UNIVERSITY OF BIRMINGHAM

HIGH FLUX ACCELERATOR-DRIVEN NEUTRON FACILITY

CYCLOTRON FACILITY

University neutrons: the high-flux accelerator facility at Birmingham

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UNIVERSITY OF BIRMINGHAM | POSITRON IMAGING CENTRE

Overview

- The facility: why and for what?
- Project practicalities: building a compact neutron facility
- Technologies
- Research

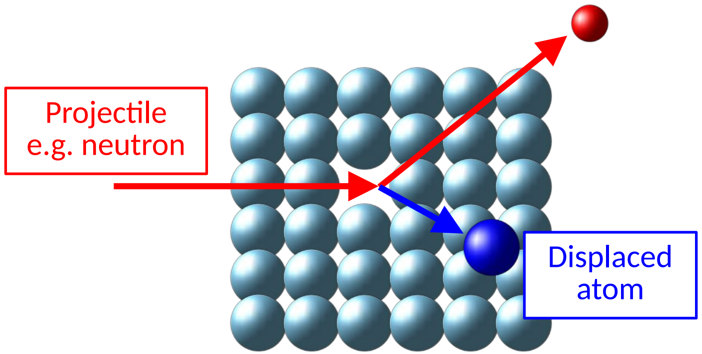
High Flux Accelerator-Driven Neutron Facility (HF-ADNeF) Commissioned 7th December 2023

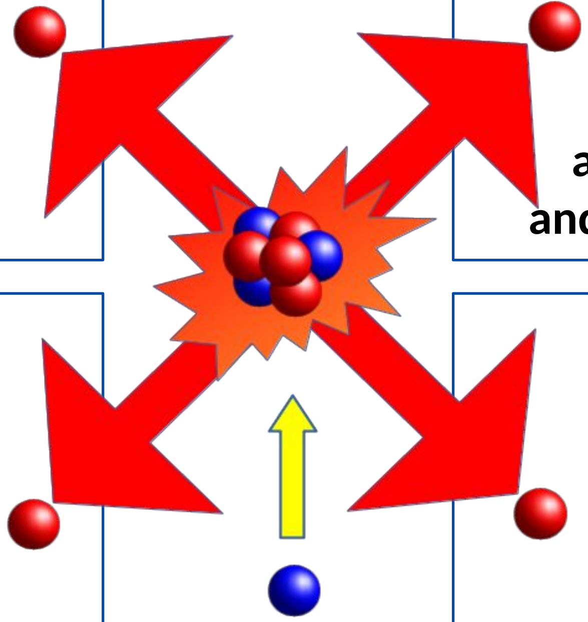
Engineering and Physical Sciences Research Council

NNUF National Nuclear User Facility

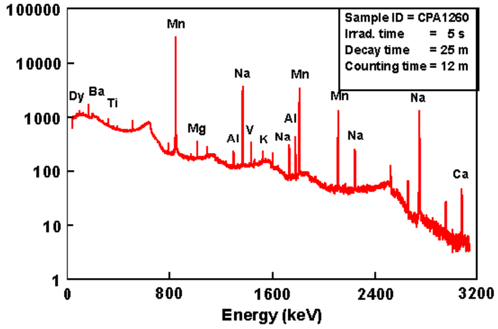
Why an accelerator-based neutron source?

Materials testing for fission & fusion

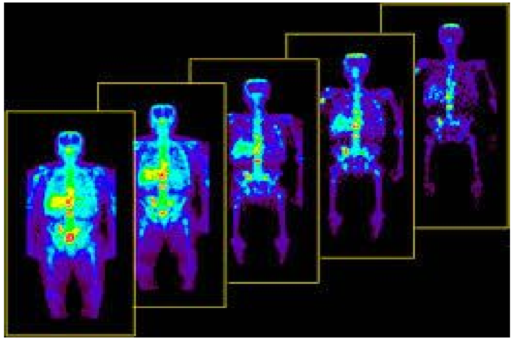




Training: students, academics and industry



NAA – Neutron Activation Analysis for culture and heritage



Medical applications: data, isotopes, radiobiology & novel therapies

Birmingham's neutron source – history

RDI 3MV Dynamitron (1970 – 2023)

- A low energy (**vertical**) accelerator, for protons up to 3 MeV.
- A high current machine (<3 mA) for materials damage studies and Boron Neutron Capture Therapy (BNCT) research.
- High neutron fluxes can be produced from protons on a lithium target.
- Machine was removed on 12th June 2023. See photo opposite (serendipitously by the same company who craned it in in the 70s).
- Lithium-copper bonding technique developed at Birmingham for high-power neutron targets[a].

[a]Lithium target reference (B'ham): Brown, Scott, Penetrating Radiation Systems & Applications, **4142** (2000); Phoenix, et al., Applied Radiation and Isotopes, **106** (2015), 49.

Boron Neutron Capture Therapy (BNCT)

- For difficult to treat head and neck tumours and metastatic cancers.
- Boron containing compound is given to a patient. After ~1 day healthy cells have released the boron whereas the cancer cells have retained it.
- A single neutron dose is then given

Neutron therapeutics machine, Helsinki Hospital.

