Proposed fast neutron beam facility at VECC and its possible applications

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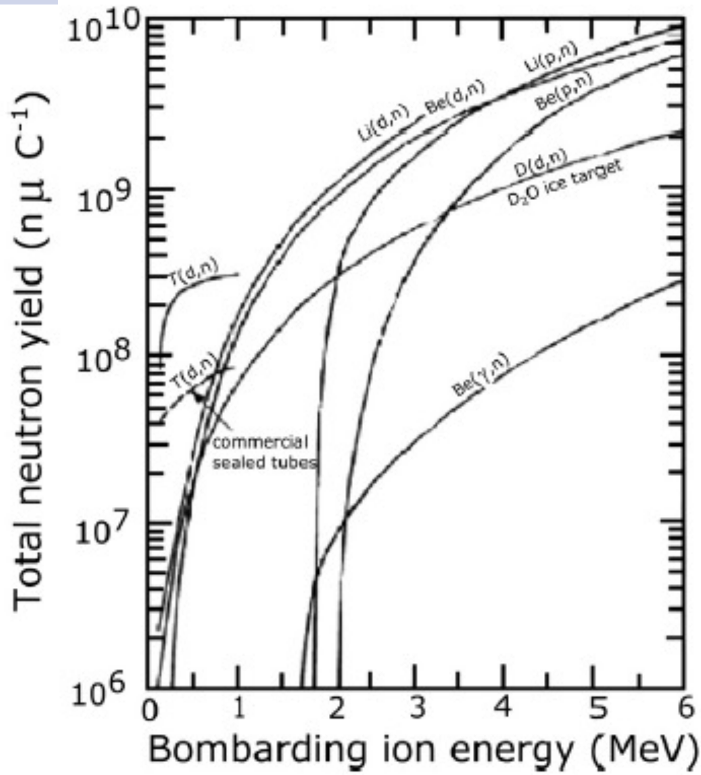
Variable Energy Cyclotron Centre

- Proton accelerator based neutron source
- Existing/Upcoming facilities in the world
- Applications: Basic and applied
- Possible facility layout
- Neutron beam characteristics
- Electron Linac based neutron source

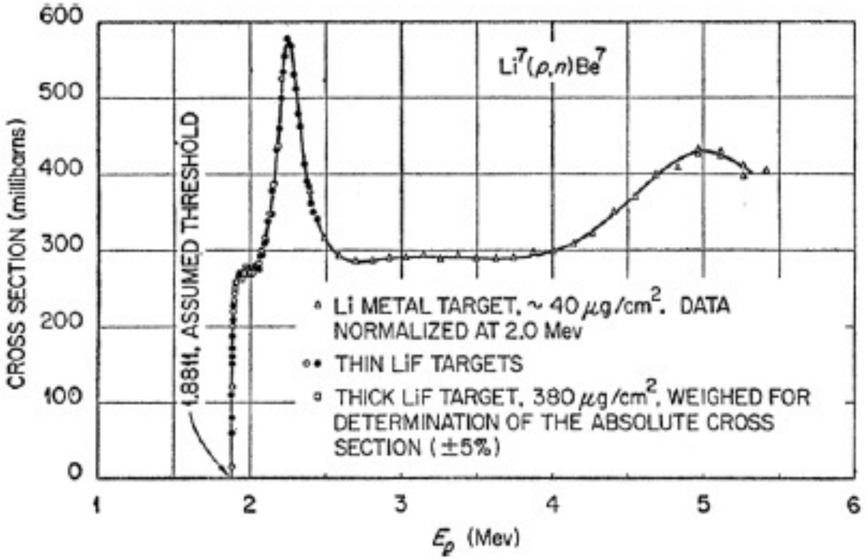
Some useful neutron generating reactions

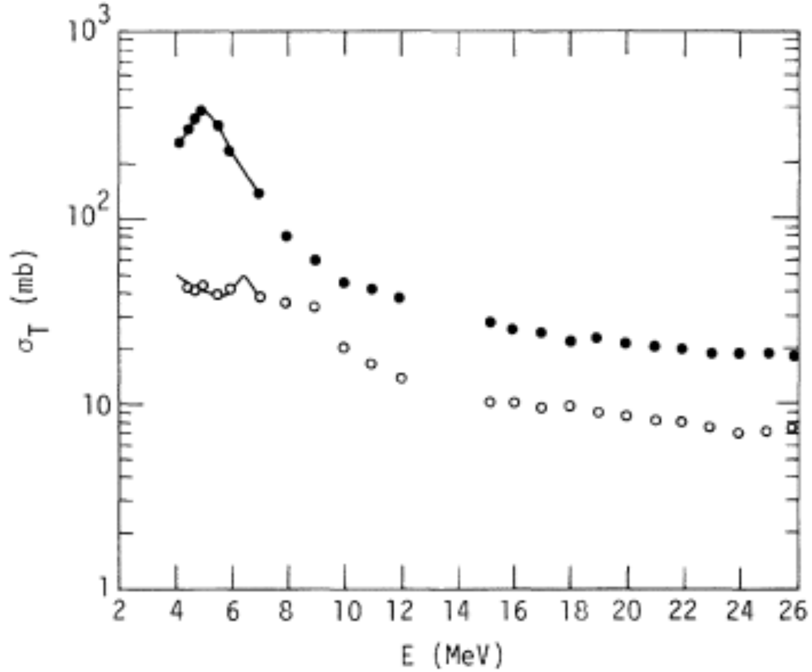
Reaction	Q-Value (MeV)	Threshold (MeV)	Minimum E_n (MeV)	Minimum E_{proj} (MeV)
$d(d, n)^3He$	+ 3.269	NA	2.45	0.15
$t(d, n)^4He$	+ 17.6	NA	14.1	0.15
$^7Li(p, n)^7Be$	- 1.644	1.881	0.03	2.5
$^9Be(p, n)^9B$	-1.850	2.059	0.02	2.5
$^9Be(d, n)^{10}B$	+ 4.362	NA	5.8	1.5
$^9Be(\gamma, n)$	- 1.66	1.66		1.66
$^{181}Ta(\gamma, n)$	- 7.57	7.57		7.57



Estimated global neutron yield in low energy nuclear reaction

S. Anderson et. al, Phys. Rep 654, 1 (2016)





^{7}Li(p, n)^{7}Be cross section as a function of energy.

C. H. Poppe et. al., PRC14, 438 (1976)

Some of the Ion accelerator based neutron source worldwide

Lab	Accelerator	Beam	Target/reactions	comments	Purpose
CPHS China (2013)	Proton Linac	13 MeV 1.25 mA	$^9Be(p,n)^9B$ Flux ~ 5x 10^{13} n/s		Cold to epithermal for imaging
CYRIC Japan (2004)	Cyclotron	70 MeV, 1μA	$^7Li(p,n)7Be$ Flux 10^6	Target water cooled, Primary beam bent by 25^0	Quasi-monoenergetic n energy range ~ 14-80 MeV
iThemba South Africa	Cyclotron	25 – 200 MeV 300 nA- 5 μA	$^7Li(p,n)^7Be$ $^9Be(p,n)^9B$ Flux 10^4		Quasi-mono-energetic beam for nuclear phys
KIRAMS South Korea	MC -50 Cyclotron	20 -50 MeV 60 μA	$^9Be(p,n)^9B$		Fast n irradiation
NEPIR Italy	Cyclotron	35 – 70 MeV 500 μA	Li, Be, W(p, n) Flux 10^{13} -10^{14} (SN) Flux 10^5 -10^7 (FN)	Slow neut 1 - 200 keV, Fast neutron up to 70 MeV	Fast n irradiation

Lab	Accelerator	Beam	Target/Reaction	comments	Purpose
LENS, USA (2005)	RFQ + 2 Linac	13 MeV 25 mA (peak)	$^{9}Be(p,n)^{9}B$ Flux $2x10^{10}$	Methane 4K	Fast n up to 11 MeV
RAON , Korea	LINAC	80 MeV			
TSL Sweden	Cyclotron	11 -175 MeV 10 μA	$^{7}Li(p,n)^{7}Be$ 4.6×10^{5}		Fast n
GANIL France	Superconducting LINAC	1-40 MeV 50 μA Pulse $1\mu s$	^{7}Li (1.5 mm thick) ^{9}Be (0.5 mm thick)	water cooled target	Fast n (1-40 MeV)
NPI, Czech Republic	Cyclotron U- 120M	20-38 MeV 10 μA	^{7}Li (2 mm) Flux~ 10^{9}	Carbon stopper	Quasi-mono-energetic n
FRANZ Germany	Linac	1.87 -2.1 MeV 200 μA	$^{7}Li(p,n)^{7}Be$ Flux 10^{9}	Neutron energy 1-200 KeV Pulse beam 0.8m	Nuclear astrophysics

