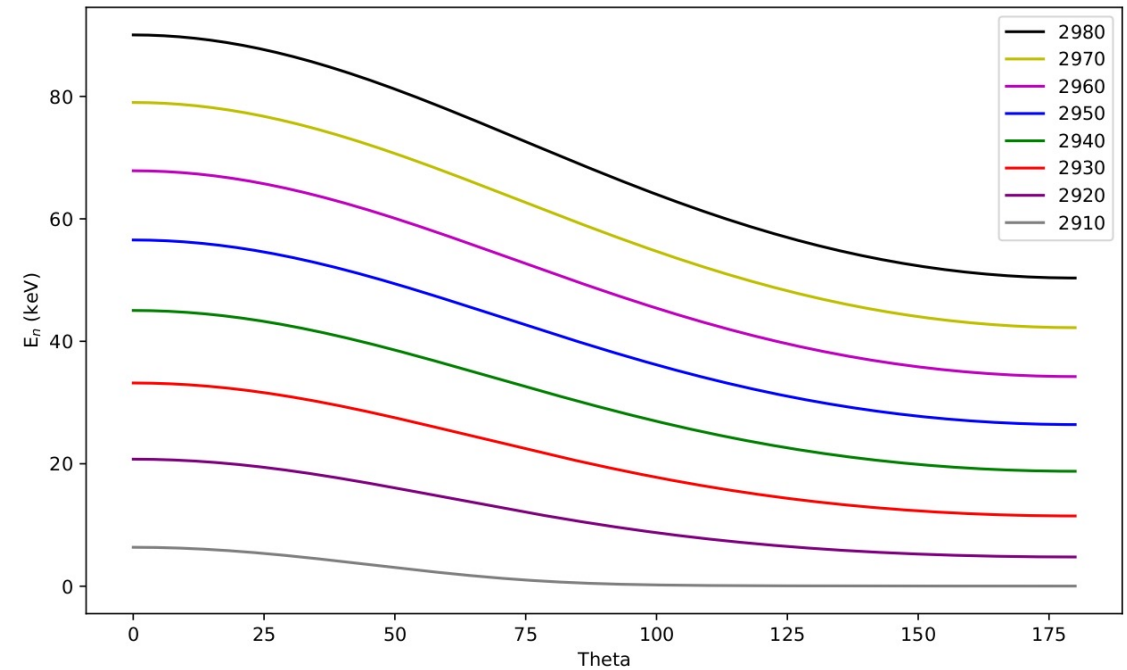
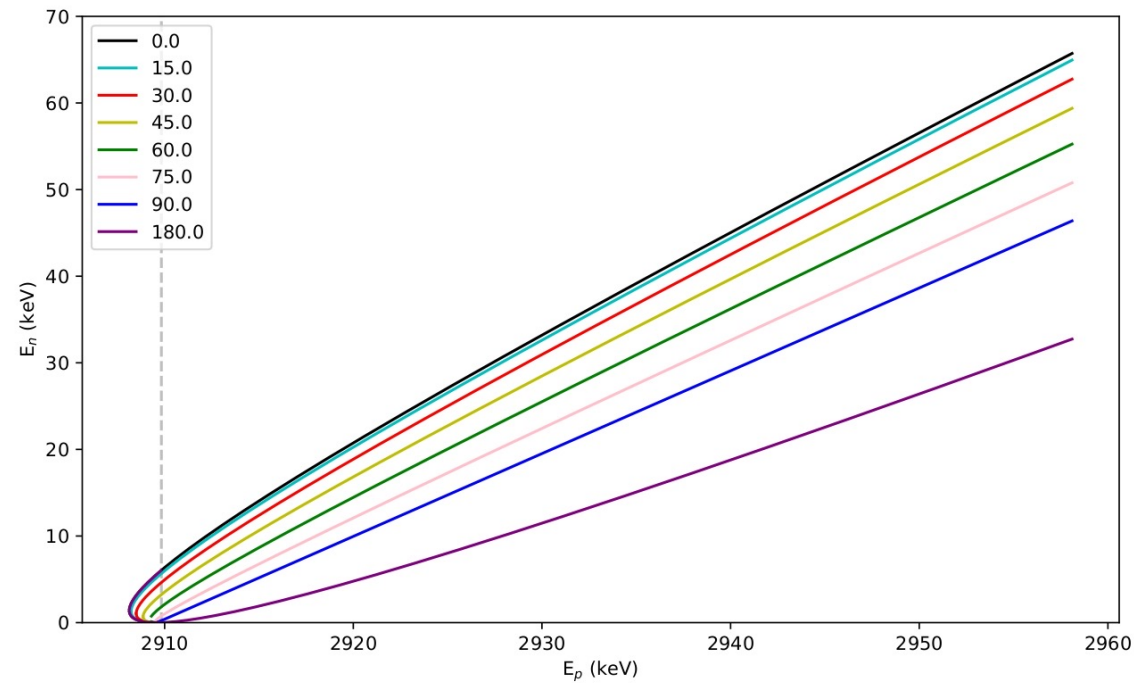
Tabulated cross section has an energy range of 1.6 to 50 MeV

