On the ultracold neutron production at pulse sources

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Outline

- Solid ortho-deuterium – the best converter for UCN production in pulse mode of a neutron source operation
- Existing pulse UCN sources with o-deuterium converters
- Transparency of UCN converters for UCN
- Premoderators
- Calculation of UCN production at TRIGA reactor
- Comparison with the experiments in Mainz
- Radiation heating of converter and cold metal container of the converter
- Conclusion

HISTORY
of deuterium as the UCN converter

Proposal: R. Golub, J.M. Pendlebury, Phys. Lett. 53A (1975) 133.

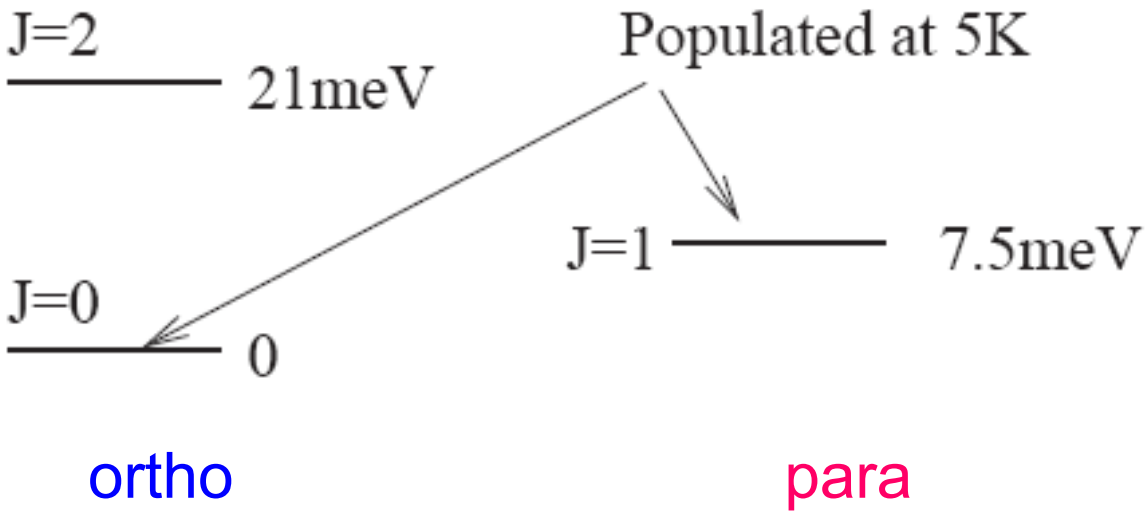
The first exp. test: I.S. Altarev, et al., Phys. Lett. 80A (1980) 413.

The first UCN production calculation (in Debye moldel of DOS)
R. Golub, K. Boning, Z. Phys. B51 (1983) 95.

The first calculation of density of states
Z.-Ch Yu, et al., Z. Phys. B 62 (1986) 137.

and then numerous investigations by Gatchina, Los Alamos, PSI, ILL and Mainz groups,
but
there are still questions

Solid o-deuterium at low temperatures exists in two forms - ortho and para:



Significant concentration of para-deuterium in a converter is a cause of UCN loss due to inelastic up-scattering by para-deuterium molecules

The neutron lifetime (survival time) in a piece of solid deuterium is determined as

$$\tau_D = (n\sigma_{loss}(v)v)^{-1}$$

$$\sigma_{loss}(v) = \sigma_s(v) + \sigma_{c,D}(v) + \sigma_{c,H}(v) + \sigma_{para}(v)$$

The solid deuterium UCN sources in action:

Los Alamos (USA): D.K.-T. Wong, et al, Nucl. Instr. Meth. A1050 (2023) 168105.

Pulsed spallation neutron source with 0.45 s width of 0.009 m A bursts of 800 MeV protons with intervals 5 s.

PSI (Switzeland): G. Bison et al., Phys. Rev. C107 (2023) 035501.

The 2.4 mA beam of 590 MeV protons directed to the UCN producing target for up to 8 s with intervals 8 min.

Mainz Univ. (FRG): J.Kahlenberg, et al, Eur. Phys. Journ. A53 (2017) 226.

100 kW power in a steady-state operation and in pulsed operation at pulse width of 30 ms with energy release up to 10 MJ with minimum permissible intervals 5 min.

Transparency of UCN converters for UCN

UCN multiple scattering on structural inhomogeneities increases the probability of the UCN loss due to capture and up-scattering

Crystal inhomogeneities depend critically on the way of solid deuterium sample preparation: from liquid or gas phase.

