International Key Comparison of Neutron Fluence Measurements in Mono-energetic Neutron Fields - CCRI(III)-K10

J. Chen[1], Z. Wang[1] and C. Rong[1]
G. Lövestam[2], A. Plompen[2] and N. Puglisi[2]
D.M. Gilliam[3], C.M. Eisenhauer[3], J.S. Nico[3] and M.S. Dewey[3]
K. Kudo[4], A. Uritani[4] , H. Harano[4] and N. Takeda[4]
D.J. Thomas[5], N.J. Roberts[5], A. Bennett[5] and P. Kolkowski[5]
N.N. Moisseev[6] and I.A. Kharitonov[6]
S. Guldbakke[7], H. Klein[7], R. Nolte[7] and D. Schlegel[7]**

Abstract

CCRI-Section III (neutron measurements) conducted a unique key comparison of neutron fluence measurements in mono-energetic neutron fields. In contrast to former comparisons, here the fluence measurements were performed with the participants' instruments in the same neutron fields at the PTB accelerator facility. Seven laboratories – the CIAE (China), IRMM (EC), NMIJ (Japan), NIST (USA), NPL (UK), PTB (Germany) and the VNIIM (Russia) - employed their primary standard reference methods or transfer instruments carefully calibrated against their primary standards, to determine the fluence of 0.144 MeV, 1.2 MeV, 5.0 MeV and 14.8 MeV neutrons and reported calibration coefficients for a selected neutron monitor and each neutron energy with a detailed uncertainty budget for the measurements.

The key comparison reference values (KCRV) were finally evaluated as the weighted mean values of the neutron fluence at 1 m distance from the target in vacuum per neutron monitor count. The uncertainties of each KCRV amounted to about 1%. The degree of equivalence (DoE), defined as the deviation of the result reported by the laboratories for each energy from the corresponding KCRV, and the associated expanded uncertainty are also reported. The deviations between the results of two laboratories each with the corresponding expanded uncertainties complete the documentation of the degrees of equivalence.

---

[1] present address: China Institute of Atomic Energy (CIAE), Beijing, PR of China
[2] present address: EC-JRC-Institute for Reference Materials and Measurements (IRMM), Geel, Belgium
[3] present address: National Institute of Standards and Technology (NIST), Gaithersburg, USA
[4] present address: National Metrology Institute of Japan (NMIJ), Tsukuba, Japan
[5] present address: National Physical Laboratory (NPL), Teddington, UK
[6] present address: Mendeleyev Institute for Metrology (VNIIM), St. Petersburg, Russia
[7] present address: Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
** corresponding author: ralf.nolte@ptb.de

1. Introduction

Mono-energetic neutron fields are often required to determine the energy-dependent response of neutron sensitive devices in order to confirm experimentally at least at certain energies the generally more detailed calculations. The International Standards Organisation (ISO) recommends a series of neutron fields well suited for the purpose [1] and various national metrology laboratories offer calibration services in these fields. According to the CIPM Mutual Recognition Arrangement (MRA), signed in October 1999 [2], these calibrations will be accepted world-wide, when the laboratories have established a quality management system conforming to ISO standard 17025 [3]. This includes support of the specifications of 'calibration measurement capabilities' (CMC) published in Appendix C of the key comparison data base (KCDB) on the BIPM web-page by means of international key or supplementary comparisons organised by consultative committees of CIPM or by technical committees of the regional metrology organisations. These comparison exercises should be carried out within certain time intervals, usually not longer than 10 years, and the results of these comparisons shall be documented in Appendix B of the KCDB showing the degree of equivalence of the participating laboratories for the particular service investigated.

Section III (neutron measurements) of the Consultative Committee for Ionising Radiation (CCRI, formerly CCEMRI) regularly conducted and evaluated international neutron fluence measurement comparisons in mono-energetic neutron fields [4 - 11]. Concerning comparisons in mono-energetic neutron fields with energies between 0.144 MeV and 14.8 MeV the last agreed report has, however, been published in 1990 [8] (see Table 1.1). Hence, new international comparisons are urgently needed in this energy range and CCRI-Section III agreed on a unique comparison exercise.

In all former comparison exercises, the laboratories were requested to produce the neutron field and to specify the (spectral) fluence with their primary standard reference instruments or calibration methods. A comparison was then performed by circulating a transfer instrument for which the energy dependent response had to be determined, or by distributing reference material to be activated in the well characterised field. The advantage of this procedure is that production, specification and application of the neutron fields are part of the comparison exercise. In the case of circulating active transfer instruments, such as moderating spheres or fission counters, the sequential use of these devices in the participating laboratories, and the regular function tests by the pilot laboratory in between resulted in a rather long time period for performing the measurements, followed by a considerable time needed for the evaluation of the reported data and for obtaining the agreement of all participants on the results obtained. Only in the case, where activation foils were distributed could the measurements be carried out simultaneously in all participating laboratories and then analysed at the pilot laboratory. In any case the transfer procedure in general contributed a non-negligible fraction to the uncertainty budget for the key comparison reference value. Moreover, very recently

CCRI (III) could not agree on a final report with the evaluation of a comparison performed with two Bonner spheres because the recommended procedures for calibrating the response of these transfer instruments for 2.5 MeV and 14.6 MeV neutrons exhibited discrepancies which could not be solved or explained [9, 11].

Table 1.1. CC(EM)RI neutron fluence measurement key comparisons since 1973 (only ISO-energies 0.144, 1.2, 5.0 and 14.8 MeV considered). Pilot laboratories have been underlined.

Comparison CCRI(III)-*	Neutron Energy / MeV	Transfer Monitor	Participating Laboratories**	Reference Date of public.	Date of Measure ments
K32.In	0.144	^{115}In-activation foil	CIAE, NMIJ, NPL, PTB, NRC	[7] 1987	1984/85
K32.U235	0.144	^{235}U-fission chamber	NMIJ, (AERE)	[8] 1990	1983/86
none	1.2				
K36.In	5.0	^{115}In-activation foil	IRMM, NPL, PTB	[6] 1984	1981
K36.U	5.0	^{235}U- and ^{238}U-fission chambers	NMIJ, IRMM, PTB, (AERE)	[8] 1990	1984/88
K37.Fe	14.8	^{56}Fe-activation foil	BIPM, NMIJ, VNIIM, IRMM, NPL, PTB	[4] 1980	1973/78
K37.U238	14.8	^{238}U-fission chamber	BIPM, NMIJ, VNIIM, IRMM, NPL	[4] 1980	1973/78
K37.Nb	14.8	Nb- and Zr-activation foils	BIPM, BARC, CIAE, NMIJ, IRK, IRMM, NPL, PTB, NIST	[5] 1984	1981
K37.U	14.8	^{238}U-fission chamber	BIPM, NMIJ, IRMM, NPL, PTB, (AERE)	[8] 1990	1984/88
P32.BS	14.8	2.5” and 9.5” Bonner spheres	BIPM, IRMM, NPL, PTB	[9] 1991	1986/90

* specification according to KCDB App. B of BIPM webpage (see http://www.bipm.org)

** former ETL and CBNM, now NMIJ/AIST and IRMM, respectively. Although not a member of CCRI, AERE participated as the pilot laboratory.

In order to overcome these problems and to cover the entire energy range from 0.144 MeV to 14.8 MeV in one exercise, Section III of CCRI agreed on a completely different concept. The PTB as the pilot laboratory offered to use their irradiation facility to produce mono-energetic neutron fields and the laboratories were requested to determine the neutron fluence at agreed conditions (see protocol). The calibration factor of a neutron monitor which should serve as the transfer instrument for comparison of the fluence measurements had to be determined. Seven laboratories - CIAE/China, IRMM/EC, NIST/USA, NMIJ/Japan, NPL/UK, PTB/Germany and VNIIM/Russia - agreed either to employ their primary standard instruments or, when the instrument or the method could not be moved to PTB, transfer instruments best suited for the purpose and calibrated in the laboratory such that the fluence measurement at PTB was directly traceable to the primary standard instrument or method used at home.

This report describes in detail the neutron fields and their specifications, the monitoring during the fluence measurements, the fluence measurement reference devices or methods employed by the participants in the framework of this comparison exercise, and the evaluation of the results reported together with detailed uncertainty budgets. Finally there follows a discussion of the key comparison reference values and the degree of equivalence for the investigated neutron fields and those laboratories having reported results.

2. Neutron Fields: Production, Specification and Monitoring

The mono-energetic neutron fields were produced at the accelerator facility of the PTB [12, 13], using the 3.75 MV Van de Graaff linear accelerator and the nuclear reactions listed in Table 2.1. The measurements were performed in a large experimental hall - 30 m wide, 24 m deep and 14 m high (Fig. 2.1). The target is positioned in the centre of the hall and the desired neutrons are emitted in the forward direction (0 degrees). In this way, undesired background due to neutron inscattering from the concrete walls and the low mass supports is kept relatively low. Nevertheless, the readings due to these room-return and air-inscattered neutrons were subtracted, if necessary and possible, by an additional measurement with an appropriate shadow cone inserted between the target and the fluence measuring device.

Table 2.1. Properties of the neutron fields (projectile energy $<E_p>$ with an uncertainty of 2 keV; neutron energy $<E_n>_{calc}$ and width ΔE_n calculated with the TARGET code; the mean neutron energy $<E_n>_{exp}$ measured with ^{3}He- or NE213-spectrometer with uncertainty δE_n).

Reaction	$<E_p>$ / MeV	Target	Backing	$<E_n>_{calc}$ / MeV	ΔE_n / MeV	$<E_n>_{exp}$ / MeV	δE_n / MeV	week
^{7}Li(p,n)^{7}Be	1.946	LiOH	Al	0.144	0.019	0.1435	0.007	1
^{7}Li(p,n)^{7}Be	1.947	LiOH	Al	0.145	0.020	0.1441	0.007	2
T(p,n)^{3}He	2.050	Ti(T)	Ag	1.2	0.091	1.205	0.020	1/2
D(d,n)^{3}He	2.300	D_2-gas	Au	5.0	0.200	5.000	0.030	1/2
T(d,n)^{4}He	0.242	Ti(T)	Al	14.8	0.431	14.820	0.070	1/2

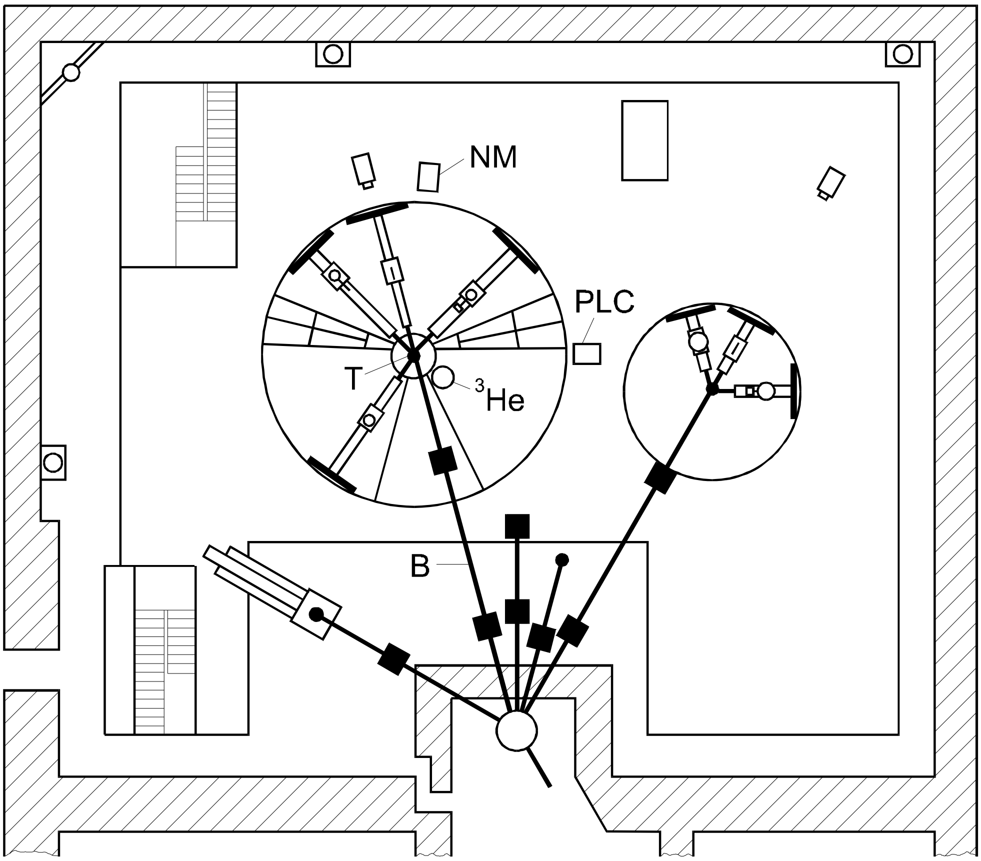


Figure 2.1. PTB experimental hall, 30 m wide, 24 m deep and 14 m high, for calibration with monoenergetic neutrons at low room return neutron background. (B = beam line; T = neutron producing target; S = four swivel arms with movable detector supports; NM, PLC, ^{3}He = neutron monitors). The neutron monitor at forward direction (NM at 17.5 degrees) was to be calibrated and the four swivel arms with supports for the fluence measuring devices were used by the participants.