Applications:

Basic research

- Nuclear data generation
- Characterize reaction mechanism
- Impose constrain on nuclear models

Applied Research:

- Material characterization for effect of high *n* flux
  - Nuclear power reactors
  - Accelerator driven system (ADS)
  - Fusion technology
- R&D on neutron detectors and dosimeters
- Production of radio isotopes

Nuclear reactions which can be studied

- (n, Light charged particle)

  (n, p)

  (n, α)

- (n, γ)
- (n, fission)
- (n, n')
- (n, xn)

Three different reaction processes are involved

Direct

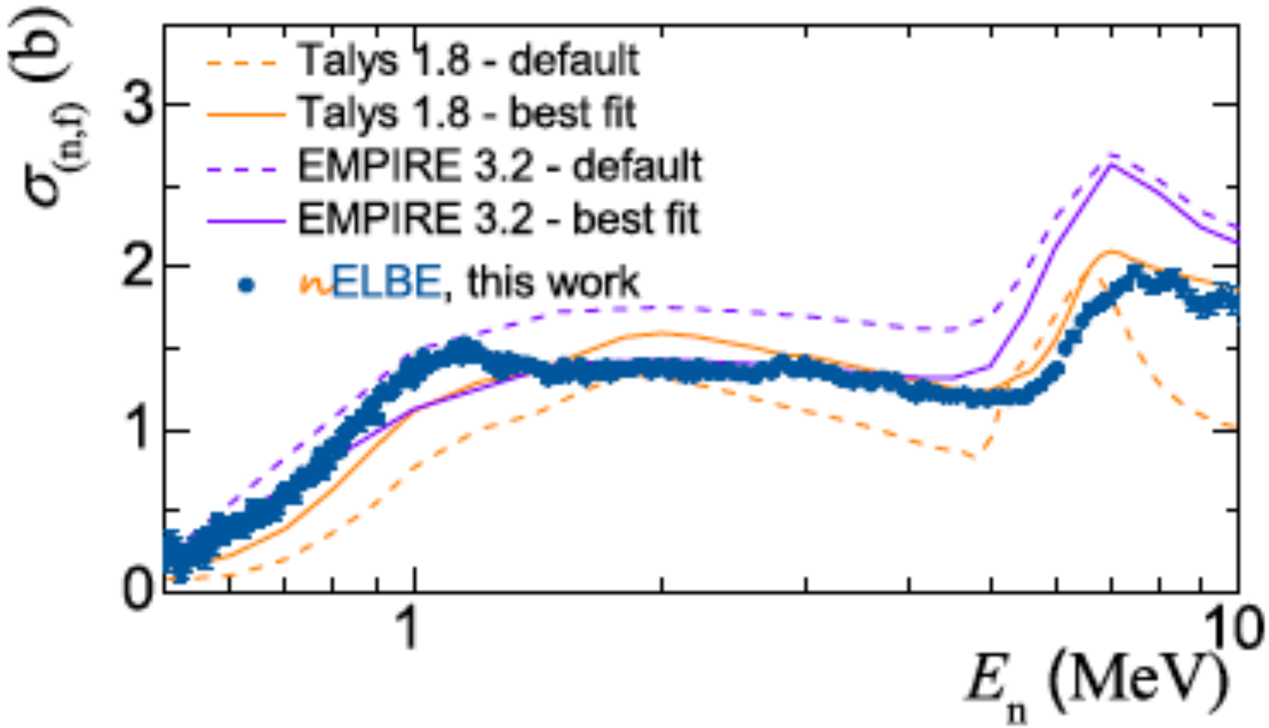
Pre-equilibrium

Statistical

TALYS and EMPIRE code

(n,f) Neutron induced fission

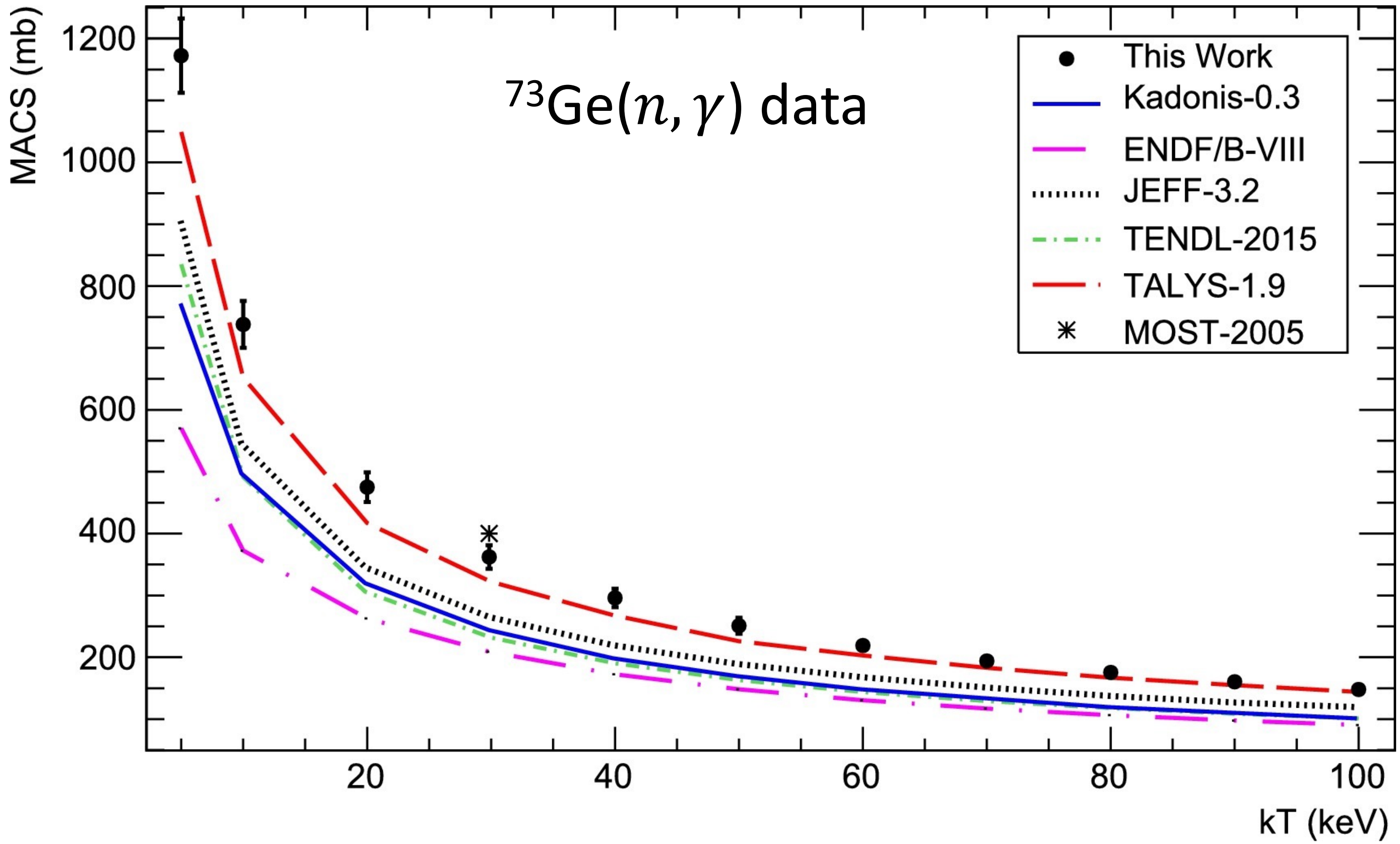
Need for more precise and accurate measurements with neutrons



Fast neutron induced fission cross section ^{242}Pu normalized to ^{235}U. Comparison of neutron induced fission cross section data with the model calculations using TALYS and EMPIRE.

