Laser for neutron beams and possible applications

S. AMADUCCI

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PIANO NAZIONALE DI RIPRESA E RESILIENZA

NEUTRON SOURCES

A large number of neutron sources are available, based on different mechanisms:

- **Radioactivity: either compound (AmBe) or pure elements (^{252}Cf – whose spectra is considered a standard for the International Atomic Energy Agency)**
    - **Continuous distribution energy distribution peaked in the MeV energy range**
    - **Gamma contamination**
    - **Intensity as high as 10^6 n/s**

- **Reactors (LENA, TRIGA RC-1 at Casaccia, ILL): research reactors are well established as continuous source of very high intensity neutron fluences**
    - **High intensity (higher than 10^{12} n/cm^{2}s) with gamma background**
    - **Shaped energy spectra (thermal to MeV), evaluated based on simulation (mainly MCNP)**

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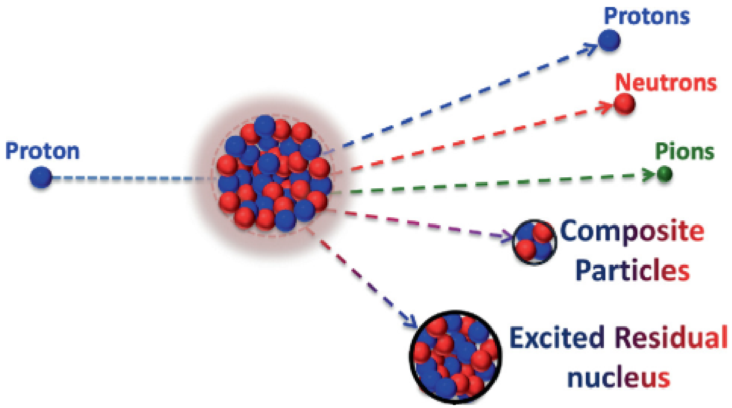
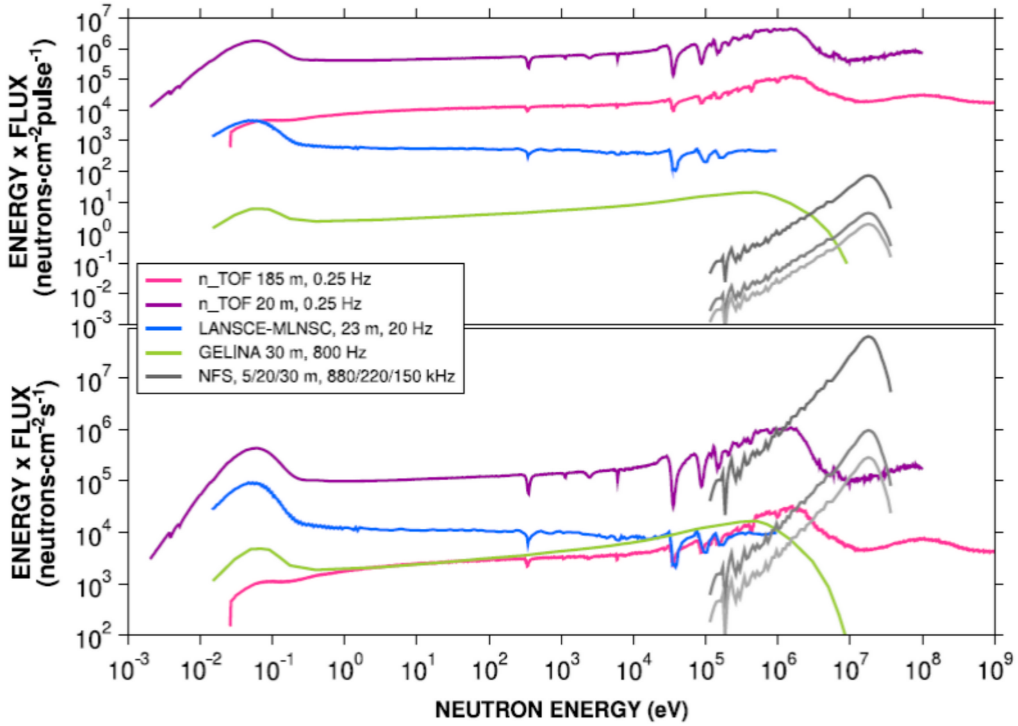
NEUTRON SOURCES

- **Spallation and Photonuclear reaction** (n_TOF, ESS, GELINA)
  - **Wide interval of neutron energy** (thermal to GeV)
  - Generally pulsed beam (time width ns)
  - Rate from 0.25 Hz to MHz
  - **Fluence as high as 10^6 n/cm^{2}pulse** in exp areas
  - Production of radioactive nuclei





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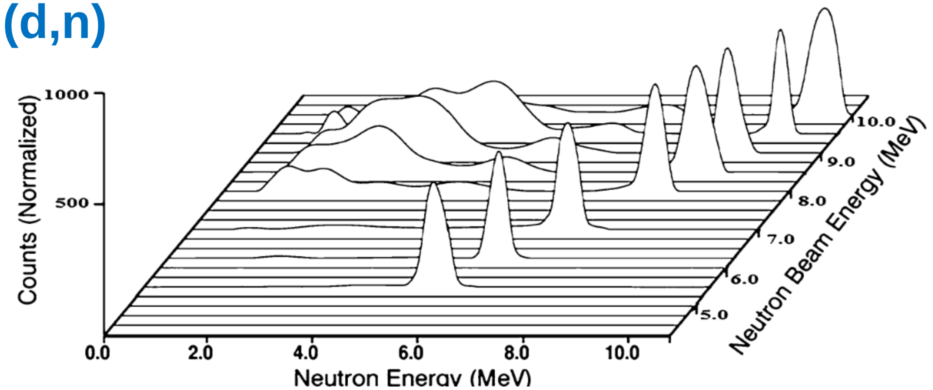
NEUTRON SOURCES

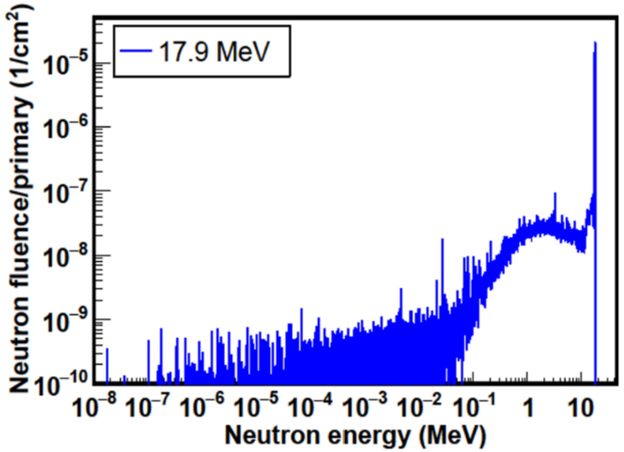
- **Nuclear reactions** (Demokritos, SARAF & Others): **quasi mono-energetic or Maxwellian spectra** produced with accelerators exploiting specific nuclear reaction
  - ^{7}Li(p,n)^{7}Be hundreds of keV and Maxwellian like distribution for Nuclear Astrophysics
  - Fusion reactions: ^{3}H(p,n)^{3}He (2 – 5 MeV), ^{2}H(d,n)^{3}He (4 – 11 MeV) and ^{3}H(d,n)^{4}He (16 – 20 MeV)
  - Typical **fluence of 10^{5}-10^{6} n/cm^{2}s**

^{2}H(d,n)



Vlastou EPJ Techniques and Instrumentation (2023) 10:4

^{3}H(d,n)



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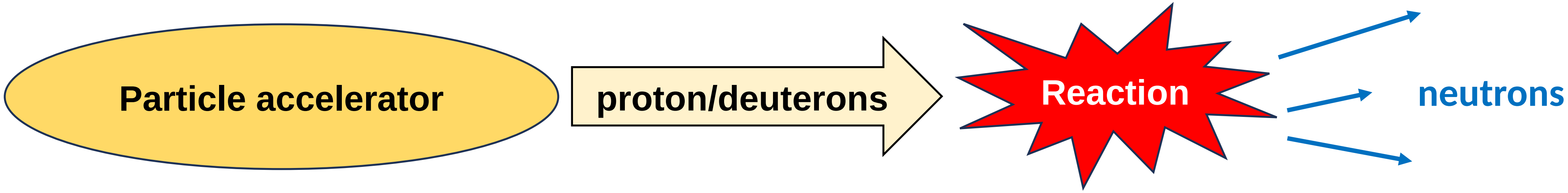
NEUTRON PRODUCTION WITH LASER

Laser Driven Neutron Sources rely on the same principles and nuclear reactions:



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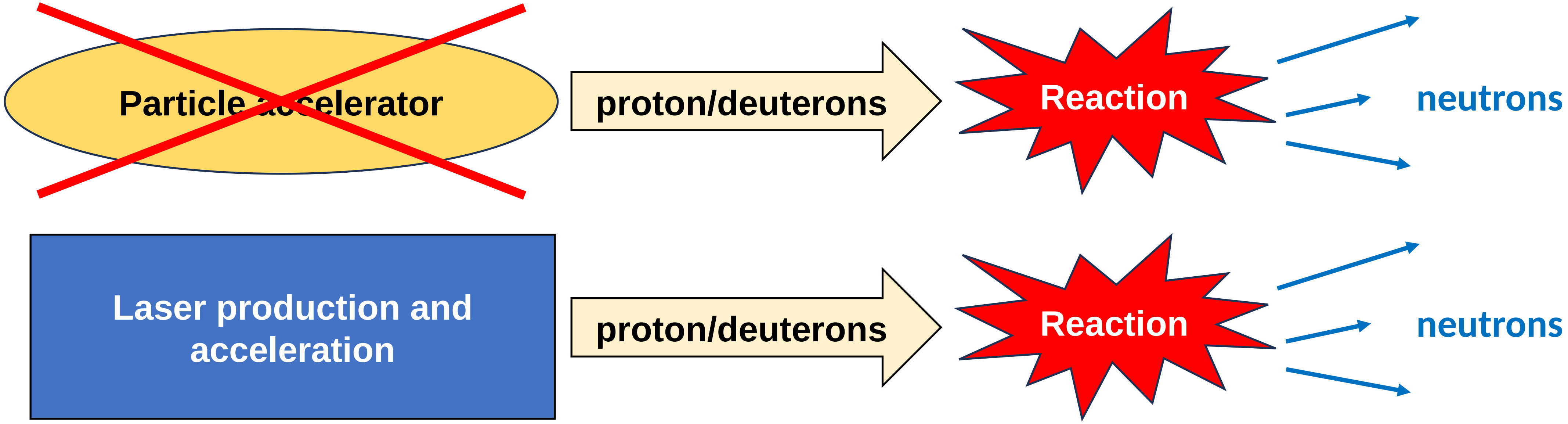

~~**Particle accelerator**~~ → **proton/deuterons** → **Reaction** → **neutrons**

Laser production and acceleration → **proton/deuterons** → **Reaction** → **neutrons**

Protons and deuterons (or electrons) are produced and accelerated by the interaction of Laser and matter.