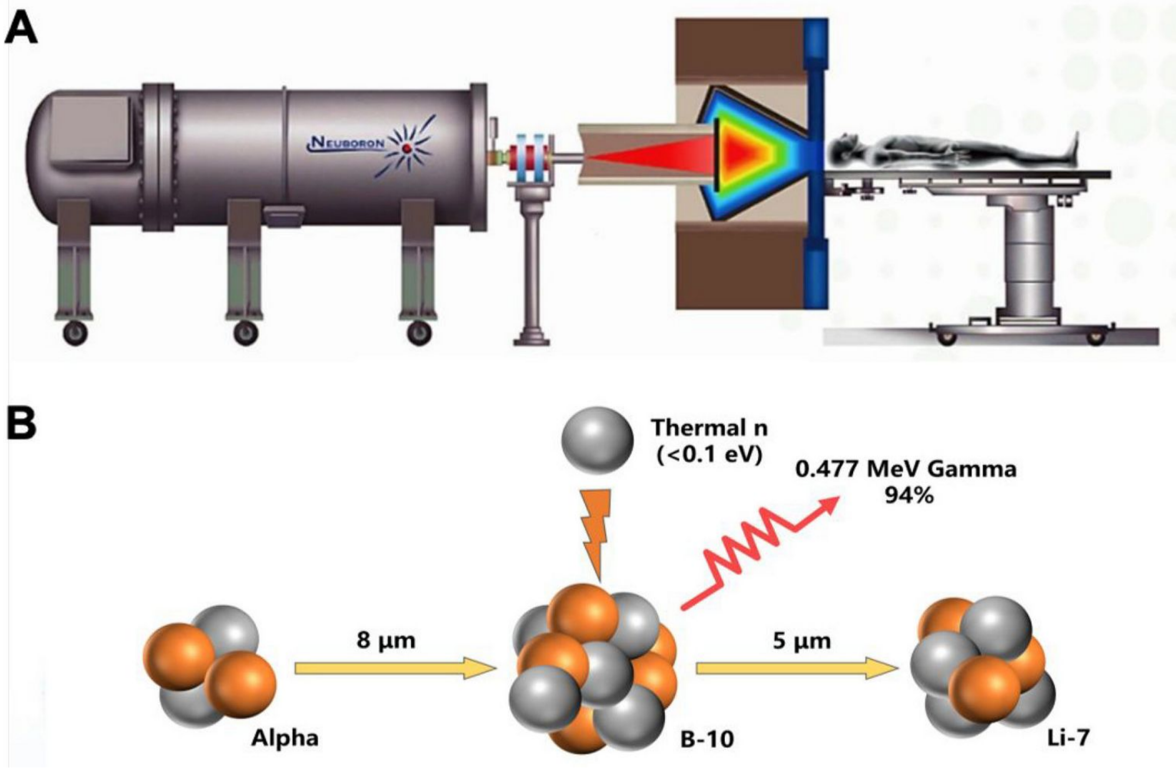
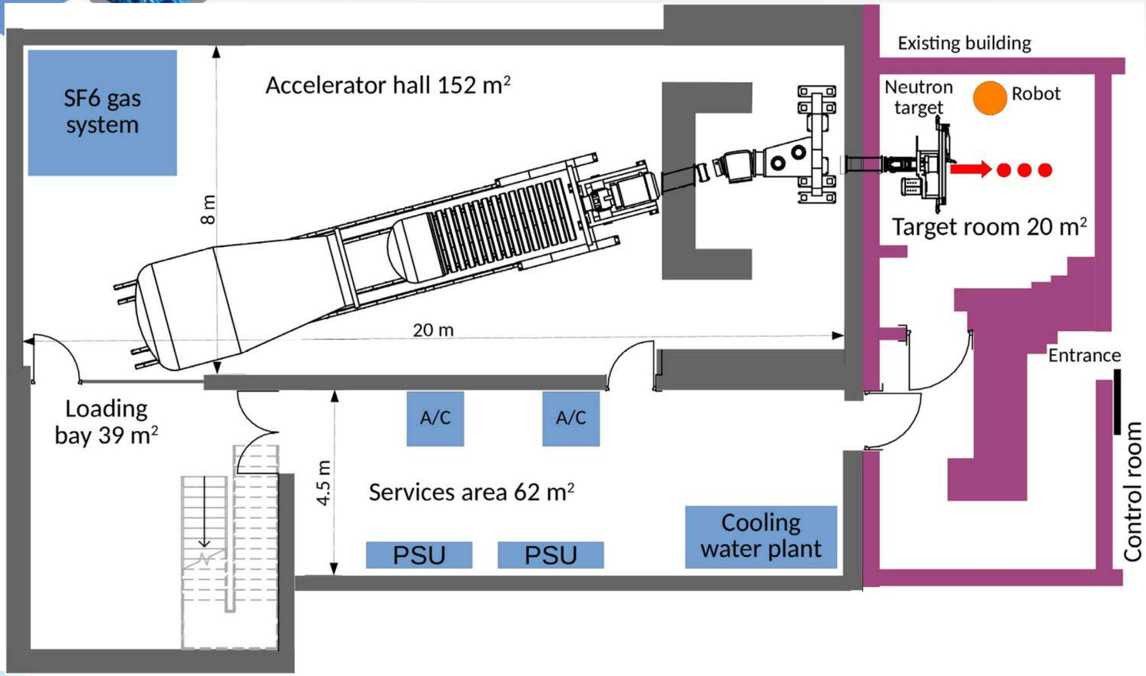


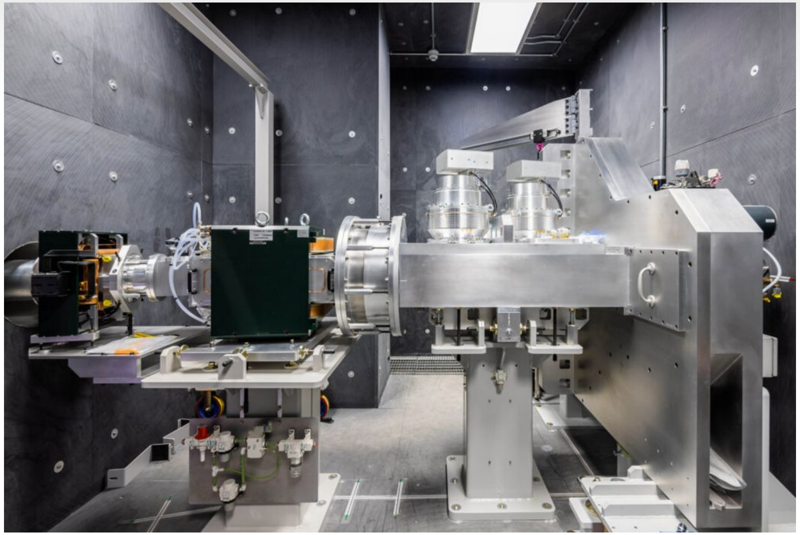
Image: Qi Dai, QiYao Yang, Xiaoyan Bao, Jiejian Chen, Min Han and Qichun Wei, Mol. Pharmaceutics 2022, **19**, 2, 363–377

Project practicalities

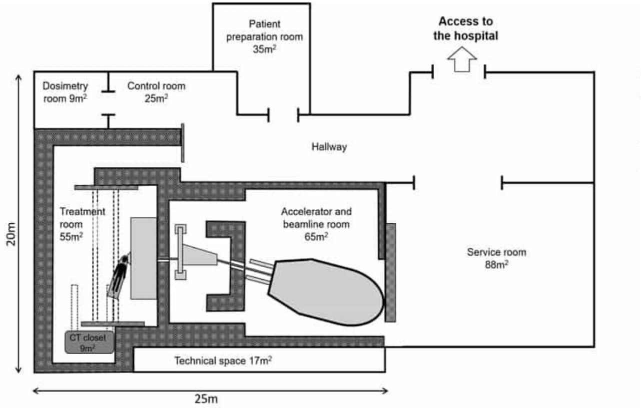


- Built on time and under budget during pandemic
- Project cost (today) ~ €15M
  (85% UK Science Council, 15% University)
- New bunker: 1-year build time
- Machine install and commissioning: 1 yr
- Lower shielding costs by building underground