T. Kogler et. al. , Phys. Rev. C 99, 024604 (2019)

(n, γ) Capture reaction

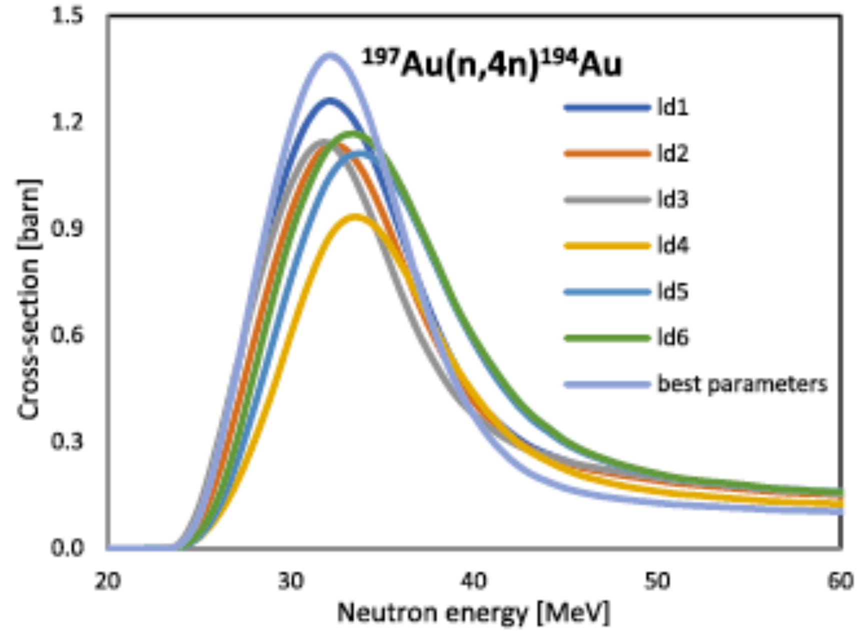


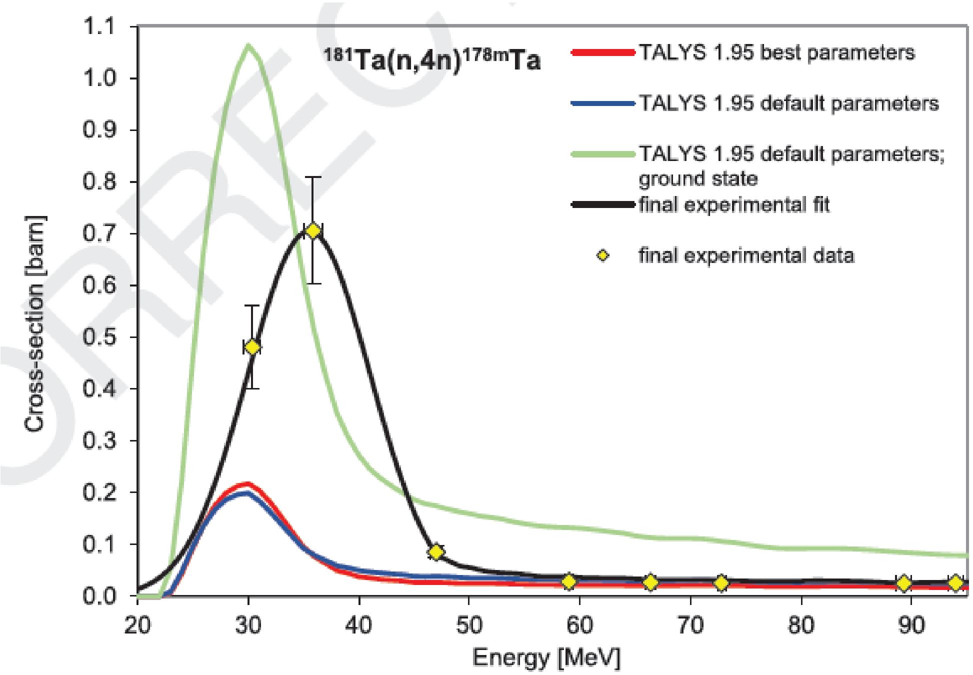
C. Lederer Woods et. al., Phys Lett B 790, 458 (2019)

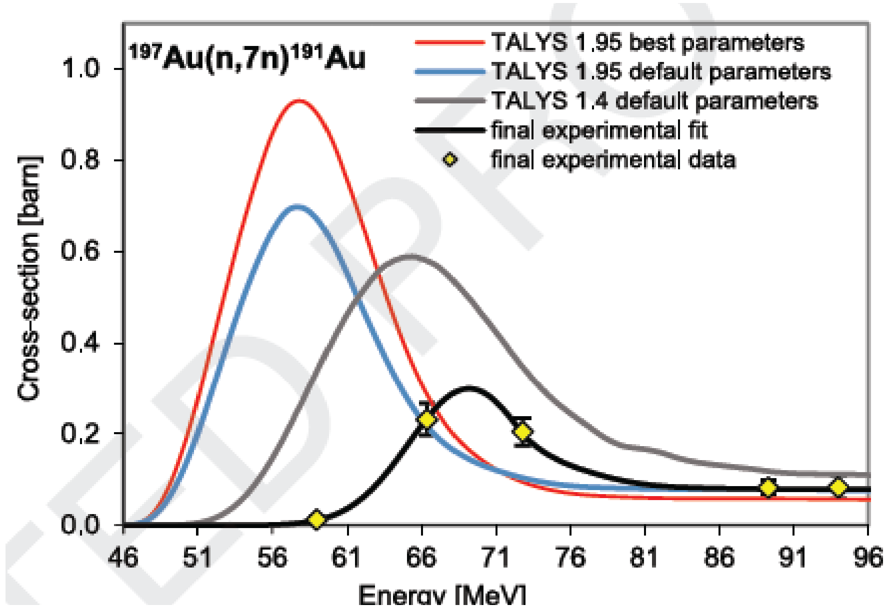
(n,xn) reaction

TALYS calculation considering different level density prescriptions

Need experimental data to constrain the model parameters





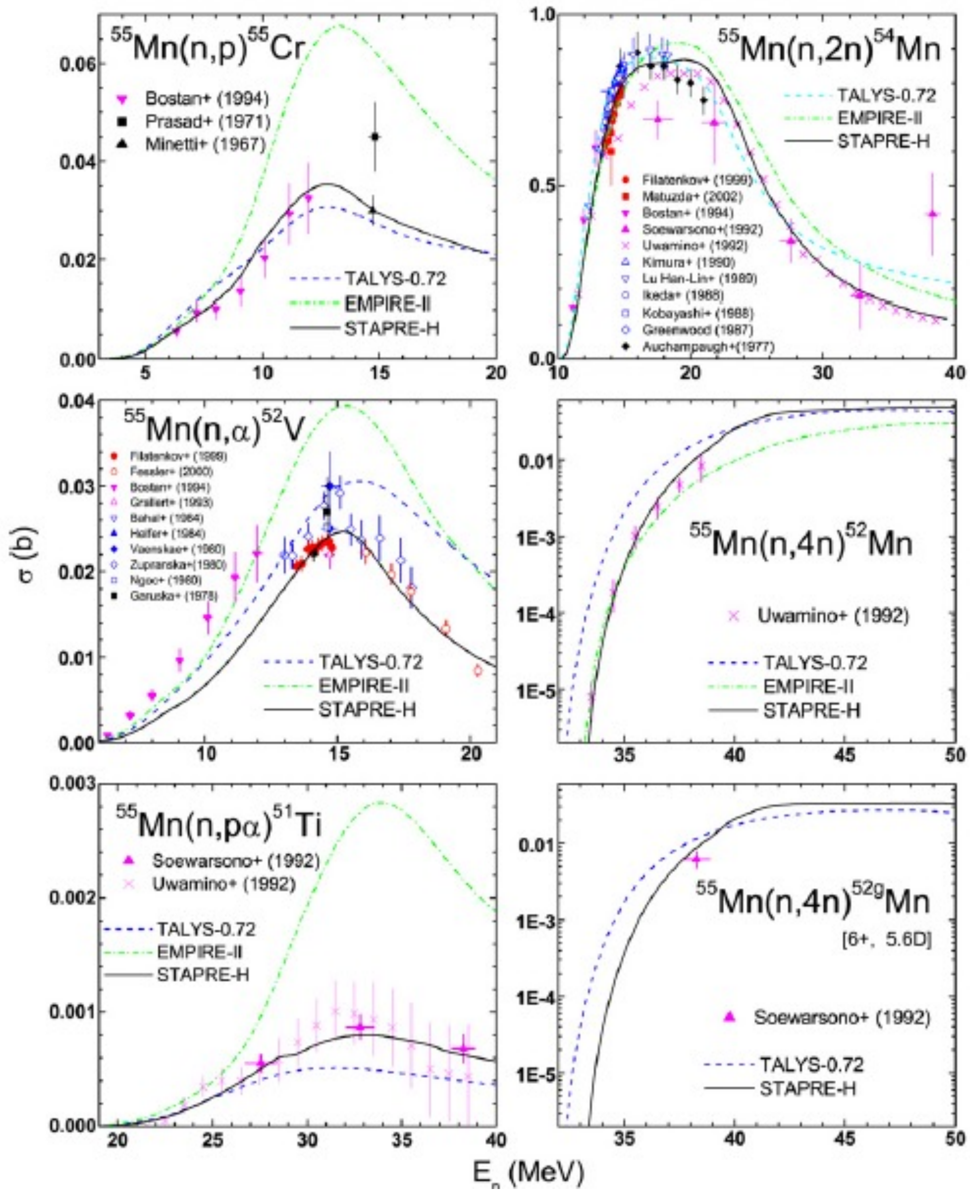


J. Vrzalova et. al. Nuclear Physics A 1031, 122593 (2023)

Neutron induced light charged particle emission
(n,p), (n,α) reaction

Data needed to benchmark the nuclear reaction codes and get the global optical model parameters