A.P. Serebrov et al.,JETP Lett. 74 (2001) 302.

K. Bodek, et al., Nucl. Instr. Meth., A533 (2004) 491.

F. Atchison, et al.,Nucl. Instr. Meth. A611 (2009) 252.

Yu.N. Pokotilovski, Nucl. Instr. Meth. A675 (2012) 29.

S. Doge, et al., Phys. Rev. C113 (2026) 044614.

There are indications that condensation from gas phase gives better results, but this important point deserves further investigation

Effect of a surface roughness

A. Anghel et al., Eur. Phys. Journ. A54 (2018) 148.

PREMODERATORS

POLYETHYLENE 77K (in Los Alamos)

METHANE

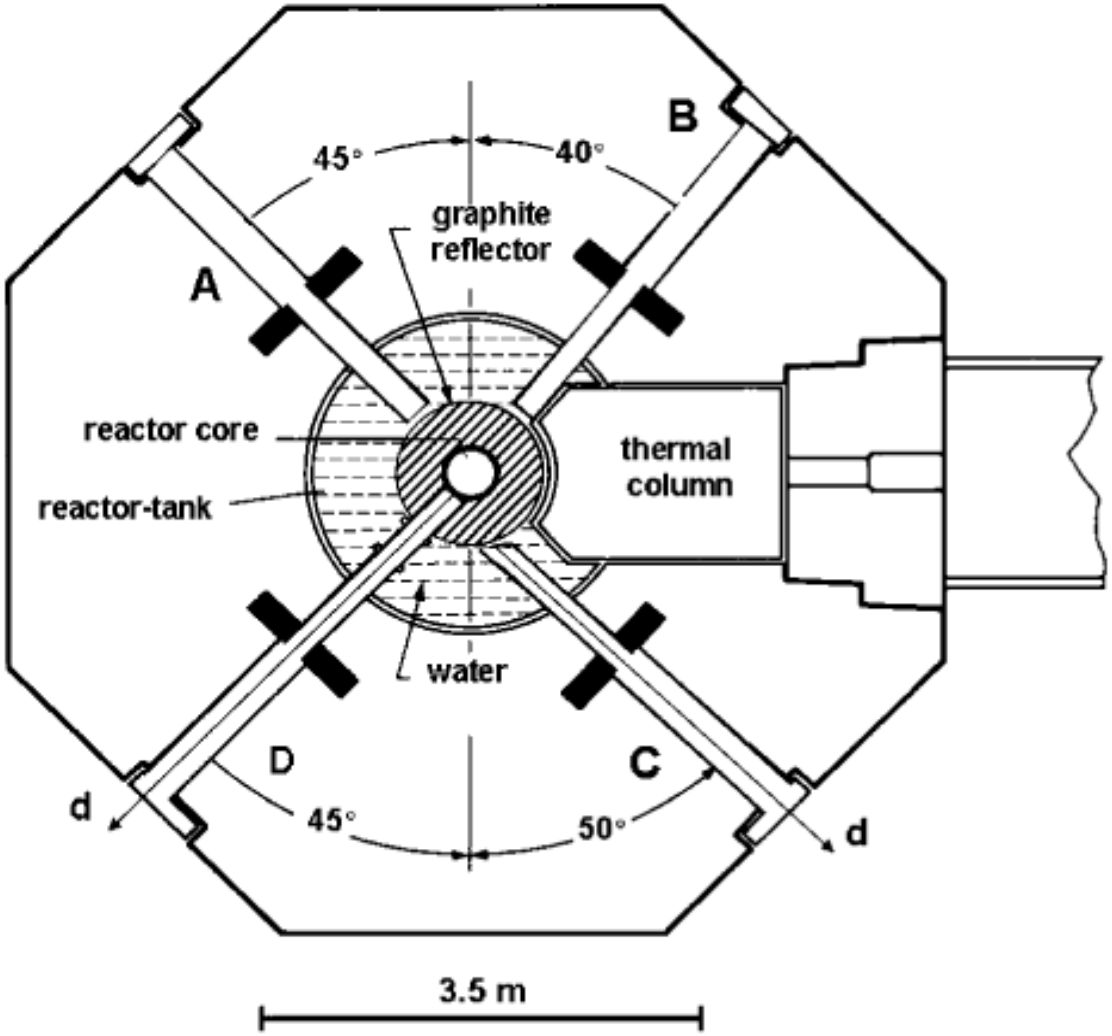
F.J. Webb, Nucl. Sci. Eng. 9 (1961) 120.
W.L. Whittemore, Nucl. Sci. Eng. 18 (1964) 182.
K.F. Graham, J.M. Carpenter, Nucl. Sci. Eng. 49 (1972) 418.