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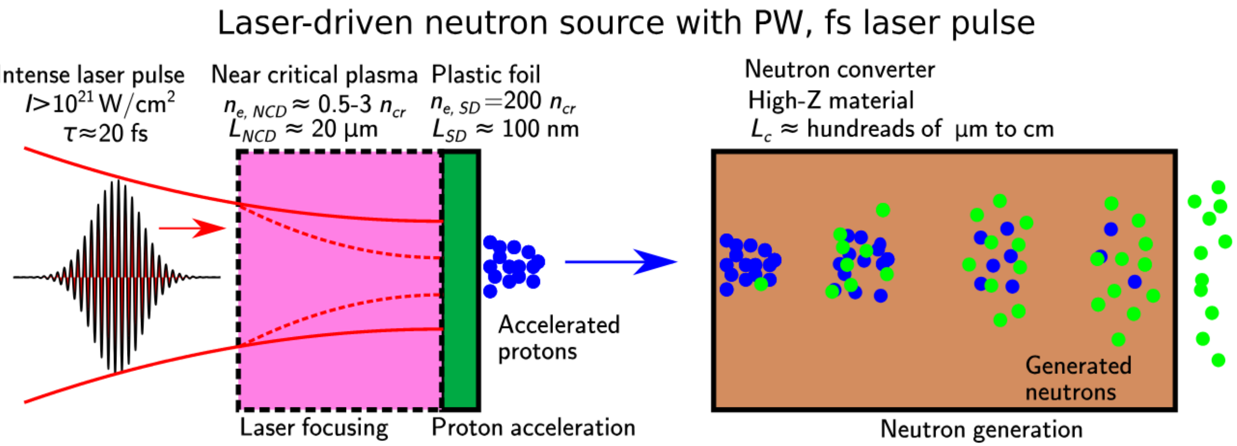
NEUTRON PRODUCTION WITH LASER

Neutron production is usually based on a double-target configuration, the so-called pitcher-catcher scheme

(1) The laser pulse hit the primary pitcher target producing high-density plasma



Horný, V.c.v., et al. Phys. Rev. C 109, 025802 (2024)

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NEUTRON PRODUCTION WITH LASER

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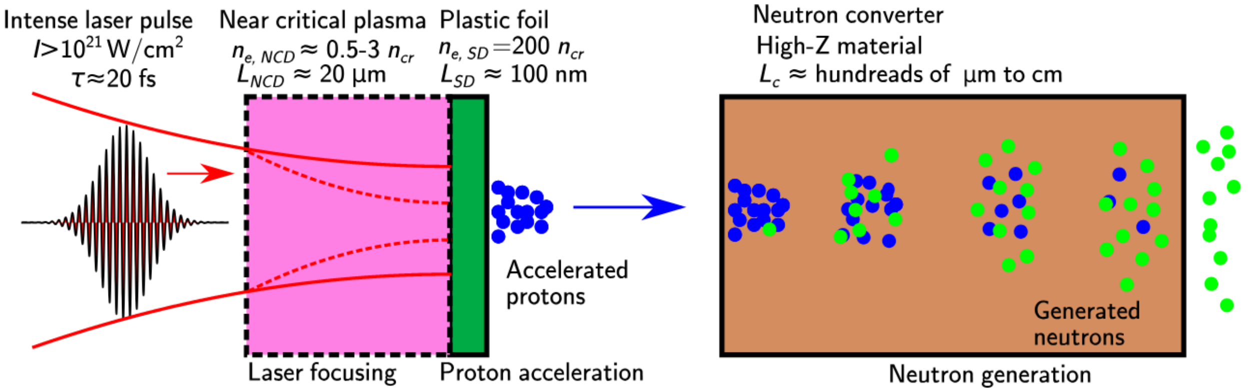
Laser-driven neutron source with PW, fs laser pulse



(1) The laser pulse hit the primary pitcher target producing high-density plasma

(2) Particles as protons, deuterons and electrons are produced and accelerated

Horný, V.c.v., et al. Phys. Rev. C 109, 025802 (2024)

NEUTRON PRODUCTION WITH LASER

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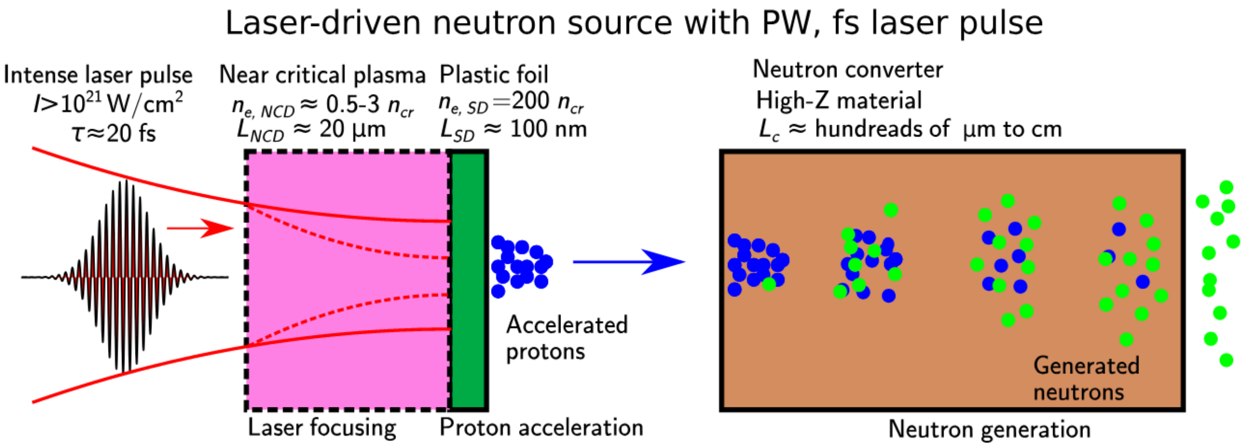
(1) The laser pulse hit the primary pitcher target producing high-density plasma



(3) Neutrons are produced by nuclear reactions of the secondary particles in the catcher

(2) Particles as protons, deuterons and electrons are produced and accelerated

Horný, V.c.v., et al. Phys. Rev. C 109, 025802 (2024)

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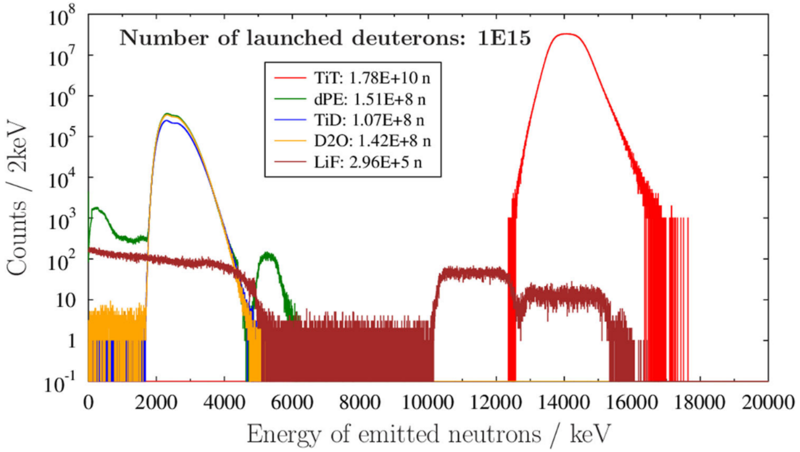
NEUTRON PRODUCTION WITH LASER

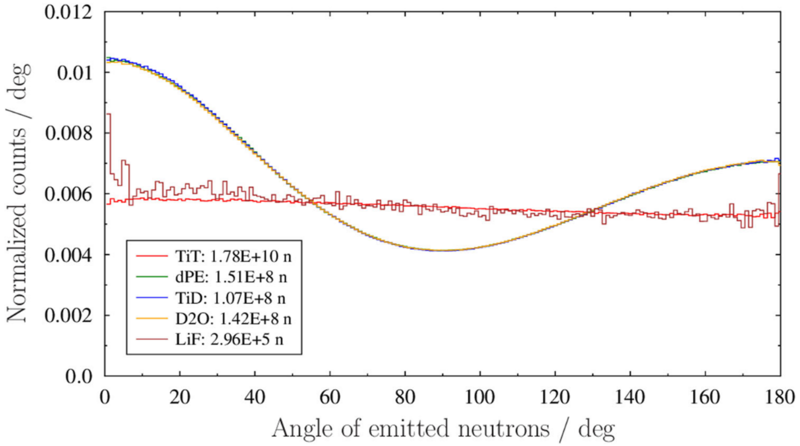
In the case of deuterons, most of the reactions involved have positive Q-value and an angular distribution of the neutrons peaked in the forward direction.

Many materials might be employed as catcher, for ^{2}H the most common include deuterized polyethylene (dPE), titanium tritide (TiT), titanium deuteride (TiD), heavy water (D_2 O), and lithium fluoride (LiF).

Reaction	Q value (MeV)	σ at 100 keV (mb)	σ at 500 keV (mb)
$^{2}H + ^{3}H \rightarrow ^{4}He + n$	17.6	5000	500
$^{2}H + ^{2}H \rightarrow ^{3}He + n$	3.3	20	60
$^{2}H + ^{6}Li \rightarrow ^{7}Be + n$	3.4	1	60
$^{2}H + ^{7}Li \rightarrow ^{8}Be + n$	15.0	1	20

Osvay, K., et al. Eur. Phys. J. Plus (2024) 139:574





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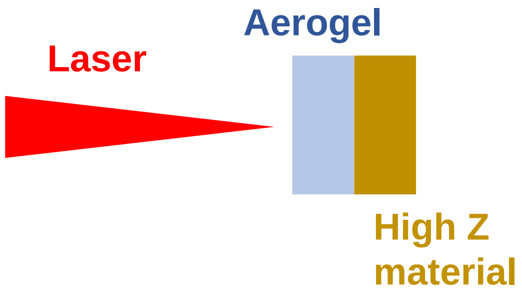
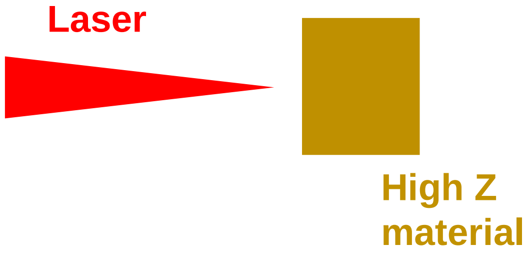
NEUTRON PRODUCTION WITH LASER

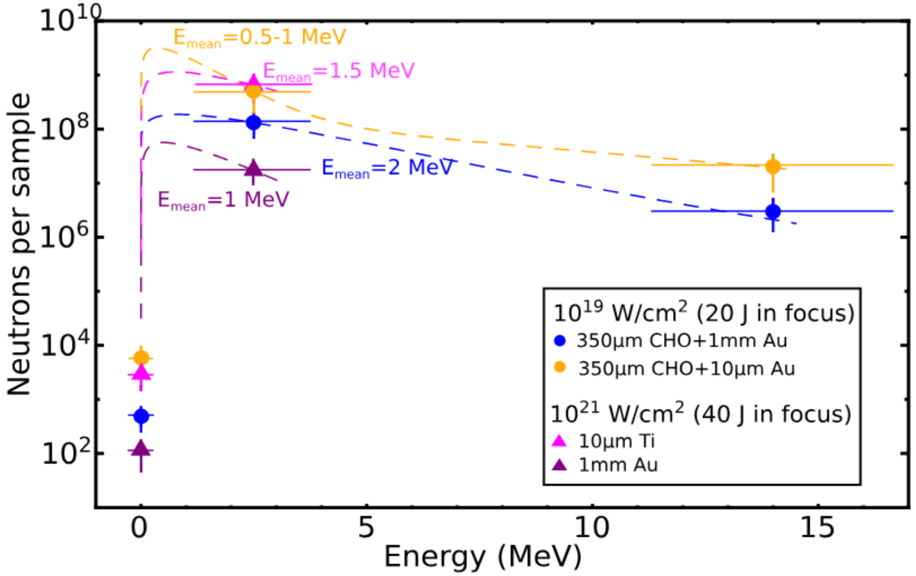
The mechanism of neutron production can be controlled by changing the pitcher-target materials and dimensions, for example by adding a proton rich (or deuterated) material as pitcher to enhance the ion contribution.



