CCRI(III)-K8.2024: Key Comparison for Thermal Neutron Fluence Measurements

Comparison Protocol

1 Introduction

During the last decades the number of thermal neutron reference calibration fields has considerably decreased as most of the research reactors with reference calibration capabilities have closed, leading in the early 2010s to only a very few available thermal reference neutron fields. That was the situation for the last comparison on thermal neutron fluence, CCRI(III)-K8, with only 4 participants and some observed discrepancies [1]. Fortunately, several new or rebuilt facilities are now available allowing a more comprehensive comparison for those kinds of fields.

Thermal neutron fields are produced by the slowing down and thermalization of fast neutrons in a moderator made of scattering medium with low neutron absorption such as graphite, water or beryllium etc. The primary neutrons can be produced by fission in reactors, by radionuclide neutron sources or by accelerator-based neutron sources. The resulting energy distribution consists of a thermal neutron peak below 0.5 eV, an epithermal component with a roughly 1/E shape between 0.5 eV and 1 keV and some residual fast neutrons. In the energy region of the thermal neutron peak, $\phi(E)$ has approximately the Maxwellian shape, proportional to $E/(kT)^2 \cdot e^{-E/kT}$, where T is the neutron temperature and E is the neutron energy. The neutron temperature T is usually slightly higher than the temperature of the scattering medium or 'moderator', because neutrons are absorbed in the moderator or escape before perfect thermal equilibrium can be achieved[2]. The thermal neutron reference fields maximize the thermal component, while keeping neutron fluence rate suitable for the calibration of thermal neutron devices.

Depending on the facility, the reference neutron fields differ significantly. In particular, the angular distribution may vary from almost isotropic to unidirectional. Furthermore, the spectral distribution can deviate from a Maxwellian or correspond to a temperature different from that of the moderator. Also the contamination of the thermal beam or field with epithermal neutrons above the cadmium cut-off energy is related to details of the construction of the facility.

2 Objectives

The goal of the CCRI(III)-K8.2024 key comparison is to compare the determination of the thermal neutron fluence at the facilities of all participants, therefore the use of transfer instruments is required.

In order to simplify the comparison, K8.2024 will focus only on the thermal neutron fluence, i.e. part of the spectra below the nominal cadmium threshold of 0.5 eV. The transfer instrument will therefore be mainly sensitive to the neutrons below the eV range energy, and unlike the previous comparison CCRI(III)-K8, there will not be different types of transfer instruments with diverse response functions to estimate the temperature parameter kT of the spectral distribution.

3 Participants

The following laboratories agreed to participate:

No.	Institute	Country	Contact person	email
1	NIM	China	Hui Zhang	zhanghui@nim.ac.cn
2	CMI	Czech Republic	Zdenek Vykydal	zvykydal@cmi.cz
3	BARC	India	Smt C Sneha	headress@barc.gov.in
4	CIAE	China	Wei Li	liwei820@163.com
5	ENEA	Italy	Marco Capogni	marco.capogni@enea.it
6	IRSN	France	Allaoua Amokrane	amokrane.allaoua@irsn.fr
7	KRISS	Korea	Hyeonseo Park	hysonseo@kriss.re.kr
8	LNMRI/IRD	Brazil	Walsan Wagner Pereira	walsan@ird.gov.br
9	NIST	United States	Jeffrey S. Nico	jeffrey.nico@nist.gov
10	NPL	United Kingdom	Kim Ward	kim.ward@npl.co.uk
11	PTB	Germany	Micro Dietz	Micro.Dietz @ptb.de
12	SCK/CEN	Belgium	Jan Wagemans	jwageman@sckcen.be
13	VNIIM	Russia	Nikolay Moiseev	n.n.moiseev@vniim.ru

Full contact information is given in Appendix A.

4 Schedule

According to the distribution of participants, in order to shorten the comparison time, the participants will be divided into two groups, each group having a transfer detector similar to the other one. Group 1 includes NIM(CN), BARC(IN), CIAE(CN), KRISS(KR), LNMRI/IRD(BR) and VNIIM(RU), group 2 includes CMI(CZ), ENEA(IT), IRSN(FR), NIST(US), NPL(UK), PTB(DE) and SCK/CEN(BE). Each group will measure the thermal neutron response of its transfer detector. During the transfer process, the stability of the transfer detector will be measured by the NIM for the group 1 and by the CMI for the group 2 respectively. At the end of the comparison cycle, the transfer detector of the group 1 will be transferred to the CMI, and the transfer detector of the group 2 will be transferred to the NIM for calibration. Finally, the NIM and the CMI will send the transfer detectors to the provider. The NIM and the CMI will cover the cost of sending the transfer instrument to the participants of each group (and of the transfer detectors to the provider at the end of the comparison) while the participants will cover the costs of returning the transfer instrument or sending it to the next participant.

The comparison will start at the same time for both groups. One month is scheduled for each participant measurement. If there is a problem with customs, participants will be given an additional month.