Facility layout



Helsinki Centre for cancer therapy



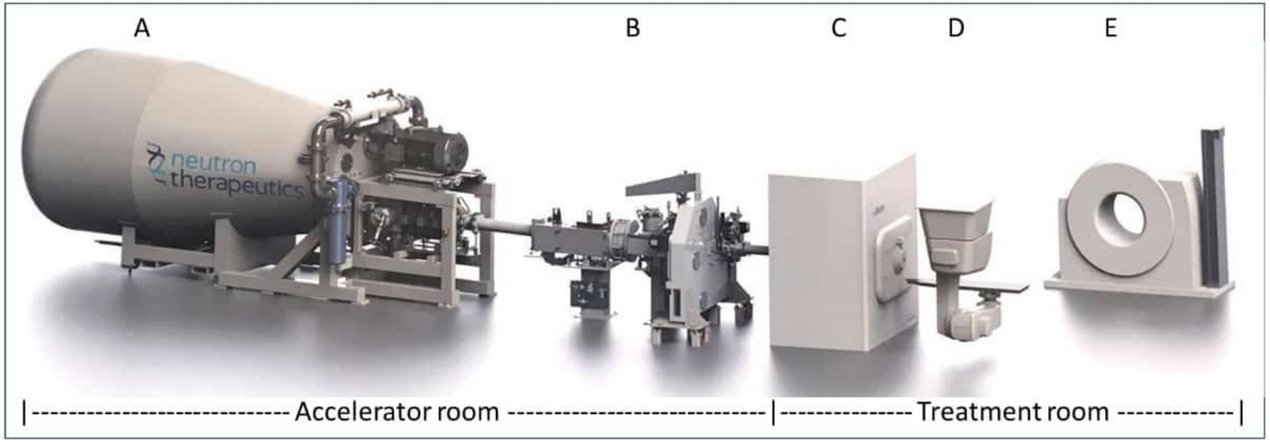
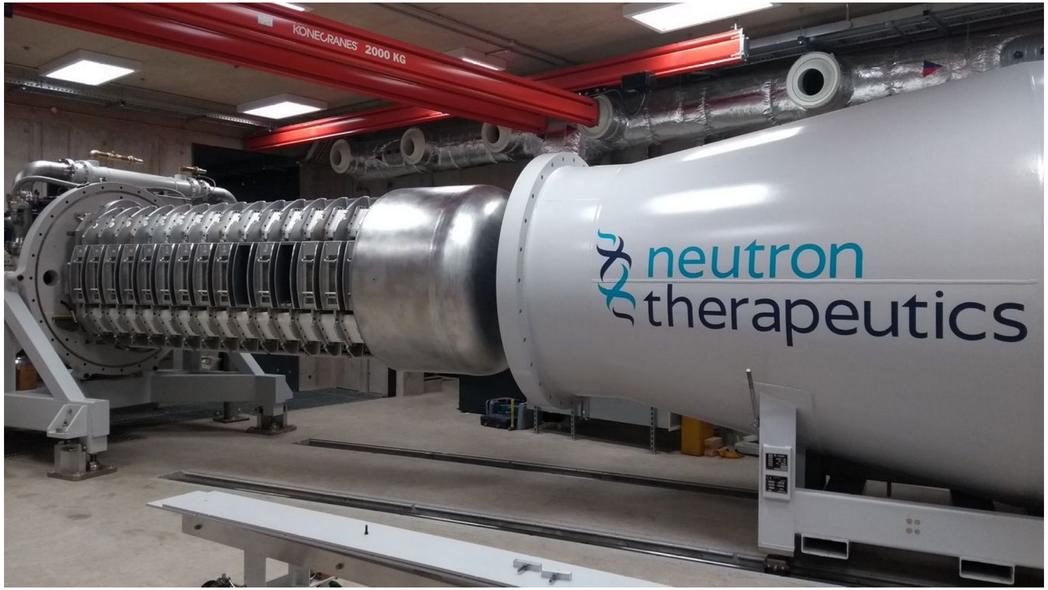
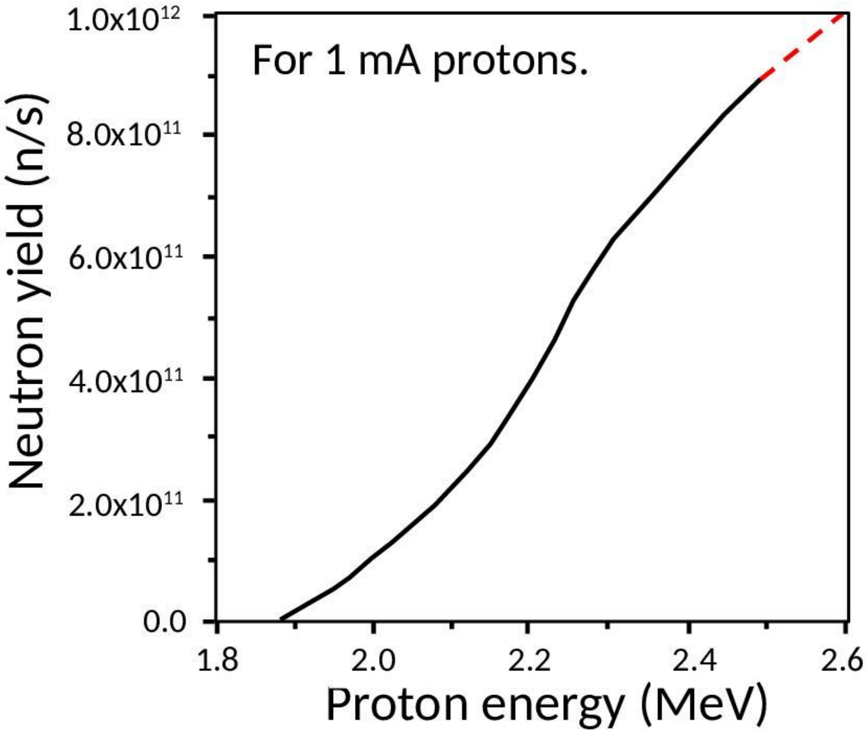


Image: Physics World, 27 Aug 2021, IOP publishing.