Neutron production mainly due to the protons generated in the aerogel



Neutron production from the electrons, higher laser intensity is needed.



Günther, M.M., et al., Nature Communications 13(1), 170 (2022) https://doi.org/10.1038/s41467-021-27694-7

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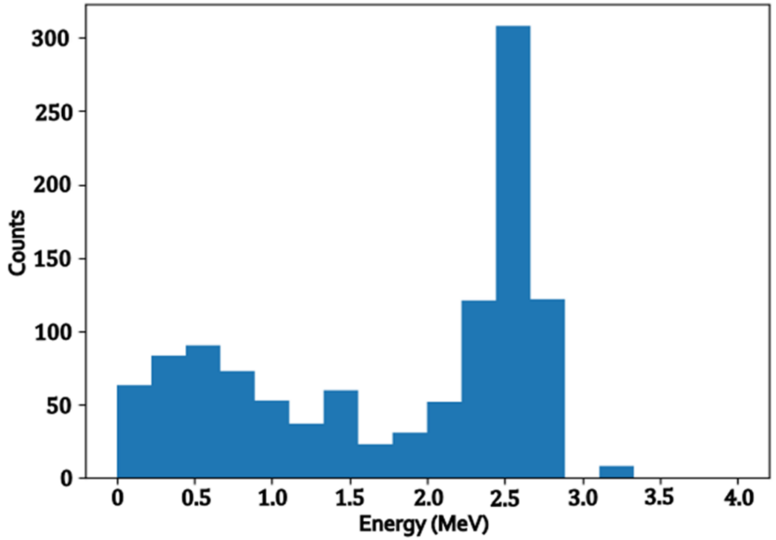
NEUTRON PRODUCTION WITH LASER

Alternative approaches based on single target are possible, in particular exploiting the ^2H + ^2H reactions taking place is a deuterated sample (e.g. D_2O).

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \textcircled{n} + 3.27\ \mathrm{MeV},$$

2.45 MeV in the center of mass



Neutron events measured in a organic scintillator (n/g discrimination based on PSD).

Neutron fluences up to 10^5 n/s with a laser of 10^{18} W/cm^2

Knight BM, et al. High Power Laser Science and Engineering. 2024;12:e2.

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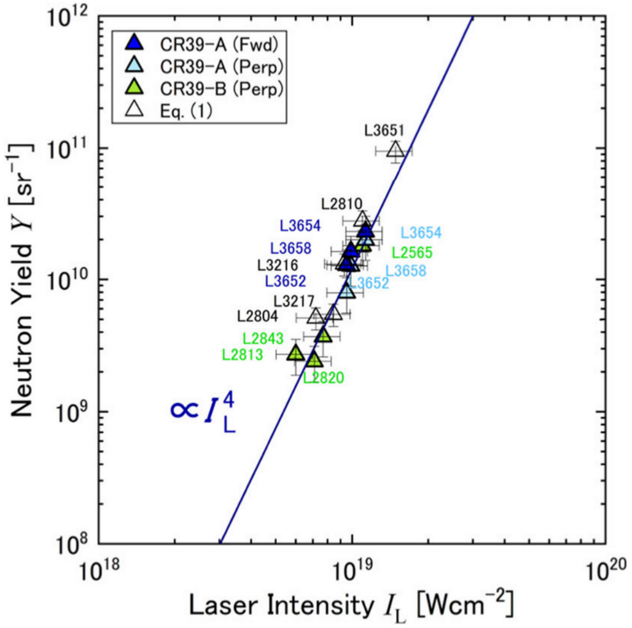
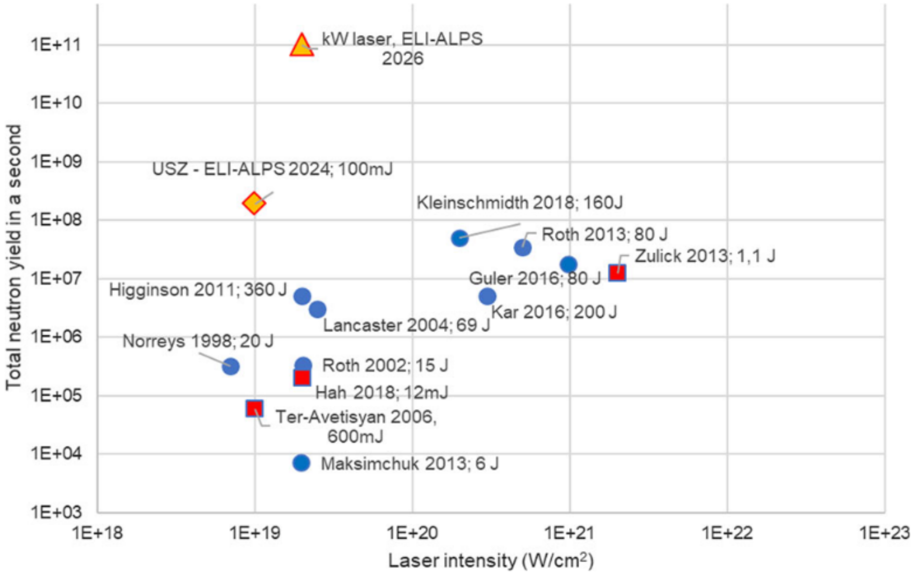
NEUTRON PRODUCTION WITH LASER

For the same conditions (pitcher-catcher), the neutron Yield scales with the Laser Intensity as demonstrate by Yogo et al. (left), yields between 10^4 and 10^{10} were produced in other facilities (right).



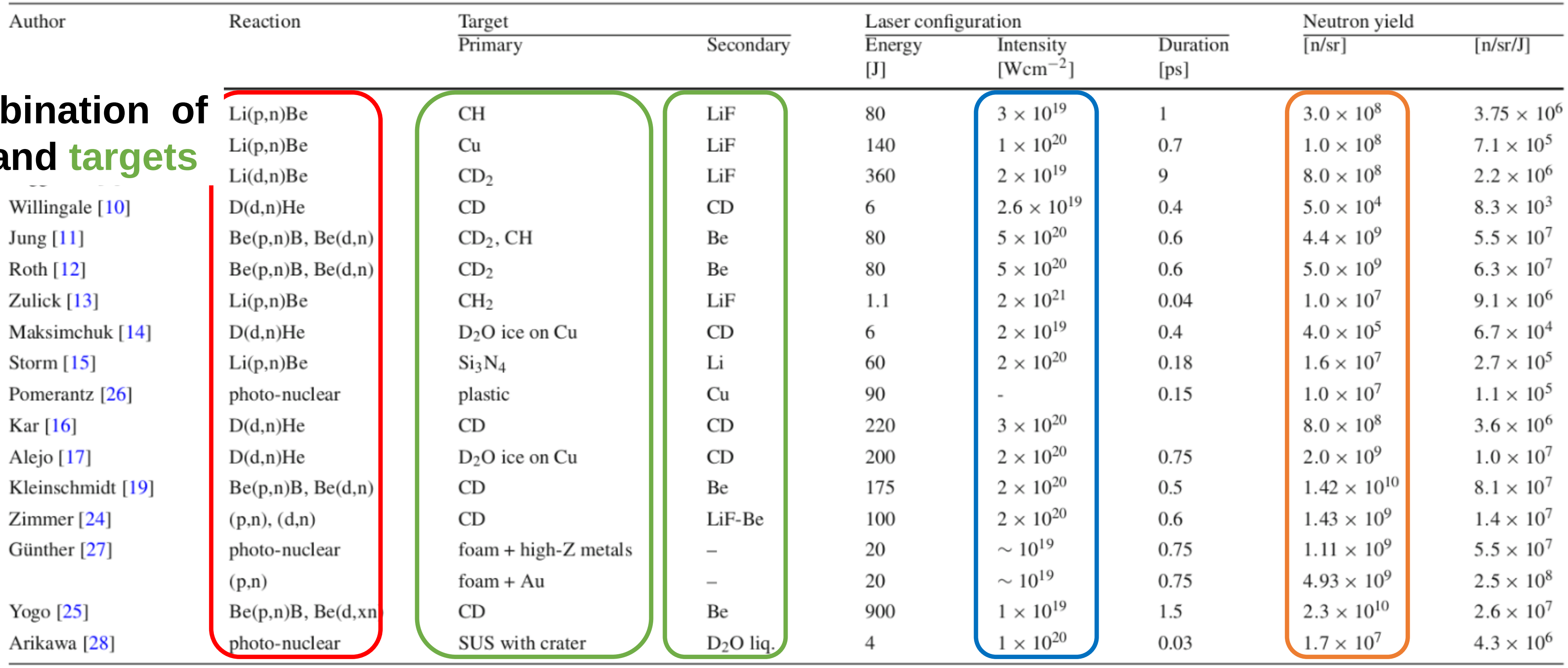


Yogo, A., et al. PHYSICAL REVIEW X 13, 011011 (2023)