Start of the comparison 2024-10

No.	Participant	Measurement at the laboratory	Transfer to next laboratory	Report of the results to BIPM
Group 1				
1	NIM(CN)	2024-10	2024-11	2024-12
	NIM*	2024-11	2024-11	

2	KRISS(KR)	2024-12	2025-01	2025-02
	NIM*	2025-02	2025-02	
3	CIAE(CN)	2025-03	2025-04	2025-05
4	BARC(IN)	2025-05	2025-06	2025-07
	NIM*	2025-07	2025-07	
5	VNIIM(RU)	2025-08	2025-09	2025-10
	NIM*	2025-10	2025-10	
6	LNMRI/IRD(BR)	2025-11	2025-12	2026-01
	NIM*	2026-01	2026-01	
7	CMI(CZ)	2026-02		2026-04
Group 2				
1	CMI(CZ)	2024-10	2024-11	2024-12
	CMI*	2024-11	2024-11	
2	NPL(UK)	2024-12	2025-01	2025-02
3	ENEA(IT)	2025-02	2025-03	2025-04
	CMI*	2025-04	2025-04	
4	SCK/CEN(BE)	2025-05	2025-06	2025-07
5	IRSN(FR)	2025-07	2025-08	2025-09
	CMI*	2025-09	2025-09	
6	PTB(DE)	2025-10	2025-11	2025-12
7	NIST(US)	2025-12	2026-01	2026-02
	CMI*	2026-02	2026-02	
8	NIM(CN)	2026-03		2026-05

* Stability test

End of the comparison	2026-05
Draft A of Report	2026-12
Comments of partners	2027-02
Draft B of Report	2027-04

Participant should inform the pilot laboratory as soon as possible if the scheduled procedure has to be changed. In case of delay of more than one month, the whole schedule might be changed in accordance with the availability of the calibration facilities of the participants. After arrival of the transfer instruments the participant should inform the pilot laboratory about the reception. Before dispatching the transfer instruments for delivery to the pilot laboratory or the next participating laboratory, the participant should inform the contact person of the pilot or the next participant giving transportation details. Information on dimensions, content, and weight of the transport containers are given in Appendix B.

5 Transfer detectors and Ancillary Equipment

The transfer detectors will be two low pressure proportional counters, SP9 type (33 mm diameter) made by Centronic filled with 0.2 kPa of ^{3}He (nominal pressure) provided by the IRSN. Two removable cadmium shells 1 mm in thickness for measuring the effect of epithermal neutrons above the cadmium threshold on the bare counters and a set of signal cables used to connect the detector and the pre-amplifiers will be provided by the NIM. Since the signal cable should be as short as possible for optimal pulse processing, the set of signal cables consists of 2 cables, with lengths of 1.5 m and 0.5 m respectively. If the 0.5 m cable is not long enough, a SHV Jack to SHV Jack adapter provided by the NIM can be used to connect the 1.5 m cable to the 0.5 m cable to extend the cable.

The response of these counters at 25 meV is about 0.05 cm^2 allowing measurements in thermal fields with fluence rates ranging from 10 $cm^{-2}\cdot s^{-1}$ to 10^5 $cm^{-2}\cdot s^{-1}$, covering the range of the fluence rates delivered by the facilities of the comparison participants.

Unlike the last comparison, the output signal of the detector will be processed by an electronic assembly consisting of a high-voltage supply, a pre-amplifier, a main amplifier and a multichannel analyzer (MCA). Except the pre-amplifier provided by the pilot laboratory, the other electronic assembly above-mentioned should be prepared by the participant, the linearity and offset of the main-amplifier and the MCA should be determined by the participant.

The events resulting from the $^3He(n, p)^3H$ reaction can be separated from those due to photons and electronic noise through the proper pulse height threshold of the MCA. The typical pulse height distribution of ^3He proportional counters is shown in Fig.1. For the low pressure SP9 counter used for the comparison, the pulse height distribution is shown in Fig. 2. Pulse heights caused by gamma-ray events are sufficient to exceed the edge energy (191 keV) of the wall effect for neutron events and superimpose on the pulse heights caused by neutrons. As a result, there is no clear separation between $^3He(n, p)^3H$ reaction signal and photon-induced signal. To ensure that there are no counts contributed by photons in the counting results, the threshold for the MCA has to be set at 30% of the main peak, and the main peak position is defined as the channel with the highest counts in the pulse height spectrum. To avoid neutron signals overflow in the MCA, the position of the main peak should be below 50% of the full scale of the MCA.

More details on the mounting and operation of the detectors can be found in the appendix.