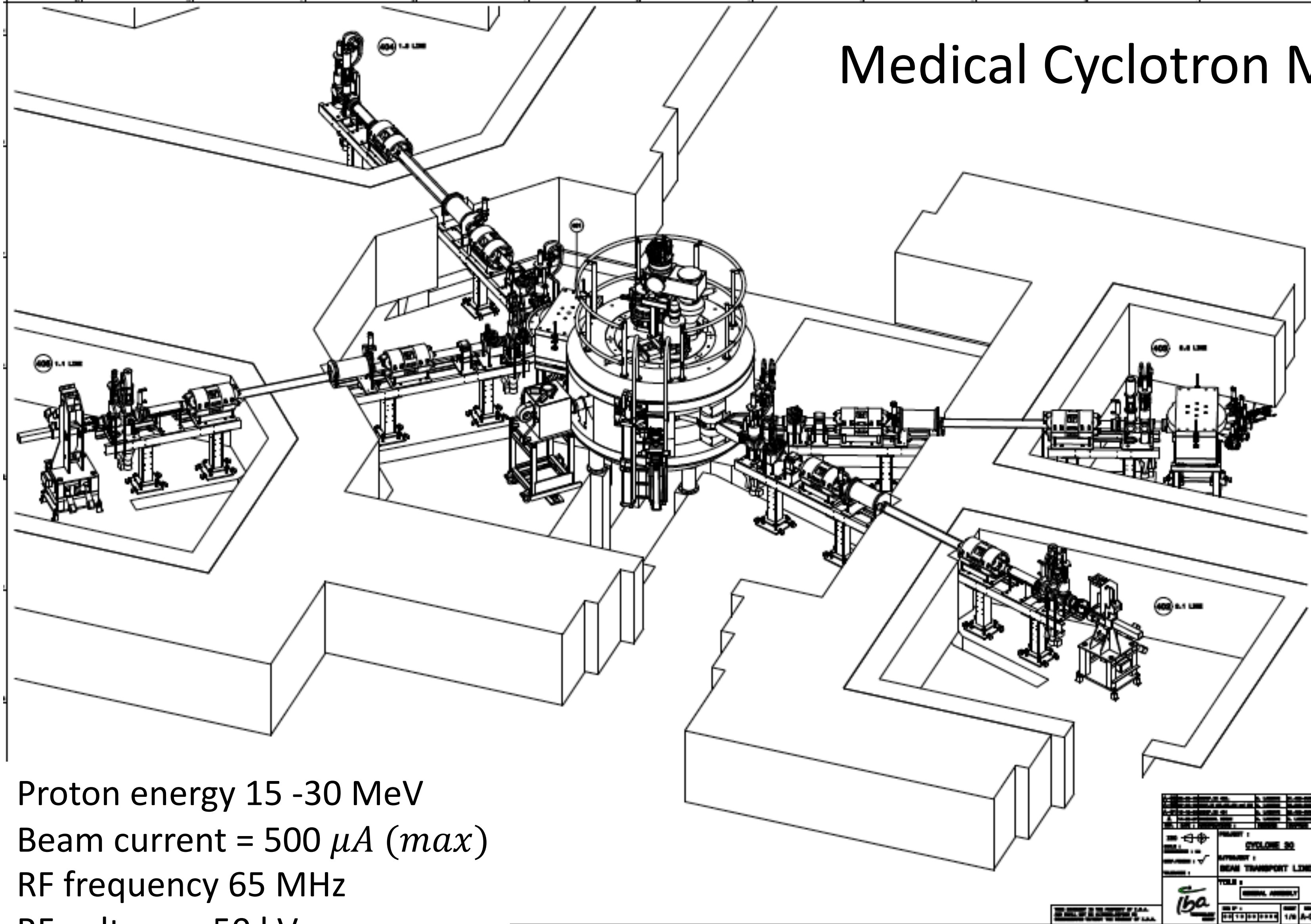
M. Avrigeanu et. al., Nuclear Physics A 806, 15 (2008)



Structural material for fusion reactor and ADS need to be studied

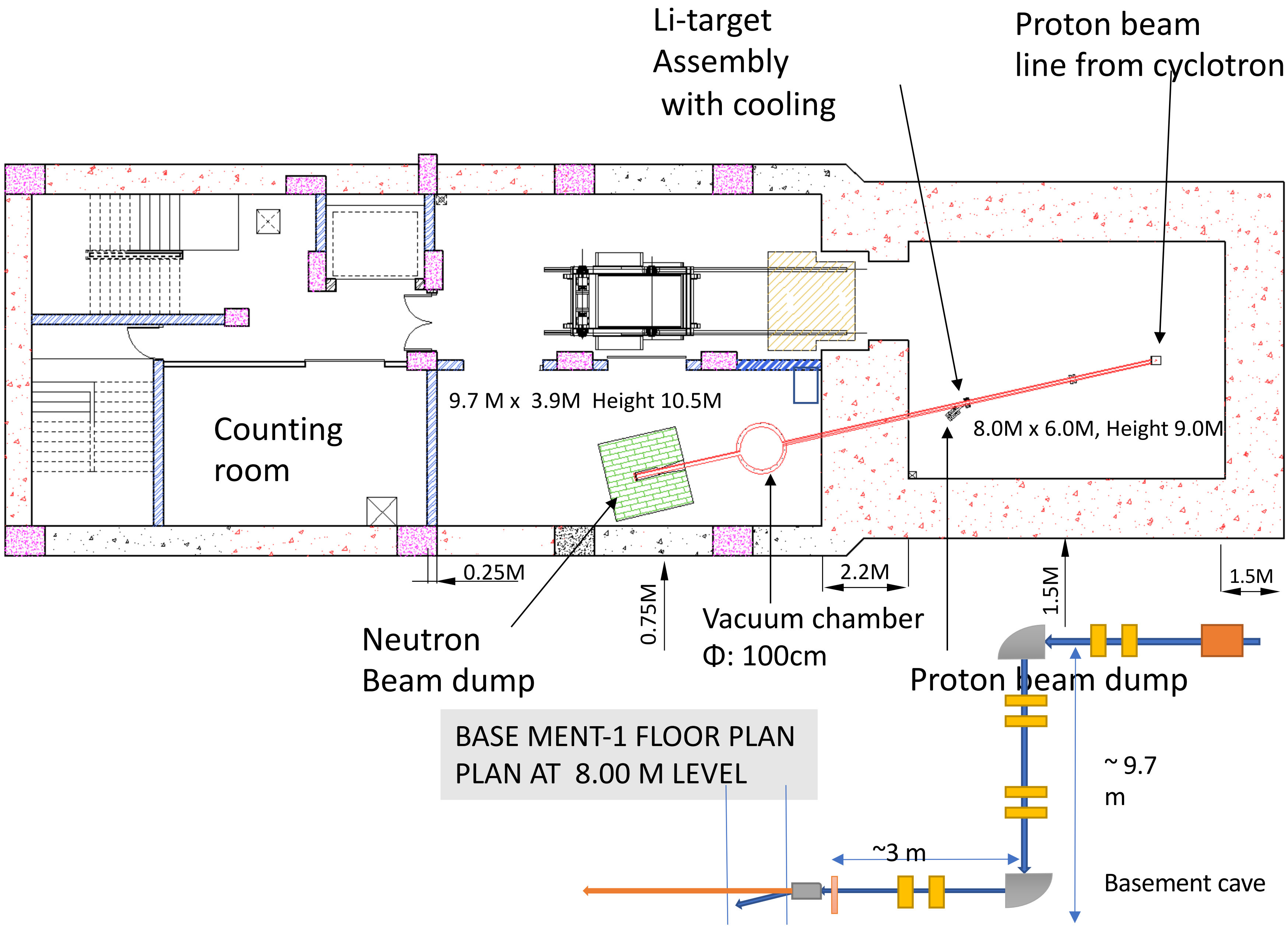
Since gas inclusions are detrimental to mechanical stability, a good knowledge of gas producing reaction (n,p), (n,α) is needed