MESITHYLENE

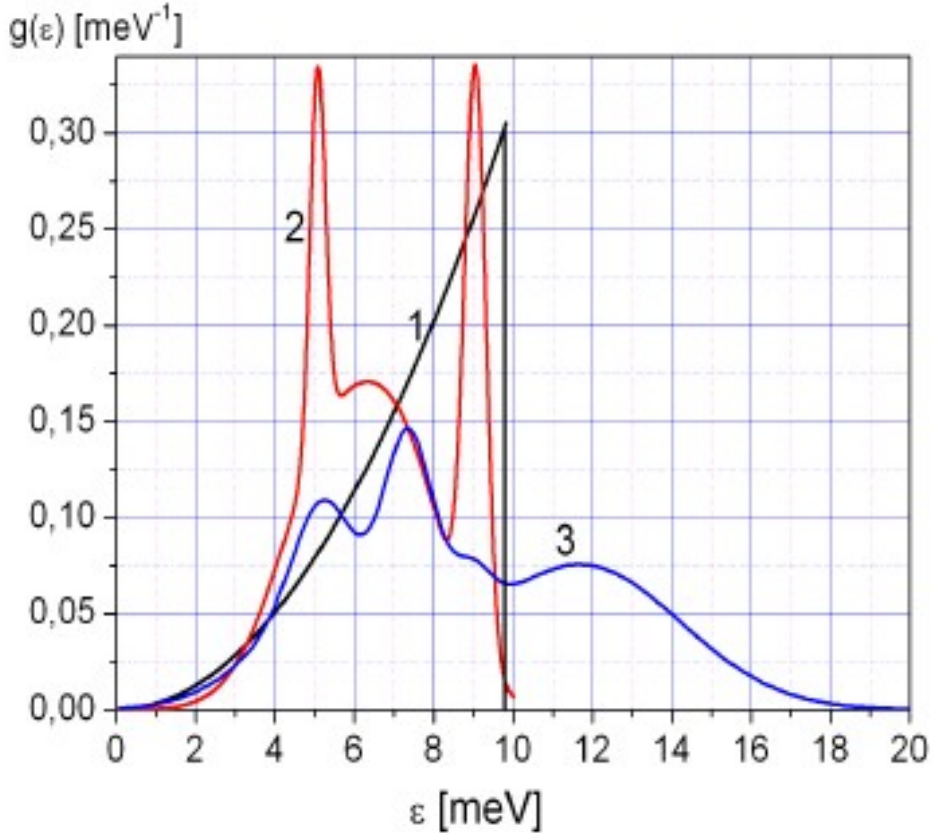
M. Utsuro, et al., Annu. Rep. Res. Reactor Inst., Kyoto Univ. 8 (1975) 17.
M. Utsuro, Journ. Phys. C9 (1976) L171.
I. Natkaniec, et al., Physica B350 (2004) E651.
C.A. Kulikov et al., Part. Nucl. Lett. 10 (2013) 230.

RADIATION EFFECTS

J.M. Carpenter, Nature 330 (1987) 358.
Shabalin et al., Rad. Phys. Chem. 67 (2003) 315.
M.V. Bulavin et al., RAD. Conf. Proc. 4 (2020) 81.