Osvay, K., et al. Eur. Phys. J. Plus (2024) 139:574

NEUTRON PRODUCTION WITH LASER

Wide combination of reactions and targets



Author	Reaction	Target Primary	Secondary	Laser configuration Energy [J]	Intensity [Wcm^{-2}]	Duration [ps]	Neutron yield [n/sr]	[n/sr/J]
	Li(p,n)Be	CH	LiF	80	3×10^{19}	1	3.0×10^{8}	3.75×10^{6}
	Li(p,n)Be	Cu	LiF	140	1×10^{20}	0.7	1.0×10^{8}	7.1×10^{5}
	Li(d,n)Be	CD_2	LiF	360	2×10^{19}	9	8.0×10^{8}	2.2×10^{6}
Willingale [10]	D(d,n)He	CD	CD	6	2.6×10^{19}	0.4	5.0×10^{4}	8.3×10^{3}
Jung [11]	Be(p,n)B, Be(d,n)	CD_2, CH	Be	80	5×10^{20}	0.6	4.4×10^{9}	5.5×10^{7}
Roth [12]	Be(p,n)B, Be(d,n)	CD_2	Be	80	5×10^{20}	0.6	5.0×10^{9}	6.3×10^{7}
Zulick [13]	Li(p,n)Be	CH_2	LiF	1.1	2×10^{21}	0.04	1.0×10^{7}	9.1×10^{6}
Maksimchuk [14]	D(d,n)He	D_2O ice on Cu	CD	6	2×10^{19}	0.4	4.0×10^{5}	6.7×10^{4}
Storm [15]	Li(p,n)Be	Si_3N_4	Li	60	2×10^{20}	0.18	1.6×10^{7}	2.7×10^{5}
Pomerantz [26]	photo-nuclear	plastic	Cu	90	-	0.15	1.0×10^{7}	1.1×10^{5}
Kar [16]	D(d,n)He	CD	CD	220	3×10^{20}		8.0×10^{8}	3.6×10^{6}
Alejo [17]	D(d,n)He	D_2O ice on Cu	CD	200	2×10^{20}	0.75	2.0×10^{9}	1.0×10^{7}
Kleinschmidt [19]	Be(p,n)B, Be(d,n)	CD	Be	175	2×10^{20}	0.5	1.42×10^{10}	8.1×10^{7}
Zimmer [24]	(p,n), (d,n)	CD	LiF-Be	100	2×10^{20}	0.6	1.43×10^{9}	1.4×10^{7}
Günther [27]	photo-nuclear	foam + high-Z metals	–	20	$\sim 10^{19}$	0.75	1.11×10^{9}	5.5×10^{7}
	(p,n)	foam + Au	–	20	$\sim 10^{19}$	0.75	4.93×10^{9}	2.5×10^{8}
Yogo [25]	Be(p,n)B, Be(d,xn	CD	Be	900	1×10^{19}	1.5	2.3×10^{10}	2.6×10^{7}
Arikawa [28]	photo-nuclear	SUS with crater	D_2O liq.	4	1×10^{20}	0.03	1.7×10^{7}	4.3×10^{6}

Yogo, A, et al. Eur. Phys. J. A (2023) 59:191

Intensity 10^{18}-10^{20} W/cm^2 → Neutron Yield 10^{4}-10^{10} n/sr

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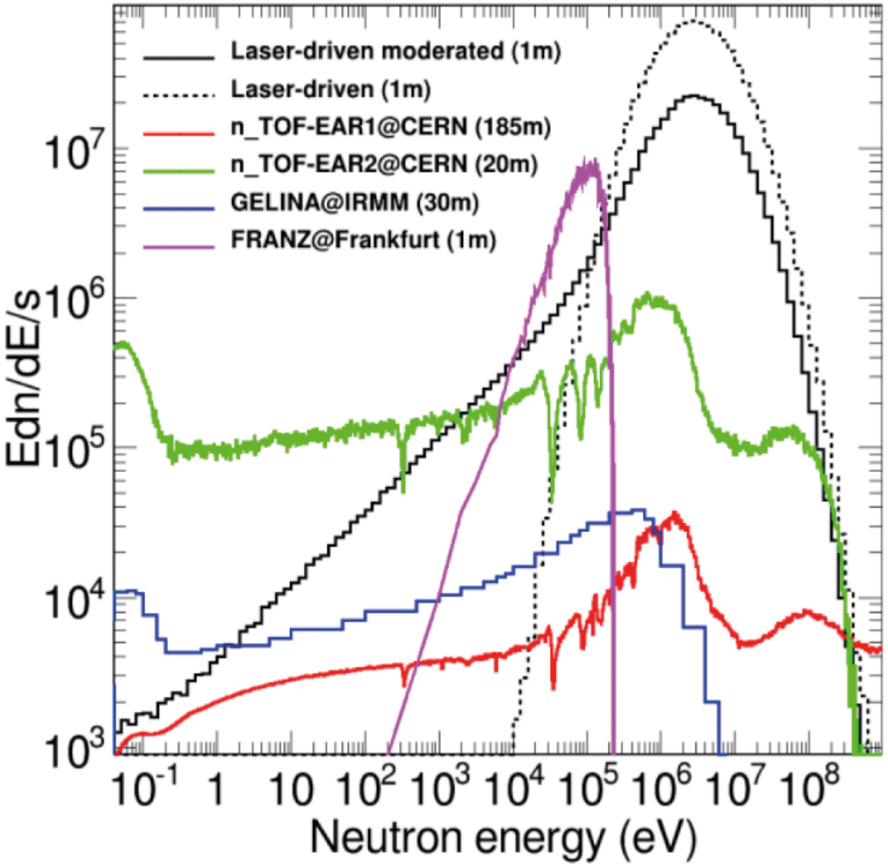
NEUTRON PRODUCTION WITH LASER

Neutron production based on laser is a promising solution to increase the availability of neutron facilities for both research and industrial applications.

- **Avoid the regulation of Nuclear Reactors**
- **Unlike the spallation based facilities it is not needed an 0.5-2 GeV accelerator (budget reduction)**
- **Can be implemented in small / medium size laboratories**



Guerrero, C. et al. The European Physical Journal A 53(5), 87 (2017)

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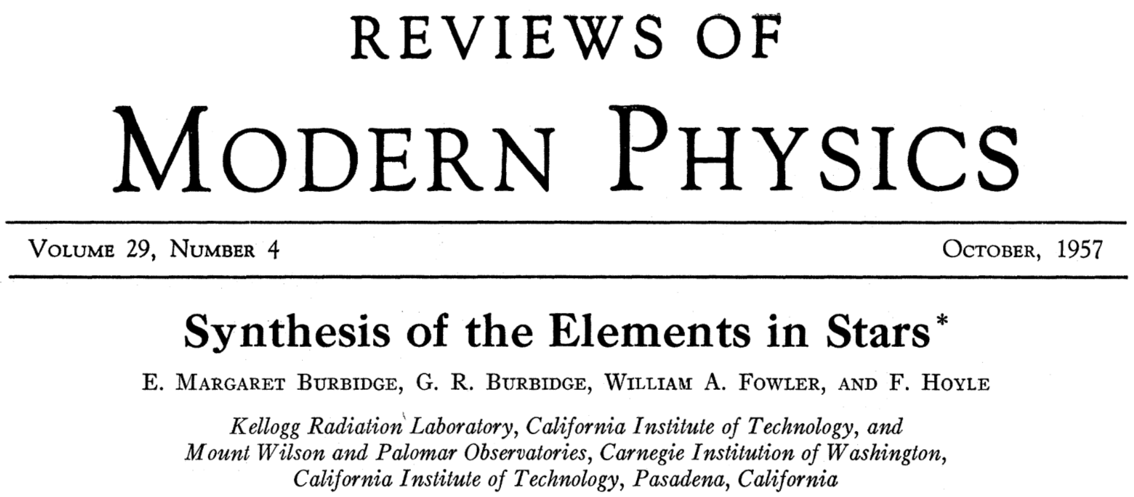
NUCLEAR ASTROPHYSICS

The synthesis of heavy elements (heavier than iron) take place is stellar environments through neutron captures and beta decays.



REVIEWS OF

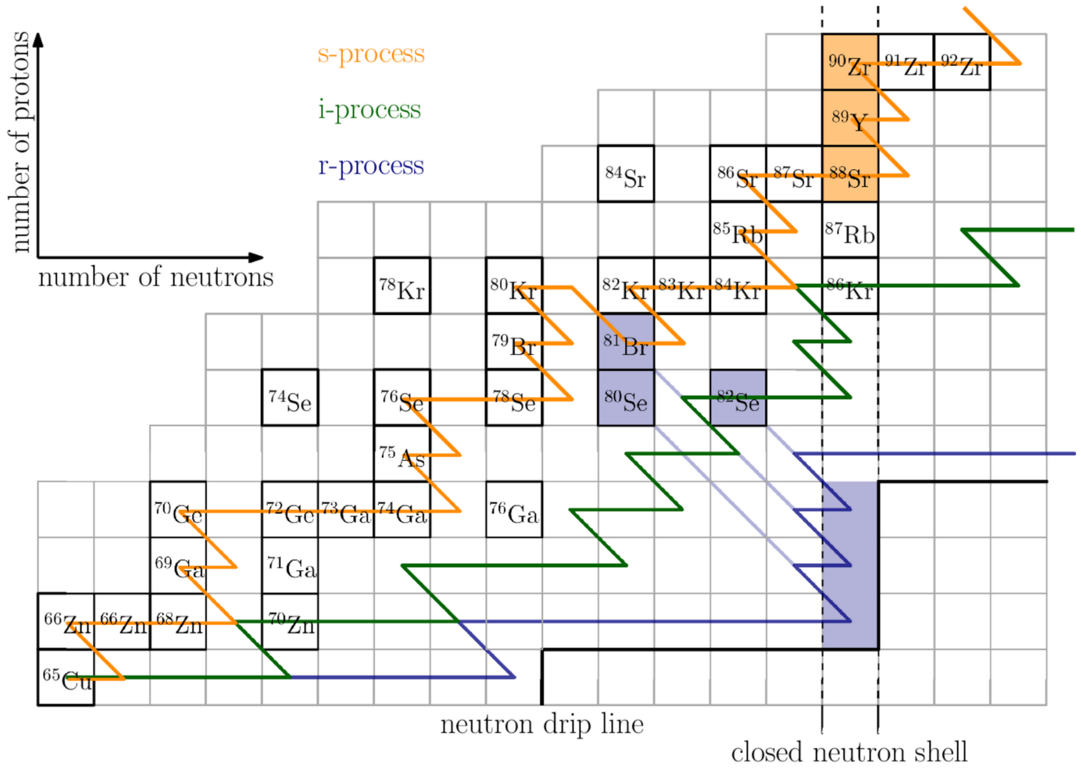
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California