# A similar reaction: $^{45}\text{Sc}(p,n)^{45}\text{Ti}$

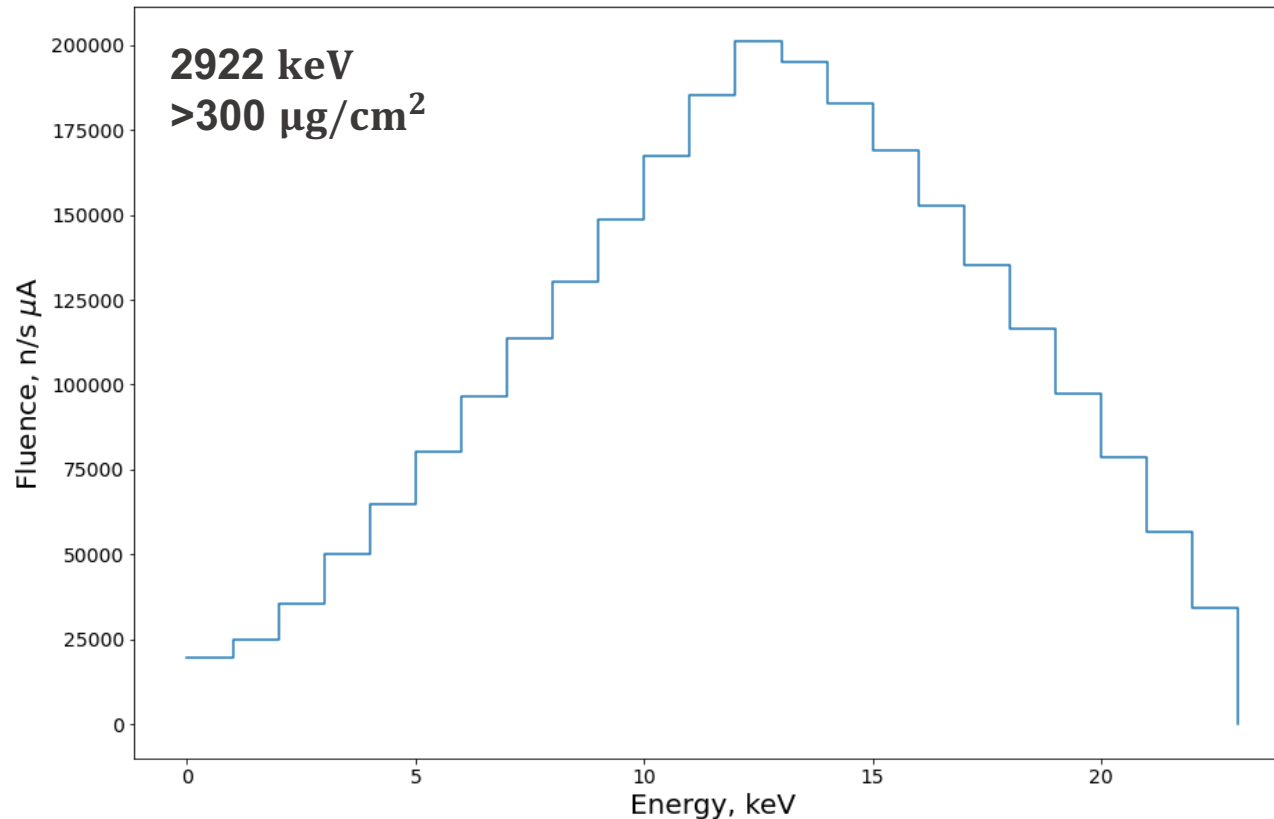
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$$Q = -2844.4 \text{ keV} \quad E_{th} = 2908.2 \text{ keV}$$