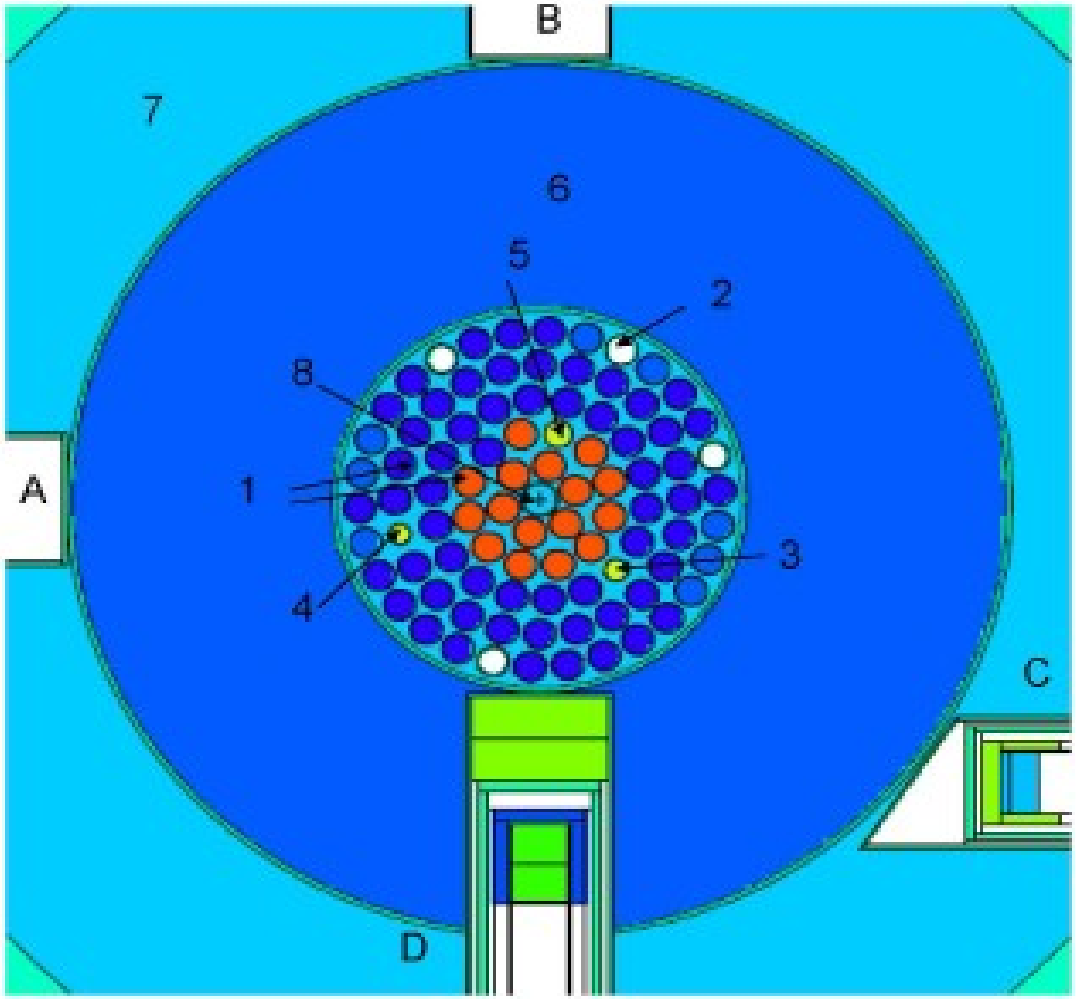


Horizontal section view of the TRIGA Mainz indicating the positions of the three radial beam tubes (A, B and D) and the tangential one (C).

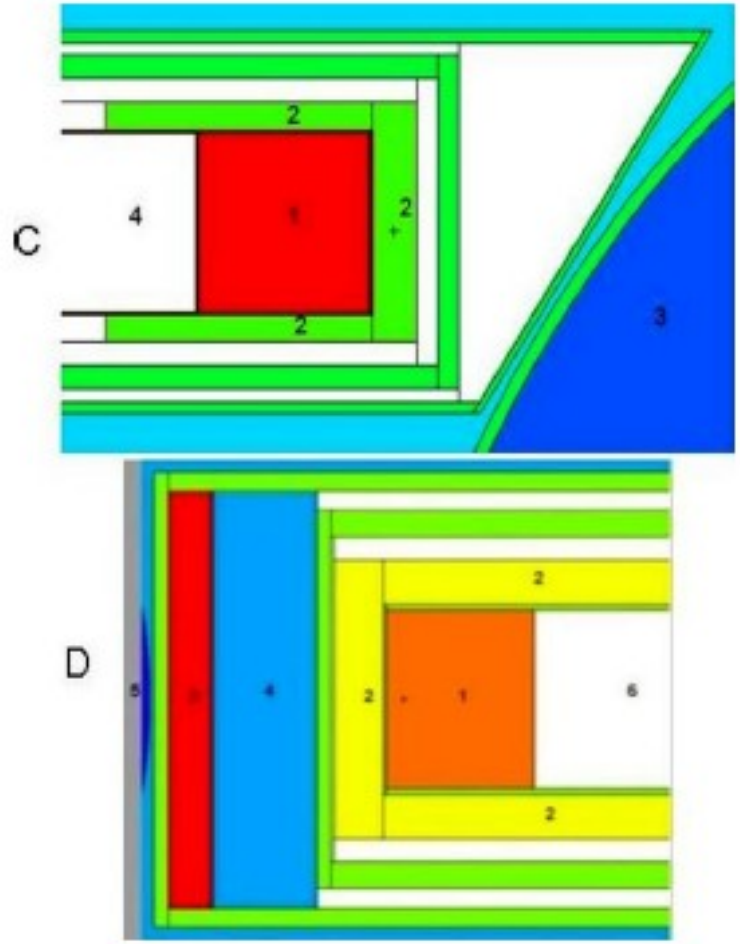


Density of states of solid o-deuterium:

1 – Debye; 2 – Z.-Ch.Yu et al., Z. Phys. B62(1986) 137;
3 – A. Frei et al., Eur.Phys.Lett. 92 (2010) 62001.

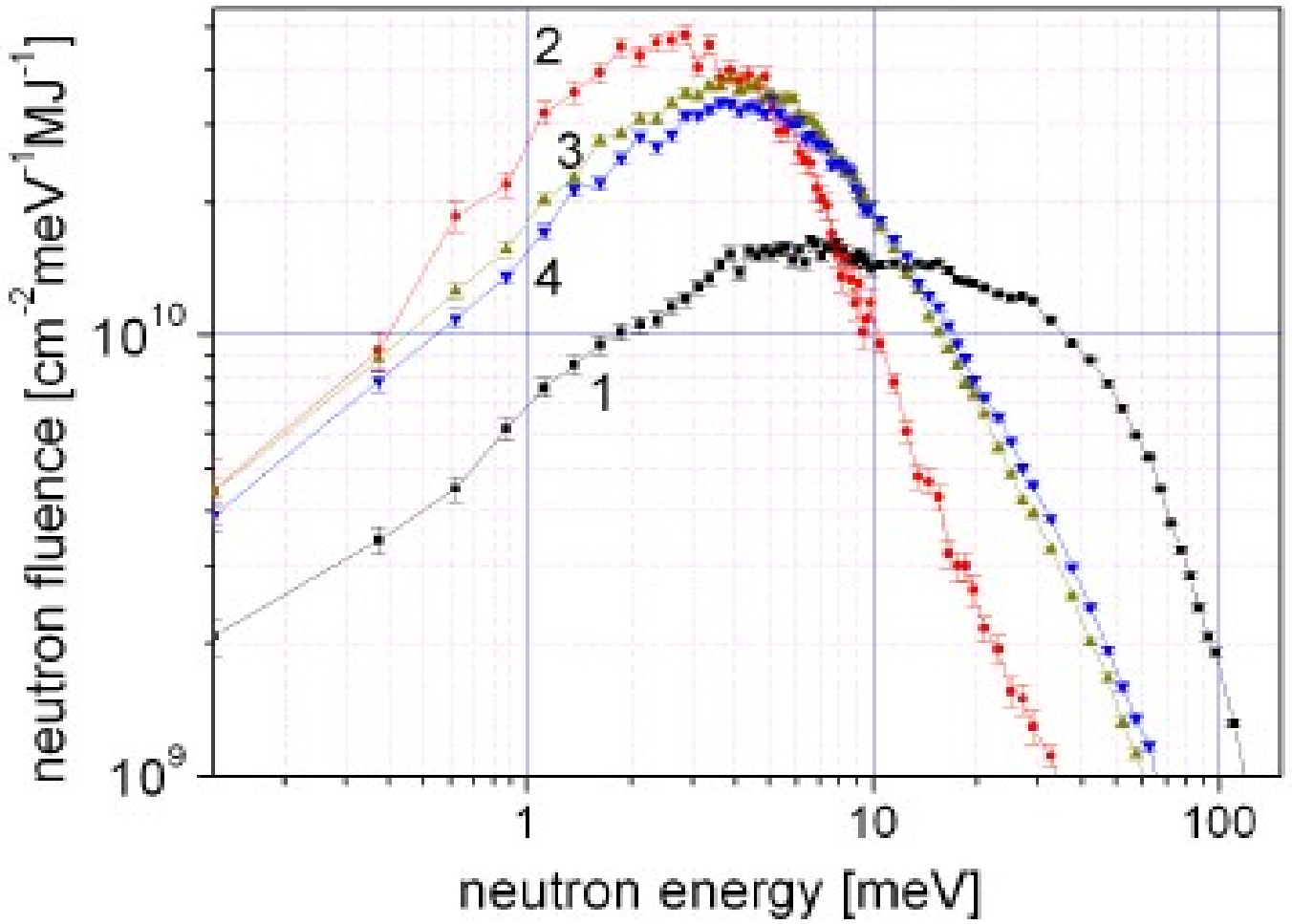


Top view of the central part of the MCNP geometry plot showing layout of the reactor core and four beamports: 1 - fuel elements, 2 - neutron source, 3 - pulse rod, 4 - shim rod, 5- trim rod, 6 - graphite reflector, 7 - reactor tank with shielding water, 8 - central channel. A,B,C and D are the beamports.