Provided that the target properties do not change with time, and either the beam profile does not change during the irradiation, or the target layer is uniform in terms of neutron production, the neutron yield should be proportional to the beam charge on the target. Irradiations were performed in open geometry and various neutron monitors positioned in forward (NM) and backward (PLC and ^{3}He) directions were used for checking the stability of the neutron production. Ratios of the different monitor rates and the beam charge then indicate any significant distortion of the neutron production. Any influence of the monitor rate by inscattering from the devices inserted at 0 degrees, *i.e.* fluence measuring devices and shadow cones, or even partial shadowing will be observed and can be corrected for (see chapter 4.2). The NM-monitor in the forward direction was finally selected as the transfer monitor for comparison of the fluence measurements of all participants since it had the best counting statistics for all reactions investigated.

The properties of the desired neutron field, *i.e.* mean neutron energy and energy width (FWHM) of the uncollided neutrons, are chiefly determined by the energy of the projectile which is well defined with a calibrated NMR within the 90 degrees bending magnet [14] and by the target parameters specified by the manufacturer. The T-loaded Ti-targets are regularly used at PTB and the properties are carefully investigated taking advantage of tof-spectrometry with ns-pulsed ion beams. Since fresh Li-targets have to be produced on purpose, the target thickness must be determined during the evaporation process. When using a deuterium gas target, the pressure, even if precisely determined with a calibrated gauge, can only be taken as an estimate for the target thickness because the effective pressure depends on the local heating by the beam current actually used. Hence, even the product of beam charge and indicated pressure is not expected to be a good monitor except for short term normalisation at stable beam conditions.

In any case it is advisable, to determine the mean neutron energy at 0 degrees and, if possible, the energy width in order to confirm these basic assumptions. For this purpose PTB employed a ^{3}He-filled proportional counter (0.144 MeV, 1.2 MeV) and an NE213 liquid scintillator (5.0 MeV and 14.8 MeV) both well specified to measure the neutron energies with reasonable uncertainties (see Table 2.1). On the basis of the parameters confirmed by spectrometry, the spectral fluence of the desired neutron field was then calculated with the TARGET code [15] and also the spectral fluence of neutrons scattered from the target assembly into the detector. When the gas target was used the spectral fluence was calculated with the SINENA code [16] for the uncollided neutrons only, because the contribution of target scattered neutrons can be regarded to be negligible (<1%, depends on the distance). All relevant calculations were provided to the participants for interpretation of their fluence measurements and for the calculation of the contribution due to target-scattered neutrons (as far as necessary), because this fraction cannot be determined experimentally. These corrections, however, require well established energy-dependent response functions for the instruments employed.

3. Neutron Fluence Measurement Devices of the Laboratories

The participants in this comparison were asked to determine the neutron fluence in the forward direction (0 degrees) at any distance up to 4 m well suited for the particular measuring device employed in the fields with different neutron energies. Section III of CCRI recommended that the primary standard instrument used in the laboratory is employed whenever possible. In cases where the primary instrument is not portable, or the standard method used in the laboratory not applicable at PTB, the participants were free to choose an appropriate transfer instrument, which, however, should have been calibrated such that the fluence measurements in the framework of this comparison exercise were directly traceable to the primary standards of the laboratory. From these measurements the fluence at 1 m distance in vacuum, *i.e.* corrected for air-outscattering, had to be derived and the ratio to the count rate of the selected monitor should be determined. Tables with all relevant monitor data and carefully evaluated correction factors were provided to all participants by the pilot laboratory. The key comparison reference value was then evaluated for this ratio.

The instruments used by the participants are listed in Tables 3.1 and 3.2. In the following only the major characteristics will be discussed in view of the most important contributions to the uncertainty budgets. Details may be found in the reports of the participants and related papers cited therein.

Table 3.1. Transfer instruments used by CIAE, IRMM and NIST and the traceability to their primary national standards

Laboratory	Neutron energy / MeV	Transfer monitor used by the laboratories	Traceability to primary standards	Remarks
CIAE	0.144	RPPC, 250 hPa pure hydrogen at 20° C	Primary standards based on σ_{np} cross section from ENDF/B-VI	Gas filling at PTB
	1.2	RPPC, 600 hPa pure propane at 20° C		Gas filling at PTB
	5.0	RP in Si-detector, Polyethylene radiator	H-content of the PE-radiator by weighing	
	14.8	RPT with Si(ΔE)- and CsI (E_R) detectors, Polyethylene radiator		
IRMM	1.2	RPT, 0.747 mg/cm^2 tristearin	Response based on σ_{np} cross section from ENDF/B-IV, H-content of radiators by weighing and chemical analysis	
	5.0	RPT, 5.466 mg/cm^2 tristearin		
	14.8	RPT, 43.75 mg/cm^2 polyethylene		
NIST	0.144	^{235}U-fission chamber, 93.18% enr., Cd-shielded	Response based on σ_{nf} cross section from ENDF/B-VI and calibration with ^{252}Cf-source (traceable to Mn-bath of NIST)	Abundancies of other isotopes well specified for corrections
	1.2	same		
	5.0	same		
	14.8	same		

Table 3.2. Transfer instruments used by NMIJ/AIST, NPL, VNIIM and PTB and the traceability to their national primary standards

Laboratory	Neutron energy / MeV	Transfer monitor used by the laboratories	Traceability to primary standards	Remarks
NMIJ/ AIST	0.144	PE-moderator sphere (BS), 24.13 cm (9.5”) in diameter, with ^{3}He-PC (SP9) as central thermal neutron detector	^{7}Li(p,n)-neutron field and RPPC	3.5” PE-BS not analysed
	5.0		D(d,n)-neutron field and RPT	^{3}He-PC E_n-spectrometer data not analysed
	14.8		T(d,n)-neutron field and AP-method	
NPL	0.144	De Pangher long counter with BF$_3$-PC as thermal neutron detector	Mn-bath calibrated radionuclide neutron sources	MCNP-calculated response
	1.2			
	5.0			
	14.8	^{27}Al-activation foil	T(d,n)-neutron field and AP-method	evaluated cross sections
VNIIM	0.144	PE-moderator sphere, 15 cm in diameter, 1 mm Cd-shield, cylindrical ^{3}He-PC	Mn- and water-bath calibrated neutron sources	calculated response function
	1.2			
	5.0			
	14.8		D(d,n)- and T(d,n)- fileds, AP-method	
PTB	0.144	RPPC (965 hPa hydrogen + 35 hPa methane)	Hydrogen content from pressure gauge and active volume related to length gauge	response based on σ_{np} cross section from ENDF/B-IV
	1.2	RPPC (600 hPa propane)		
	5.0	RPT (two PC + Si-det.) 10.086 mg/cm^2 tristearine and 30 kPa CO$_2$	H-content of radiator by weighing at IRMM	
	14.8	same		

3.1. D.I. Mendeleyev Institute for Metrology (VNIIM) [17]

Since the associated particle (AP) method, employed at VNIIM as the primary standard reference method to determine the fluence of 2.5 MeV and 14.8 MeV neutrons, could not be transferred to PTB, the laboratory decided to specify the energy dependent response of a moderator detector by means of Monte Carlo calculations normalised by calibrations with two mono-energetic and various radionuclide source neutrons. In this way, the fluence measurements with the transfer neutron monitor were traceable to the primary standards of the laboratory, namely the AP-method and the Mn-bath used to determine the emission rate of the neutron sources. The response of the polyethylene moderator, 150 mm in diameter and covered by 1 mm Cd, is rather high, in particular for neutron energies around 500 keV, because the central thermal neutron detector is a voluminous cylindrical proportional counter filled with 710 kPa ^{3}He-gas.

Although all experimental calibrations confirmed the calculated response in the energy range of interest to better than 2%, the standard uncertainty of the response was estimated to be between 2.5% and 5% increasing with energy from 0.144 MeV to 14.8 MeV (see App. B.1 and the VNIIM-report [17]). This conservative estimate is possibly a result of the fact that the response decreases by almost a factor of ten for the energies up to 14.8 MeV such that corrections for target-scattered neutrons become significant. However, all additional experimental and methodological uncertainties were estimated to be negligible such that the uncertainties reported for the fluence measurements were dominated by the uncertainty estimated for the response at the desired neutron energy.

3.2. National Metrology Institute of Japan (NMIJ/AIST) [18]

The primary standard instruments and methods used at NMIJ (former ETL) for reference in neutron fluence measurements were also not portable and NMIJ finally decided to specify two moderator detectors (Bonner Spheres) as transfer instruments. The response of two polyethylene spheres, 24.13 cm (9.5") and 8.89 cm (3.5") in diameter with spherical ^{3}He-proportional counters in the centre (Centronic model SP9) were simulated with the MCNP code. The calibration measurements at NMIJ were performed exactly in the same way as the comparison measurements at PTB. The desired energies were produced using the same reactions and the spectral fluence of the desired uncollided neutrons and of those neutrons scattered from the target assembly into the detector were calculated in a very similar way as at PTB with the TARGET code but using a home-made Monte Carlo code [19]. Unfortunately, a T-loaded Ti target could not be used at NMIJ for the production of 1.2 MeV needed to establish the traceability to the primary standard instrument used to determine the fluence of 1.2 MeV neutrons. Hence, the measurements performed by NMIJ in the course of the comparison exercise could not be adequately analysed.

In case of 0.144 MeV neutrons, the fluence is measured at NMIJ with a proportional counter filled with 955.5 kPa hydrogen and an admixture of 34.7 hPa methane. The simulated response functions [20] well reproduce the measured pulse height spectra and the uncertainty of 2.4% chiefly results from uncertainties of the n-p scattering cross section and of the calculational model, i.e the uncertainty of the sensitive volume filled with hydrogen.

A single silicon detector is used to measure 5 MeV recoil protons from a polyethylene radiator. While the simulation of the response function contributed, conservatively estimated, with only 1.5% and the hydrogen content of the radiator could be specified with an uncertainty of 1%, the dominant contribution to the uncertainty budget resulted from uncertainties in the stopping power of the recoil protons [21] in the radiator (2%). Again, the uncertainty evaluated for the fluence determination at PTB is almost the same as for the calibration at NMIJ.

Finally, the associated particle method was applied to calibrate the moderator detector with 14.8 MeV neutrons [22]. The rather low uncertainty of this calibration was essentially kept for the measurements at PTB.

For details of the uncertainty budgets see Appendix B.2 (and the NMIJ-report [18]).

Since the corrections for the low-energy room-return neutrons were much higher for the 3.5" than for the 9.5" Bonner sphere, only the latter device was finally used as transfer instrument. The uncertainties evaluated for the calibration of the PTB monitor were only slightly higher than the uncertainties achieved for the response of the transfer detector in the very similar fields at the NMIJ. Hence, the uncertainty budgets for the primary standard instruments and methods dominate the uncertainty budgets of the fluence measurements at PTB.

3.3. Institute of Reference Materials and Measurements (IRMM) [23]

A proton recoil telescope was introduced at the IRMM (former CBNM) almost 30 years ago as the primary standard reference instrument for the measurement of the fluence of neutrons in the energy range from 1 MeV to 20 MeV. The Los Alamos type instrument consists of two pill-box proportional counters filled with CO_2 and Ar (or Kr) in front of a Si-surface barrier detector thick enough to stop 5 MeV recoil protons, but not 14.8 MeV protons. Material and thickness of the radiator in front of this detector telescope were selected to optimise the efficiency for the neutrons to be measured and the energy distribution of recoil protons to be analysed. The efficiency, first calculated by the designer of the instrument about 40 years ago [24], has been recalculated with a formalism published 20 years later [25]. Uncertainties of the internal and external geometry determined with calibrated length meters, the hydrogen content of the radiators determined by weighing and chemical analysis, the differential n-p cross section from an internationally accepted evaluated data base, the procedure of analysing the recoil proton peak and the background and finally the counting statistics contribute with similar weights to the uncertainties evaluated for the fluence measurement at PTB (2.6 - 2.7%, see for details Appendix B.3 and the IRMM-report [23]).

Since an RPT cannot be applied for fluence measurements of 0.144 MeV neutrons and the hydrogen proportional counter [26], employed in former comparison exercises by and at IRMM, was not available for this purpose, IRMM did not participate in the comparison exercise at the lowest neutron energy.

3.4. *China Institute of Atomic Energy (CIAE)* [27]

The CIAE employed the primary standard reference instruments normally used for the neutron energies investigated in the framework of this key comparison.