# A similar reaction: $^{45}\text{Sc}(p,n)^{45}\text{Ti}$



	CRITERIA	2922 keV ( $>300 \mu\text{g}/\text{cm}^2$ )
$\phi_T$	$> 10^9 n_{epi}/\text{cm}^2\text{s}$	2516064 n/(s $\mu\text{A}$ )
$\phi_{epi}/\phi_T$ (%)	-	98.63
$\phi_{epi}/\phi_{fast}$	$> 20$	26.77
$\phi_{epi}/\phi_{thermal}$	$> 100$	122.62
$J_n/\phi_{epi}$	$> 0.7$	1.04
$\dot{D}_{fast}/\phi_{epi}$	$< 2 \cdot 10^{-13}$	$5.28 \cdot 10^{-30}$
$\dot{D}_\gamma/\phi_{epi}$	$< 2 \cdot 10^{-13}$	$1.01 \cdot 10^{-17}$

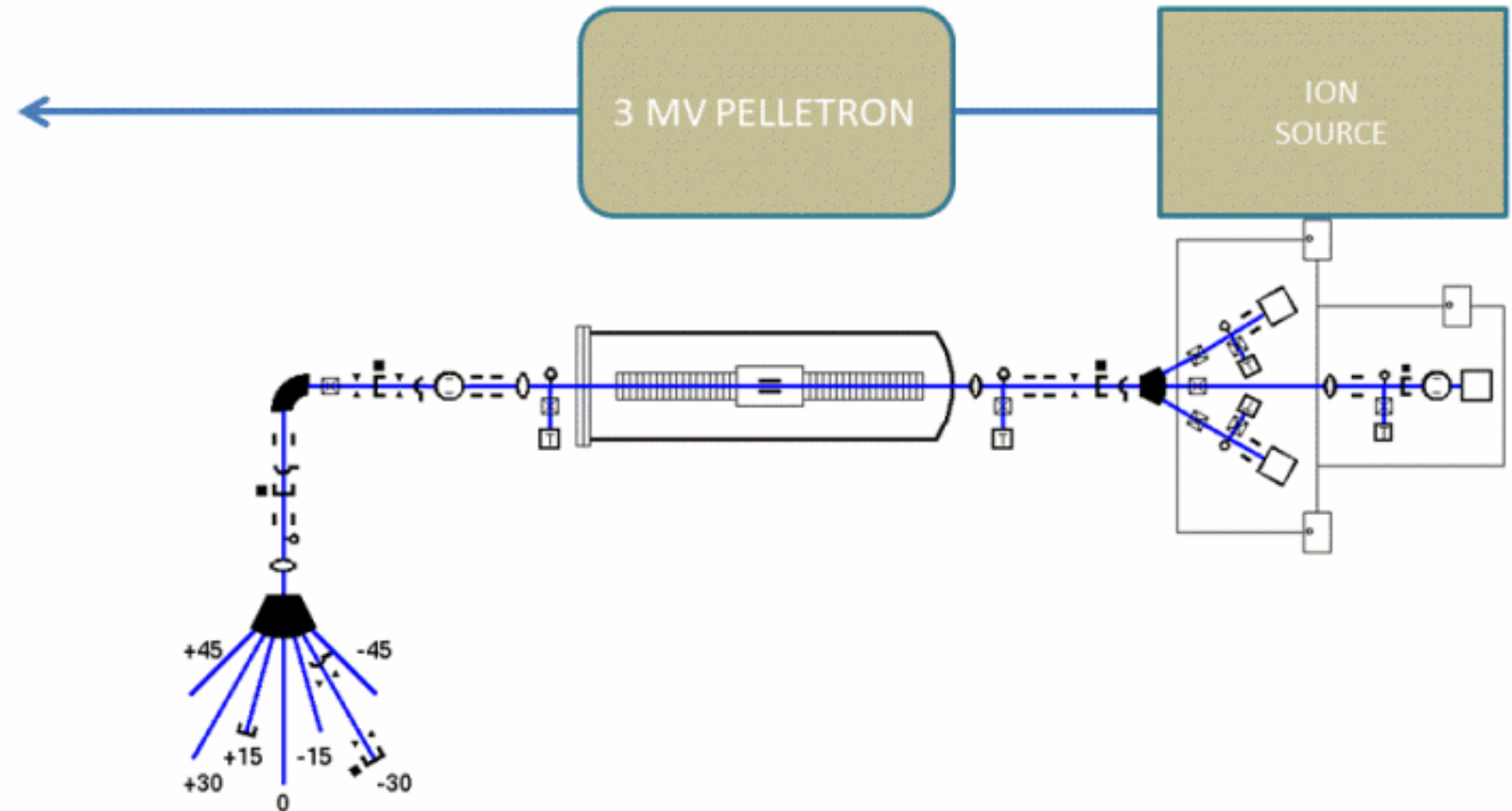
# Our team's previous experience



**CNA:** Centro Nacional de  
Acceleradores, Sevilla

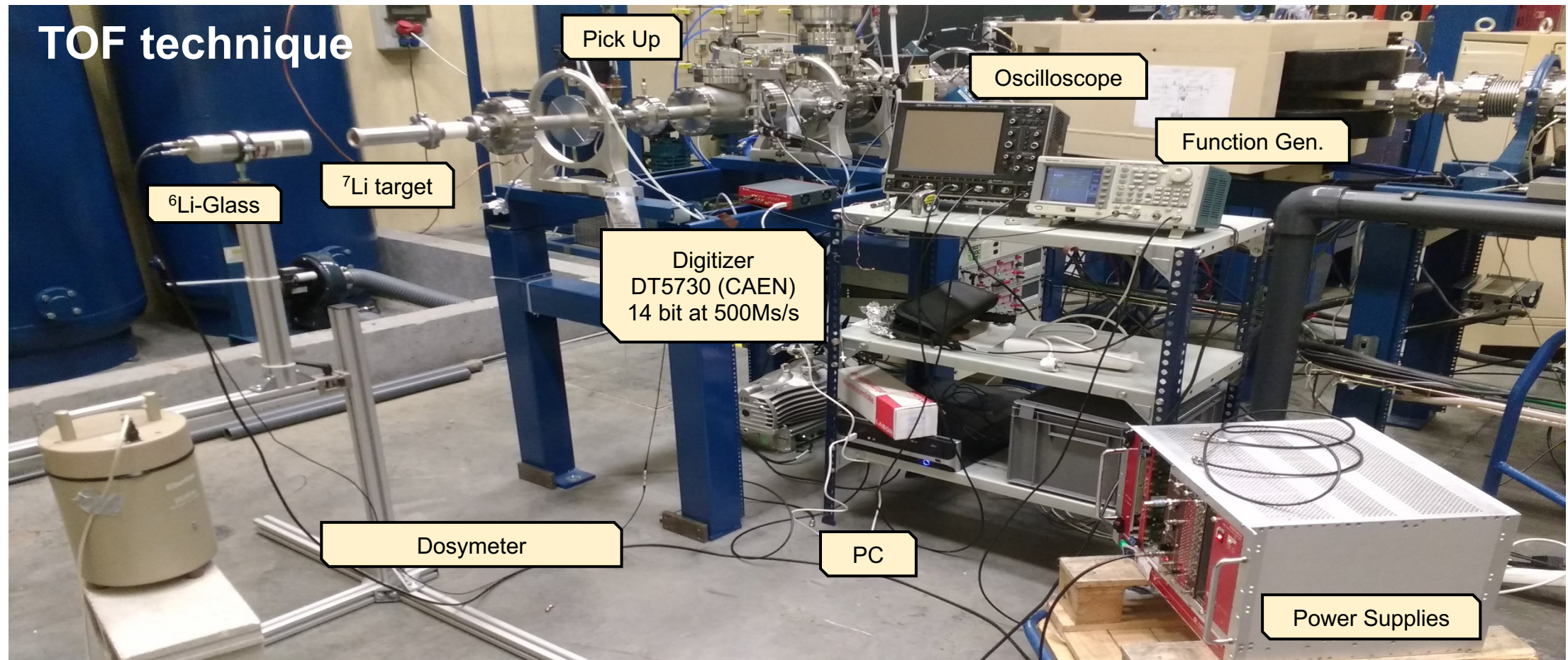
**Miguel Macías Thesis**  
**HiSPANoS (HiSPALis**  
**Neutron Source) at CNA:**  
installation and  
commissioning of the first  
neutron time of flight  
beamline in Spain