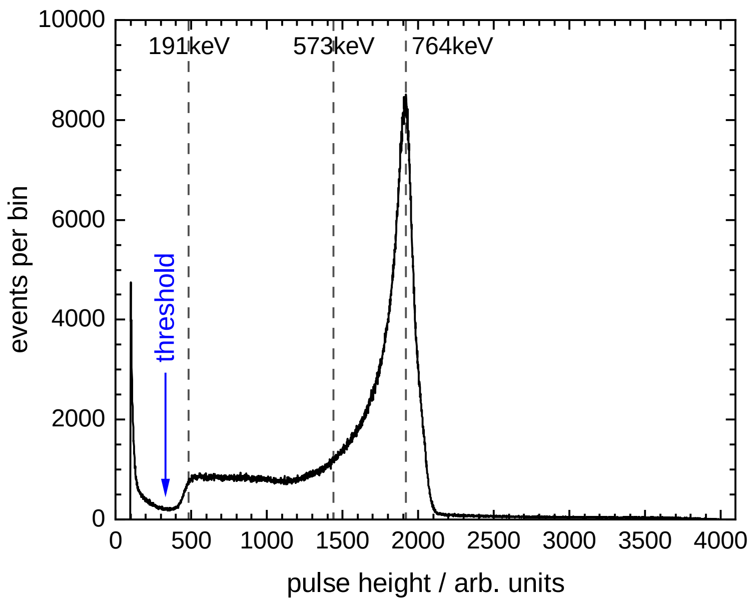


Fig. 1 Typical pulse height distribution of the ^3He counter

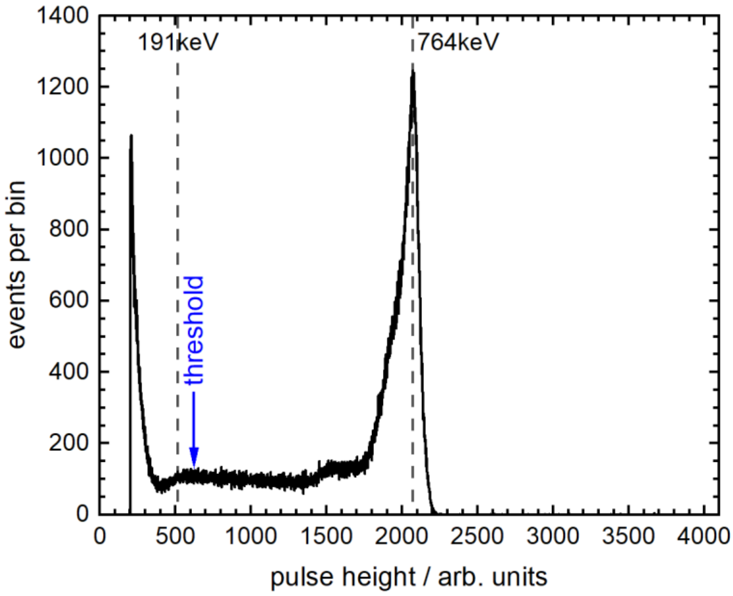


Fig. 2 Pulse height distribution of a low-pressure ^{3}He counter

6 Determination of the Response

Participants shall determine the thermal neutron fluence response R_{ref} of the counters for a homogeneous unidirectional irradiation with 25.3 meV monoenergetic neutrons. The measured response, R_{lab}, can be expressed as:

$$R_{\mathrm{lab}} = \frac{\left(N - \frac{M}{M_{\mathrm{Cd}}} N_{\mathrm{Cd}} \right)}{\Phi_{\mathrm{lab}}} \tag{1}$$

Where,

N, number of counts in the counter without cadmium shell for a homogeneous unidirectional neutron radiation, and corrected for background, threshold, deadtime and anisotropy of detector response. Corrections for the loss of neutron counts due to higher threshold, and for the anisotropy of the detector response, will be provided by the pilot laboratory;

N_{Cd}, number of counts in the counter with cadmium shell for a homogeneous unidirectional neutron radiation, corrected for background, deadtime and anisotropy of detector response;

M, number of counts in the monitor, corrected for background and deadtime, related to N, if the thermal field is not produced through a radionuclide neutron source;

M_{Cd}, number of counts in the monitor, corrected for background and deadtime, related to N_{Cd}, if the thermal field is not produced through a radionuclide neutron source;

The neutron fluence rate, Φ_{lab}, below the cadmium cut-off energy in the spectrum, $\Phi(E)$, is measured using gold-foil activation and is expressed as:

$$\Phi_{\text{lab}} = \int_{0}^{E_{\text{Cd}}} \Phi(E)\,\mathrm{d}E \tag{2}$$

The actual irradiation conditions for each participant may differ, primarily in the temperature parameter of the Maxwellian spectral distribution and the fraction of epithermal neutrons below the cadmium cut-off energy. To match the reference conditions of neutron irradiation with an energy of 25.3 meV, participants should then apply the correction factor k, yielding:

$$R_{\text{ref}} = k \cdot R_{\text{lab}} \tag{3}$$

where the correction factor k is defined as:

$$k = \frac{R(2.53 \cdot 10^{-8}\,\text{MeV})}{\int_{0}^{E_{\text{Cd}}} R(E) \cdot \left(\Phi(E)/\Phi_{\text{lab}}\right)\mathrm{d}E} \tag{4}$$

Where,

$R(E)$, calculated response of the counter without cadmium shell at the neutron energy E, provided by the pilot laboratory with its uncertainty;

$R(2.53 \cdot 10^{-8}\ \text{MeV})$, the fluence response of the counters for a homogeneous unidirectional irradiation with neutrons of 25.3 meV energy derived from $R(E)$ provided by the pilot laboratory;

7 Report

The report to be delivered for the evaluation of the results has to include the following details:

- A brief description of the calibration facility and the methods used for characterising and/or monitoring the neutron field or beam.
- Specification of the energy distribution of the neutron fluence (Φ_E/Φ) and the total fluence Φ (below the nominal cadmium threshold at 0.5 eV) at the calibration point, with a documentation of the traceability.
- Description of the measurements carried out with the transfer instruments including readings N and N_{Cd} of the transfer instruments, M and M_{Cd} of the used monitors (if any), measurement times and pulse-height spectra of the detectors measured in coincidence with the discriminator signal.
- Evaluation of the response R_{ref} under reference conditions including the values of all correction factors as well as a description of how these values were calculated.
- Evaluation of an uncertainty budget for R_{ref}. All uncertainties have to be specified as standard measurement uncertainties for a coverage factor $k = 1$. The recommendations of the Guide to the Expression of Uncertainty in Measurement [3] should be followed.