A proportional counter filled with hydrogen or propane was used to measure the fluence of mono-energetic neutrons with energies 0.144 MeV or 1.2 MeV, respectively. The response function is calculated with the MCWALL code taking into account n-p scattering in the gas and wall effects at the surface of the active volume [28]. In- and outscattering of neutrons by the detector assembly are corrected separately by means of MC-simulations. Major contributions to the uncertainty budget come with comparable fractions from the determination of the active gas volume and the hydrogen content, the evaluated total n-p scattering cross section, the comparison of calculated and measured responses, the various corrections to be made and the counting statistics. In total, a 2% uncertainty resulted for the fluence measurements (see App. B.4 and the CIAE-report [27]).

Different recoil proton detectors were employed to determine the fluence of 5.0 MeV and 14.8 MeV neutrons. In the case of 5 MeV neutrons the recoil protons from a polyethylene radiator are simply measured in a Si-surface barrier detector, while for the measurements in the 14.8 MeV neutron field coincidence measurements of a thin Si detector (ΔE-signal) and a CsI crystal (E_R-signal) are carried out in order to reduce the background normally caused by the high energy neutrons in a single detector. The efficiency is calculated with a home-made code on the basis of an analytical approach. The uncertainty budget is dominated by uncertainties of the inner and outer geometry parameters and the evaluated differential n-p scattering cross section relevant for the calculation of the efficiency. Contributions due to the counting statistics, the analysing procedure and the various corrections are negligibly small. The uncertainties of the hydrogen content of the radiators and of the differential n-p cross section, however, seem to be underestimated and the resulting uncertainties of about 2% may therefore be a bit too optimistic.

3.5. *National Institute for Standards and Technology (NIST)* [29]

NIST employed a ^{235}U-fission chamber in all neutron fields. The rather large and massive construction is completely shielded with 1 mm Cd in order to reduce the reading due to thermalized room-return neutrons. For shadow cone measurements at 1 m distance the readings still amounted to up to 10.7% chiefly caused by neutron inscattering from the massive outer support of the detector. The U-layer is enriched to 93.15% only, but the abundancies of other isotopes are specified such that corrections could be reliably calculated on the basis of evaluated cross sections.

The relative energy dependent neutron detection efficiency is simply determined by the fission cross section which can be taken from evaluated data files with uncertainties less than 1% [30]. The efficiency of the fission chamber was calibrated in absolute scale by means of a ^{252}Cf-neutron source which was calibrated in the NIST Mn-bath and is in this way traceable to the emission rate of the NIST#1 primary standard Ra/Be(γ,n)-neutron source. Also the procedure of subtracting the contribution of neutrons scattered from the massive support into the fission layer was checked with the ^{252}Cf-source and an appropriate shadow cone. The comprehensive MCNP-simulations were supported in this way. Nevertheless, the largest fraction of the total uncertainties evaluated for the fluence measurements at PTB resulted from these experimental problems with the reference instrument (see Appendix B.5 and the NIST-report [29]).

3.6. National Physics Laboratory (NPL) [31]

Two different long counters are normally used at NPL to determine the fluence of neutrons with energies up to 5 MeV. Owing to the lower size and weight, the De Pangher long counter [32] was moved to PTB. The much lower neutron detection efficiency compared with the McTaggart type long counter which is the more commonly used NPL primary standard instrument was, however, not a real disadvantage owing to the reasonable neutron yield of the fields produced at PTB.

Very recently, the neutron response and the effective centre of the long counter were calculated using the MCNP code and re-calibrated using all radio-nuclide sources available at NPL [33]. The emission rates of the radio-nuclide neutron sources were calibrated in the NPL Mn-bath with uncertainties less than 1% and the relative spectral fluence was taken from evaluations or own measurements. Since measurements were carried out at various distances in order to support the analysing procedure, the response to room-return neutrons had carefully to be subtracted. To be as close as possible to the procedures applied at home, NPL also used their own shadow cones.

The associated particle method used at NPL with the 150 kV accelerator to specify the T(d,n)-neutron field [34] could not be transferred. Hence, it was decided to use activation foils for the fluence measurement at 14.8 MeV. Traceability to the primary standard method is well established with highest accuracy for the activation of ^{56}Fe- or ^{27}Al-foils. Owing to the longer half-life and the necessity to transport the activated foil from PTB to NPL for analysis, Al-foils were selected, and to increase the statistical accuracy two foils were simultaneously irradiated back-to-back. For the first time, the long counter was also employed in the 14.8 MeV field for fluence measurements. Although the results were in excellent agreement with the activation measurements, only the activation data were reported for the comparison. However, the consistency of the results for 14.8 MeV neutrons strongly supported the decision, to use the new specifications of the De Pangher long counter for reference instead of the old response [35] used in all former comparison exercise (for details of the uncertainty budgets see App. B.6 and the NPL-report [31]).

3.7. Physikalisch-Technische Bundesanstalt (PTB) [36]

PTB employed the primary standard instruments which were already used in all former comparison exercises. The specifications, measurements and the analysing procedures are essentially unchanged, while the uncertainty budgets have been re-investigated by applying the GUM-workbench [37] code (see Appendix B.7 and the PTB-report [36]).

The active volume of the recoil proton proportional counter [38] is well defined by the cylindrical outer cathode and guard tubes partially surrounding the central anode wire. Different fillings are used for the two energies in order to optimise the ratio of neutron to photon response such that the photon response could be eliminated by an appropriate lower pulse height threshold. The response function is simulated with the MCWALL code [27] (also applied by CIAE) taking into account wall effects only. A linear relationship of measured pulse height to the recoil proton energy deposited in the active volume is assumed (and was experimentally confirmed). The response functions were calculated for the TARGET calculated spectra including the target-scattered neutrons. Neutron in- and outscattering at the detector assembly were checked to cancel out. The neutron fluence at the centre of the detector was then obtained from the fit of the simulated to the measured pulse height spectra. The uncertainty budget (2.1%) takes into account the uncertainties of the internal and external geometry, the total n-p scattering cross section, and, with largest fraction, the quality of the calculated response function (degree of agreement in shape) and the fitting procedure (variation with the threshold and statistics).

The recoil proton telescope [39] used for the determination of the fluence of 5.0 MeV and 14.8 MeV neutrons is almost identical with the system employed by IRMM. The tristearin radiator was prepared at IRMM by evaporation on a 0.5 mm thick Ta-backing. The hydrogen content of the homogeneous layer (10.085 mg/cm^2, 30 mm in diameter) was calculated from the weight determined at IRMM and the chemical formula to 12.445% in weight with an uncertainty of 0.03%. A chemical analysis at IRMM resulted in 12.4% with an uncertainty of 0.7%. The efficiency is calculated on the basis of the inner geometrical parameters and the formulae derived by the inventor [24]. The major fractions of the uncertainty (about 2/3) come from the uncertainties of the inner and outer geometry (small distance between target and RPT) and the evaluated differential n-p scattering cross sections. Counting statistics and the procedure applied to evaluate the net peak content contribute another 1/3 of the uncertainty evaluated for the reported neutron fluence.

4. Measurements

The experiments were carried out within two weeks in March 2001. The accelerator was run 24 hours a day and the four different neutron fields were realised at least once per week. During the 1st week four participants shared the four swivel arms with movable supports for their devices. 24 hours of beamtime were sufficient for up to four participants to perform the neutron fluence measurements at each neutron energy. The same sequence of experiments was then performed in the second week with the other participants.

PTB participated in both campaigns and measured the neutron fluence at each energy at least four times in order to demonstrate the reproducibility of the neutron fields from week to week. The stability of the neutron production was regularly checked during one day with three neutron monitors and the beam charge.

4.1. Mean Neutron Energy and Spectral Fluences

The projectile energies from the Van de Graaff accelerator were selected to obtain the desired mean neutron energy for given target parameters. From simulations with the TARGET- and SINENA-code the expected mean neutron energy $<E_n>_{calc}$ was calculated from the spectral fluence of uncollided neutrons (see Table 2.1). At the beginning of each campaign the pilot laboratory checked the predictions using the ^{3}He-spectrometer at 70 cm or the NE213-scintillation spectrometer fixed at 629.5 cm in front of the target. The measured neutron energies $<E_n>_{exp}$, also listed in Table 2.1, well confirmed the predictions within the experimental uncertainties of 0.5 to 1.2%.

On the basis of the actual target and projectile parameters and for the geometry of the detector-systems used (distance and size) the spectral fluence of the desired uncollided neutrons Φ_{uc} and the target scattered neutrons Φ_{sc} were calculated with the TARGET code, normalised to unit fluence Φ_{uc} .When the gas target was employed only the spectral fluence of uncollided neutrons was calculated with the SINENA code. All relevant spectra were provided to the participants [40] for correction of their fluence measurements. One example for each neutron energy is shown in Fig. 4.1.

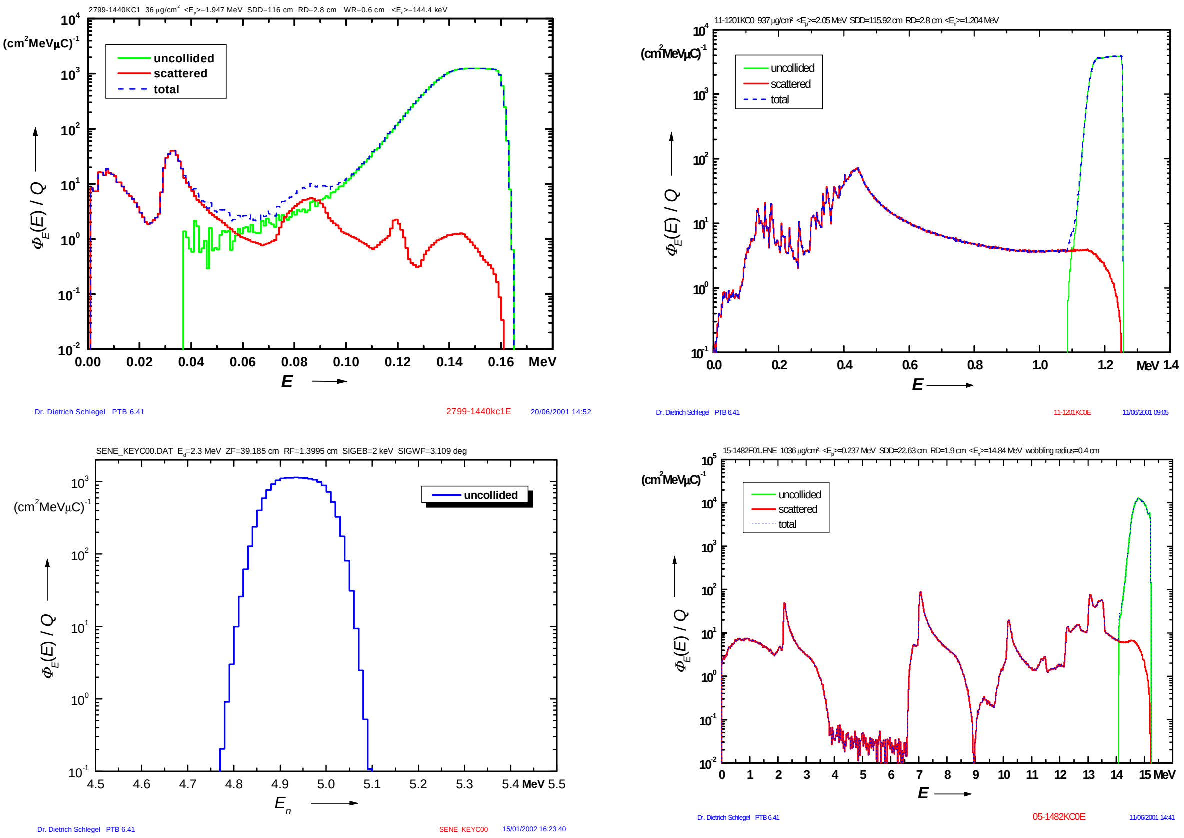


Figure 4.1. Spectral neutron fluence Φ_{tot} (blue) composed of uncollided neutrons Φ_{uc} (green) and neutrons scattered from the target assembly into the measurement point Φ_{sc} (red) as calculated with the TARGET code for the 0.144 MeV (upper left), 1.2 MeV(upper right) and 14.8 MeV (lower right) neutron fields. In case of the 5.0 MeV field (lower left), the SINENA code was used considering uncollided neutrons only, because target scattering is negligible (<1%).

4.2. Neutron Monitoring

For each measurement, a set of monitor data was recorded in a multi-scaler (MS) file, namely total measurement time, digitised beam charge, total counts of three neutron monitors and of a Geiger-Mueller gamma counter. These data were used to calculate the mean beam current (target load), count-rates (for dead-time corrections) and the ratios of the monitor rates.