**Supervisors: J. Praena**  
**And B. Fernández**



# Our team's previous experience

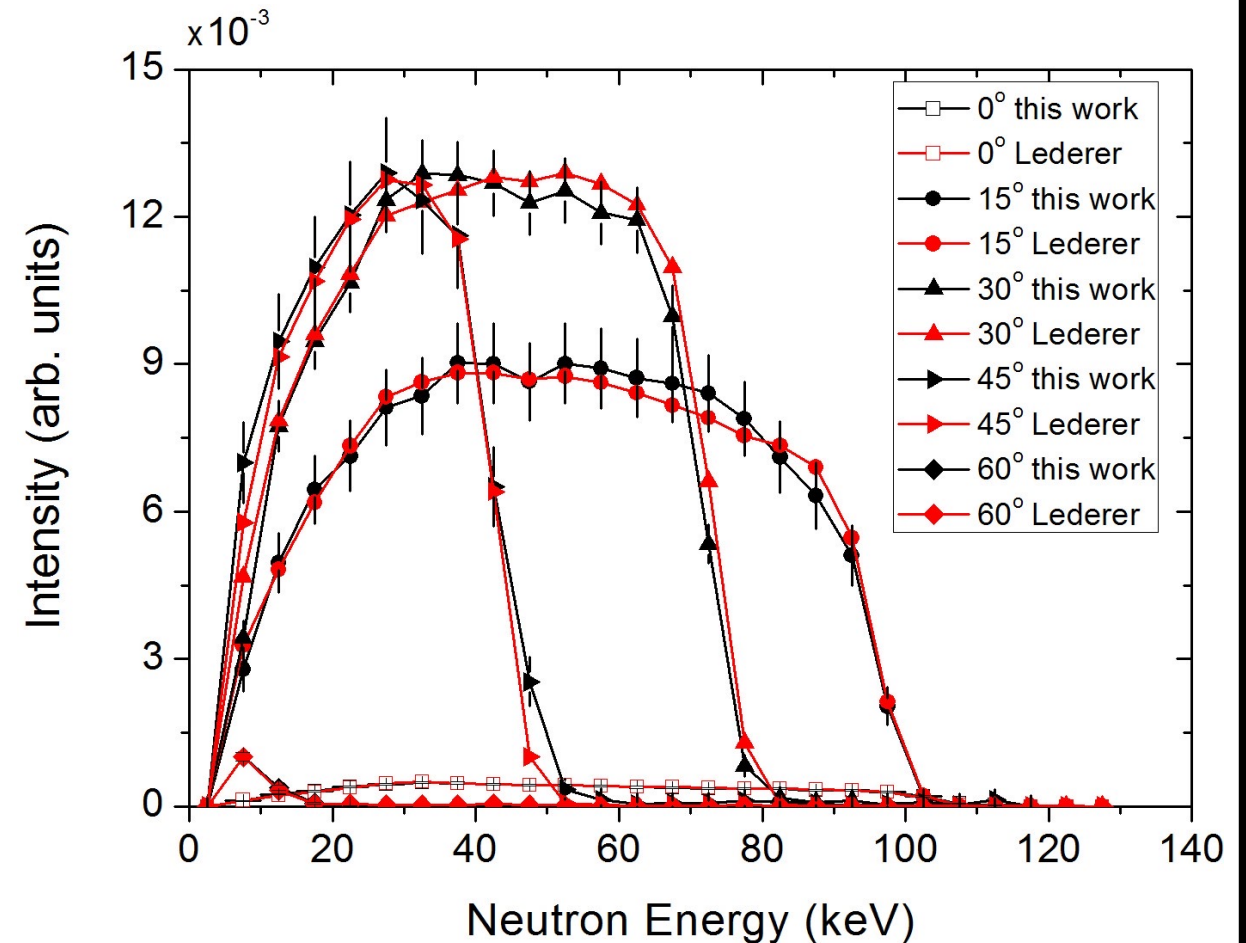
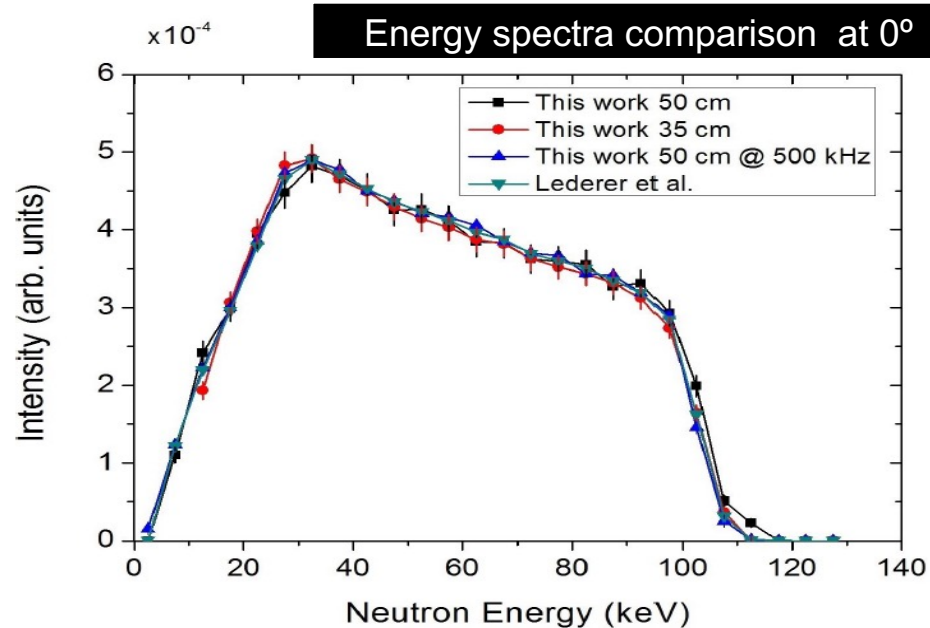
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# Our team's previous experience



## TOF technique ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction



# More about BNCT

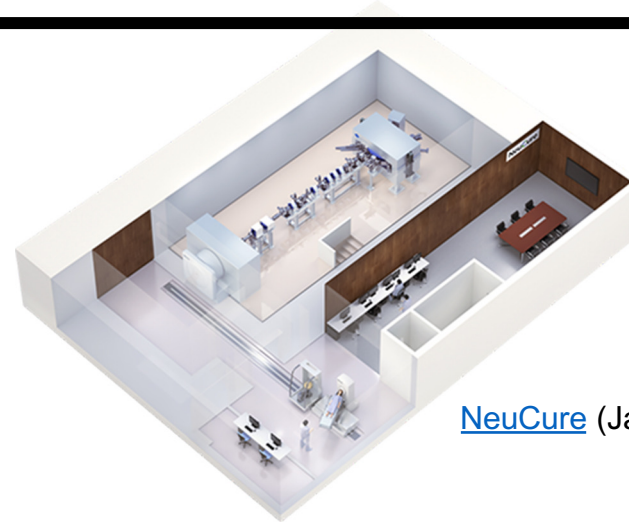
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A **neutron beam** is necessary to perform the treatment:

- ❑ **Nuclear reactors:** has been the only way for a long time, limiting the therapy potential:
  1. Logistic problems.
  2. Not optimized neutron beam.
- ❑ **Accelerator-Based** neutron sources for NCT:
  1. Open the possibility to implement this therapy in hospitals.
  2. Development in Russia, Italy, UK, Israel, Japan, Argentina, China or Finland.
  3. From reactor beams to more versatile and safety AB-BNCT beams.

**NeuCure and NeuBoron already working**



[NeuCure](#) (Japan)



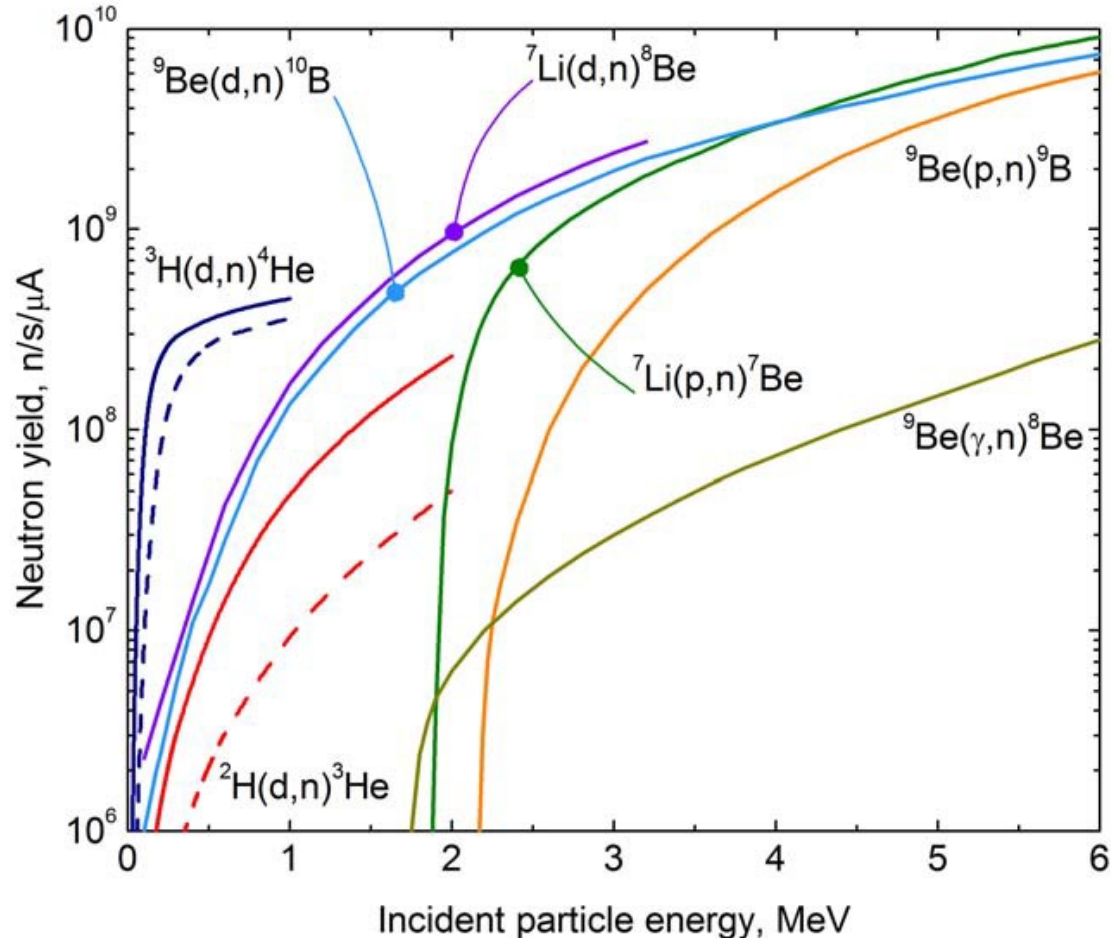
[NeuBoron](#) (China)