Medical Cyclotron MC30

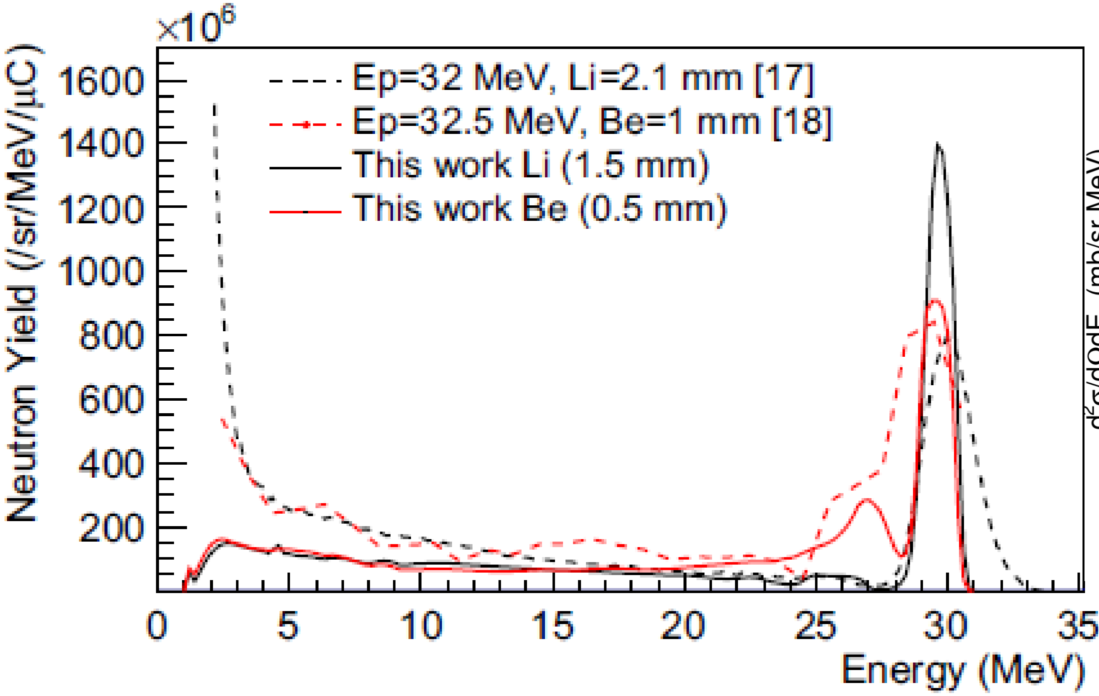


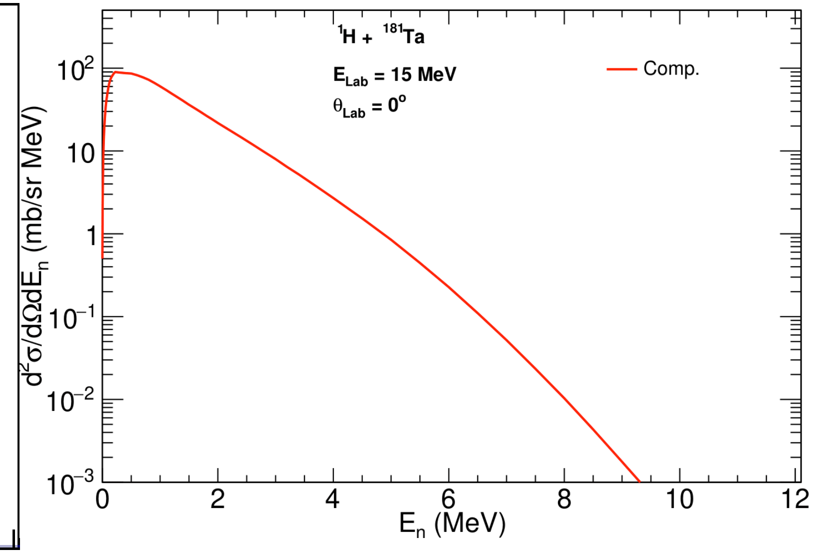
Proton energy 15 -30 MeV
Beam current = 500 $\mu A \ (max)$
RF frequency 65 MHz
RF voltage = 50 kV
Extraction radius = 67 cm
Magnetic filed = 1.1 T
Multi cusp arc type ion source
H^- carbon stripper

Schematic of the proposed neutron beam facility at the MC



Neutron energy spectra measured at 0^0 for 32 MeV proton





X. Ledoux et. al., Eur. Phys. J. A 57, 257 (2021)
Y. Uwamino et. al., Nucl. Instr. Methds. A 271, 546 (1988)

p + Li reaction produces more neutrons than p + Be

Contribution in quasi-mono-energetic peak is **49%** in p + Li and **32%** in p+ Be

Melting points of Lithium, Beryllium, Tantalum are **180^0C, 1287^0 and 3020^0C**

Specifications of the proposed neutron beam facility

Neutron energy in the range ~13 to 28 MeV [^{7}Li(p, n)]

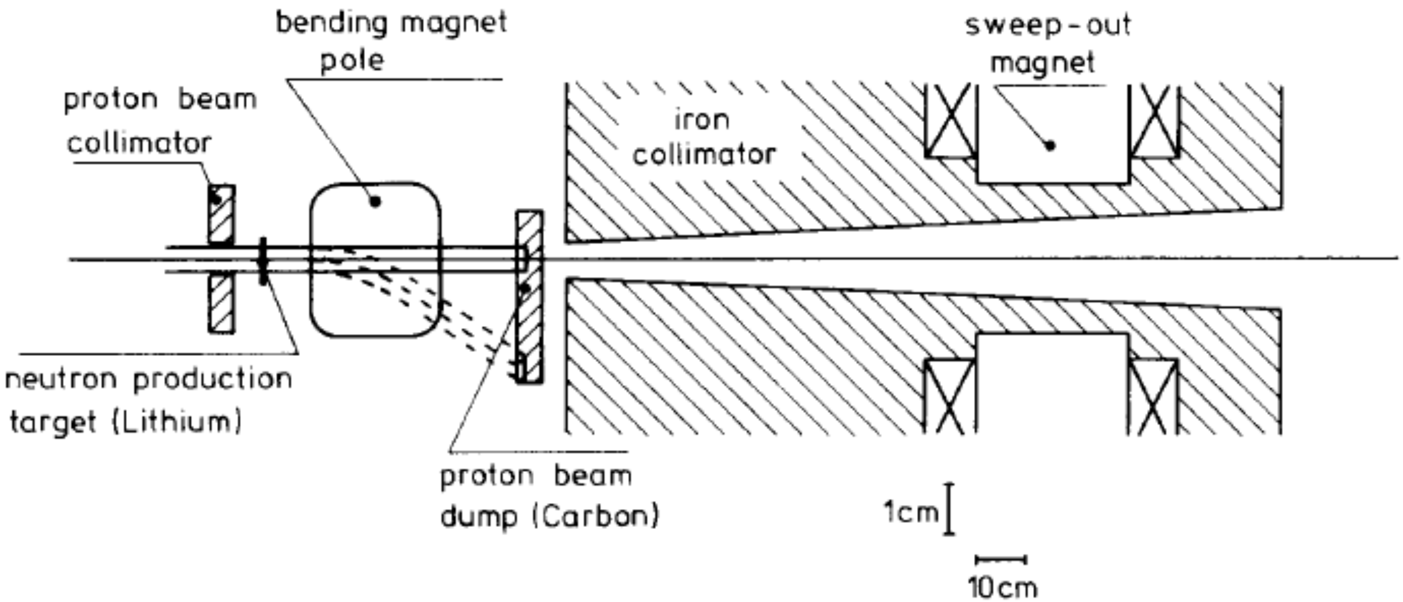
Flux for 50μA proton at the conversion point= 7.2×10^{10}n/s

Flux for 50μA proton at a distance of 4m from the conversion point ~ 10^5 n/cm^{2}s