In Fig. 4.2 the ratios of the forward (NM, Fig. 4.2 upper diagram) and backward (PLC, Fig. 4.2 lower diagram) neutron monitors to the beam charge are shown relatively normalised to the first (or the mean of all) measurement NM_0 or PLC_0, respectively, for a one day campaign with 1.2 MeV neutrons. Both graphs show the same trend. The mean of all measurements in free field geometry, *i.e.* with no detector or shadow cone at 0 degrees in position, is close to one and do not scatter by more than 0.5% confirming that in this case of using a T-loaded Ti-target also the charge is a good monitor. In addition, the different influence of proportional counters, moderator spheres and telescopes is obvious. Inscattering from the measurement device into the monitor is largest for the telescope close to the target, but can be reliably corrected to free field conditions.

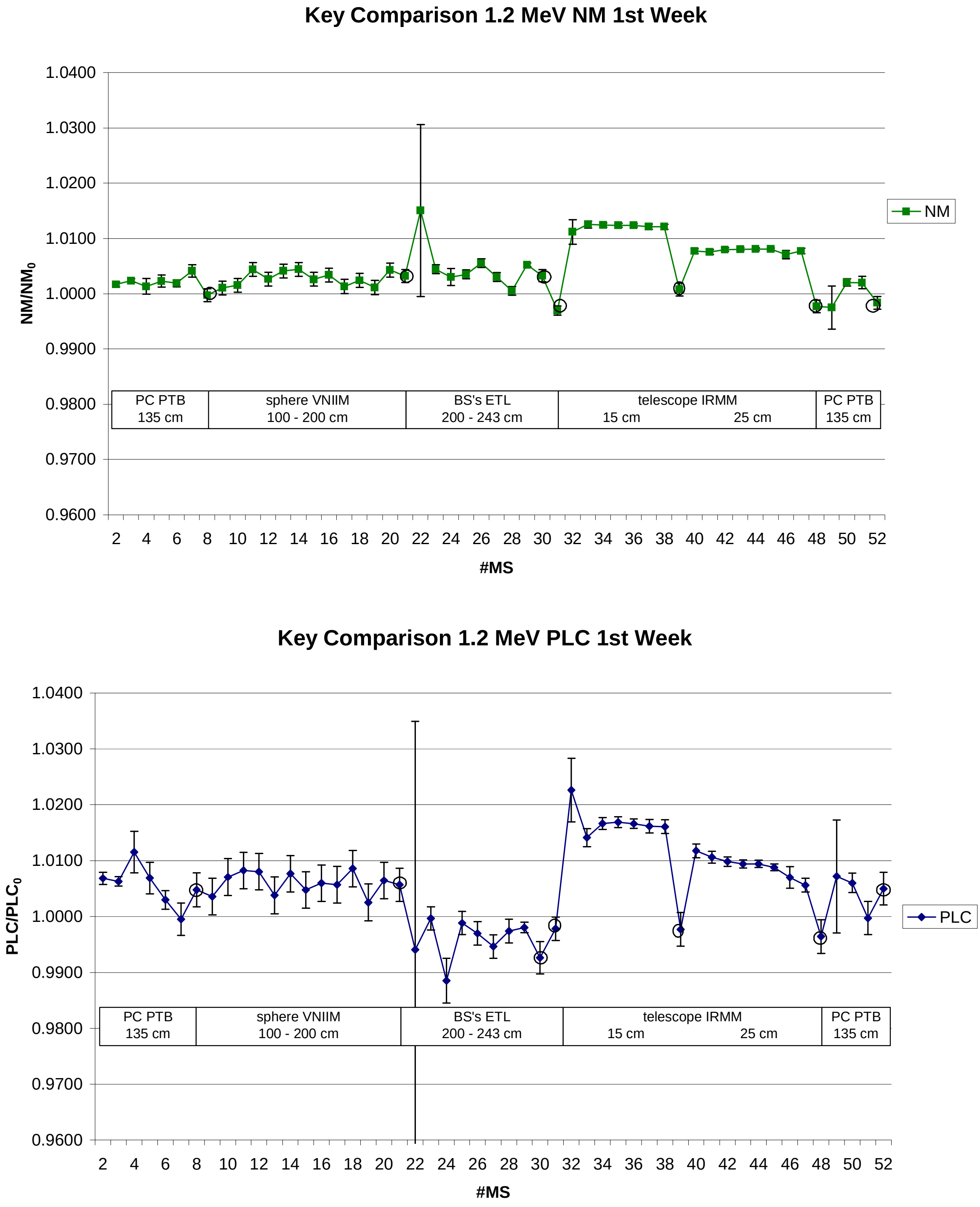


Figure 4.2. Count rates of the neutron monitors NM (upper part) and PLC (lower part) in the 1.2 MeV neutron field (1st week), normalised for unity beam charge and relative to the first free geometry measurement (NM_0) or to the mean value of all free geometry measurements ($<PLC_0>$) indicated by a circle around the data points.

Using, however, a T-loaded Ti-Target for the production of 14.8 MeV a continuous increase of the neutron yield per projectile charge by about 2% has been observed in the second week (Fig. 4.3 upper diagram). The drift could be fitted by a linear increase. The diagrams provided to the participants then showed the monitor data corrected for a constant yield per charge in free geometry (Fig. 4.3 lower diagram).

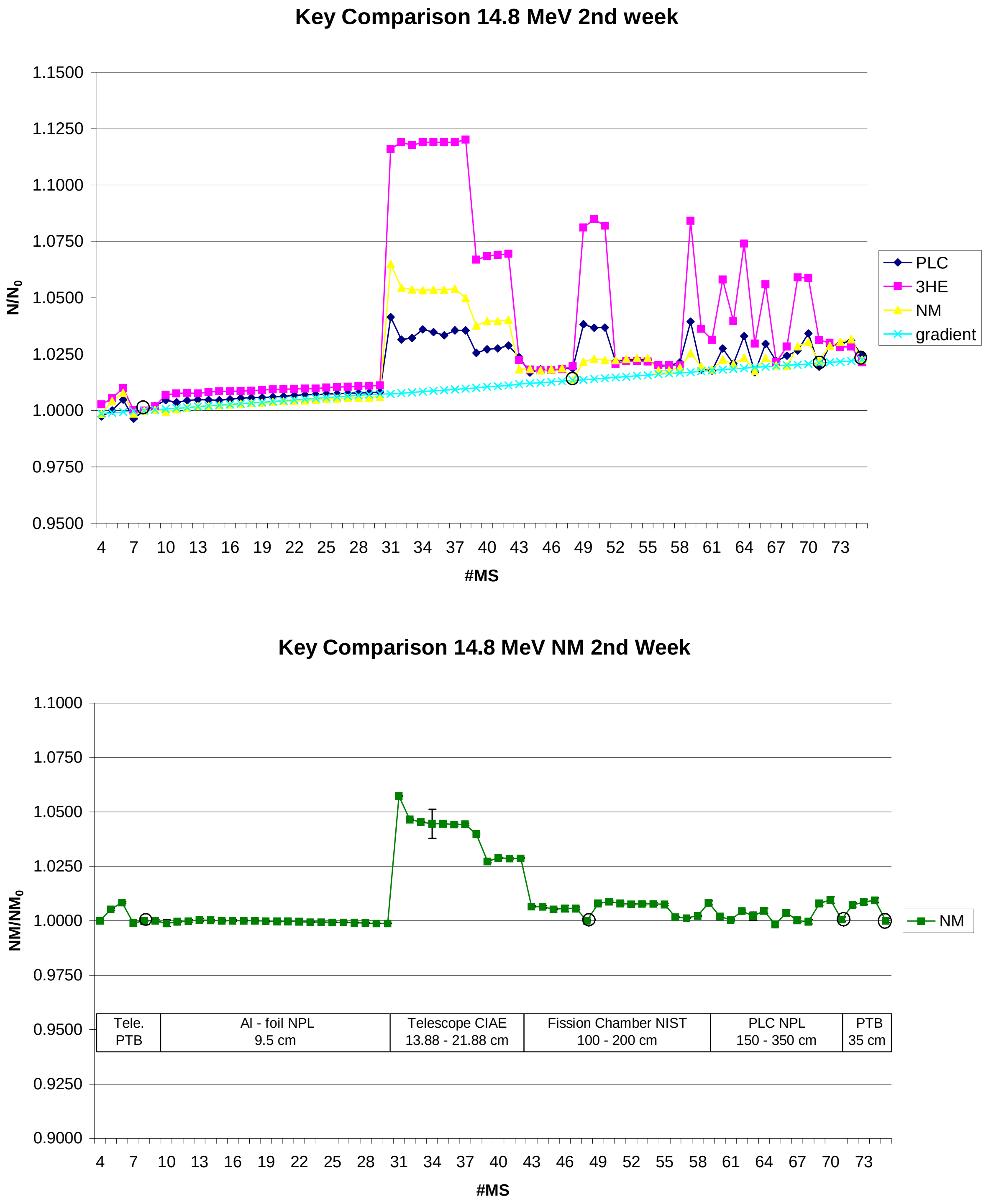


Figure 4.3. Count rates of three neutron monitors (N = NM, PLC and ^{3}He) in the 14.8 MeV field, normalized for unity charge relative to the first free field measurement MS#9 (a: upper part) and the same data re-normalized to the gradient of the free field data indicated in the upper graph (b: lower part).

Since the counting statistics were in all measurements best for the monitor positioned in forward direction chiefly due to the yield distribution of the neutron producing reaction and the high efficiency of the long counter type monitor, the NM monitor was selected as the transfer instrument for which the participants had to determine a calibration coefficient C, defined as neutron fluence at 0 degrees and 1 m distance in vacuum per NM count corrected for deadtime losses and inscattering. In some cases the NM monitor was partially shadowed by large devices such as the NPL long counter, the NIST fission chamber or large shadow cones inserted close to the target, such that the partial shadowing or even reduced air-inscattering overcompensated the expected inscattering from this device. In these cases, the NM rate had to be slightly increased.

The relevant tables and graphs were provided by the pilot laboratory to all participants [40]. The evaluated reference fluence had to be divided by the NM counts recorded during the fluence measurement and corrected with the factors listed in the tables. While the uncertainty of NM counting statistics was negligibly small, an uncertainty of 0.5% may be considered in the uncertainty budget for the procedure to evaluate the correction of the NM count, chiefly due to the scatter of all reference values measured in free field geometry.

4.3. Fluence Measurements of the Participants

The participants were requested to determine the neutron fluence at 0 degrees and 1 m distance, corrected for air-outscattering. The detection system, installed on one of the swivel arms, could be moved and aligned in any desired position at 0 degrees. Any distance to the target between 9 cm for the Al-activation foils and up to 400 cm for the long counter and the moderator detectors were realised. In all cases, that detectors were employed at distances larger than 100 cm, additional measurements were carried out with appropriate PTB shadow cones between target and detector. Only NPL used their own shadow cones in the arrangement usually also realised at NPL. However, additional measurements with similar PTB cones exhibited no difference within counting statistics demonstrating that the shielding properties of NPL and PTB shadow cones were comparable.

Measurement and analysis of the rough data followed a general scheme:

1. fluence measurement in the optimal position(s)
2. determination of background due to in-scattered neutrons with the recommended shadow cone or in the case of RPT an additional measurement without the radiator in order to correct for reactions in the radiator backing or in case of the production of 5 MeV neutrons also a background measurement with an empty target
3. correction for dead-time losses
4. evaluation of the net count rates, spectra or activations
5. interpretation of these results in terms of the neutron fluence at the point of measurement, corrected for the contribution due to target scattered neutrons folding the spectral fluence provided by the pilot laboratory with the energy-dependent detector response

6. calculation of the fluence of neutrons with the desired energy for a distance of 100 cm from the target in vacuum, i.e. corrected for air-outscattering if necessary,
7. relating this fluence to the corresponding NM-counts corrected for dead-time losses and inscattering/shadowing and, finally,
8. evaluation of the uncertainty budget according to the ISO recommendation GUM [37] and documentation as detailed as necessary for the evaluation of the comparison exercise.

The measurements were carried out in sequence as listed in Table 4.1 and 4.2. The results were then reported, partially after a revision requested by the evaluator, by the participants for comparison. Tables A.1 (0.144 MeV) to A.4 (14.8 MeV) in Appendix A contain all data finally considered in the evaluation with the associated uncertainties.