8 Evaluation and Publication of the Results

The results reported by the participants will be evaluated by the NIM and the CMI. The key comparison reference values (KCRV)[4] will be calculated for each of the two transfer instruments as the weighted mean of the results reported by the participants not considered as outliers after statistical tests. Reciprocals of the uncertainties reported by the participants will be used to calculate the weights. From the KCRV and the specified uncertainties, the degree of equivalence (DoE) will be calculated.

After discussion and approval of the draft A report by all participants, the draft B will be circulated to the whole CCRI(III) for review. The final report of the comparison will be published on part C of the Key Comparison Data Base of the BIPM and in Metrologia.

As the pilot laboratories will also participate in the comparison, all reports will have to be sent to the BIPM. The BIPM will forward the reports to the pilot laboratories after the pilot laboratories have sent their own reports.

Reference

[1] R. Nolte, R. Böttger, J. Chen, H. Harano and D.J. Thomas, *International key comparison of thermal neutron fluence measurements — CCRI(III)-K8*, Metrologia 52 (2015) 06011

[2] J. G. Williams and D. M. Gilliam, *Thermal neutron standards*, Metrologia 48 (2011) 254-262

[3] ISO/IEC Guide 98-3:2008 - *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995)

[4] M.G. Cox, *The Evaluation of Key Comparison Data: An Introduction*, Metrologia 39 (2002) 587-588 and
M.G. Cox, *The Evaluation of Key Comparison Data*, Metrologia 39 (2002) 589-595

Appendix A: Full contact information of the participants

Participant	Institute	Address	Contact person
1	NIM	National Institute of Metrology P. R. China No.18, Bei San Huan Dong Lu, Chaoyang Dist, Beijing, P.R.China Phone:+86-10-64525006 / Fax:+86-10-64214927	Hui Zhang zhanghui@nim.ac.cn
2	CMI	Czech Metrology Institute Okružní 31, 638 00 Brno, Czech Republic Phone: +420 266 020 299 Shipping address: Czech Metrology Institute Laboratory of Neutron Metrology Radiová 1a, 102 00 Praha 10, Czech Republic	Zdenek Vykydal zvykydal@cmi.cz
3	BARC	Radiation Safety Systems Division, Health Safety & Environment Group Bhabha Atomic Research Centre, Trombay, Mumbai, Maharashtra (400085), India Phone: +22-25595074 / Fax: +22-25505313/25505151	Smt C Sneha headrss@barc.gov.in
4	CIAE	Sanqiang Road 1#, XinZhen, Fangshan District, Beijing, China, 102413	Wei Li liwei820@163.com
5	ENEA	ENEA – Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (INMRI) Casaccia Research Center, Anguillarese street 301 – I-00123 Rome (Italy)	Capogni Marco marco.capogni@enea.it Silvi Luca luca.silvi@enea.it
6	IRSN	IRSN/PSE-SANTE/SDOS/LMDN Cadarache, Bat 159 BP3 F-13115 Saint Paul Lez Durance, France Phone: +33(0)442199700	Allaoua Amokrane amokrane.allaoua@irsn.fr
7	KRISS	Korea Research Institute of Standards and Science 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Rep. of Korea Phone: +82-42-868-5788 / Fax: +82-42-868-5671	Hyeonseo Park hyeonseo@kriss.re.kr
8	LNMRI/IRD	IRD - Instituto de Radioproteção e Dosimetria LN - Laboratório de Metrologia de Nêutrons Av. Salvador Allende, s/n - Barra da Tijuca 22783-127 - Rio de Janeiro – RJ, Brazil Phone:+55 21 2173-2870 / Fax: +55 21 2173-2709	Walsan Wagner Pereira walsan@ird.gov.br
9	NIST	National Institute of Standards and Technology	Jeffrey S. Nico

		100 Bureau Dr., Stop 8461 Gaithersburg, MD 20899, USA Phone: 1-301-975-4663 / Fax: 1-301-926-1604	jeffrey.nico@nist.gov
10	NPL	National Physical Laboratory Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom Phone: +44 20 8943 7087	Ward Kim kim.ward@npl.co.uk
11	PTB	Physikalisch-Technische Bundesanstalt (PTB) Department 6.4 Neutron Radiation Bundesallee 100 38116 Braunschweig Germany Phone: +49 531 592 6425	Mirco Dietz Mirco.Dietz@ptb.de
12	SCK/CEN	SCK-CEN / Laboratory for Nuclear Calibrations (LNK) Boeretang 200, B-2400 Mol, Belgium Phone: +32 14 33 23 89 or +32 14 33 2005	Wagemans Jan jwageman@sckcen.be
13	VNIIM	D.I.Mendeleyev Institute for Metrology 19, Moskovsky Pr. St. Petersbyrg 190005, Russian Federation +7 812 323 96 14 / +7 812 713 01 14	Nikolay Moiseev n.n.moiseev@vniim.ru

Appendix B: Details on transport container

One package will be sent with the following dimensions and weight.