Courtesy of D.Vescovi

NUCLEAR ASTROPHYSICS

s(slow)-process

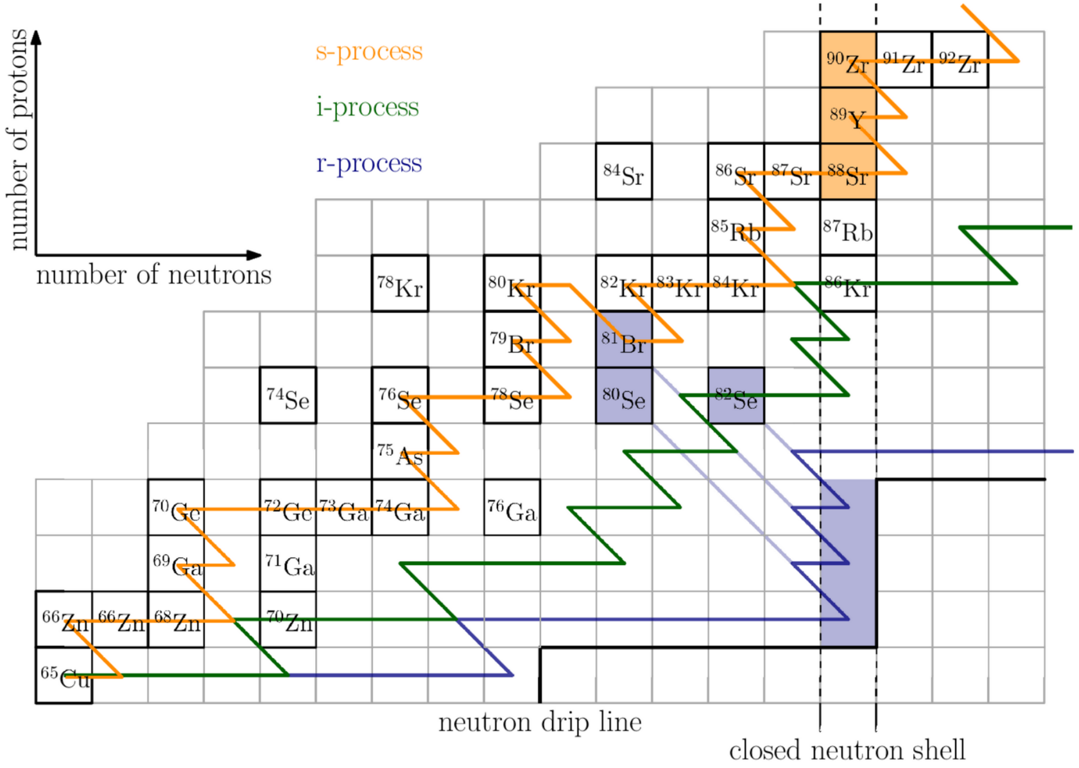
- Low neutron density (about 10^7 n/cm^3)
- Asymptotic Giant Branch (AGB) and massive stars

i(intermediate)-process

- Intermediate neutron density (10^{15} n/cm^3)
- AGB, white dwarfs, massive stars…

r(rapid)-process

- High neutron density ($>10^{21}$ n/cm^3)
- Supernovae and compact binary mergers



Courtesy of D.Vescovi

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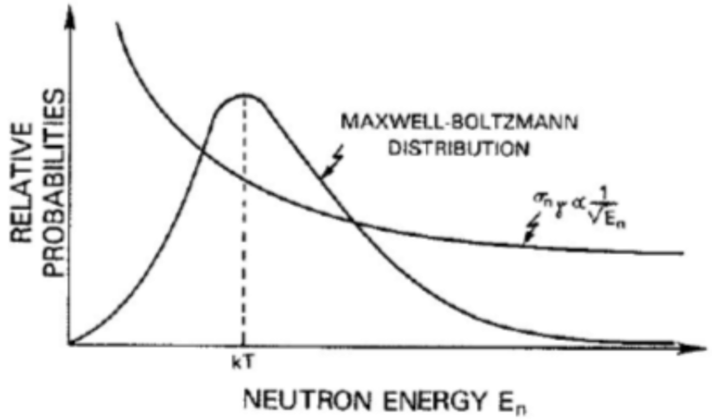
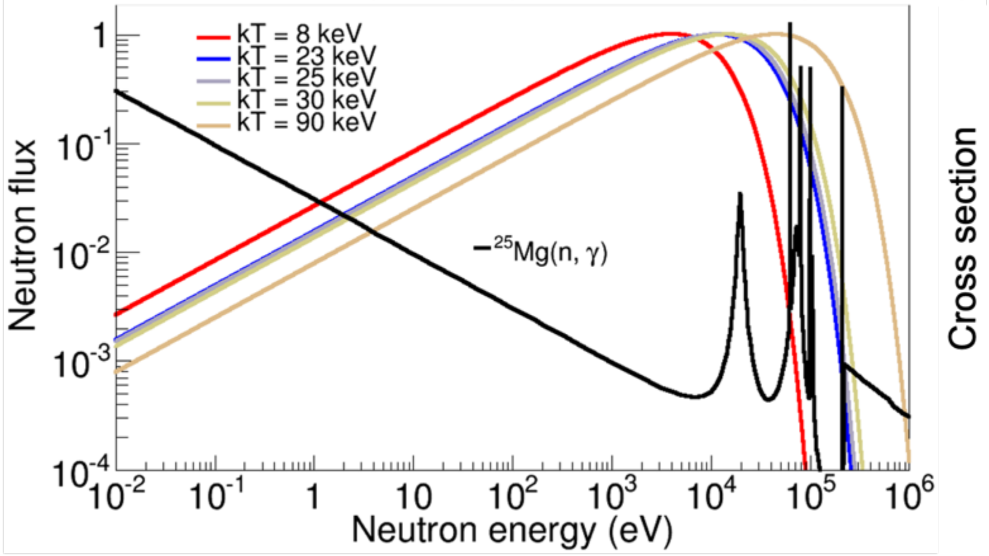
MAXWELLIAN AVERAGED CROSS SECTION

For Nuclear Astrophysics the quantity of interest is the Maxwellian Averaged Cross Section (MACS), i.e. the convolution of the cross section with the neutron energy distribution in stars (temperatures between 5 and 100 keV).



$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^{\infty} \sigma(E) E e^{-E/(kT)} dE$$

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)



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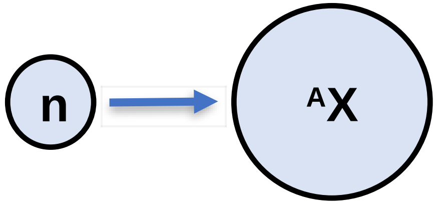
ACTIVATION

Activation is a well-established technique to perform integral measurements of neutron reaction cross sections, in particular for (n,γ) of interest for Nuclear Astrophysics.



Neutron irradiation with very well-known spectra (possibly Maxwellian)

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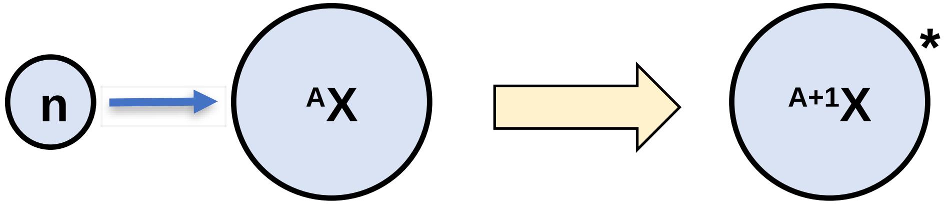

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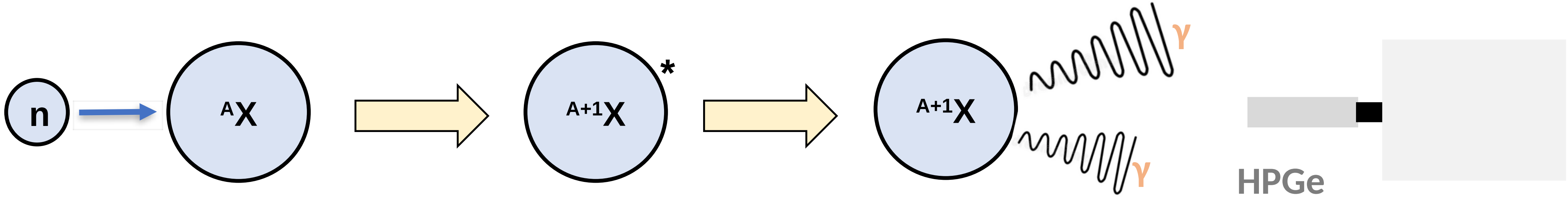

Neutron irradiation with very well-known spectra (possibly Maxwellian)

Measurement of the activity of thought the radiation emitted by the daughter nucleus (generally with HPGe)

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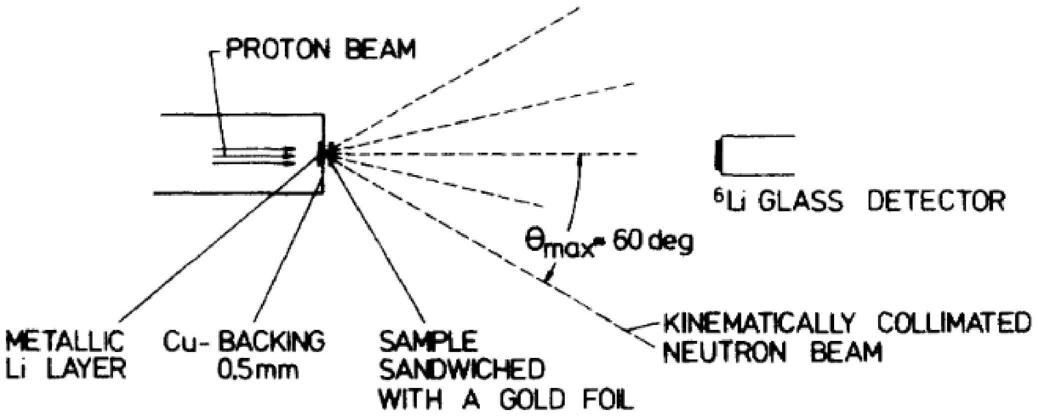
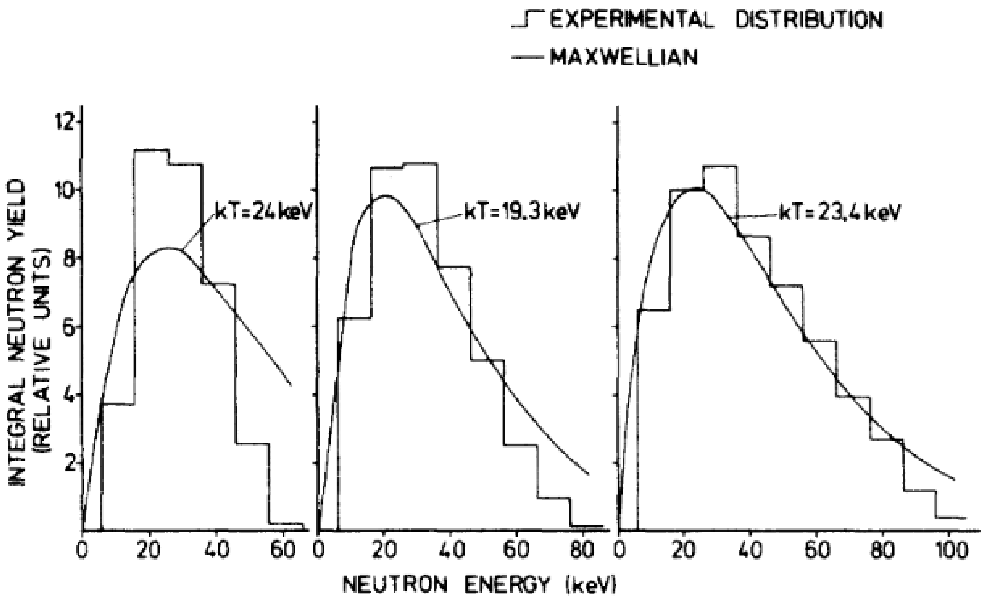
ACTIVATION

Historically neutrons are produced by protons thought the ^{7}Li(p,n) reaction, by exploiting the threshold reaction and fine tuning the proton beam it is possible to produce a Maxwellian like distribution.