Table 4.1. Schedule for the key comparison in the 1st week of the comparison at PTB

Date	E_n / MeV	Laboratory	Measuring System	Distance / cm	Angle	
19.3./20.3.01	0.144	PTB	^{3}He RPPC (H_2/CH_4)	70 116	0	Neutron energy Neutron fluence
		NMIJ	3.5" BS; SP2-PC 9.0" BS; SP2-PC cyl. ^{3}He counter	123.4 + * 117 + * 46		
		VNIIM	spherical moderator cyl. ^{3}He	100 – 200		
		PTB	RPPC (H_2/CH_4) ^{3}He	116 70		Neutron fluence Neutron energy
20.3./21.3.01	1.2	PTB	^{3}He RPPC (H_2/CH_4)	70 116	0	Neutron energy Neutron fluence
		NMIJ	3.5" BS; SP2-PC 9.0" BS; SP2-PC cyl. ^{3}He counter	200 + * 242.5 + * 45.8		
		IRMM	RPT	15, 25		
		VNIIM	spherical moderator cyl. ^{3}He	100 – 200		
		PTB	RPPC (C_3H_8) ^{3}He	115 70		Neutron fluence Neutron energy
21.3./22.3.01	5.0	PTB	RPT NE 213	39.2 629.5	0	Neutron fluence Neutron energy
		NMIJ	3.5" BS; SP2-PC 9.0" BS; SP2-PC cyl. ^{3}He counter	150 + * 300 + * 45.8		
		IRMM	RPT	15, 25, 35		
		VNIIM	spherical moderator cyl. ^{3}He	100 – 300		
		PTB	NE 213 RPT	629.5 39.2		Neutron energy Neutron fluence
22.3./23.3.01	14.8	PTB	RPT NE 213	37.6 629.5	0	Neutron fluence Neutron energy
		NMIJ	3.5" BS; SP2-PC 9.0" BS; SP2-PC cyl. ^{3}He counter	150 + * 350 + * 47.1		
		IRMM	RPT	15, 25, 35		
		VNIIM	spherical moderator cyl. ^{3}He	100 – 300		
		PTB	NE 213 RPT	629.5 37.6		Neutron energy Neutron fluence

* Radius of the spheres

Table 4.2. Schedule for the key comparison in the 2nd week of the comparison at PTB

Date	E_n / MeV	Laboratory	Measuring System	Distance / cm	Angle	
26.3./27.3.01	0.144	PTB	^{3}He RPPC (H_2/CH_4)	70 116	0	Neutron energy Neutron fluence
		CIAE	RPPC (H_2)			
		NIST	^{235}U-fission chamber			
		NPL	DePangher Long Counter	150 - 250		
		PTB	^{3}He RPPC (H_2/CH_4)	70 116		Neutron energy Neutron fluence
27.3./28.3.01	1.2	PTB	^{3}He RPPC (C_3H_8)	70 116	0	Neutron energy Neutron fluence
		CIAE	RPPC (C_3H_8)	100 - 150		
		NIST	^{235}U-fission chamber	100		
		NPL	DePangher Long Counter	150 - 400		
		PTB	^{3}He RPPC (C_3H_8)	70 116		Neutron energy Neutron fluence
28.3./29.3.01	5.0	PTB	NE 213 RPT	629.5 39.2	0	Neutron energy Neutron fluence
		CIAE	RPT	10.5		
		NIST	^{235}U-fission chamber	100		
		NPL	DePangher Long Counter	200 - 300		
		PTB	RPT NE 213	39.2 629.5		Neutron fluence Neutron energy
29.3./30.3.01	14.8	PTB	NE 213 RPT	629.5 37.6	0	Neutron energy Neutron fluence
		NPL	Al-foils	9		
		CIAE	RPT	14 - 22		
		NIST	^{235}U-fission chamber	100/200		
		NPL	DePangher Long Counter	150 - 350		
		PTB	RPT NE 213	37.6 629.5		Neutron fluence Neutron energy

5. Discussion of the Results

5.1. Reproducibility of the Fields

The monitor-ratios discussed in chapter 4.2 already demonstrated the stability of the neutron fields during a one day measurement campaign. In order to guarantee, that the measurements carried out in sequence in two weeks, partially using fresh targets, were comparable the pilot laboratory measured the neutron fluence at least four times. As can be concluded from Tables A.1.1 to A.4.1 and Figures A.1. to A.4, the reproducibility was excellent. In general, the PTB fluence data obtained at different days for the same neutron energy agreed to better than 0.5% except for the 5 MeV neutrons. In case of the measurements with the gas target, the scatter of the PTB fluence measurements amounted to about 2% with respect to their mean value. No plausible explanation can be given for this unexpected behaviour.

5.2. Evaluation of the Results of all Participants

The participants were requested to report only one result for each energy even if the fluence was determined with different methods. Hence, PTB reported the weighted mean of all measurements also taking into consideration the correlation of uncertainties. NPL analysed the long counter measurements with the response functions used in all former comparison exercises, but finally reported the data for all neutron energies up to 5 MeV obtained with the response function based on recent comprehensive MCNP simulations and the re-calibration with radio-nuclide sources although the determination of the effective centre was not finally solved for the new data set.

For all data, listed in Tables A.1.1 to A.4.1, three mean values were calculated, namely:

a. the unweighted mean value (u.m.). The uncertainty reflects the scatter of the data of all participants.
b. the weighted mean value (w.m.) using the reported uncertainties for weighting. In this procedure we neglected any correlation of the uncertainties although some uncertainty budgets obviously include contributions of the same origin. Even in the case of the uncertainties considered for the (differential) n-p scattering cross sections this assumption seems, however, to be justified, because the laboratories partially refer to different evaluated data sets. Concerning the specification of the hydrogen content of tristearin radiators used in the RPT of IRMM and PTB, the correlation cannot clearly be deduced from the IRMM certificates. In general, however, the measurement and analysing methods are sufficiently different to support the assumption.
c. the median (med) of the results. In all cases the median agrees with the weighted mean within the evaluated uncertainty. The median will not be discussed further.

The mean values and the associated uncertainties are also listed in Tables A.1.1 to A.4.1.

All data reported for one neutron energy together with the associated uncertainties are shown in Figures A.1 to A.4 in chronological order and compared with the weighted mean both in absolute and relative scale, which were finally adopted as the key comparison reference value KCRV. The results will be discussed in detail for all four energies separately in the next sections.

5.2.1. Fluence of 0.144 MeV Neutrons

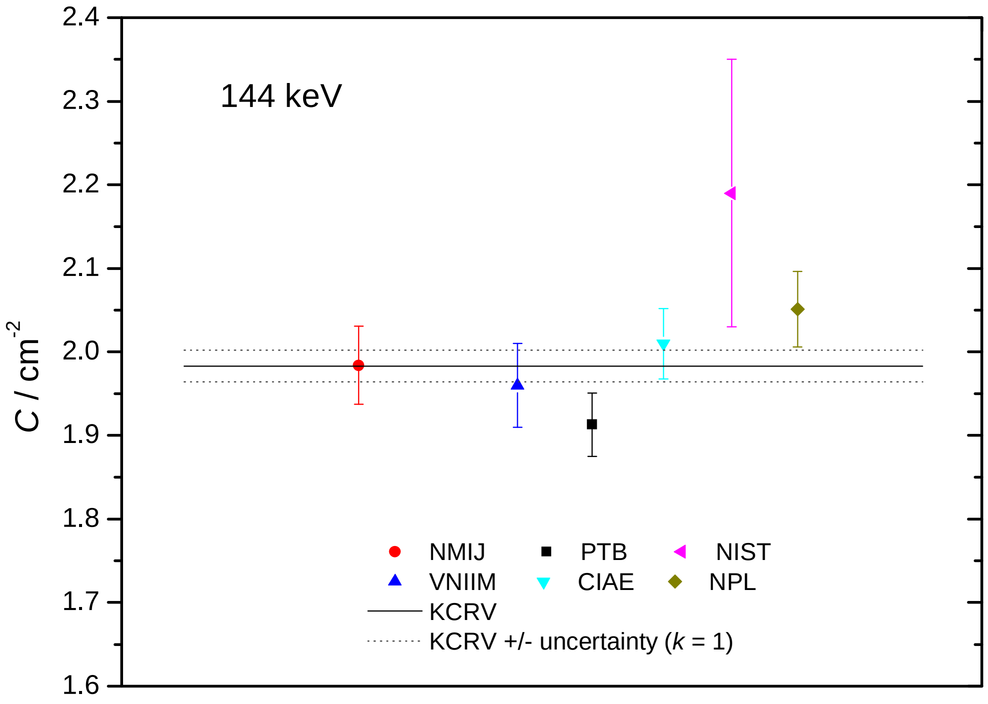


Figure 5.1. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction ^{7}Li(p,n)^{7}Be (0.144 MeV). The weighted mean is shown as key comparison reference value KCRV.

Fig. 5.1 shows that all data are rather close to the mean value. However, the scatter of the data, *i.e.* the uncertainty of u.m., is twice the uncertainty of the weighted mean and corresponds with a rather high χ^2-value of 1.6 for the w.m.-value, indicating that either the uncertainties were partially evaluated too optimistically or some methodological or metrological problems might have been overlooked. In particular, the large discrepancy between the results of NPL and PTB must be investigated. Nevertheless, the overall agreement is still satisfying for this energy.

5.2.2. Fluence of 1.2 MeV Neutrons

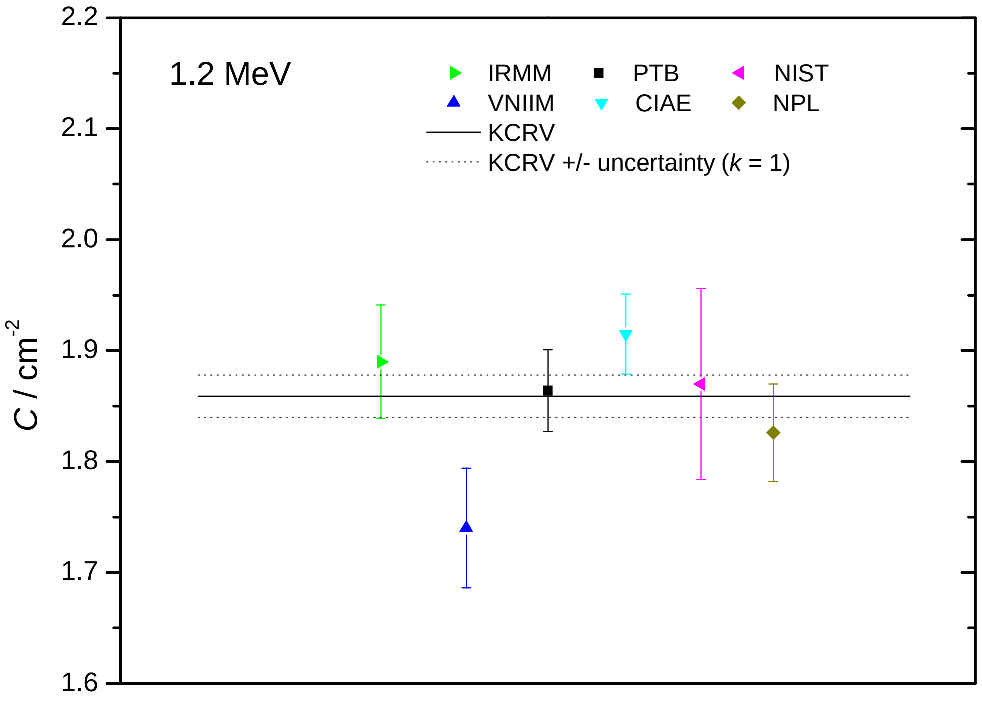


Figure 5.2. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction T(p,n)^{3}He (1.2 MeV). The weighted mean is shown as key comparison reference value KCRV.

A comparison of fluence measurements of mono-energetic neutrons was for the first time conducted for 1.2 MeV neutrons and the reported results are essentially consistent (see Fig. 5.2). The VNIIM-value exhibits the largest deviation from the reference value, but the influence on the weighted mean is rather low due to the relatively large uncertainty. The reduced χ^2-value, however, improves from 1.7 to 0.66, if the VNIIM result is ignored. Nevertheless, the weighted mean of the complete data set is taken as the KCRV. Unfortunately, the data set could not be completed, because the measurements performed by NMIJ at PTB could not be complemented by calibration measurements at NMIJ. Nevertheless, five different methods - RPPC (2x), RPT, LC, U-FC and BS - were successfully employed by six laboratories. The agreement is very good at partially low uncertainties of about 2 % reported by the laboratories.