2mm thick Lithium target, primary beam will pass through the target

Pulse neutron bean is required for time of flight measurements

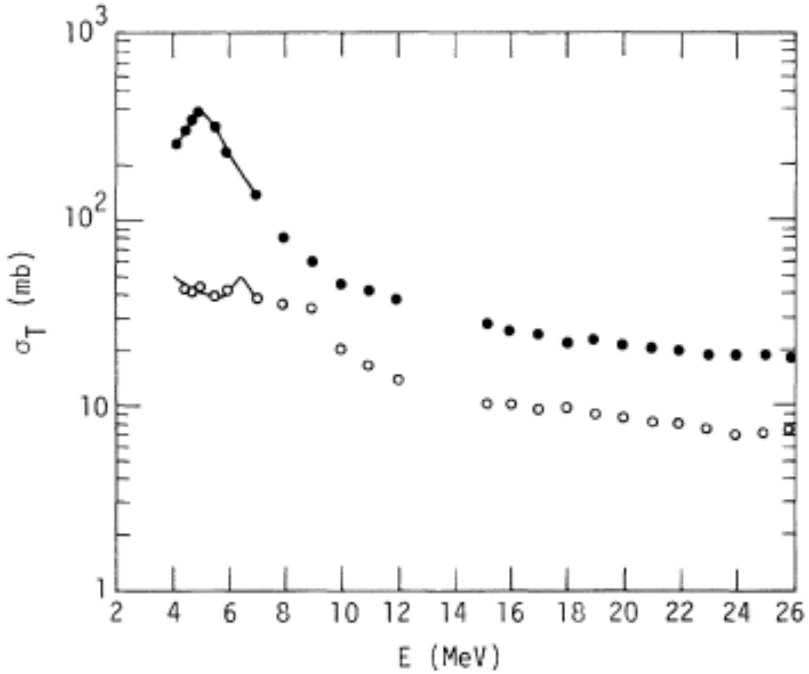
Typical arrangement of production target and neutron collimator



C. Dupont et. al., NIMA 256, 197 (1987)

Expected Neutron Flux

Total cross section for $^{7}Li(p, n0)^{7}Be$ and $^{7}Li(p, n)^{7}Be$



C. H. Poppe et. al., PRC14, 438 (1976)

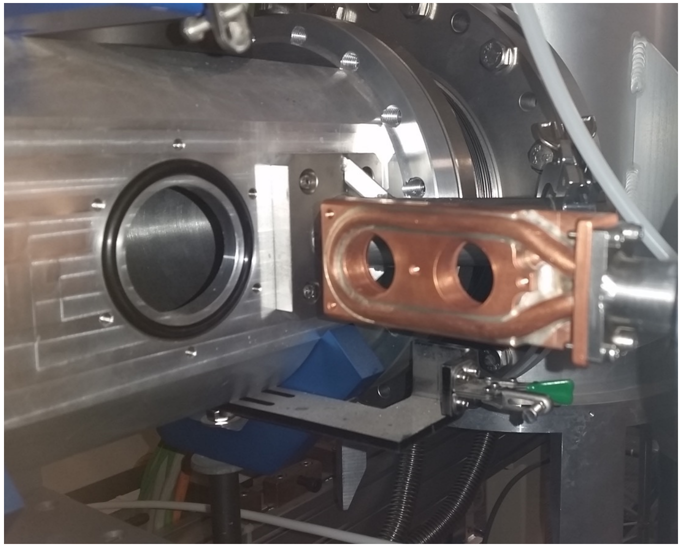
Proton Energy (MeV)	Cross-section (mb)	Flux at the converter position (n/s)	Flux at 1m from the convertor (n/s)	Flux at 2m from the convertor (n/s)	Flux at 4m from the convertor (n/s)
15	25	7.175×10^{10}	1.79×10^{6}	4.48×10^{5}	1.12×10^{5}
18	21	6.027×10^{10}	1.51×10^{6}	3.77×10^{5}	0.94×10^{5}
21	20	5.74×10^{10}	1.43×10^{6}	3.59×10^{5}	0.89×10^{5}
24	20	5.74×10^{10}	1.43×10^{6}	3.59×10^{5}	0.89×10^{5}

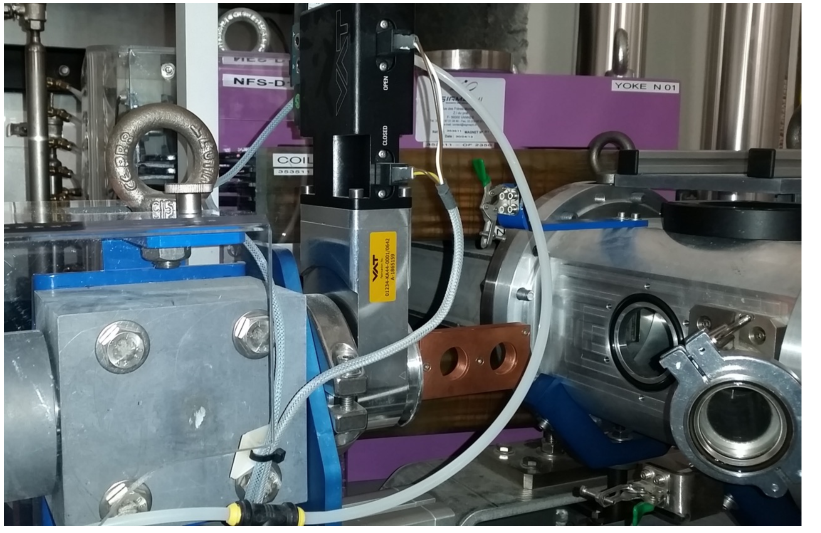
Estimated heat production in the target

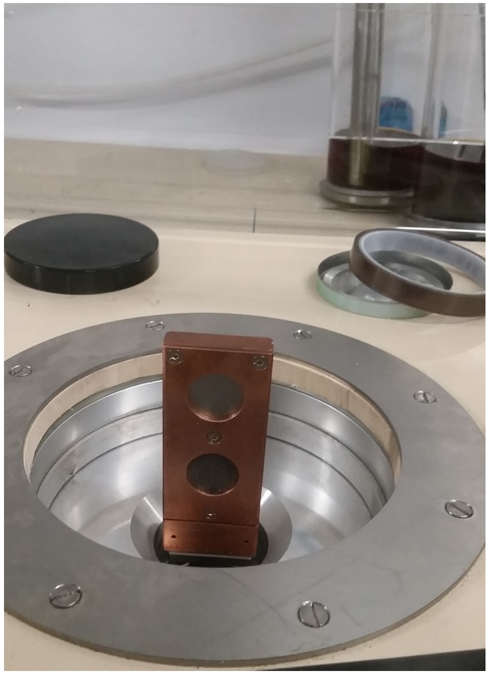
Proton energy (MeV)	Max power (kW)	Actual power (kW) Thickness		Energy loss (MeV) Thickness		Energy Remaining (MeV) Thickness	
		1 mm	2mm	1 mm	2mm	1 mm	2mm
15	0.75	0.08	0.16	1.56	3.30	13.34	11.61
18	0.9	0.07	0.14	1.32	2.74	16.55	15.15
21	1.05	0.06	0.12	1.15	2.37	19.70	18.49
24	1.2	0.05	0.10	1.03	2.10	22.80	21.74
27	1.35	0.05	0.10	0.94	1.90	25.87	24.91
30	1.5	0.04	0.09	0.86	1.74	28.92	28.05