High Flux Accelerator-Driven Neutron Facility

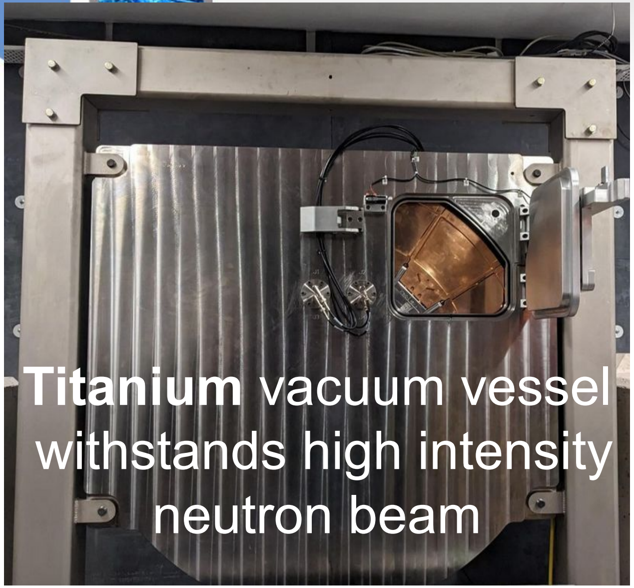
The electrostatic accelerator is designed for beams of protons and deuterons and currents of <50 mA, nominally at up to 2.6 MeV, but 2.8 MeV is the maximum.





Neutron yield figure adapted from figure 2 of J.C. Yanch *et al.*, Medical Physics **19** 709 (1992).

Project technologies in numbers



Titanium vacuum vessel withstands high intensity neutron beam

- High current ion beams: **117 kW** on target (2.6 MeV protons at 45 mA); 45 mA → 2.8×10^{17} protons/sec.
- Up to **1×10^{12} neutrons per cm^2** per second (yield >1×10^{13} neutrons per second).
- Target comprises 16 lithium-coated copper petals around 1 m diameter target wheel rotating at **600 rpm**.
- **300 litres** of cooling water per minute through copper petals.
- **40% electrical efficiency** to beam.
- Target life over **1000 hours.**

Graphite moderator for simultaneous **thermal neutrons ~10^9 cm^{-2} s^{-1}**

Target-handling robot

Cu target petal

Neutron production

Proton & deuteron beams accelerated to 2.6 MeV		
	protons (*p*)	deuterons (*d*)
Reaction	$^{7}Li(p,n)^{7}Be$	$^{7}Li(d,n)^{8}Be$
Q-value	−1.64 MeV	**+15.03 MeV**
Max. *n* energy	0.9 MeV	17.2 MeV

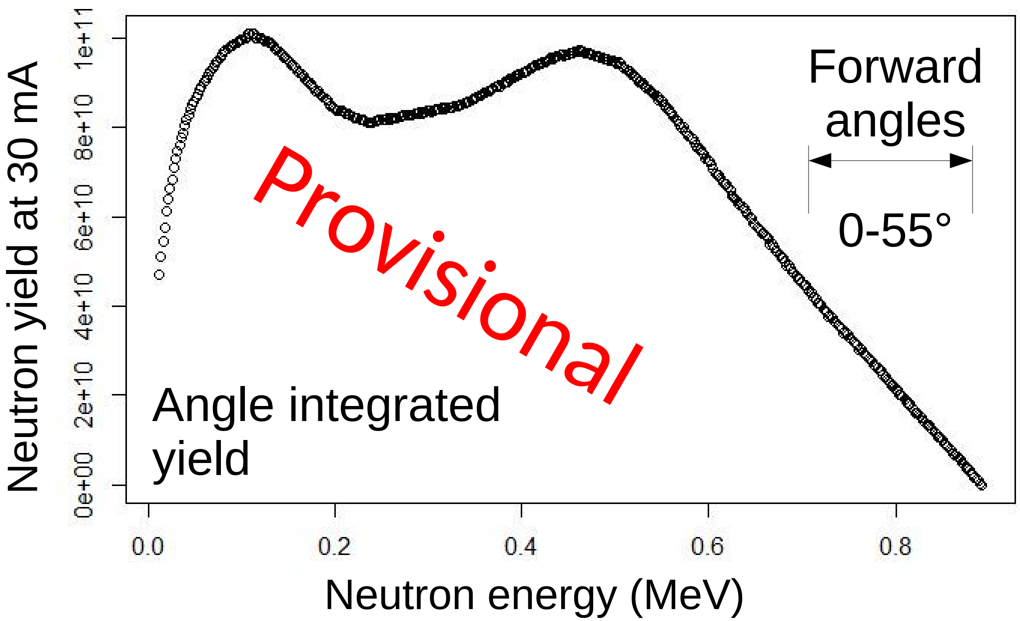
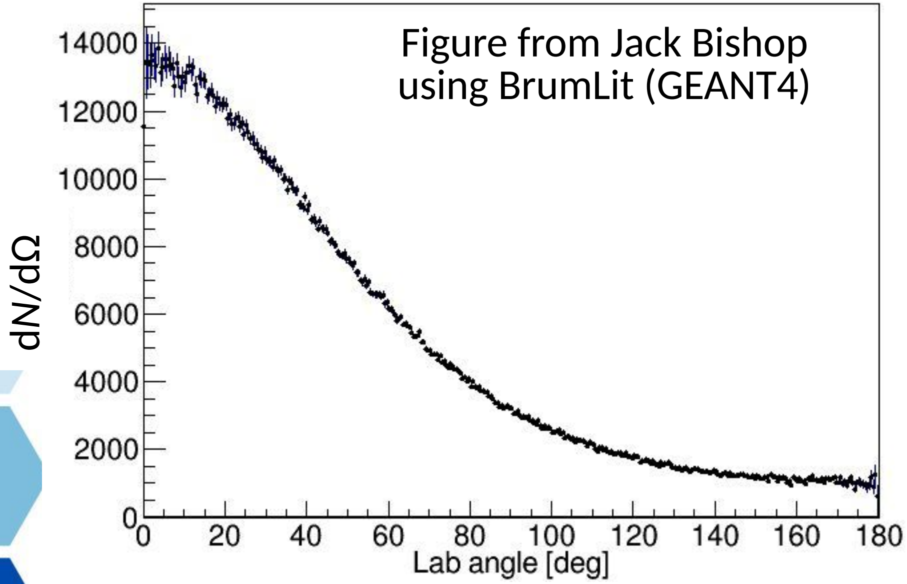


Figure by Ben Phoenix with input from Daniel Minsky (CNEA, Argentina), MCNP.