Dimensions: 52 × 42 × 19 cm^3

Weight: 5.8 kg

Main contents: Centronic SP9 counter, ORTEC 142PC pre-amplifier, Cadmium shell, 2 signal cables, SHV Jack to SHV Jack adapter

The transport container will be locked with a customs lock whose code number is 123.

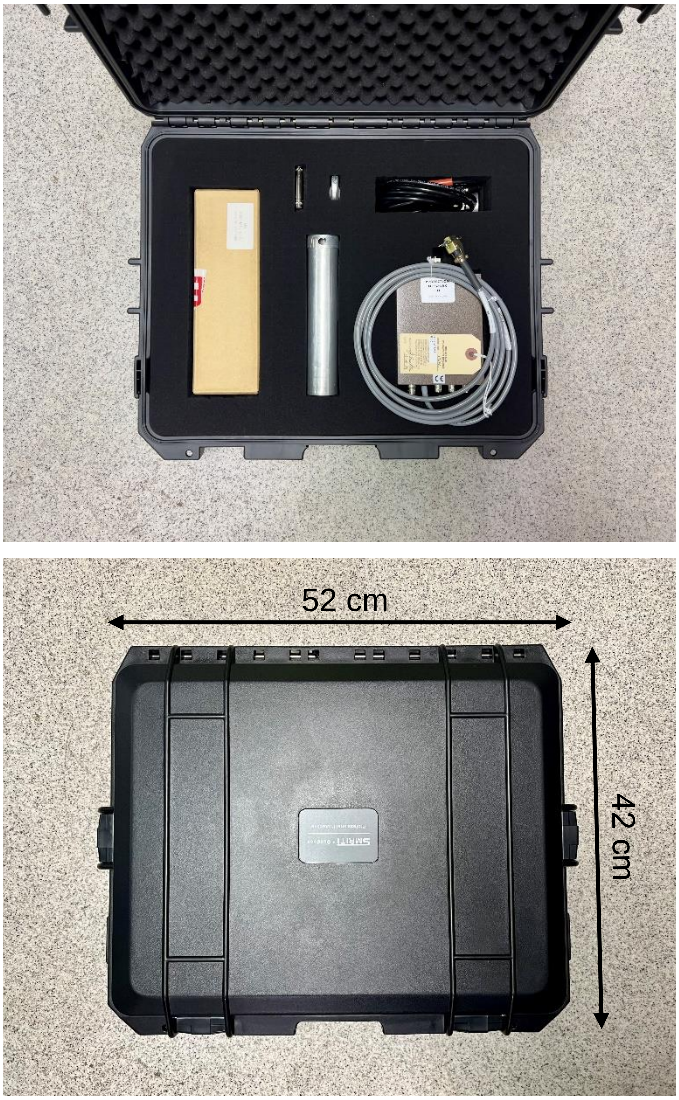


Fig. B1 Transport container

Appendix C: Instruction for use of the equipment used for the comparison

C1 General Remarks

Two spherical ^{3}He detectors of the Centronic SP9 type were chosen for the comparison. The two bare detectors have nominal ^{3}He pressures of 0.2 kPa. For the determination of the fluence of epithermal neutrons, two shields with 1 mm thickness of cadmium layer for the bare counter, pre-amplifier (ORTEC 142PC) and 2 high-voltage signal cables with a length of 0.5 m and 1.5 m are provided. The output signal of the pre-amplifier will be processed by the main amplifier and MCA prepared by the participant.

C2 Operation of the ^{3}He Proportional Counters

The bare counter with the irradiation direction is shown in Fig. C1. As can be seen from this figure, the bare SP9 has a nose and a stem with a SHV socket on the opposite side of the spherical sensitive volume. The serial numbers of the SP9 counters are 2131-085 and 2131-086, respectively. They are indicated on the stem together with the nominal pressure, and the appropriate voltage can be found in the test results sheet in its original package.

Fig. C1 SP9 counter and the irradiation direction

Fig. C2 shows the mounting of the bare counter in the cadmium shell. The counter is inserted into the cylindrical shield, and the SHV socket of the detector will be fixed in the bottom cap. Upon assembly completion, the equipment is revealed as depicted in Fig. C3. When mounting the detectors inside the shields, any excessive force has to be avoided to prevent damage to the counters! The dimensions of the shields are shown in Fig. C4.

For the bare counter, the point of reference is in the center of the spherical sensitive volume. The corresponding point of reference for counter inside shield is on the axis of the cylinder at the distances from the end cap indicated in Fig.C4, the position is marked by lines engraved in the housing.

For the bare counter, the symmetry axis must be oriented perpendicular to the neutron beam direction. The same applies for the measurements with the cadmium shells.