H. Beer and F. Käppeler, Phys. Rev. C **21**, 534 – Published 1 February, 1980

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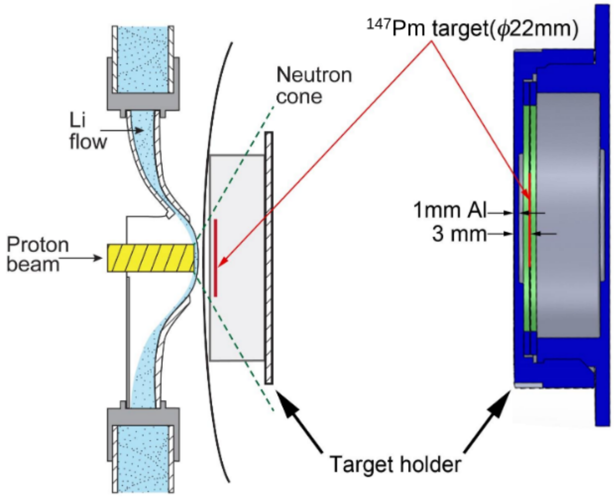
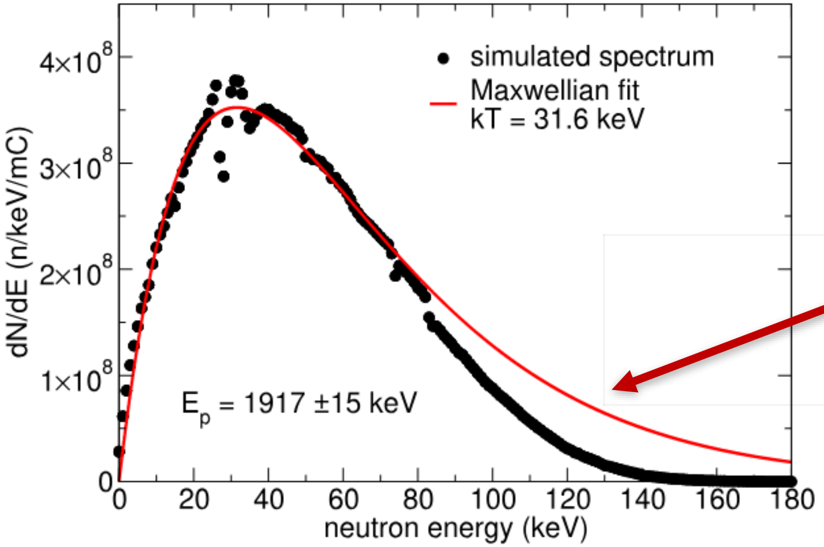
ACTIVATION

To face higher currents, liquid lithium targets have been implemented (LiLiT@SARAF) but despite the optimizations differences are present in the high energy tail of the Maxwellian like distribution.





Correction needed!

Paul, M., et al. EPJ Web of Conferences 232, 01003 (2020)

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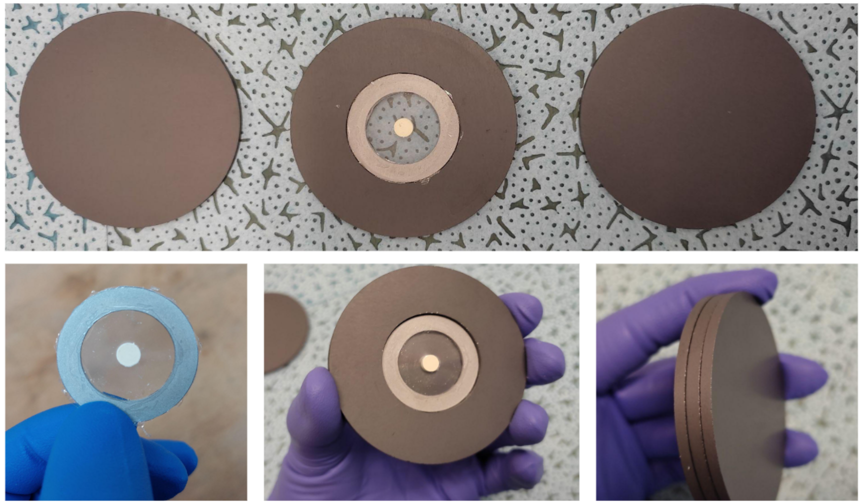
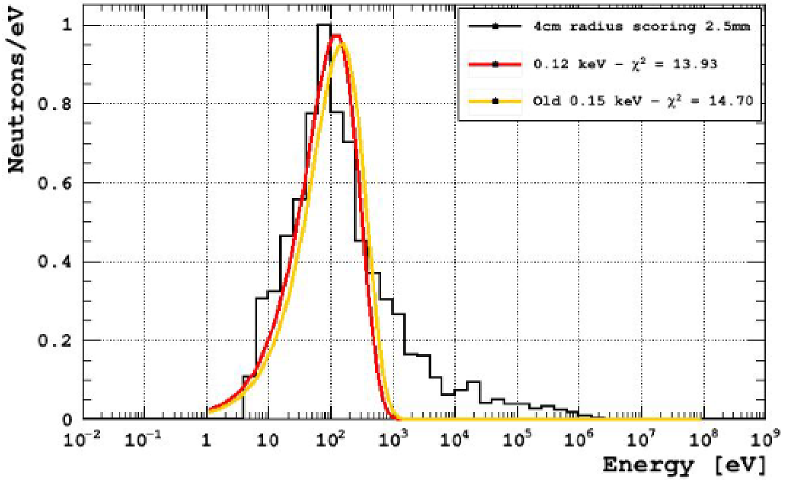
ACTIVATION

The high degrees of freedom in the combination of targets for neutron production at Laser Facilities might be exploited to improve the Maxwellian distribution, starting from the well-established ^{7}Li(p,n).
Additionally, the energy spectra can be modified also with a moderator and at the sample level, by using combination of neutron absorbers (a campaign is ongoing at n_TOF).





Courtesy of E. Stamati

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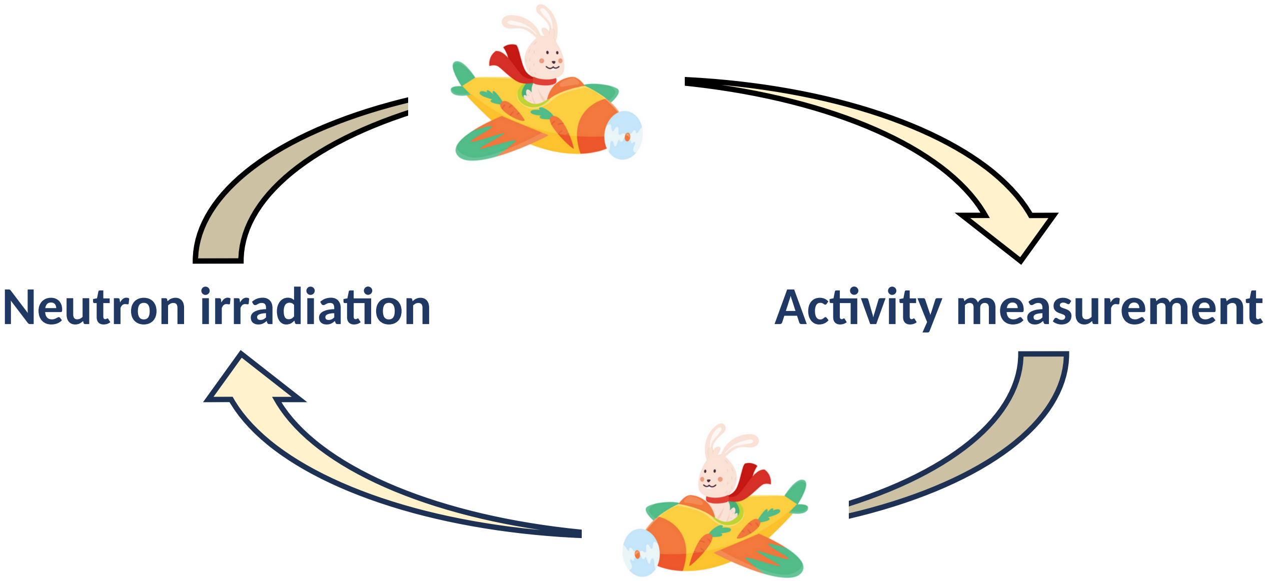
ACTIVATION

In most interesting cases, the half-life of the ^{A+1}X nucleus is the main limitation for the measurement, the implementation of a dedicated setup for cyclical irradiation/measurement would allow to investigate reaction that at present are not accessible.



Neutron irradiation

Activity measurement

With The use of a rabbit system to move the sample from the irradiation position to the HPGe isotopes with half-life in the order of few seconds might be accessible!

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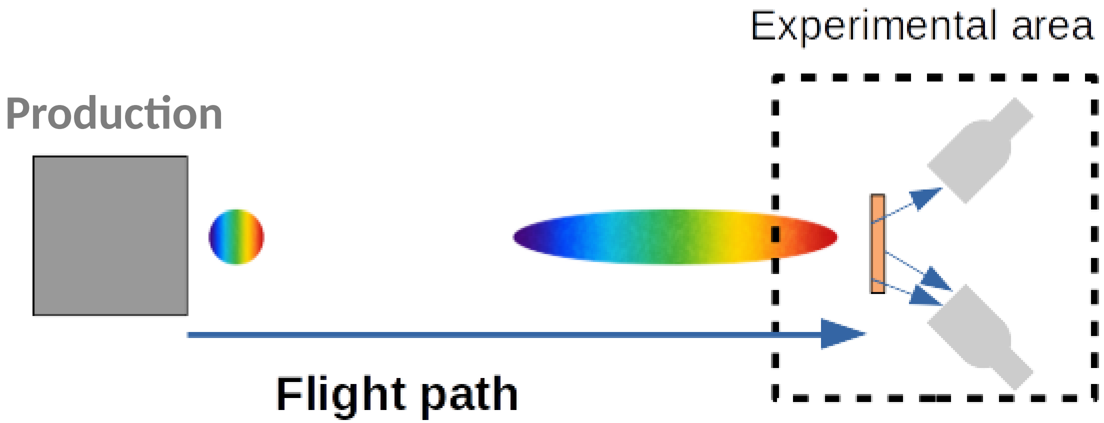
TIME OF FLIGHT

To measure differential cross section the neutron energy is usually determined by the time-of-flight (ToF) technique, measuring the time between the neutron production and the detection of the reaction products.