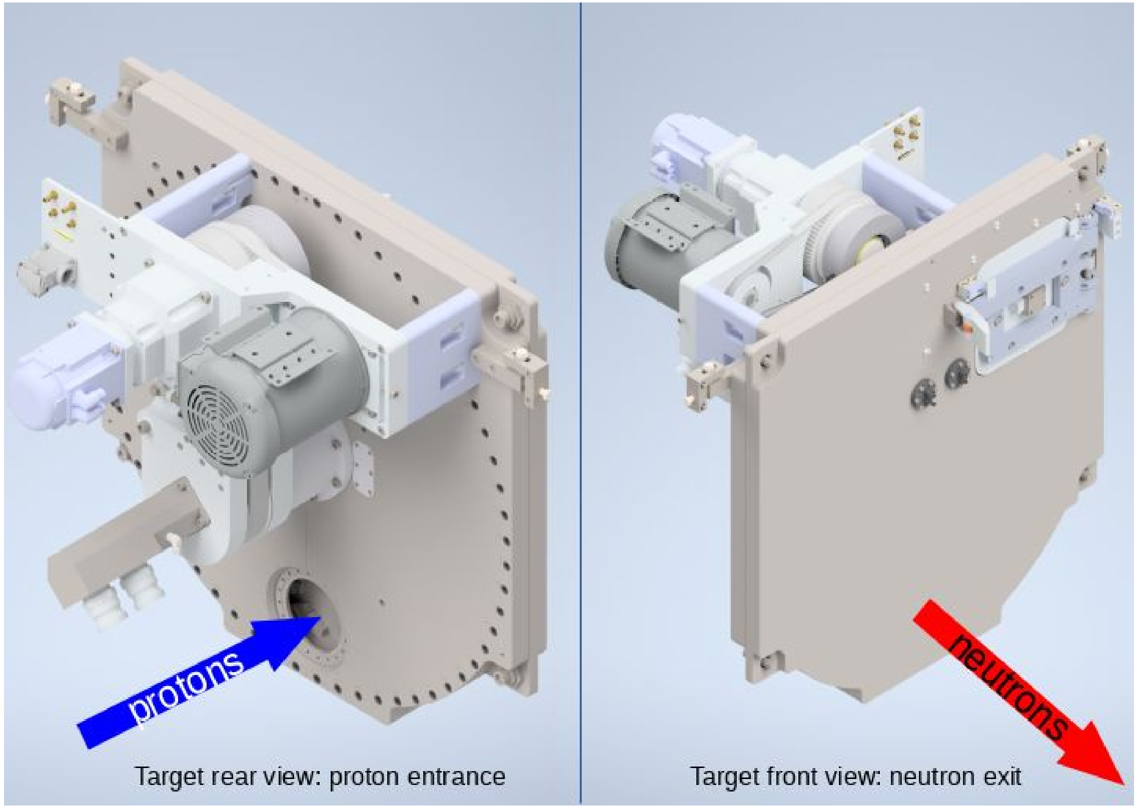


Beam energy is below threshold for reactions on most materials other than lithium.

Target activity can reach 6 TBq of ^{7}Be (53 days). After five-years of storage petals <20 Bq!

Neutron production – target petals

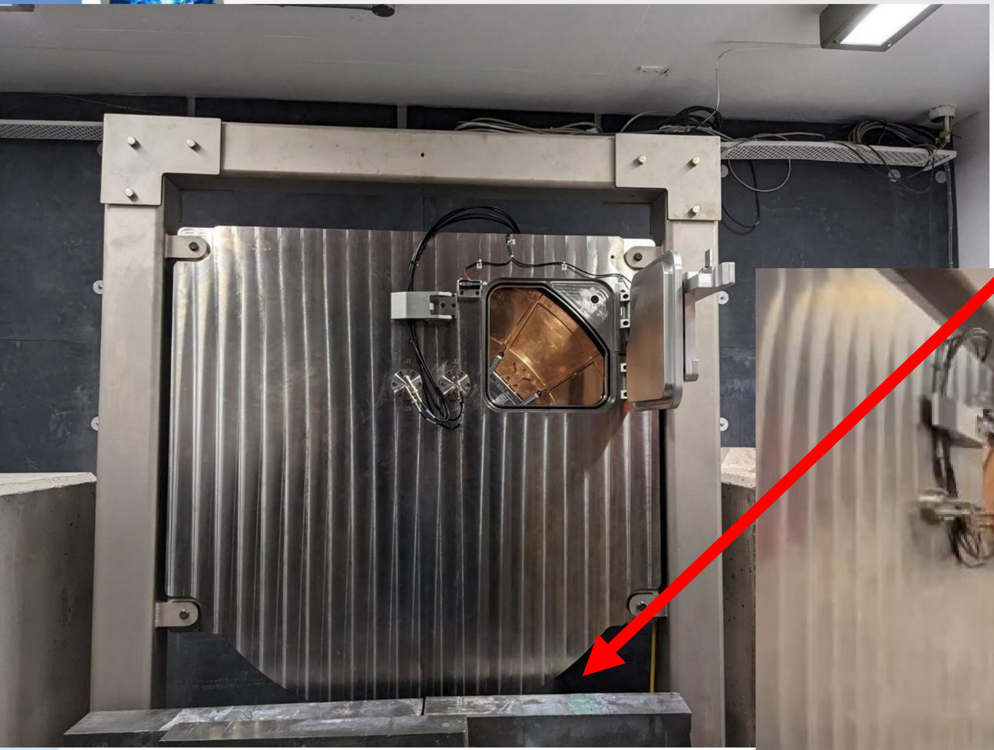
Proton beam current 30-50 mA at 2.6 MeV. Target lifetime > 1000 hrs.
Copper petals are main expense. Micro-channel cooling – 50% water by area.



Target (back): Copper with microchannel cooling back

Target (front): copper blank. A ~ 300 μm of natural lithium coating typically present.

Target change robot – TWEak



Thermal neutrons from graphite moderator under target structure.

Activity per target (16 petals) can reach 6 Tbq (^{7}Be).