5.2.3. Fluence of 5 MeV Neutrons

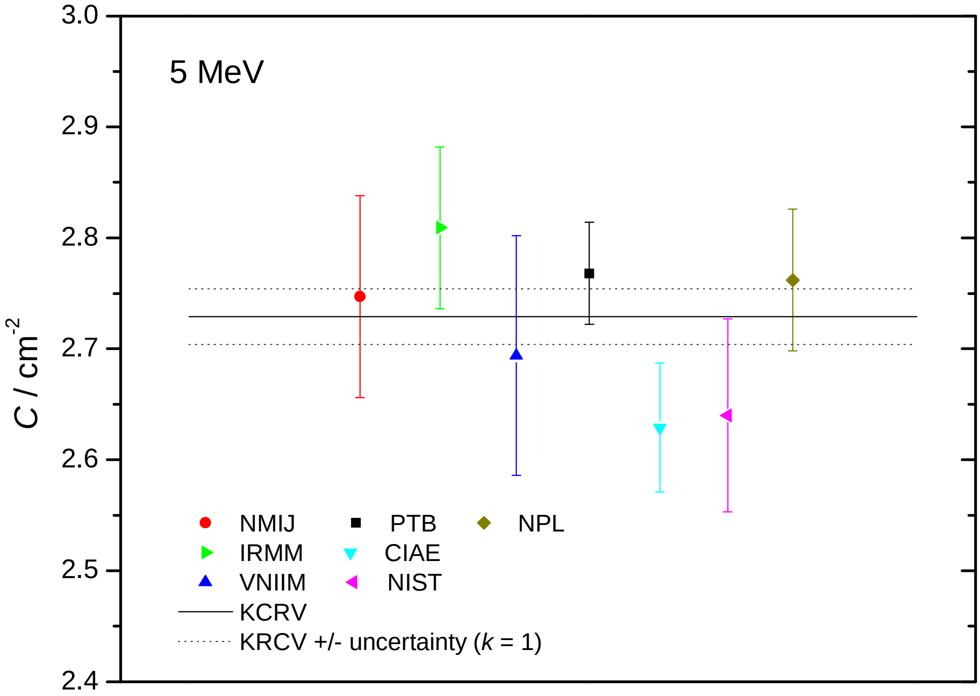


Figure 5.3. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction D(d,n)^{3}He (5.0 MeV). The weighted mean is shown as key comparison reference value KCRV.

In former comparison exercises, 5 MeV neutrons were produced with solid targets, *i.e.* D-loaded Ti-layers on Ag- or Ta-backings, and required additional measurements with a pure Ti-target (blank) in order to subtract the background due to (d,n)-reactions in the Ti-layer and in the backing [41]. Due to self-target build-up in the backing, similar irradiation histories are then required for both targets. The use of a gas target with a fresh Au-backing results in almost mono-energetic neutron fields, because (gas in)-(gas out) net spectra can be obtained and the amount of target-scattered neutrons is much reduced (<1%) if compared with low-mass solid targets [42]. However, the repeated fluence measurements of PTB exhibited a much larger scatter of their four monitor calibration factors (2%) than observed for all other energies (<0.5%). Nevertheless, the corrections of the NM-count rate seem to be as reliable as for all other energies, because the free geometry measurements exhibit good stability, at least for a freshly filled target.

Taking into account all data reported for the measurements at different days, the agreement is very good with the best χ^2-value (1.06). The largest deviation from the weighted mean is still lower than two standard deviations reported by the laboratories.

5.2.4. Fluence of 14.8 MeV Neutrons

The production of 14.8 MeV neutrons through the T(d,n)-fusion reaction requires only low energy accelerators. Hence, this source is used world-wide in many research and national metrology laboratories and the measurements should therefore have a sound basis for the determination of the neutron fluence (rate). Indeed, lowest uncertainties are achieved, in particular if (time correlated) associated particle measurements can be employed as an absolute method for determining the neutron fluence. Although these methods could not be transferred to PTB for comparison, transfer devices were calibrated without significant loss of the achievable uncertainty.

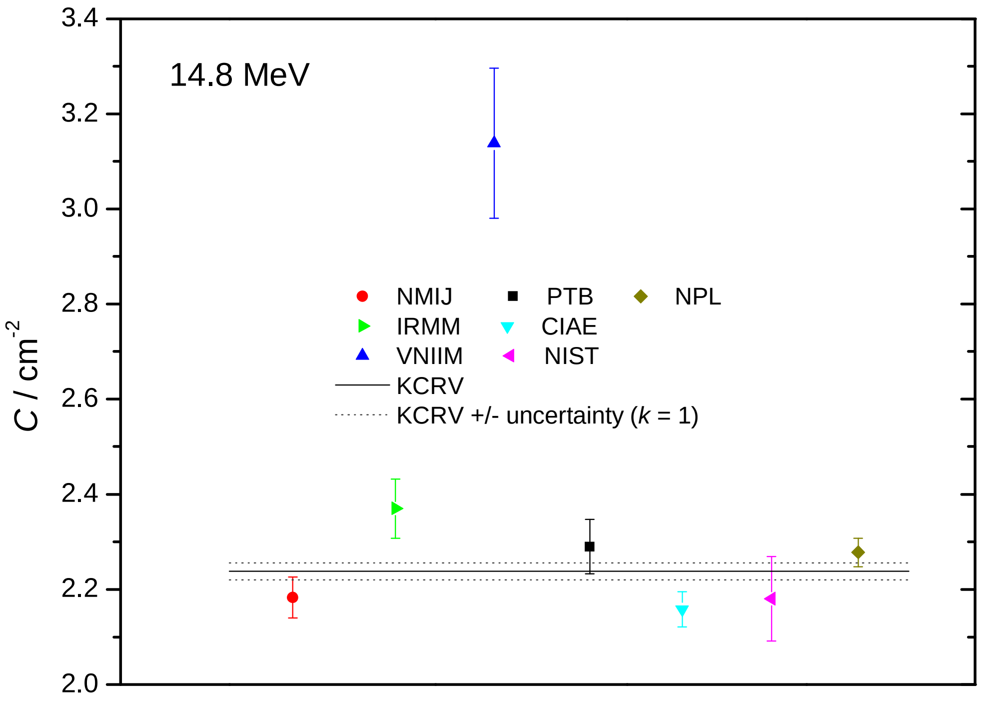


Figure 5.4. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction T(d,n)^{4}He (14.8 MeV). The weighted mean without the VNIIM data is shown as key comparison reference value KCRV.

The data reported for this widely used neutron field show the largest scatter of all data sets (see Fig. 5.4) corresponding with a χ^2-value of 7.7. The large uncertainty of the u.m. is chiefly caused by the VNIIM-result which is about 30% off the weighted mean value. The w.m. is, however, not much influenced by this input due to the comparably large associated uncertainty. Nevertheless, the w.m. value still exhibits a large χ^2-value of 2.81 even if the obvious out-layer is completely excluded from the analysis. It should also be noted, that the three results obtained with recoil proton telescopes are discrepant by up to 9.5% although the uncertainties do not exceed 2.6% each. The IRMM data are slightly, but systematically higher than the PTB results for both 5 MeV and 14.8 MeV neutrons although instruments of almost identical design were employed. The specification of this classical instrument should therefore be re-investigated and, if possible, standardised taking into account analytical approaches as well as modern simulation techniques for the calculation of the efficiency, but also considering relativistic kinematics, internationally agreed and commonly accepted n-p cross section data and a comparison of the procedures applied to determine the hydrogen content of the various radiators applicable. In addition, the analysis and interpretation of the measured rough data must be critically inspected for systematic problems which may have been overlooked up to now. These data are very discrepant and the comparison indicates systematic problems. This non-satisfying result requires and should encourage considerable improvements.

In summary for all neutron fields:
After a critical review of the evaluation of all data sets we come to the conclusion, that the weighted mean values of the data sets should be reported as key comparison reference values for the calibration coefficient of the transfer monitor in the mono-energetic neutron fields (see Appendix A and Table 7.1).

6. Degree of Equivalence

According to the CIPM MRA, the degree of equivalence (DoE) must be established for each comparison, which can provide traceability for a calibration measurement capability announced in KCDB Appendix C by the laboratory. The DoE shall be calculated as the deviation of the value reported by the laboratory from the key comparison reference value evaluated in the framework of an internationally accepted key comparison [43]. When calculating the expanded uncertainty ($k = 2$) of each deviation, it must be taken into account that the uncertainty reported by the laboratory is also considered in the evaluation of the weighted mean value. According to [43] the deviations and the associated uncertainties are calculated and listed in Tables A.1.2 to A.4.2.

The degree of equivalence is shown in Figures 6.1 to 6.4 for the four neutron energies for which the fluence (rate) measurements have been compared.

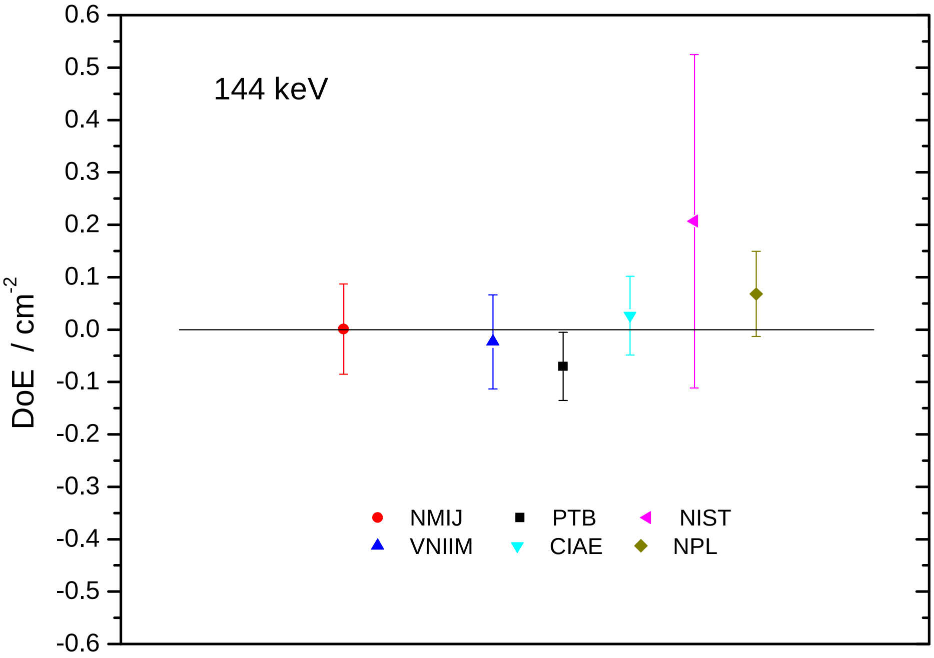


Figure 6.1. Degree of equivalence DoE defined as the deviation of the result reported by the laboratory from the KCRV and the expanded uncertainty for 144 keV neutrons (see Table A.1.2).

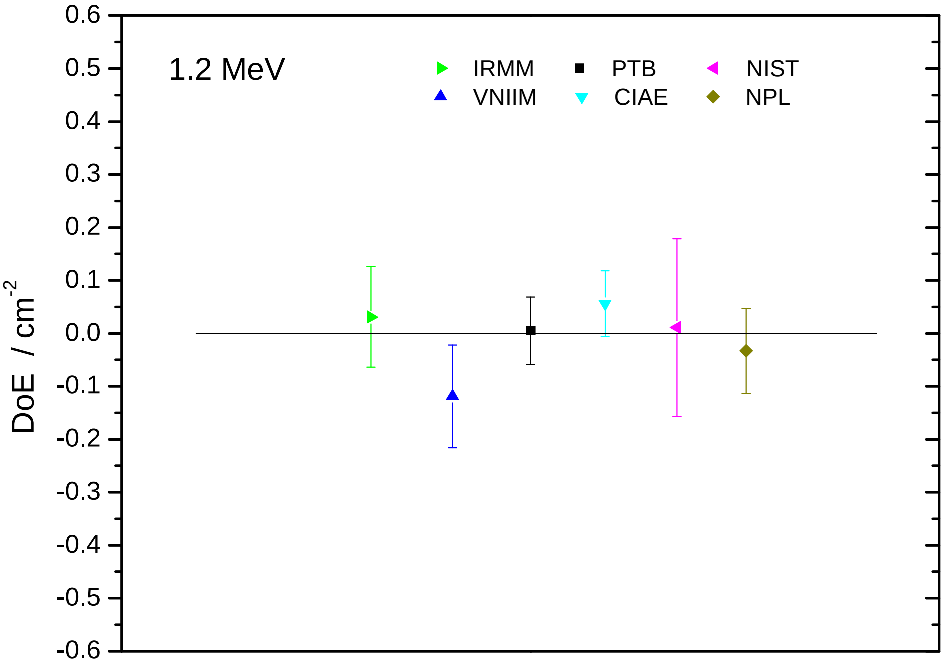


Figure 6.2. Degree of equivalence DoE defined as the deviation of the result reported by the laboratory from the KCRV and the expanded uncertainty for 1.2 MeV neutrons (see Table A.2.2).