$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{L^2}{tof^2 \cdot c^2}}} - 1 \right)$$

$$\frac{\Delta v}{v} = \frac{1}{L}\sqrt{v^2 \Delta t^2 + \Delta L^2}$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma\frac{\Delta v}{v}$$

- **Resolution increase with longer flight path and short pulse**
- **Resolution decrease for wide source (e.g. spallation target)**

Improved by the narrow and small laser pulse

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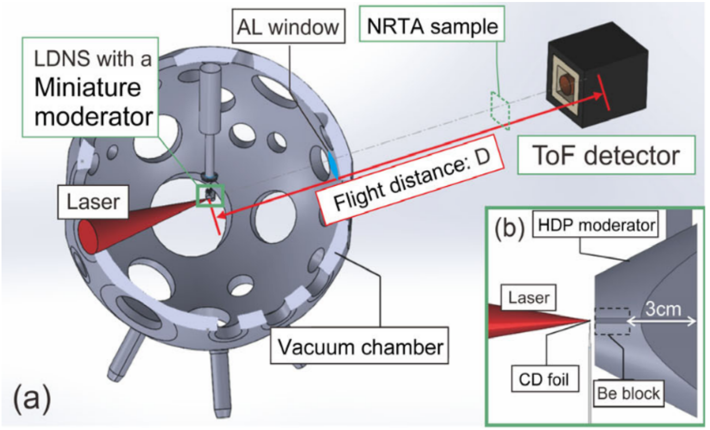
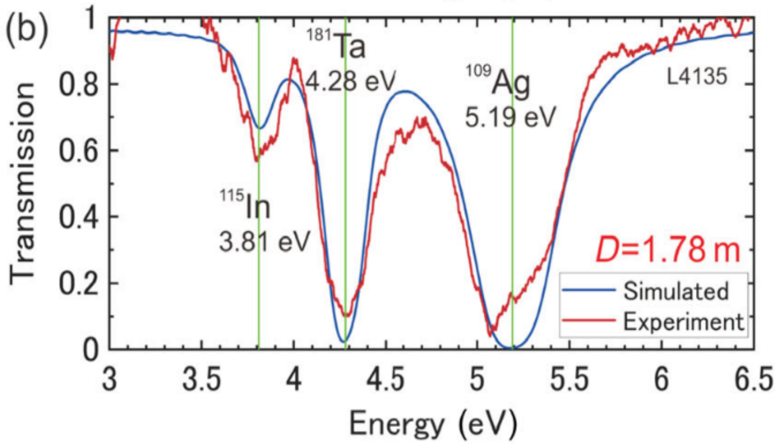
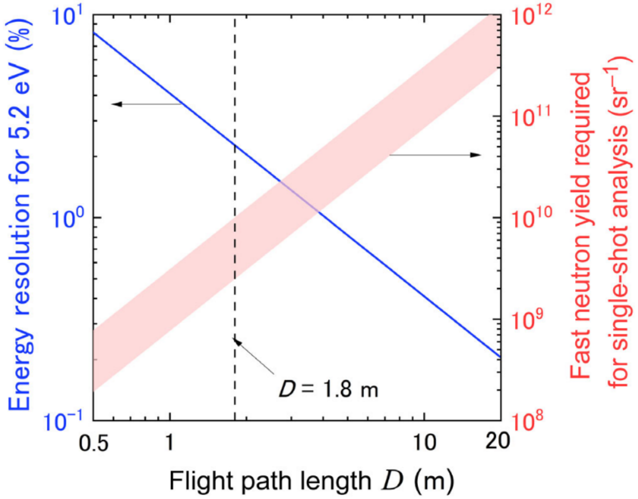
TIME OF FLIGHT

Time-of-flight have been applied at a Laser Driven Neutron facility in the thermal and epithermal range, using a polyethylene moderator, for the measurement of ^{181}Ta resonance absorption.







For a flight path of 1.78 m an energy resolution of 2.3% was reached at 5 eV using a Li Glass detector.

Yogo, A., et al. PHYSICAL REVIEW X 13, 011011 (2023)

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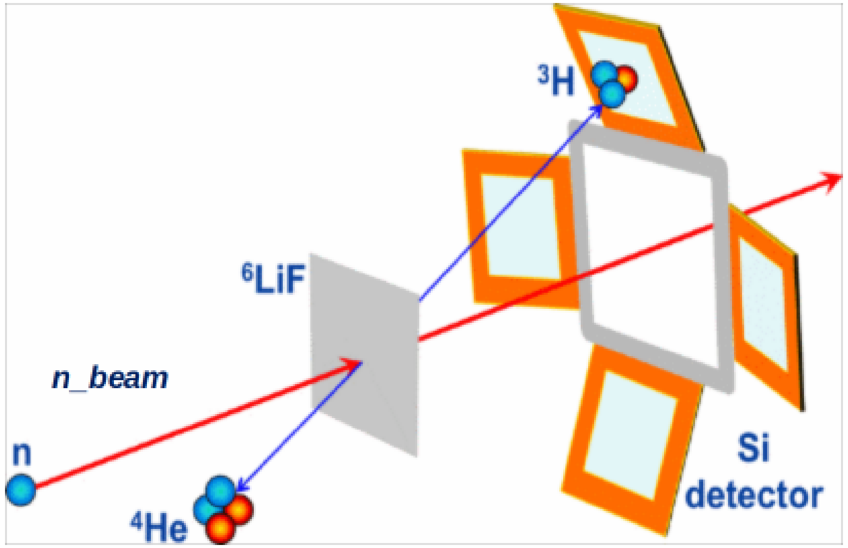
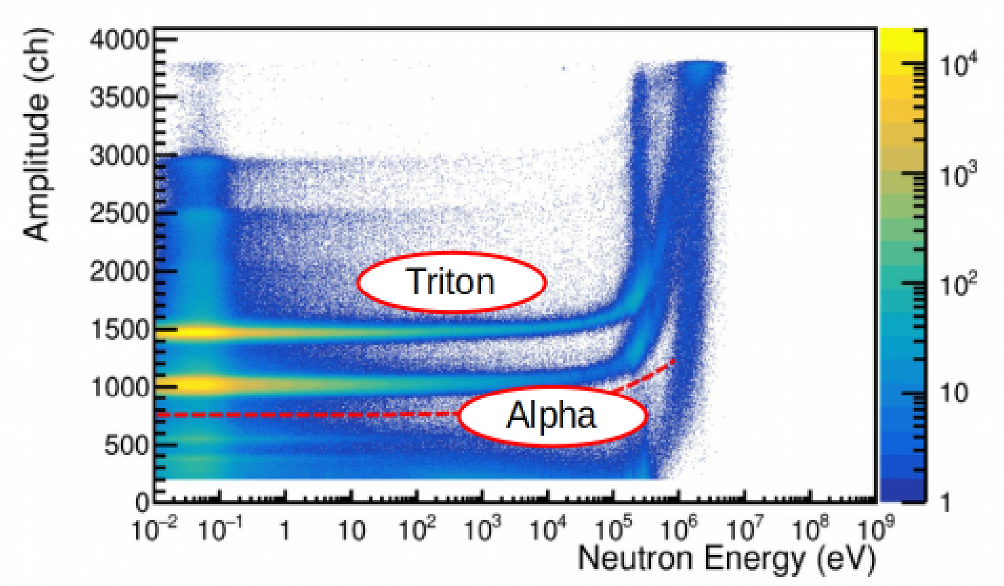
DIAGNOSTIC AND DETECTORS FOR FLUX

Depending on the experimental conditions and needs a large number of detectors are available for neutron flux measurement. SiMon2 is a low background neutron flux monitor for energies <1MeV developed at INFN-LNS composed of 4 off-beam silicons, the reaction ^{6}Li(n,t)^{4}He is used to convert neutrons in charge particles.





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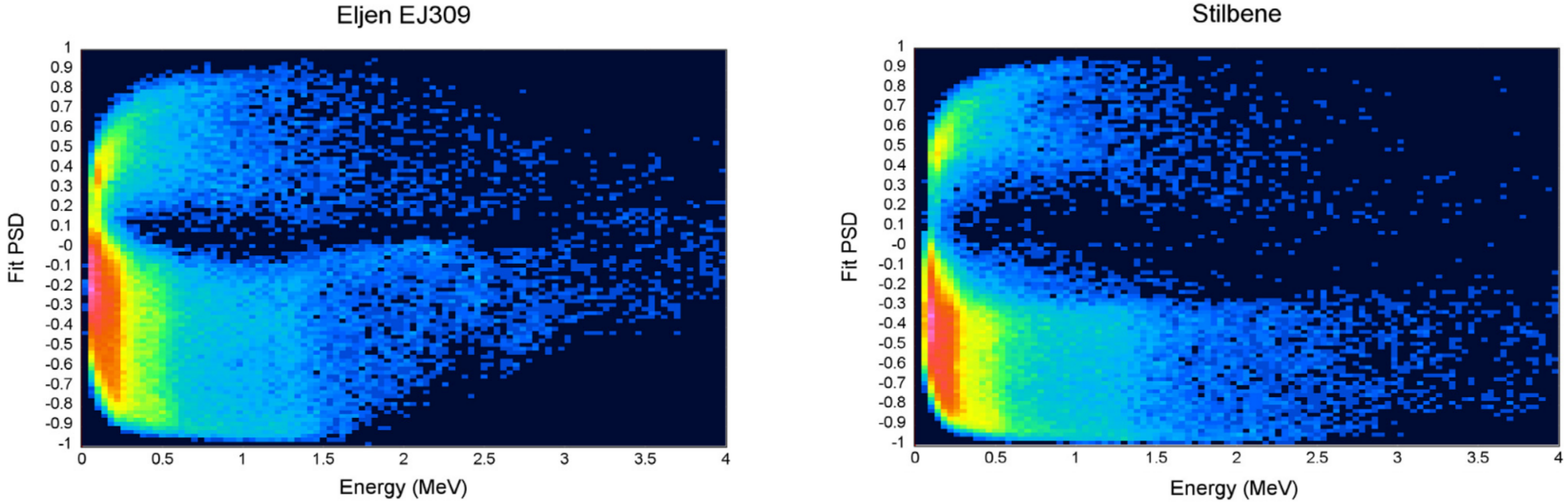
DIAGNOSTIC AND DETECTORS FOR FLUX

Lithium glass detectors are the well-established standard for transmission measurement, thanks to their high efficiency and fast response.

Other detectors to be considered for neutron detection at energies >1MeV are **organic scintillators with PSD capabilities** for n/γ. In particular **stilbene crystals** demonstrated to have high discrimination power, crucial for the high X-ray background of such a facility.