UK neutron sources – accelerator based

Source	Production method	Details	Intensity
National Physical Laboratory (NPL)	3.5 MV Van de Graaff	p, d, <80 μA. Targets Sc, LiF, D, T… (air cooled)	E.g. 13-19 MeV (T) 0.05-0.63 MeV (Li) $2x10^{7}$ /s/cm^{2} Mono energetic
AWE, Aldermaston	Electrostatic 350 kV	d ions, <15 mA. Target tritium (TBq) (water cooled)	14 MeV <$2.5x10^{11}$ /s
Rutherford Appleton Laboratory	ISIS – Spallation (RFQ+Linac+Synchrotron) 800 MeV protons at <200 μA 50 Hz. 160 kW, W target+Ta clad 30 beam lines. Two examples given used for irradiation.	E.g. ChipIR: White neutron source with neutron energies up to 800 MeV	$1x10^{7}$ /s/cm^{2} [10-800 MeV, $5.8x10^{6}$ /s/cm^{2}]
		E.g. EMMA: Thermal neutrons – water moderated. 25 meV Maxwell-Boltzmann + epithermal tail	<$2x10^{6}$ /s/cm^{2} pulsed at 40 Hz
	NILE (DC beams but pulsing available)	DT source	14 MeV <$1x10^{8}$ /s/cm^{2}
		DD source	2.5 MeV <$1x10^{5}$ /s/cm^{2}
High flux Accelerator-Driven Neutron Facility, Birmingham	2.6 MV electrostatic	p, d, 50 mA. Target Li (water cooled)	0.1-1 MeV <$1x10^{12}$ /s/cm^{2} (p)

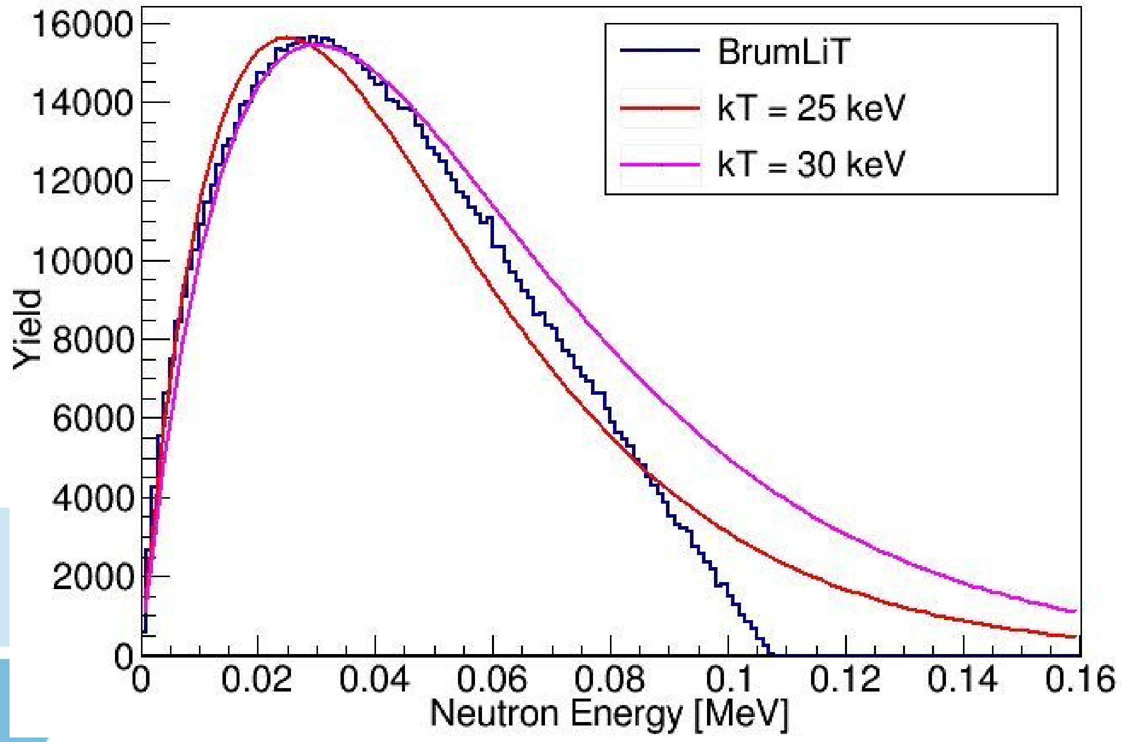
HF-ADNeF — research/impact opportunities

- **Nuclear materials research** under neutron irradiation [fission/fusion communities including associated industries, e.g. CCFE, First-light fusion, NNL etc.].
- **Nuclear fission and fusion data**, e.g. neutron capture cross section data [fission/fusion and nuclear physics communities].
- **Nuclear waste management** — understanding the long term effects of radiation on material characteristics [nuclear industry/NDA/NNL, nucl. eng. academics].
- **High power target development** [other facilities inc. medical and fusion devices, ourselves (future liquid lithium target) and the fusion community (fuel breeding)].
- **Medical physics** — from radiobiology to boron neutron capture therapy developments, e.g. for BNCT. Medical isotope cross sections measurements and production.
- **Industrial and space research** on the effect of radiation [detectors and space research communities — extension of cyclotron work in these areas].
- **Nuclear Metrology** — calibrated and controllable neutron source availability and testing new radiation monitoring systems [neutron source standards and characterisation, e.g. the National Physical Laboratory].
- **Nuclear (astro)physics** — the neutron spectrum is close to that in stellar environments [nuclear physics/nuclear astrophysics communities — feasibility grant (STFC)].

Towards nuclear astrophysics measurements at HF-ADNeF

At 1.912 MeV proton energy (threshold 1.88 MeV), the neutron spectrum is a close approximation to a Maxwell-Boltzmann distribution at lower neutron energies.

- Measurement of (n,γ) cross sections
- Nuclear astrophysical production of elements via the s-process.
- Nuclear data – (n,γ) cross sections also important for waste/decommissioning