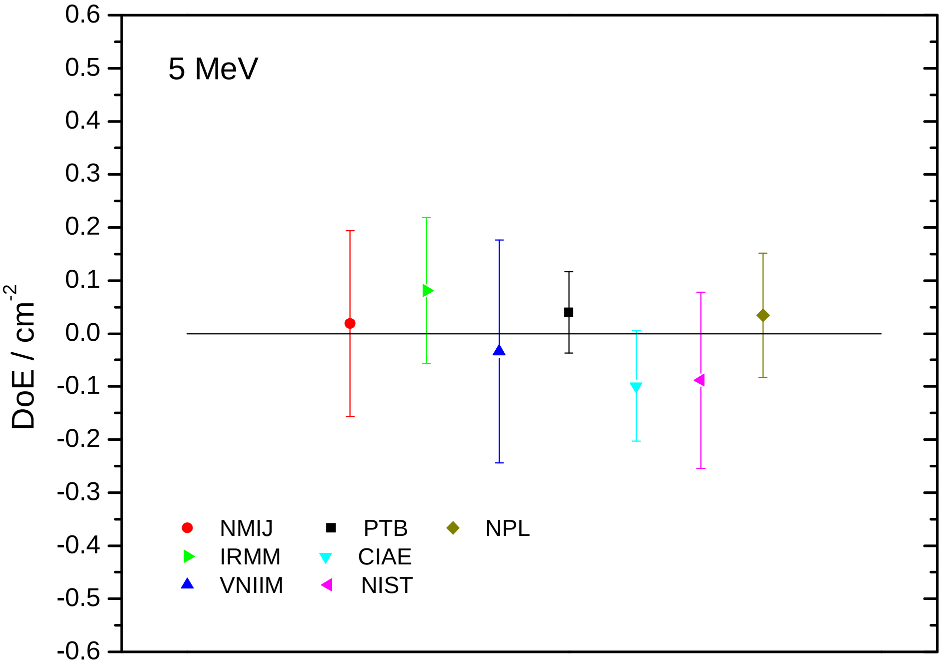


Figure 6.3. Degree of equivalence DoE defined as the deviation of the result reported by the laboratory from the KCRV and the expanded uncertainty for 5.0 MeV neutrons (see Table A.3.2).

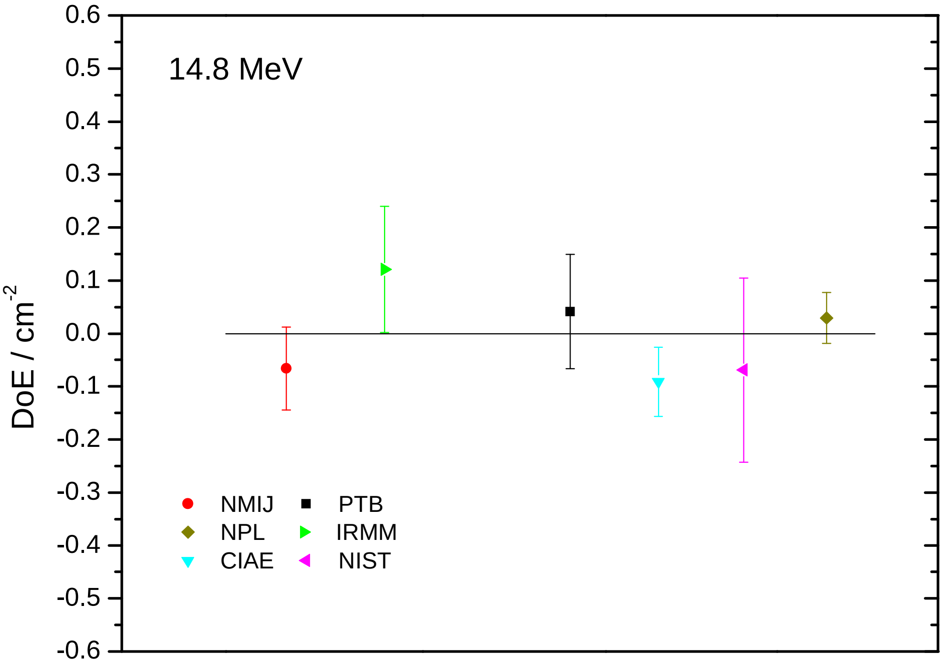


Figure 6.4. Degree of equivalence DoE defined as the deviation of the result reported by the laboratory from the KCRV and the expanded uncertainty for 14.8 MeV neutrons (see Table A.4.2).

7. Summary and Conclusions

The key comparison of the determination of the fluence of mono-energetic neutrons was successfully conducted in March 2001 at the accelerator facility of PTB in Braunschweig, Germany. Seven laboratories authorised by their national metrology organizations employed either their primary standard fluence measuring devices, or appropriate transfer instruments traceable to their primary standards, in order to determine the fluence of 0.144 MeV, 1.2 MeV, 5.0 MeV and 14.8 MeV neutrons. Only four neutron energies were selected from the ISO recommended standards for practical reasons. However, this allowed the performance of most instruments and methods used for the entire energy range to be tested as far as the systems were transportable and applicable in the framework of this comparison exercise.

Stable monitoring and control measurements demonstrated the reproducibility and the stability of the neutron fields. Irradiations were performed in open geometry and with rather low room-return neutron background such that no significant uncertainty resulted from the experimental conditions and procedures. The pilot laboratory provided the spectral fluence of the desired uncollided, and therefore almost mono-energetic neutrons, and of the neutrons scattered in the target assembly. The monitor data recorded during the measurement campaigns in which the laboratory participated were also provided for correction and interpretation of the measurements. The participants determined the fluence in vacuum at a common point of measurement, at 0 degrees and a distance of one metre, related this fluence to the properly corrected reading of a selected neutron monitor and evaluated a detailed uncertainty budget.

The reported data were then evaluated. The weighted means of all data obtained for one neutron energy served as key comparison reference value. The results are summarized in Table 7.1.

Table 7.1. Key comparison reference values KCRV, determined as weighted mean of calibration coefficients C reported by the laboratories (uncertainties for k = 1)

Neutron energy / MeV	KCRV / cm^{-2}	rel. uncertainty of the KCRV / %	χ^2/ν
0.144	1.983	0.98	1.594
1.2	1.859	1.00	1.700
5.0	2.729	0.93	1.063
14.8	2.238	0.80	2.812

All results are shown in Fig. 7.1 in absolute scale together with the weighted mean value.

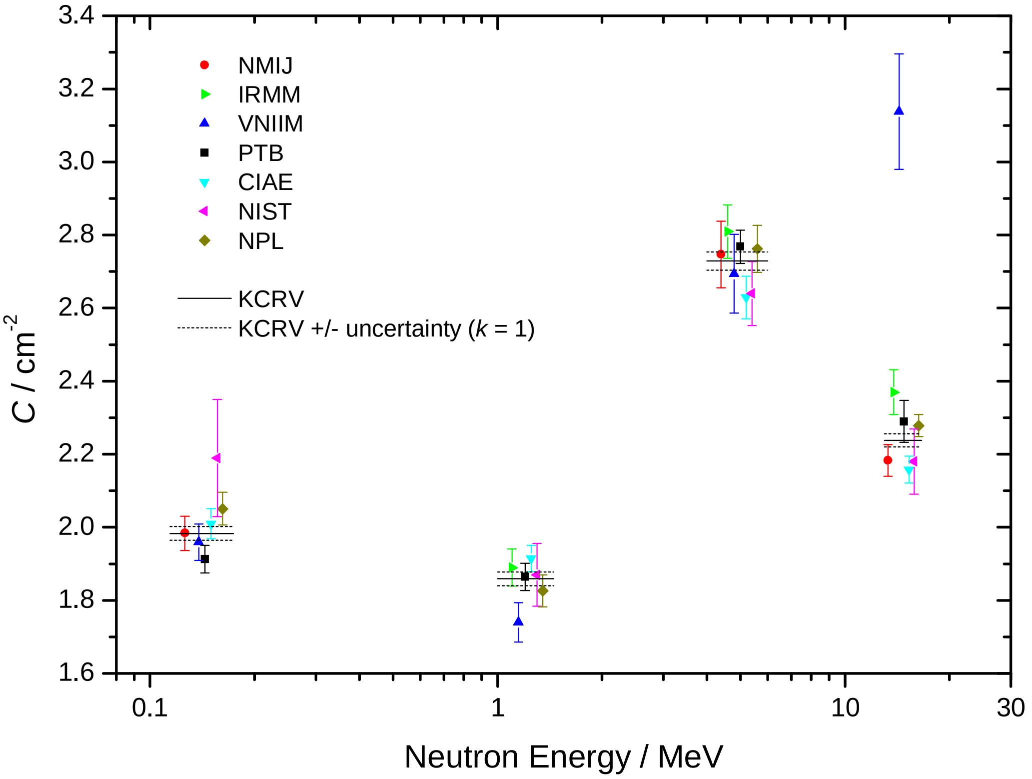


Figure 7.1. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reactions ^{7}Li(p,n)^{7}Be (0.144 MeV), T(p,n)^{3}He (1.2 MeV), D(d,n)^{3}He (5.0 MeV) and T(d,n)^{4}He (14.8 MeV). The weighted means of the agreed data sets are shown as key comparison reference values KCRV.

For 5.0 MeV neutrons the scatter of the data results in a reduced χ^2-value which is sufficiently close to 1 to indicate, that the values and their uncertainties have been correctly estimated, while the larger scatter of the 0.144 MeV and 1.2 MeV data indicate some inconsistency of the methods used to determine the fluence with the reported uncertainties. The largest scatter is observed for the fluence measurements in the 14.8 MeV neutron field. Even if an obvious out-layer is excluded from the analysis, the scatter of the data is still unacceptably high. Such a result indicates that the fluence measurement methods and/or the evaluation of the uncertainty budget must be re-investigated.

The key comparison has been evaluated with the results submitted by the participants up until November 2002. The objective of any key comparison is to determine the capabilities of the participating NMIs at the date of measurement and evaluation. Except for the one removed data set, the degree of equivalence is satisfying for all other results obtained.

8. Re-Investigations since 2003

The results obtained in the framework of this key comparison instigated some re-investigations of the properties of the primary standard or transfer instruments employed.

CIAE recalculated the neutron flux attenuation in the entrance window of the recoil proton telescope with recently evaluated cross sections [44]. This revision resulted in an increase of the 14.8 MeV neutron fluence per monitor count by about +1.3% towards the KCRV evaluated for this energy.

Also VNIIM recognized that old and partially wrong cross sections were taken into account for the MC-simulation of the energy-dependent response of their moderator-type transfer instrument [45]. A significant improvement was achieved for the entire energy range of interest and all requested calibration factors were revised towards the KCRV. The calculated responses are still in satisfying agreement with the experimental calibrations performed with well calibrated radio-nuclide neutron sources such that these measurements are still traceable to the national primary standards for neutron energies up to 10 MeV. The calculated 14.65 MeV response, however, cannot be traced back to the absolute fluence measurement by means of the associated (charge) particle method which is applied at VNIIM for absolute fluence measurements for the T(d,n)-reaction. As the consequence, VNIIM requested to remove the VNIIM-data from DoE-calculations for this particular energy.

The situation is completely different in the case of recent evaluations of the fluence of 144 keV, 1.2 MeV and 5.0 MeV neutrons measured by the NPL with their De Pangher long counter. The MCNP-simulations of the energy-dependent efficiency and effective centre, started already in 1996, were not completed when the analysis of the measurements at PTB was requested. Nevertheless, NPL reported results based on the best knowledge of the properties of their primary standard instrument at that time. Inconsistencies of the results, in particular concerning the calculation of the effective centre, required further investigations and resulted already in June 2003, half a year after the evaluation, in provisionally revised fluence values per monitor count [46]. These investigations were very recently finished and published [47]. Based on these results, NPL would have reported slightly revised calibration factors which all move towards the KCRV.

Not surprisingly, the revised results based on re-investigated properties of the primary standard or transfer instruments considerably improves the data set, as shown in Figures 8.1 to 8.4, which include the additional data listed in Tables C.1 to C.4 (see Appendix C).

The improvements are obvious and remarkable, but these results cannot be used for reference in order to support CMCs.

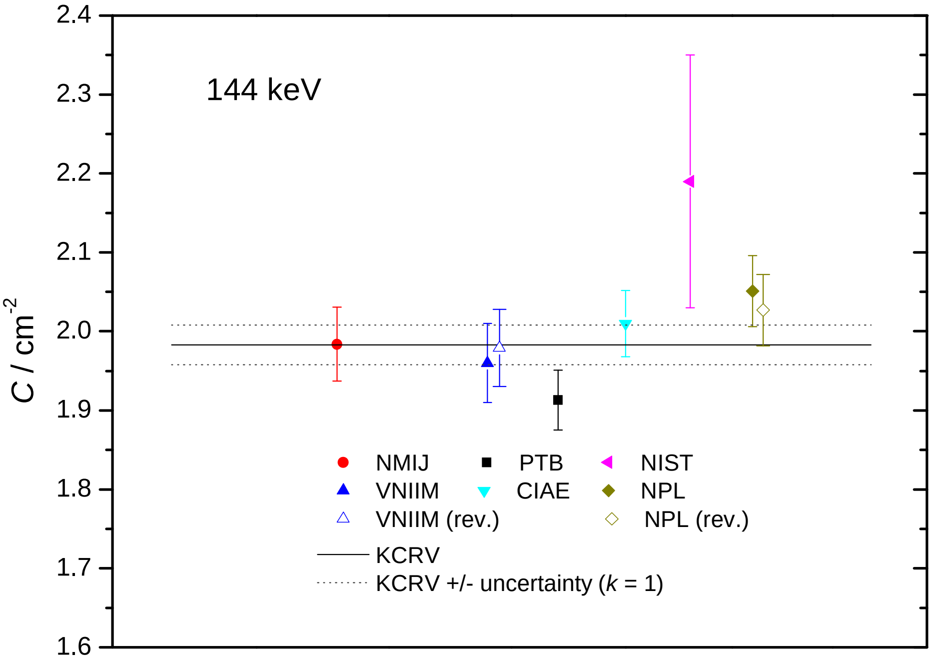


Figure 8.1. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction ^{7}Li(p,n)^{7}Be (0.144 MeV), including the revised data listed in Table C.1 in Appendix C. The key comparison reference value KCRV is also shown.