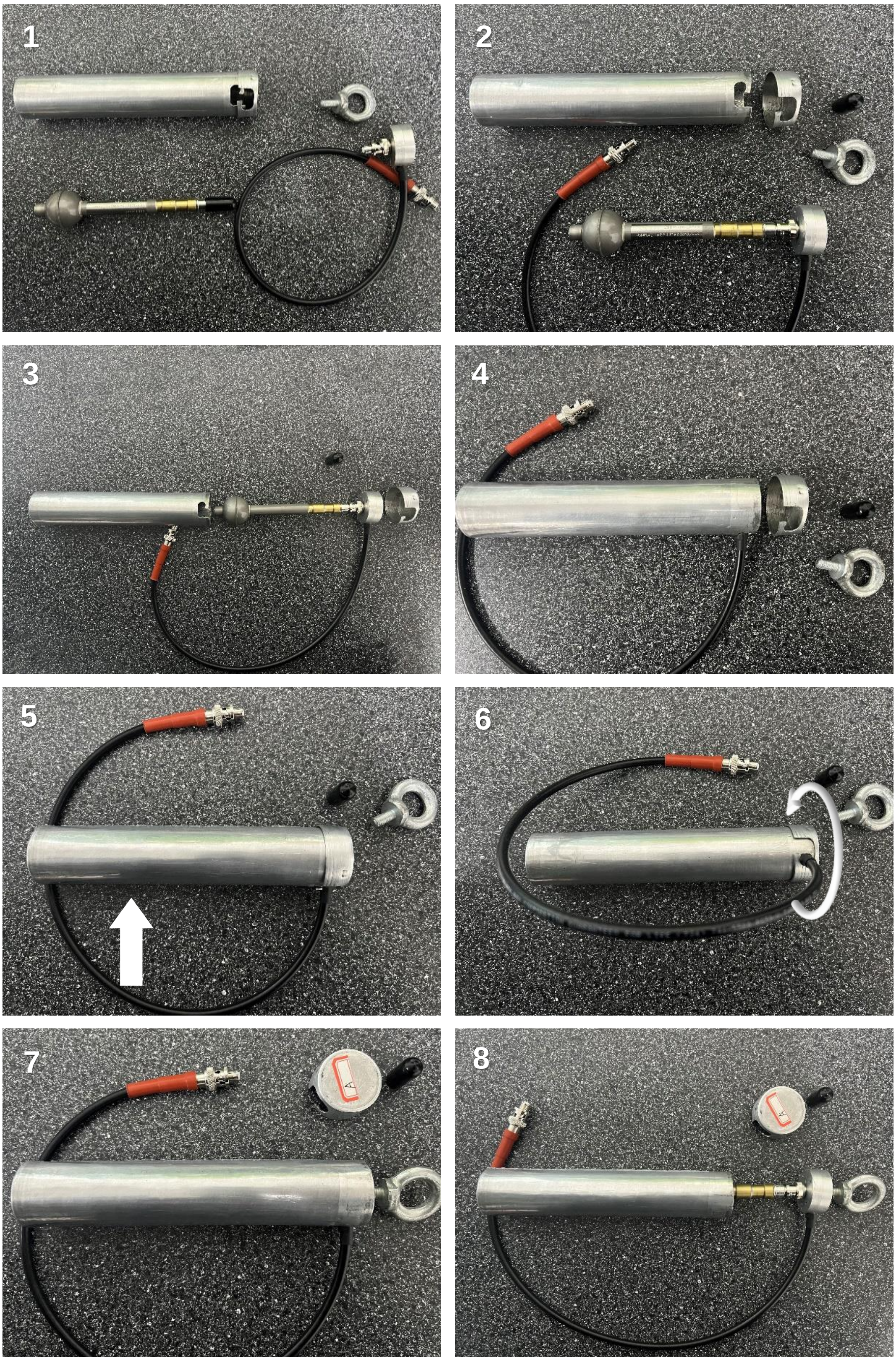


Fig. C2 Insertion of the bare counter into the cadmium shell.
The beam has to be incident perpendicular to the stem of the counter.

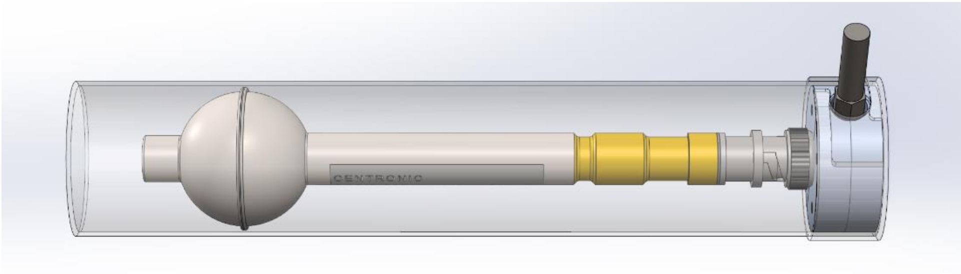
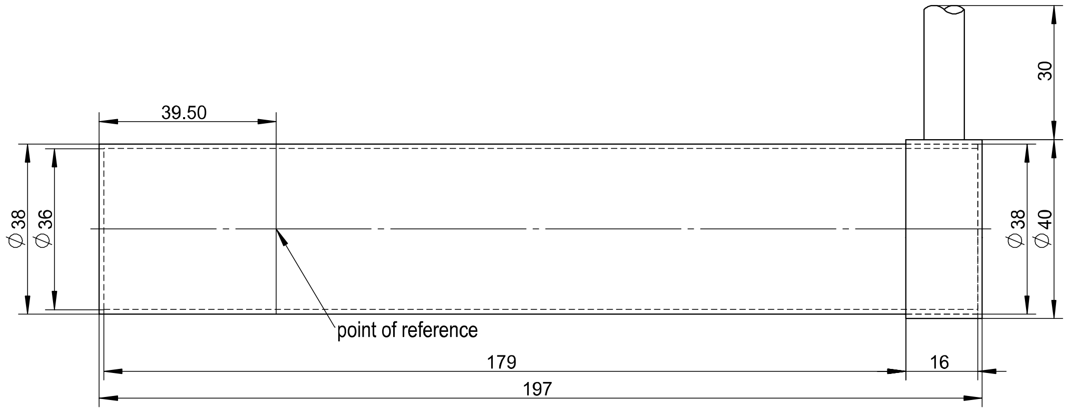