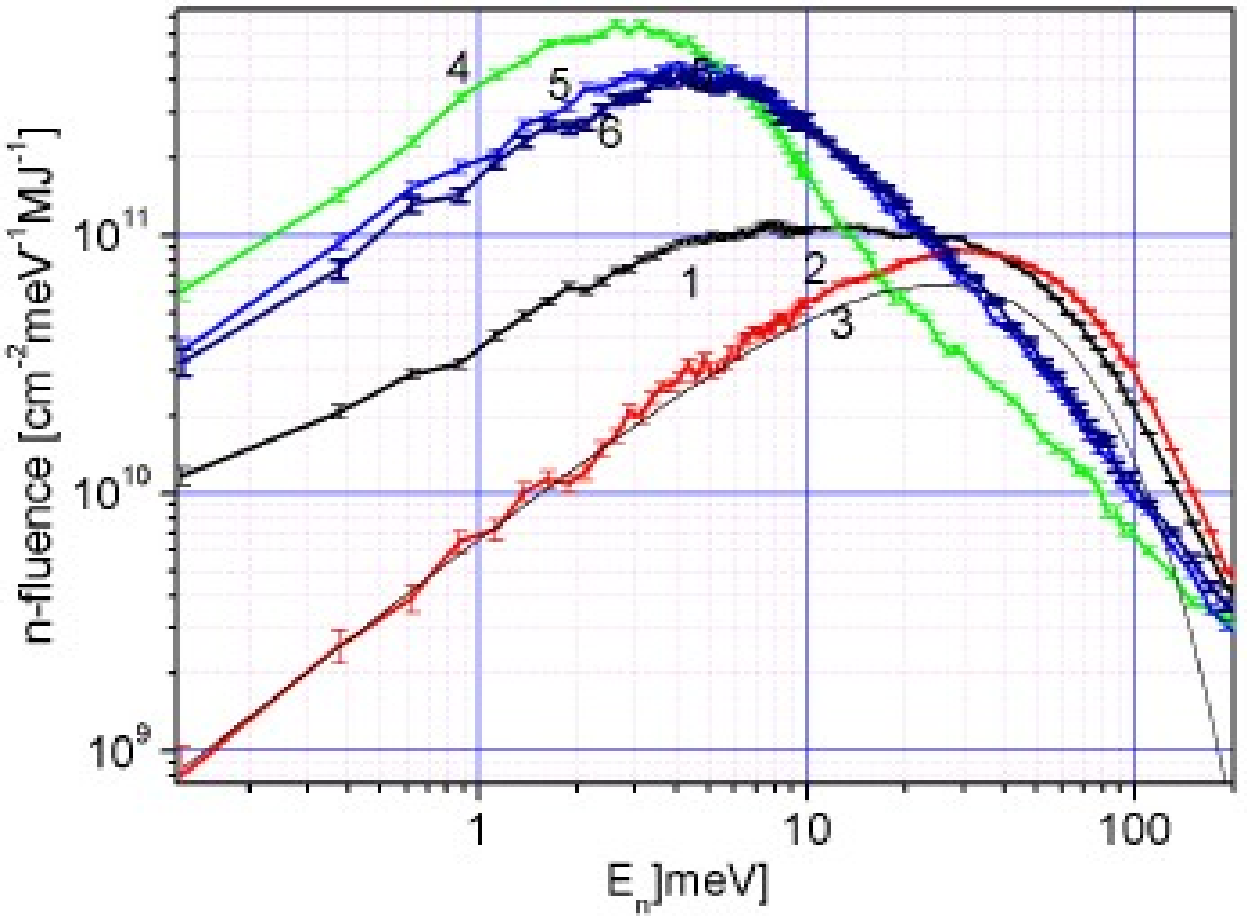


MCNP geometry plots showing layout of the solid deuterium converter and pre-moderator at the tangential beamport C and at the radial beamport D. For the beamport C: 1 - UCN converter, 2 - pre-moderator, 3 - graphite reflector, 4 - UCN guide.