Willem G.J., et al. Nuclear Inst. and Methods in Physics Research, A 954 (2020) 161204

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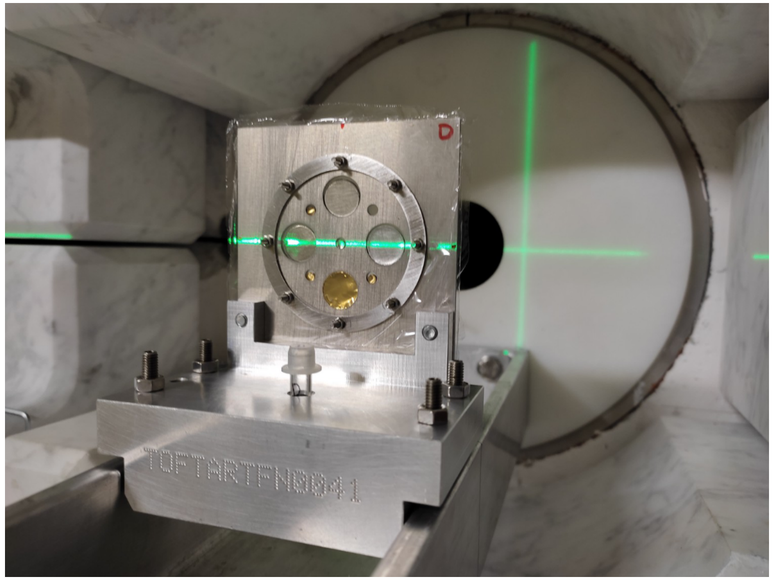
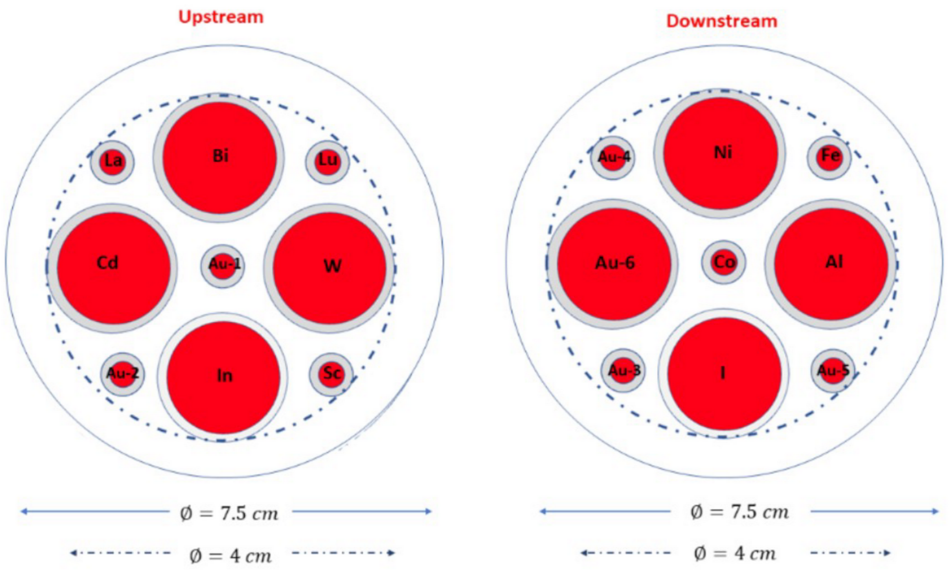
FLUX MEASUREMENT WITH ACTIVATION

The neutron flux measurement with active detectors can be combined and validated with a campaign based on activation, by assembling matrix of samples with very well-known cross sections and a the support of Monte Carlo simulations.



n_TOF collaboration



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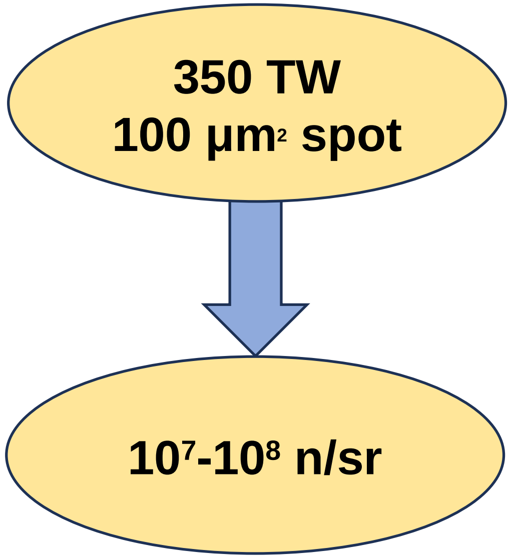
LASER DRIVEN NEUTRON SOURCE AT LNS

At the Laboratori del Sud a high power laser named I-LUCE, with up to 350 TW is under construction, it's a good opportunity to include neutron production.



350 TW
100 μm^2 spot

10^7-10^8 n/sr

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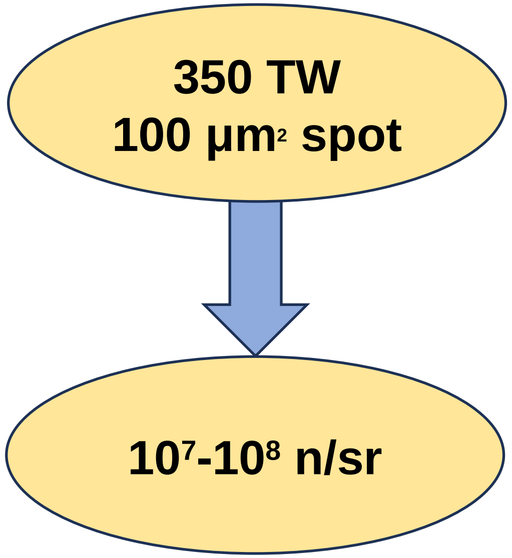
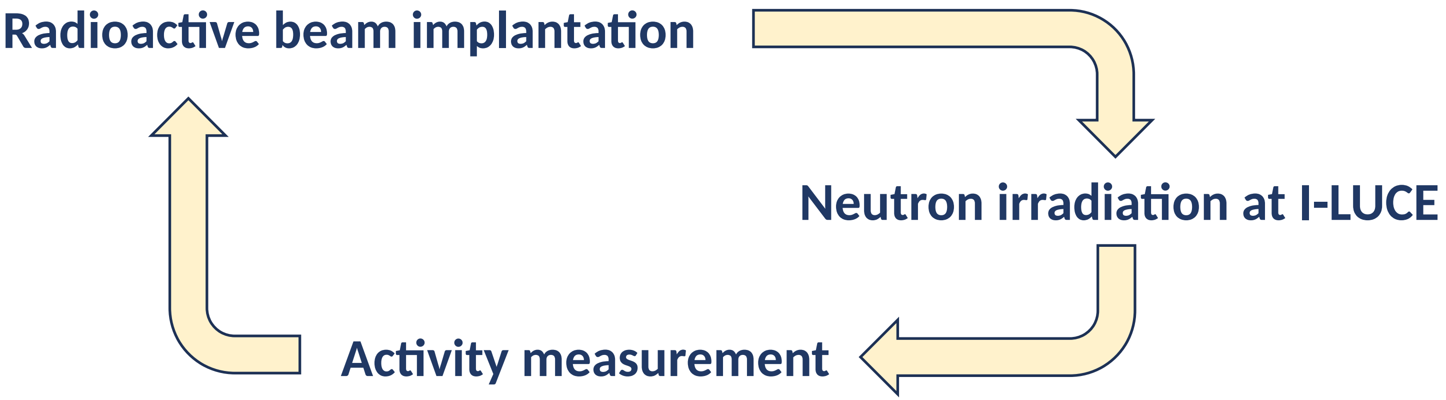

350 TW
100 µm² spot

10^7-10^8 n/sr

Possible integration with accelerator complex and radioactive beam implantation?


Radioactive beam implantation

Neutron irradiation at I-LUCE

Activity measurement

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OTHER APPLICATIONS

Intense neutron sources from laser have a wide range of technological and industrial applications:

- **Neutron scanning and not destructive analysis**
- **Homeland security**
- **Irradiation of biological samples and therapeutic application of fast neutrons**
- **Energy production and nuclear waste transmutation**

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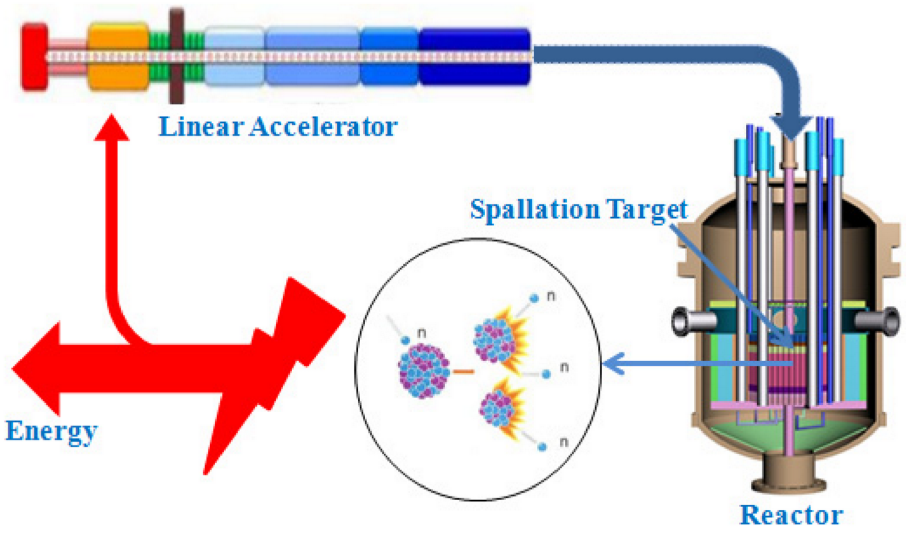
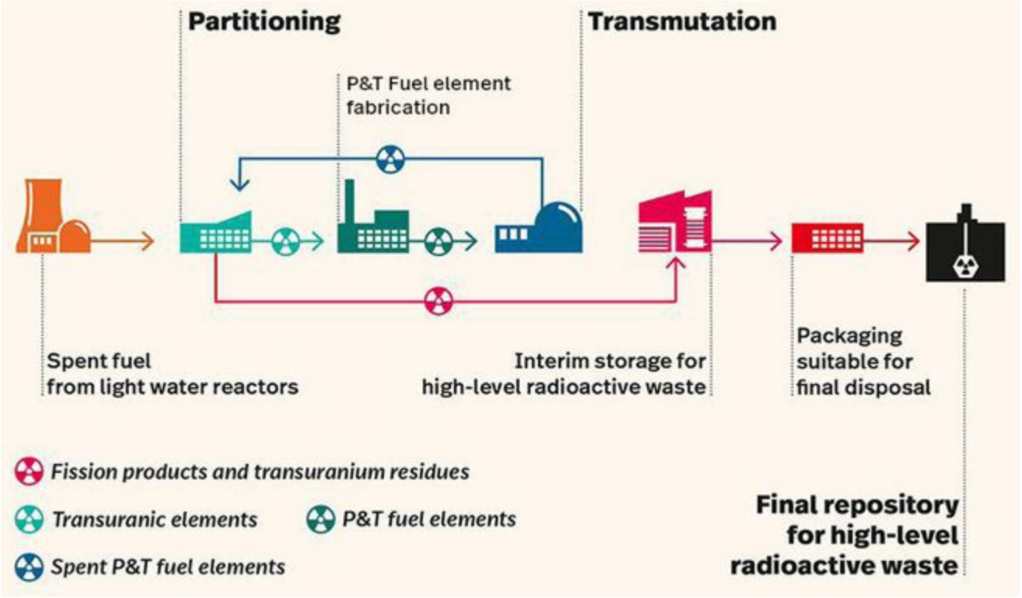
NUCLEAR ENERGY

Accelerator Driven System are sub-critical reactors powered with an external accelerator which generates a fast neutron spectra by spallation. Similar neutrons might be generated with a laser source?





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Thank you for your attention

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