Fig. C3 Schematic diagram of the bare SP9 counter in cadmium shell.



Cadmium sleeve

Fig. C4 Outer dimensions of the shields for the bare SP9 counter.

C3 Operation of the electronic set

The counters output will be processed by an electronic set consisting of a high-voltage supply, a pre-amplifier (ORTEC 142PC), a main amplifier and an MCA, the connection diagram of the complete set of measuring devices is shown in Fig. C5.

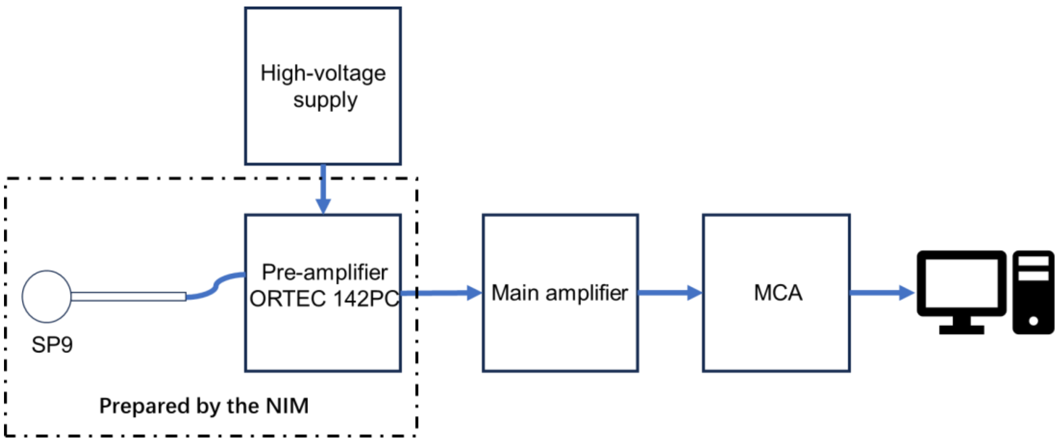


Fig. C5 Measurement system connection diagram (up panel) and the connection status of the detector, high-voltage signal cable and the pre-amplifier (down panel)

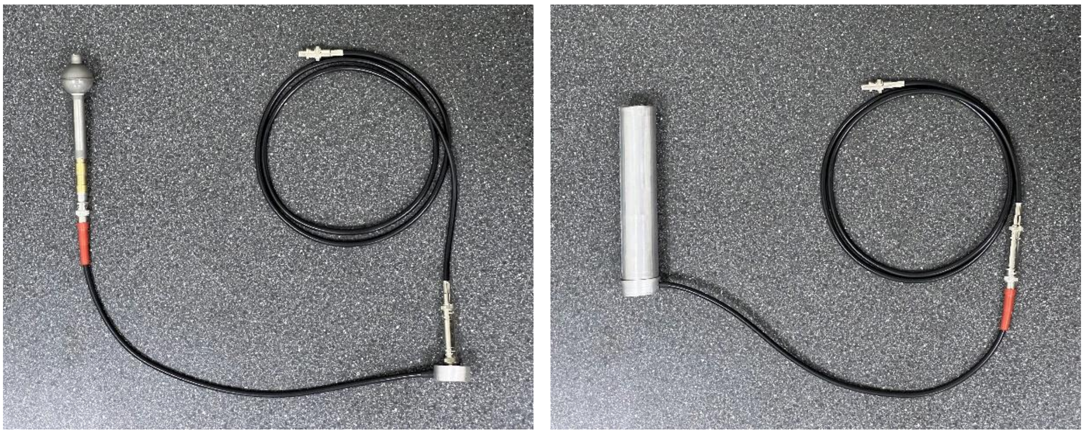
The high voltage supplying to the detector should be set according to the specification of the detector **(730 V for SP9 with serial number 2131-085 and 731 V for SP9 with serial number 2131-086),** the gain of the main amplifier should be adjusted to meet the requirement of the main peak position, the shaping time of the main amplifier must be 2 μs.

The amplifier has to be adjusted, so that the position of the main 764 keV peak will be below 50% of the full scale of the MCA range to identify potential pulse overlapping. To ensure that there are no counts contributed by photons in the counting results, the threshold for the MCA spectrum integration has to be set at 30% of the main peak, i.e. to energy of 229 keV.