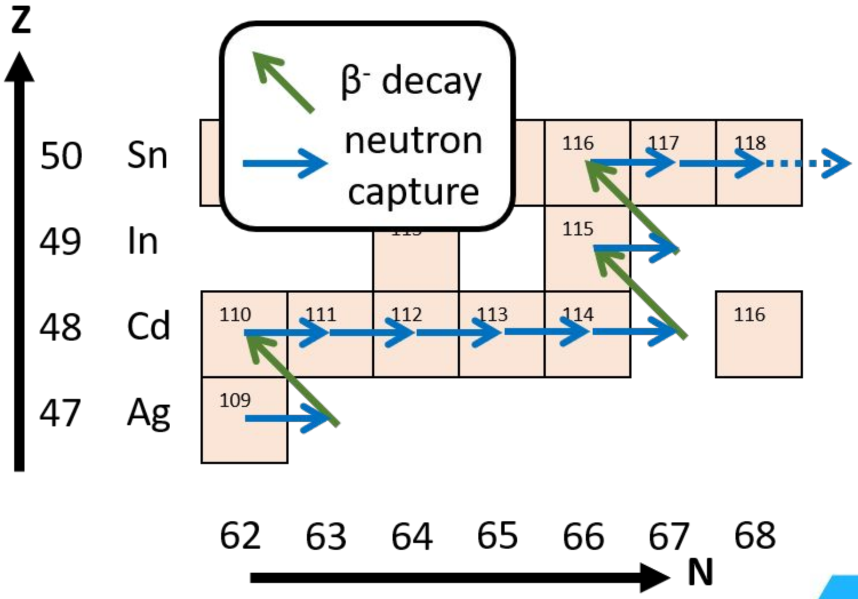
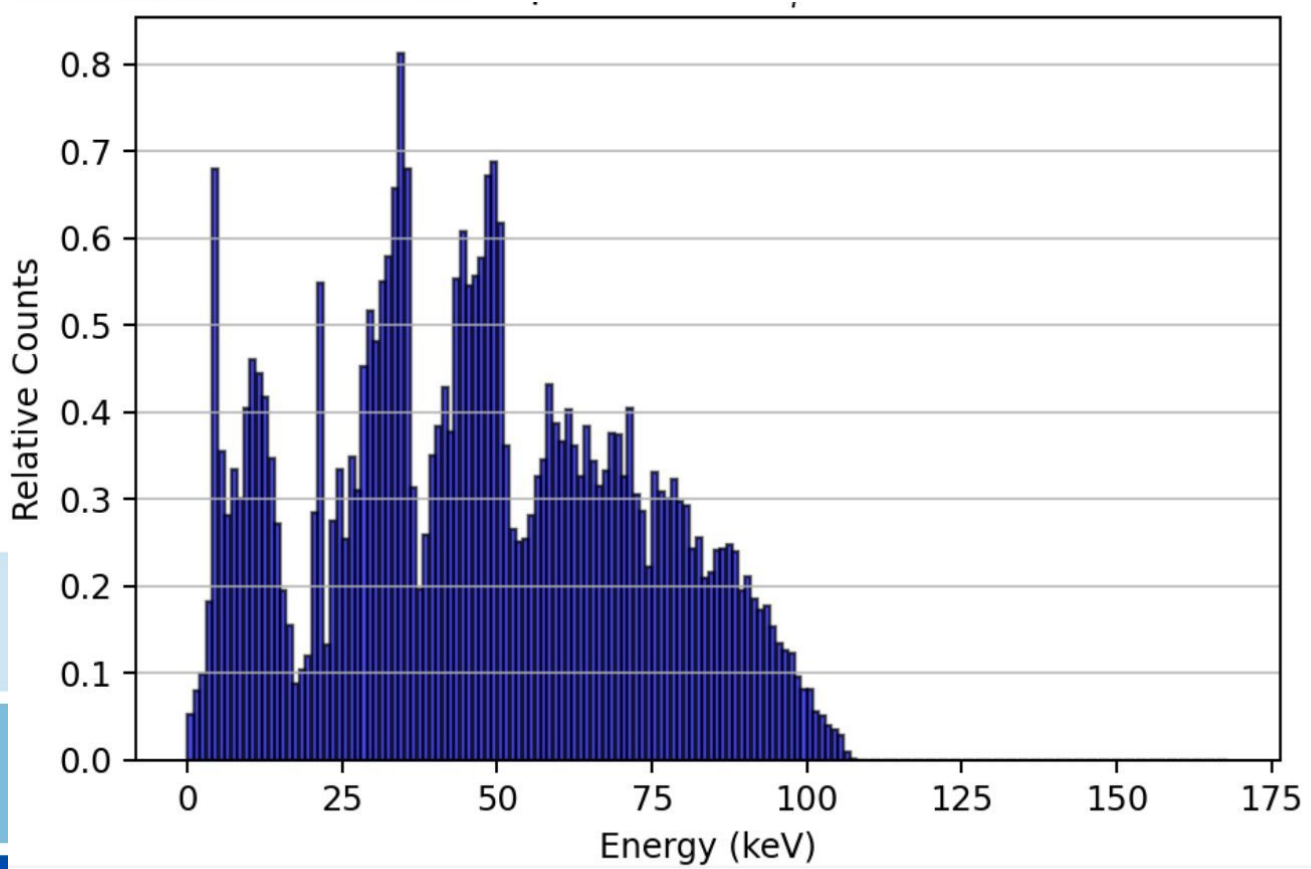


Figure from Jack Bishop

STFC-funded feasibility study

Towards nuclear astrophysics measurements at HF-ADNeF

At 1.912 MeV proton energy (threshold 1.88 MeV), the neutron spectrum is a close approximation to a Maxwell-Boltzmann distribution at lower neutron energies.