Chilled water cooled 2 mm thick Lithium target would be suitable

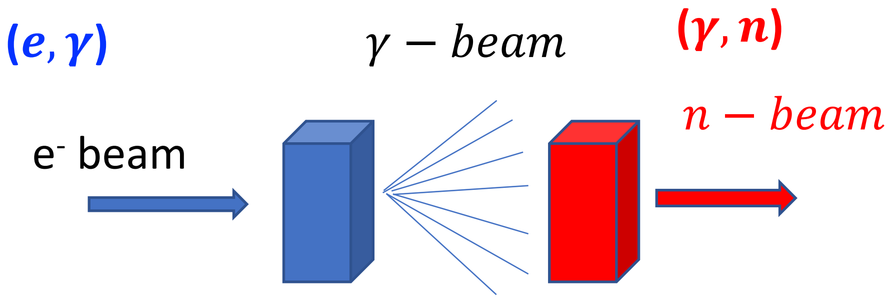
Target Facility at NFS GANIL



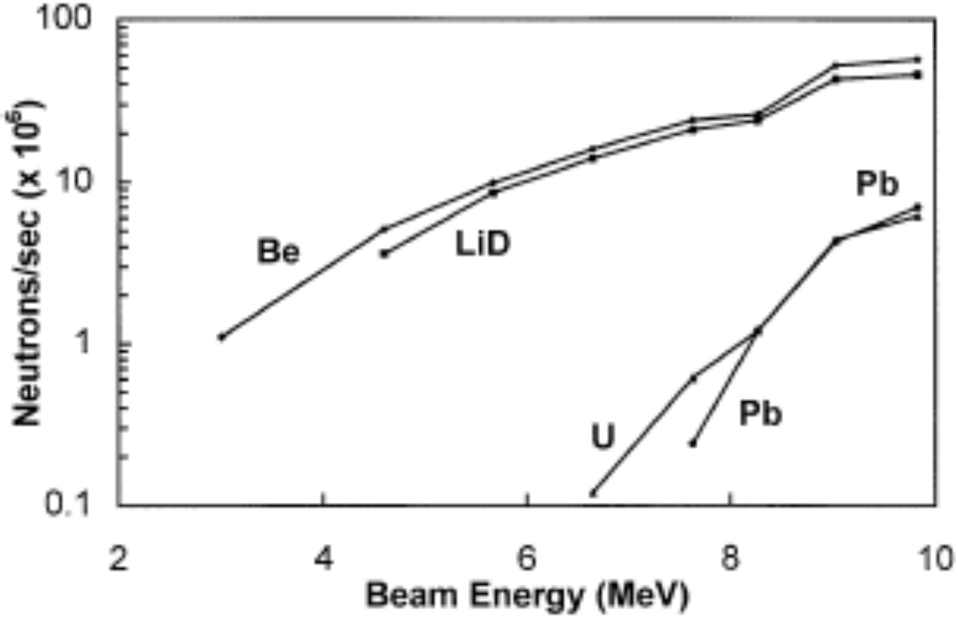




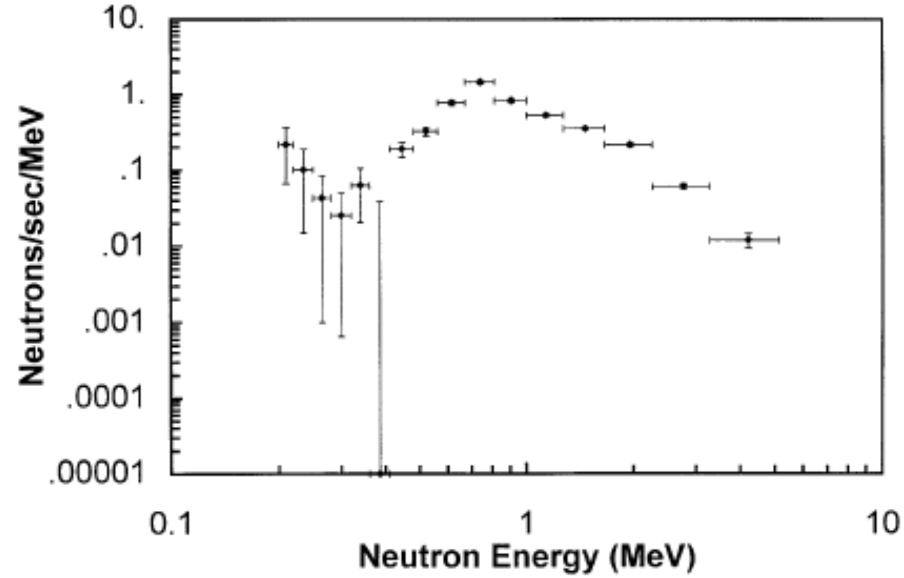
e^- accelerator driven neutron source



Neutron yield distribution from (e, γ) followed by (γ, n) reaction



Neutron yield distribution as a function of electron beam energy



Neutron energy spectrum from Be target irradiated with 9.83 MeV Bremsstrahlung photon beam.

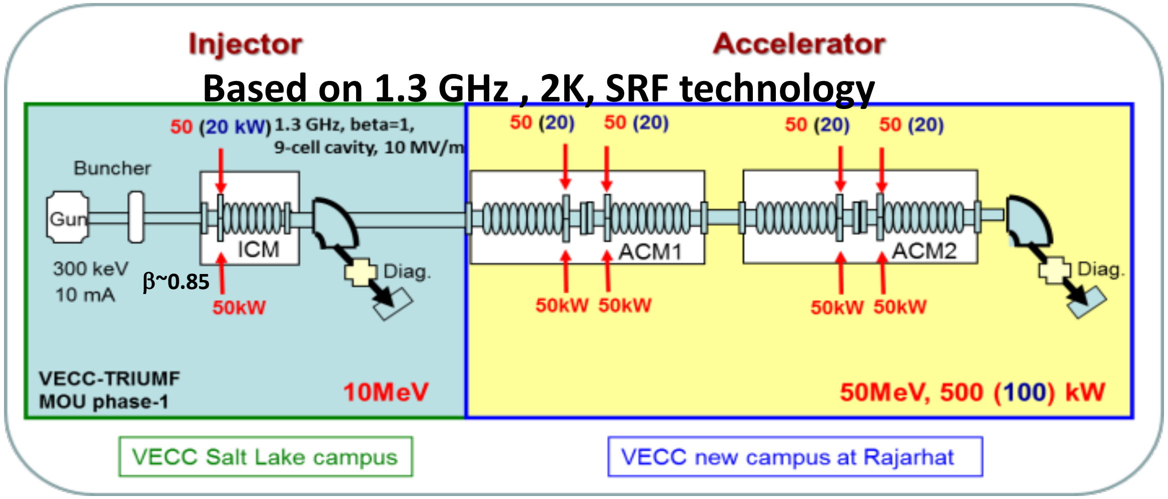
V. L. Chakhlov et. al., NIMA 422, 5 (1999)

Some of the e^- accelerator based neutron sources worldwide

Lab	Accelerator	Beam	Target/Reaction	Comments	Purpose
UTCANS –U Tokyo	Electron	Electron 35 MeV, 0.375 kW, 250 mA (peak)	$W(\gamma, n)$	Polyethylene moderator 8×10^{11} n/s	Nuclear data generation
		Electron 3.95 MeV, 0.3 kW 95 mA (peak) 200 Hz	$W(\gamma, n) + Be(\gamma, n)$	Polyethylene moderator 2×10^{9} n/s	On site non destructive inspection
HUNS Japan	Electron	35 MeV, 30 uA, 1kW, 100 Hz	$(e, \gamma), (\gamma, n)$	Water/coupled methane $1.6\ 10^{12}$ n/s	Radiation effect, detector development, Astrophysics
GELINA, Belgium	Electron	140 MeV, 407 – 75 uA	Rotating Uranium target	Water moderator 1.6×10^{12} - 2.5×10^{13} n/s	Nuclear data, neutron resonance