Reminder: set the high voltage to zero and switch off the output of the high-voltage supply before connecting or disconnecting a counter and the electronic devices!

C4 Operation of the cable connection and extension

When connecting a bare detector, use the red end of the 0.5 m long cable for the SP9 connection; conversely, for a cadmium-coated detector, use the opposite end. If the signal cable needs to be extended, please connect the cable as shown in Fig. C6, the total length is 2 m.



(a) the bare counter (b) the counter in cadmium shield

Fig. C6 Extension of high-voltage cables

Appendix D: $R(E)$, $R_{\mathrm{Cd}}(E)$ and $R(2,53 \cdot 10^{-8}\ \mathrm{MeV})$

The response $R(E)$, $R_{\mathrm{Cd}}(E)$ will be used in the calculation of the reference response R_{ref} in Eq. (2), corresponding to the bare counter and the counter with cadmium shell, respectively. The responses, as calculated using MCNP, are shown in Fig. D1. The response was obtained by counting the number of $^{3}He(n, p)T$ reaction for the parallel neutron beam perpendicular to the symmetry axis of the counter. The reference response $R(2.53 \cdot 10^{-8}\ \mathrm{MeV})$ for the bare counter is (0.00468±0.00001) cm^2.

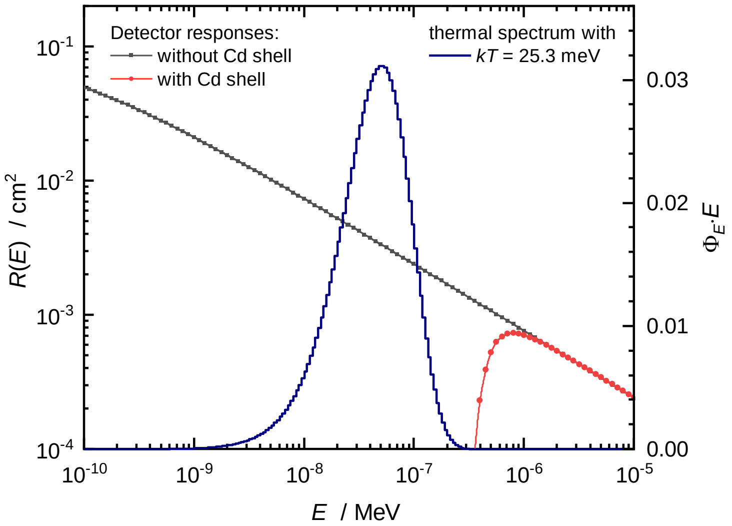


Fig. D1 Response function of SP9 counter (left axis). The response of the SP9 counter was calculated using the MCNP for parallel neutron beam perpendicular to the symmetry axis of the counter. Also shown is the relative Maxwellian spectral fluence distribution for *kT* = 25.3 meV (right axis).

Note: Detailed data will be provided by the pilot laboratory at a later time.

Appendix E: Directional dependence of SP9 counter response

The angular distribution of the spectral fluence in the thermal neutron reference radiation field may require corrections if the field is not unidirectional irradiation. The directional dependence of SP9 counter response as well as response in isotropic field will be provided by the pilot laboratory for the calculation of the correction factor, as shown in the figure E1, with a reference radiation direction of 90°. An MCNP model of the detector will be provided to the participants by pilot laboratory.

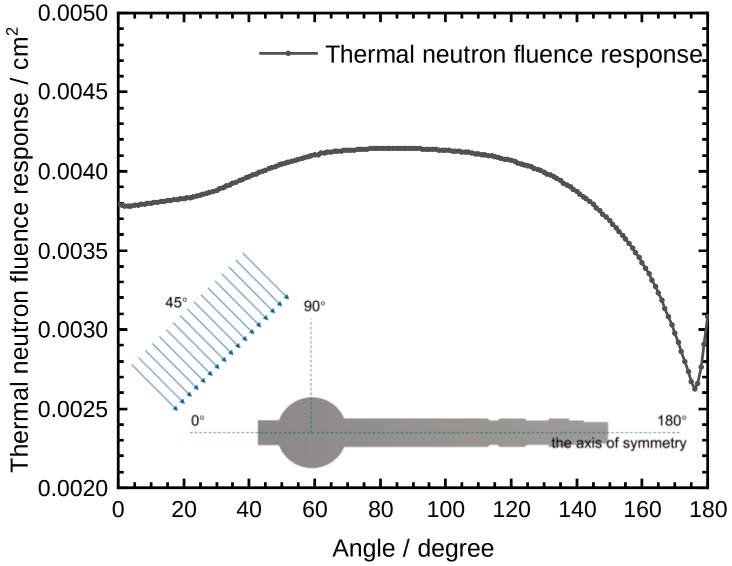


Fig. E1 Directional dependence of SP9 counter response. The response of the SP9 counter was calculated using MCNP for parallel neutron beams with a Maxwellian distribution for the temperature parameter *KT* of 293.6 K. 0°, the angle between the neutron beam and the detector symmetry axis, represents that the beam is incident parallel to the symmetry axis from the direction of the counter “nose”, and 90° represents that it is incident perpendicular to the symmetry axis.

Note: Detailed data will be provided by the pilot laboratory at a later time.