For the beamport D: 1 - UCN converter, 2 - pre-moderator, 3 - Bismuth shielding, 4 - graphite, 5 - edge of the reactor core, 6 - UCN guide



Neutron spectra in the solid deuterium converter at the tangential beamport C. Pre-moderators types are: 1 - no pre-moderator, 2 - methane at 20 K (phase II), 3 - mesitylene at 20 K, 4 - mesitylene 67 \%, toluene - 33 \% at 20 K.



Neutron spectra in the solid deuterium converter at the radial beamport D, deuterium converter diam. 6.6x5 cm is at 10 K. The pre-moderators types are: 1 - no pre-moderator, deuterium convertor; 2 - no pre-moderator, no deuterium ; 3 - thermal neutron Maxwell-Boltzmann flux (T=300 K) with total fluence 4E12/MJ ; 4 - methane at 20 K (phase II); 5 - mesitylene at 20 K; 6 - mesitylene 67 \%, toluene - 33 \% at 10 K.

The number of the UCN produced in unit volume of a converter per one reactor pulse is

$$\rho_{UCN} = n_D \int_{E_{CN}} \int_{E_{UCN}} \varphi(E_{CN}) \sigma(E_{CN} \to E_{UCN}) dE_{CN} dE_{UCN},$$

One phonon inelastic neutron scattering cross section for mono-atomic substance in the incoherent approximation

$$\frac{d\sigma}{d\epsilon d\Omega} = \frac{b_{incoh}^2}{M} \frac{k_1}{k_0} \kappa^2 \frac{\hbar^2}{2\epsilon\left(1 - e^{-\epsilon/kT}\right)} g(\epsilon) e^{-\gamma\kappa^2}$$

$$\gamma = \frac{\hbar^2}{2M} \int \frac{g(\epsilon)}{\epsilon} coth\left(\frac{\epsilon}{2kT}\right) d\epsilon$$

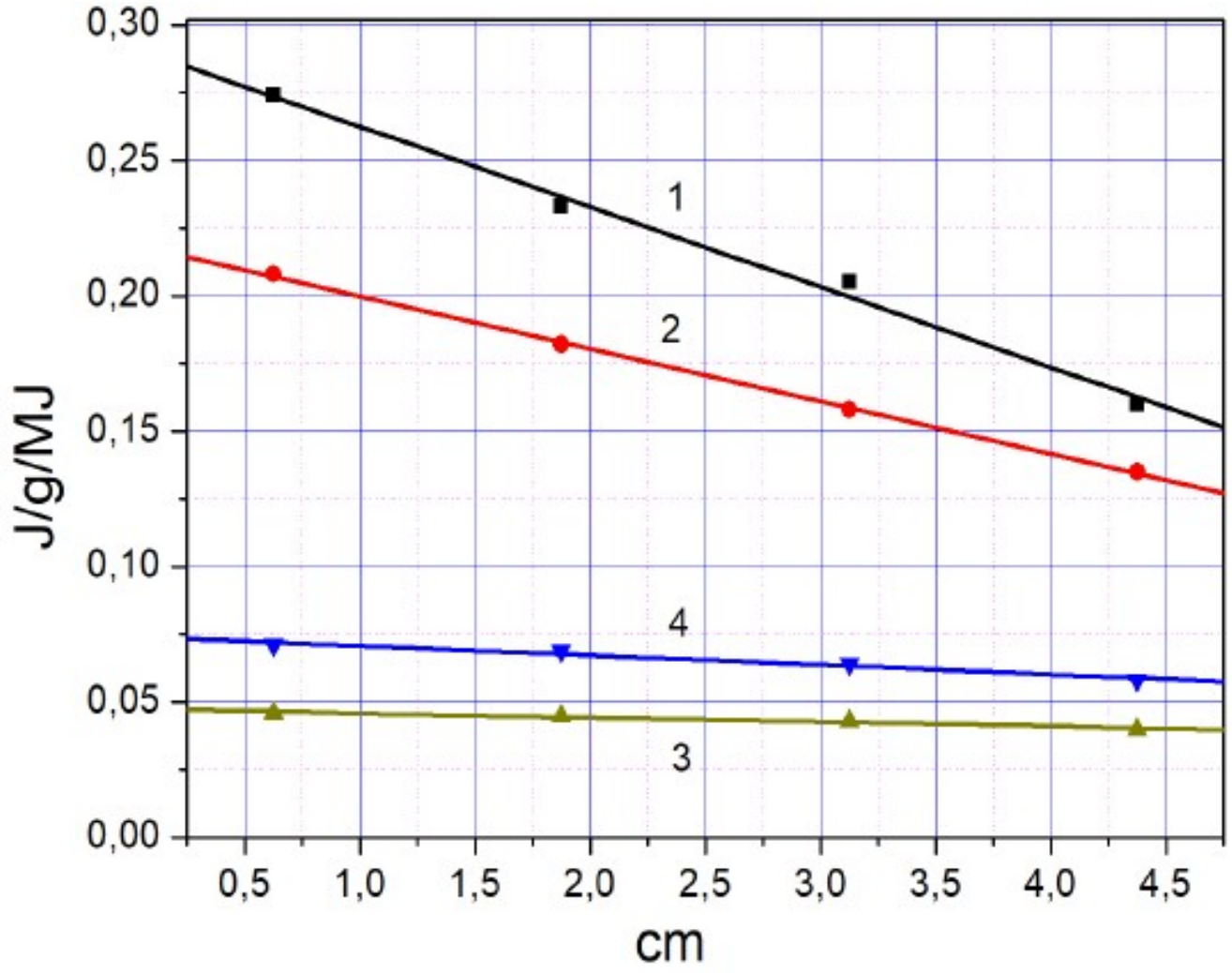
$$\sigma(E_{CN} \to E_{UCN}) = \frac{d\sigma}{d\epsilon} = \frac{\sigma_0}{\mu} \sqrt{\frac{E_{UCN}}{E_{CN}}} (1 - e^{-\epsilon/kT})^{-1} g(\epsilon) e^{-\tilde{\gamma}\epsilon}$$