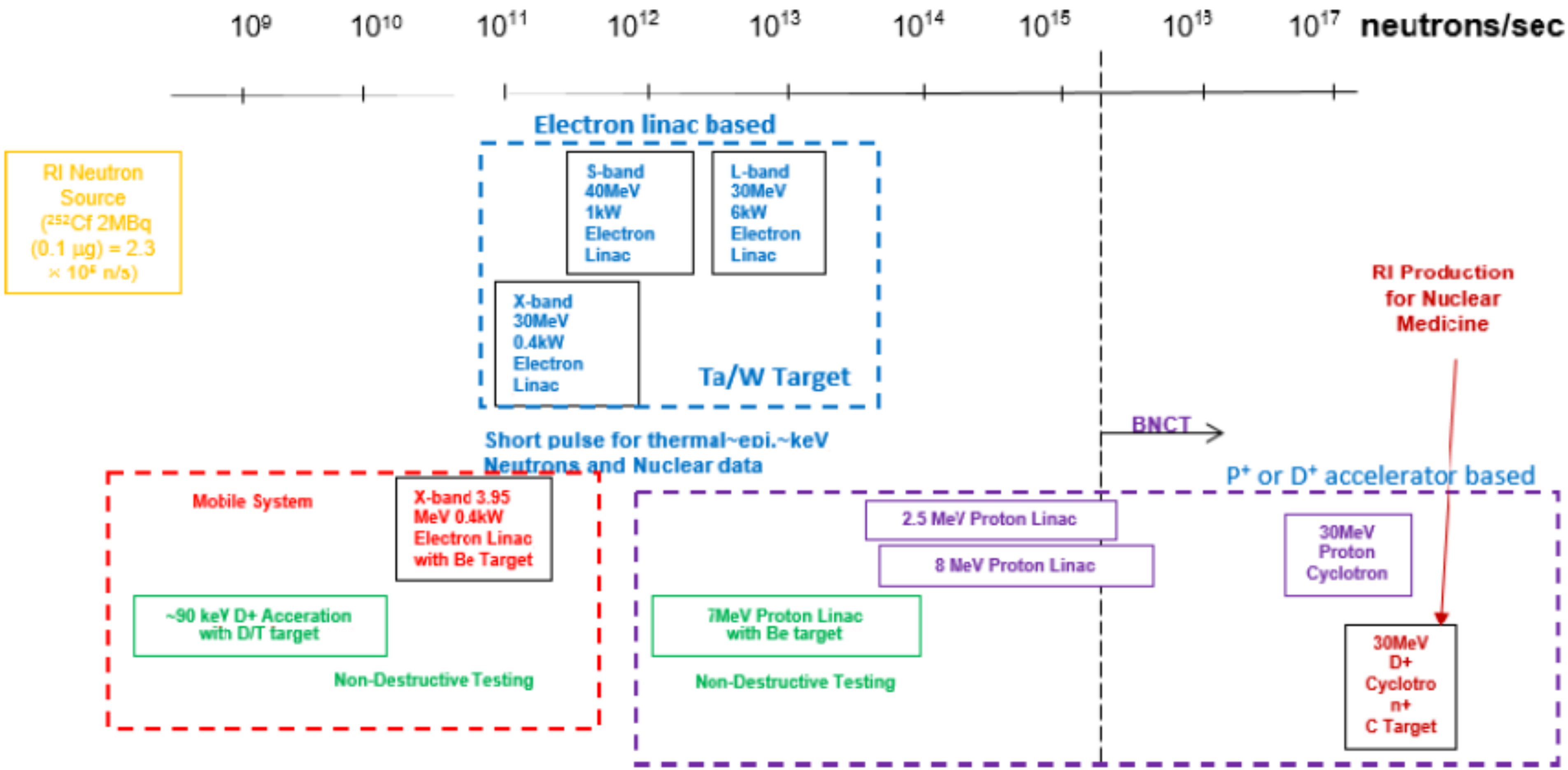
Lab	Accelerator	Beam	Target/Reaction	Comments	Purpose
GLARPI, USA	e^- Linac	60 MeV, 8uA, 12kW, 400 Hz	Tantalum	Water-graphite moderator 10^{12} n/s	Nuclear data measurement
BELDNS, Argentina	e^- Linac	25 MeV, 20 -30 uA	Lead target water cooled	6 $\times 10^{11}$ n/s	Nuclear cross section measu
Pohang Accl Lab, Korea	e^- Linac	80 MeV, 30 -60 mA (peak)	Water cooled tantalum target	2 $\times 10^{12}$ n/s	Nuclear data
KURRI Linac Kyoto Japan	e^- Linac	30 MeV, 1uA, 6kW	Tantalum	Water moderator 3$\times$ 10^{11} n/s/cm2	Neutron resonance, neutron imaging
n@BTE Italy	e^- Linac	510 MeV, 0.04 kW, 50 Hz	Tungsten,	Lead / Polyethylene shielding 8 $\times$10-7 n/cm2/primary beam	Calibration, methodology
nELBE Germany	Superconducting	40 MeV, 100 kHz –	Liquid Lead,	10^{13} n/s	Transmutation of nuclear

Schematic of Superconducting Electron Linac



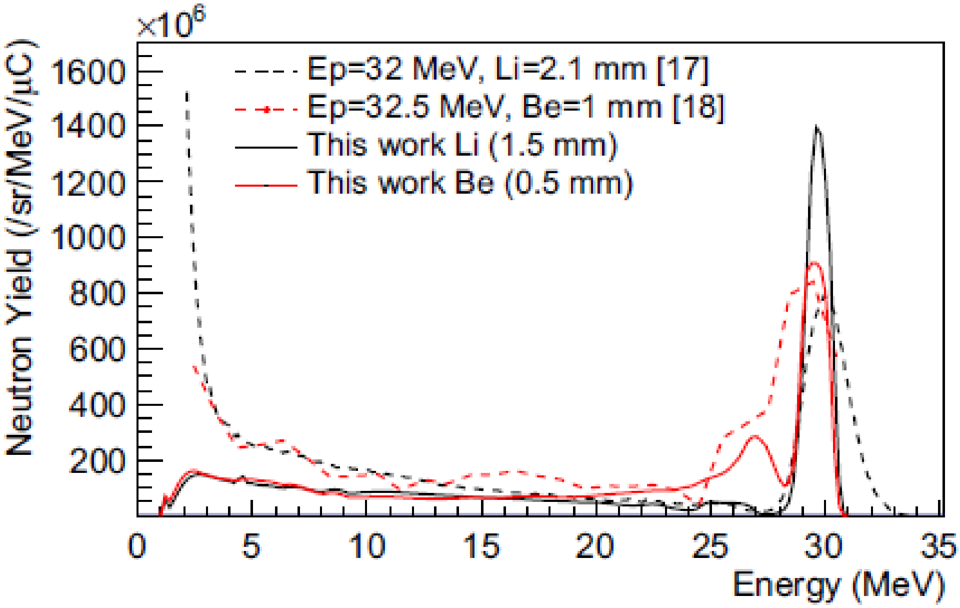
Input beam parameters :
Beam energy, current = 300 keV, 10 mA (max), 2 mA (typical)
Energy spread = ± 1.0 keV
Bunch length = 170 ps FWHM ≡ ±20° @650 MHz
Charge in each bunch = 16 pC (max); 3.2 pC (typ.)
Normalized emittance (ε) =30 pi. mm. mrad

Output beam parameters :
Beam energy = 50 MeV
Energy spread = 100 keV
Beam current = 2 mA (typical)
Bunch length = 30 ps
Un-normalized emittance (ε) =0.4 pi. mm. mrad

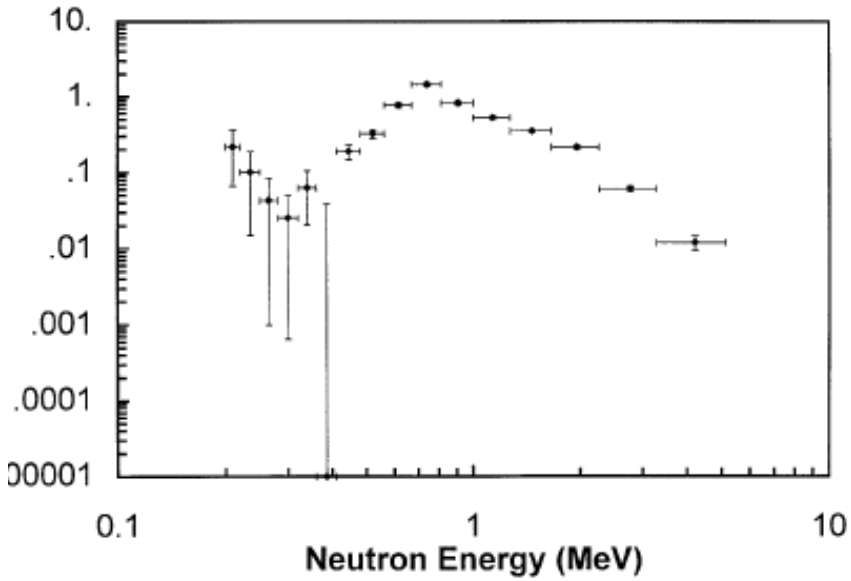


S. Anderson et. al, Phys. Rep 654, 1 (2016)

Typical Neutron energy spectra



7Li(p,n) reaction for Ep = 32 MeV



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V. L. Chakhlov et. al., NIMA 422, 5 (1999)

X. Ledoux et. al., Eur. Phys. J. A 57, 257 (2021)
Y. Uwamino et. al., Nucl. Instr. Methds. A 271, 546 (1988)

Summary

- Proposed neutron beam facility using MC30 has been discussed.
- Possibility to use electron Linac for the generation of neutron beam is also presented.
- Neutron spectra using two different accelerators would be different.
- A variety of nuclear physics experiments e.g. (n, p), (n, α), (n, xn), (n, γ), and (n, f) can be performed using the proposed neutron beam facility.

Thank you