Currently limited by scattering through 4 mm-thick Ti wall

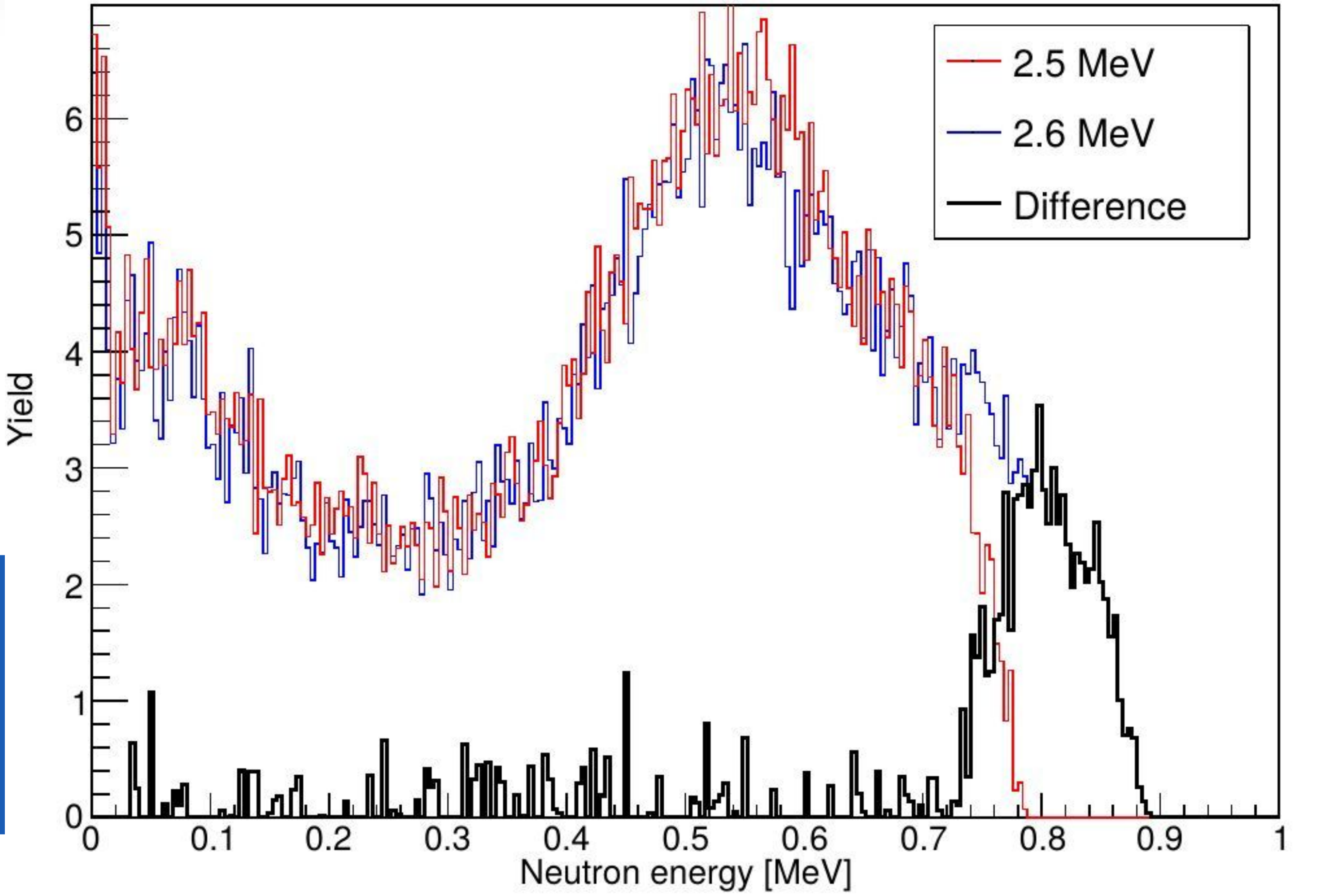
Figure from Jack Bishop

Maximum energy measurements

- Running two measurements, one at E*p* = 2.6 MeV and one at Ep = 2.5 MeV.

- Difference between the two gives pseudo-Gaussian around E*n* = 0.8 MeV.

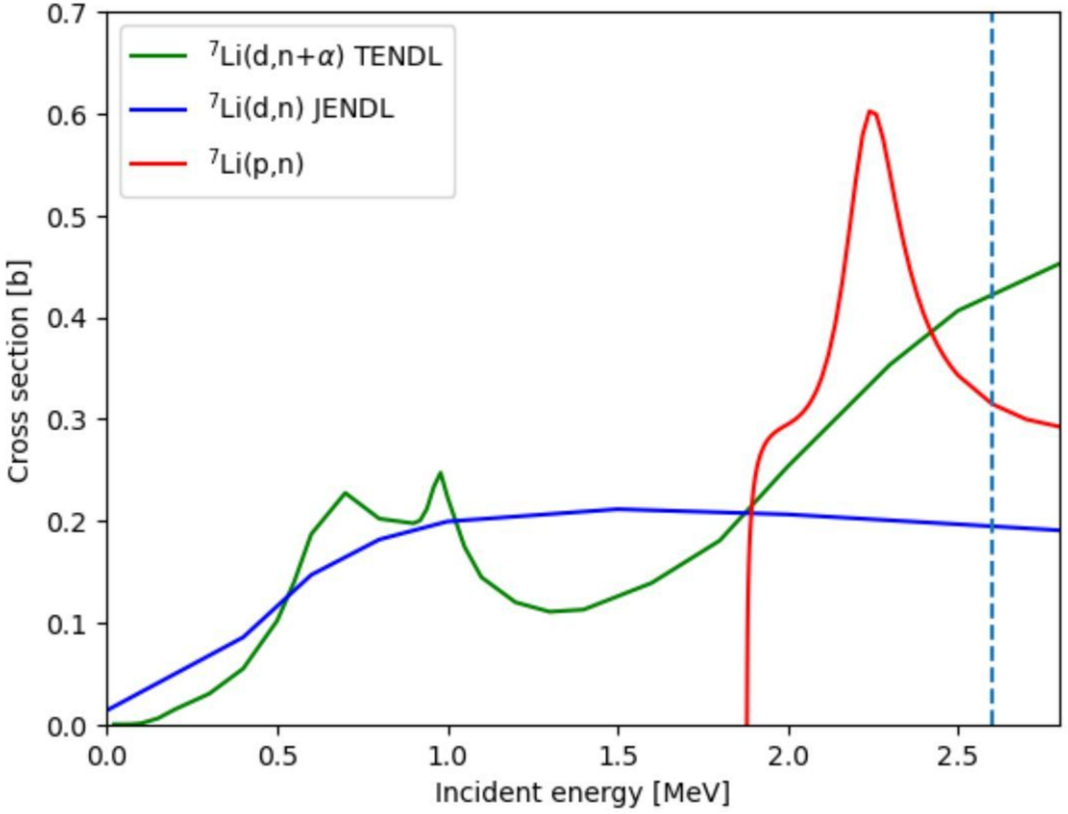
High intensity available allows for measurement of small samples with cross sections down to µb within few hours of beam with good statistics



Deuteron beams project

Moving to deuteron beam allows for both:

- Higher total flux (2-5 times higher)
- **Fast neutrons up to 17 MeV**
- Additional contribution from deuteron breakup/excited states
- Current work starting to model *d* + ^{7}Li neutron production
- Shielding upgrades required
- *d*(*d*,*n*) along the beamline
- More intense, higher E neutrons



Conclusions

Accelerator-based neutron sources are **versatile** and **small** and **quick to build** ~ 2 years. Could be Stepping stone to research reactor.

Neutrons up to 17 MeV for a **wide range of applications** are readily available.

- Nuclear data
- Fundamental science
- High power targets R&D
- Radiation hardness for space
- Environment, agricultural & heritage uses
- Fusion technology
- Medical applications
- Nuclear waste
- Training

Collaborators & acknowledgements

HF-ADNeF team (Physics): Martin Freer (PI), Ben Phoenix, Jack Bishop, Tendai Makuwatsine, Stuart Green, Tzany Kokalova. Funded through the NNUF programme via EPSRC and University of Birmingham.

Carl Wheldon
Director

Jack Bishop
Neutron Lead

Ben Phoenix
Technical Lead

A Birmingham Laboratory Portrait, CW, TzKW, JB, Y-LC, BP, DH, Nuclear Physics News, 34 issue 4 (2024) p4-8 (5 pages).

Thanks for listening.
Any questions?