The calculated one phonon UCN production ($UCN/cm^3/MD$) in solid deuterium at 10 K.

Premoderators	DOS [1]	DOS [2]	Debye DOS
beamport C, no pre-mod.	514	447	538
beamport C, methane	931	715	860
beamport C, mesitylene	1056	833	1024
beamport C, mesit.+tol	984	784	961
beamport D, no pre-mod.	$3.34 \cdot 10^3$	$2.97 \cdot 10^3$	$3.58 \cdot 10^3$
beamport D, methane	$1.36 \cdot 10^4$	$1.05 \cdot 10^4$	$1.29 \cdot 10^4$
beamport D, mesitylene	$1.32 \cdot 10^4$	$1.05 \cdot 10^4$	$1.3 \cdot 10^4$
beamport D, mesit.+tol	$1.22 \cdot 10^4$	$9.82 \cdot 10^3$	$1.22 \cdot 10^4$

1 – Z.-Ch.Yu et al., Z. Phys. B62(1986) 137;

2 – A. Frei et al., Eur.Phys.Lett. 92 (2010) 62001.



The calculated energy deposition in the solid deuterium converter and in stainless steel nose at the radial beamport D in dependence of the distance from the nose bottom: 1 - deuterium, no pre-moderator; 2 - deuterium, methane pre-moderator; 3 - stainless steel nose, no pre-moderator; 4 - stainless steel nose, methane pre-moderator.

COMPARISON OF CALCULATIONS AND MEASUREMENTS

The calculated UCN production at the radial beamport D in the o-D converter of diam. 6.6x5 cm (160 ml) with methane (mesitylene) premoderator in 10 MJ pulse was 2.2×10^7

The maximum reported number of stored UCN at the radial beamport D was 2.7×10^5 in a 32 l bottle with para-hydrogen premoderator.

This two orders of magnitude ratio of the numbers of produced and stored UCN is the result of the UCN losses in the converter and the guide seems too large and can (should) be decreased!

Our calculations for a converter with methane and mesitylene premoderators give 4 times larger UCN production than without pre-moderator.
The measurements at the beamport D for the 8 mol solid deuterium converter with all tested pre-moderators: deuterium, hydrogen and methane have shown only 30 % gain in the UCN production compared to the UCN production without pre-moderator.

CONCLUSION

Solid o-deuterium proved to be the best converter for UCN production in pulse mode, but there is still space for further work: geometric form of deposited converter, inhomogeneities, effect of premoderator

In spite of low power of the reactor the TRIGA UCN source is now ranked among the best UCN sources (ILL PF-2, Los Alamos, PSI, ILL SUN-2) in the world and has potential to store up to several millions UCN in one pulse