[Neutron Therapeutics](#) (Finland)

# More about BNCT

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## Current production reactions for BNCT

Reaction	Q Value [MeV]	Threshold Energy [MeV]	Minimum Product Energies [MeV]
${}^2\text{H}(d,n){}^3\text{He}$	+3.269	NA	${}^3\text{He}$ : 0.82   n: 2.45 *
${}^3\text{H}(d,n){}^4\text{He}$	+17.589	NA	${}^4\text{He}$ : 3.54   n: 14.05
${}^7\text{Li}(p,n){}^7\text{Be}^\dagger$	-1.644	1.880	${}^7\text{Be}$ : 0.21   n: 0.03
${}^7\text{Li}(d,n){}^8\text{Be}$	+15.031	NA	${}^8\text{Be}$ : 1.68   n: 13.35
${}^9\text{Be}(p,n){}^9\text{B}$	-1.850	2.057	${}^9\text{B}$ : 0.18   n: 0.023
${}^9\text{Be}(d,n){}^{10}\text{B}$	+4.361	NA	${}^{10}\text{B}$ : 0.40   n: 3.96

# More about BNCT



Institute	Accelerator	Beam energy	Intensity	Reaction	Max. n energy
Kyoto Univ, Japan (in clinical trials)	Cyclotron	30 MeV	1 mA	$^9\text{Be}(p,n)$	28 MeV
Helsinki Univ. Cent. Hospital, Finland	Electrostatic (Hyperion)	2.6 MeV	30 mA	$^7\text{Li}(p,n)$	0.89 MeV
Budker Institute, Novosibirsk, Russia	Vacuum insulated Tandem	2.5 MeV	2 mA	$^7\text{Li}(p,n)$	0.79 MeV
IPPE Obninsk, Russia	Cascade generator KG-2.5	2.3 MeV	3 mA	$^7\text{Li}(p,n)$	0.57 MeV
Birmingham Univ., UK	Electrostatic (Dynamitron)	2.8 MeV	1 mA	$^7\text{Li}(p,n)$	1.1 MeV
Tsukuba Univ., Japan	RFQ-DTL <sup>a</sup>	8 MeV	10 mA	$^9\text{Be}(p,n)$	6.1 MeV
CNEA Bs. As., Argentina	Tandem Electrostatic. Quadrupole	1.4 MeV 2.5 MeV	30 mA 30 mA	$^9\text{Be}(d,n)$ $^7\text{Li}(p,n)$	5.7 MeV 0.79 MeV
INFN, Italia	RFQ <sup>a</sup>	5 MeV	50 mA	$^9\text{Be}(p,n)$	3.1 MeV
SOREQ, Israel	RFQ-DTL <sup>a</sup>	4 MeV	2 mA	$^7\text{Li}(p,n)$	2.3 MeV
LBNL, USA	Electrostatic	2.5 MeV	50 mA	$^7\text{Li}(p,n)$	0.79 MeV
National Cancer Center, Japan	RFQ <sup>a</sup>	2.5 MeV	20 mA	$^7\text{Li}(p,n)$	0.79 MeV
Xiamen Humanity Hospital, China	Electrostatic (VITA)	2.5 MeV	10 mA	$^7\text{Li}(p,n)$	0.79 MeV
Nagoya Univ., Japan	Electrostatic (Dynamitron)	2.8 MeV	15 mA	$^7\text{Li}(p,n)$	1.1 MeV
Gachon Univ. Gil Med. Center, S.Korea	RFQ-DTL <sup>a</sup>	10 MeV	8 mA	$^9\text{Be}(p,n)$	8.1 MeV
Southern Tohoku Hosp, Fukushima, JP	Cyclotron	30 MeV	1 mA	$^9\text{Be}(p,n)$	28 MeV
Granada Univ., Spain	Electrostatic (Hyperion)	2.1 MeV	30 mA	$^7\text{Li}(p,n)$	0.35 MeV

## Current projects