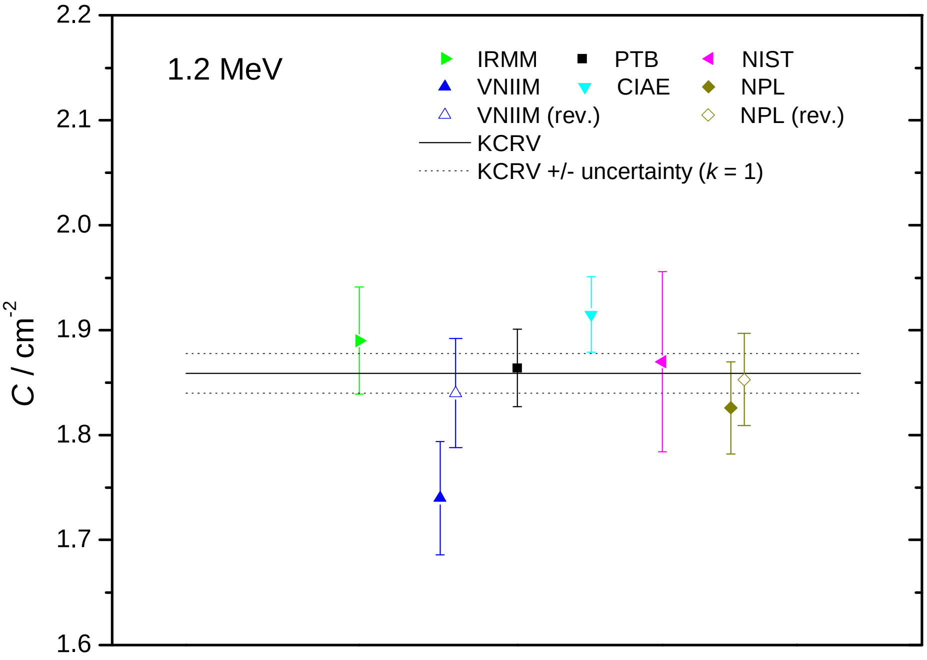


Figure 8.2. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction T(p,n)^{3}He (1.2 MeV), including the revised data listed in Table C.2 in Appendix C. The key comparison reference value KCRV is also shown.

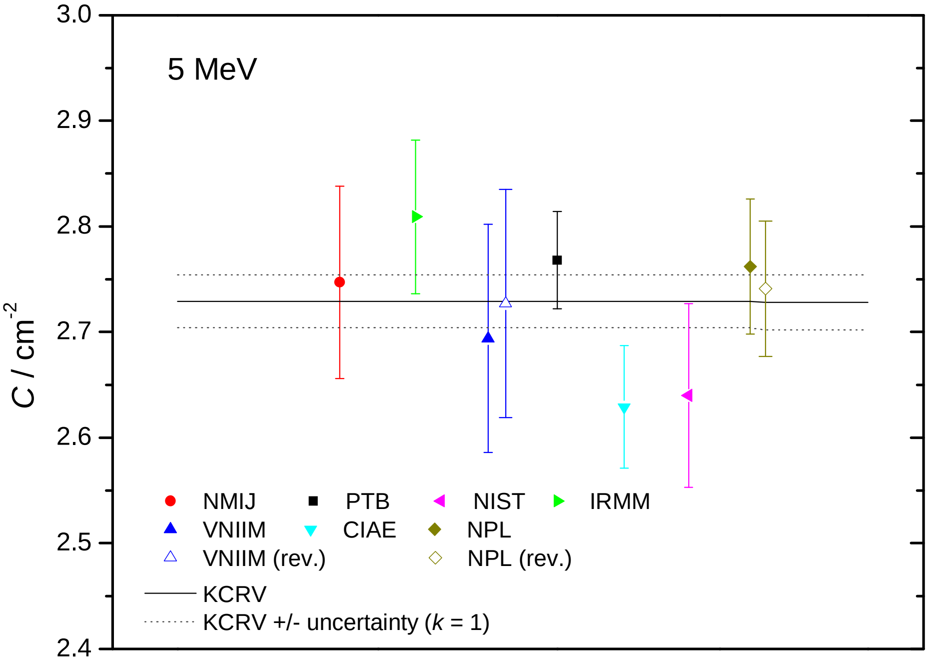


Figure 8.3. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction D(d,n)^{3}He (5.0 MeV), including the revised data listed in Table C.3 in Appendix C. The key comparison reference value KCRV is also shown.

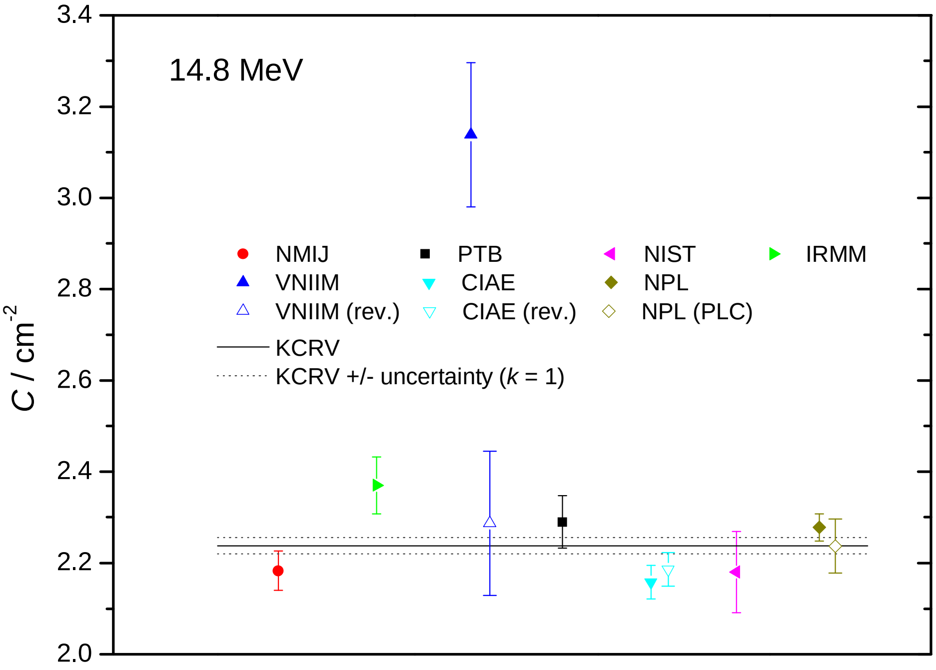


Figure 8.4. Calibration coefficient *C*, determined as neutron fluence in vacuum at 0 degrees and 1 m distance from the target per count of the NM neutron monitor positioned at 17.5 degrees and 6 m distance, for the reaction T(d,n)^{4}He (14.8 MeV), including the revised data listed in Table C.4 in Appendix C. The key comparison reference value KCRV is also shown.

Acknowledgement

The participants in this comparison exercise gratefully acknowledge the help of the technical staff of the PTB accelerator, in particular W. Beverung, O. Döhr, H. Eggestein, M. Hoffmann and T. Heldt. The continuous support in setting-up and aligning the detector systems and stable beam conditions were important preconditions for the success of the comparison exercise. Special thanks go also to S. Löb, PTB, who analysed the rough monitor data and compiled the tables provided to all participants.

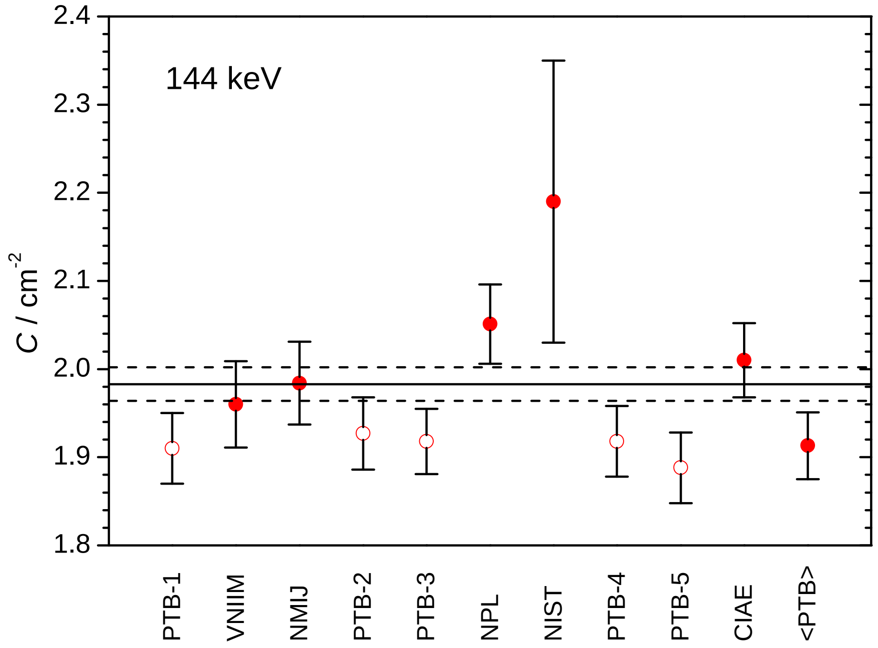
9. Appendices

9.1. Appendix A: Data Reported by the Participants and Results Evaluated for all Energies

Table A.1.1: Results for 144 keV neutron fluence measurements (final data until 19/11/02)

Laboratory	Calibration coefficient *C* / cm^{-2}	Abs. Uncert. / cm^{-2}	Rel. Uncert.	Deviation from w.m. / cm^{-2}	Deviation uncertainty (*k* = 2) / cm^{-2}
PTB-1	1.910	0.040	2.09%		
VNIIM	1.960	0.049	2.51%	-0.023	0.090
NMIJ	1.984	0.047	2.38%	0.001	0.086
PTB-2	1.927	0.041	2.12%		
PTB-3	1.918	0.037	1.92%		
NPL	2.051	0.045	2.20%	0.068	0.081
NIST	2.190	0.160	7.30%	0.207	0.318
PTB-4	1.918	0.040	2.10%		
PTB-5	1.888	0.040	2.12%		
CIAE	2.010	0.042	2.10%	0.027	0.075
<PTB> (1-5)	1.913	0.038	2.01%	-0.070	0.065
unweighted mean (u.m.)	2.018	0.036	1.78%		
weighted mean * (w.m.)	1.983	0.019	0.98%		
median	1.997				
χ^2-value for w.m.	1.594				

* adopted as key comparison reference value KCRV



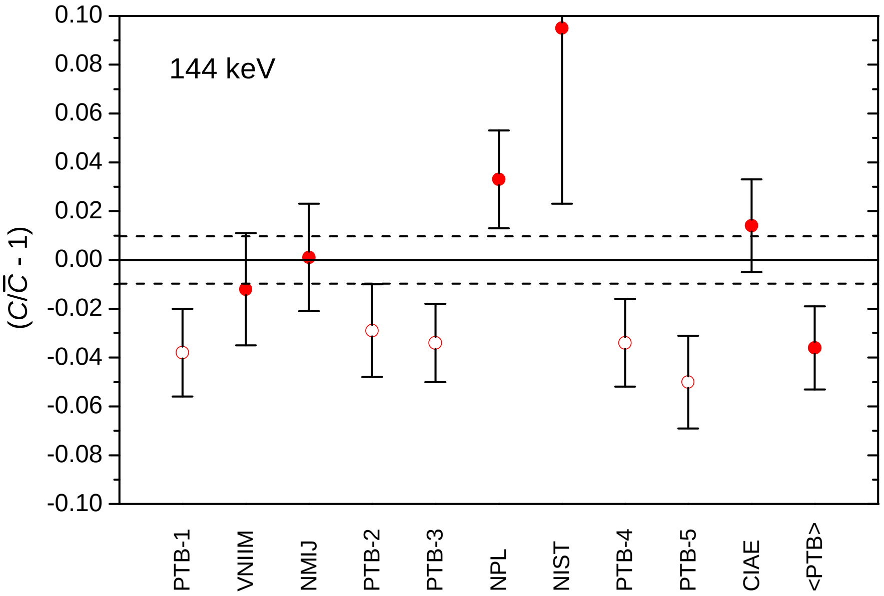


Figure A.1. Calibration coefficient C of a neutron monitor positioned at 17.5 deg and 606 cm to the target defined as the fluence of 0.144 MeV neutrons from the ^{7}Li(p,n)-reaction at 0 deg and 100 cm distance (in vacuum) per monitor count , absolute (upper) and relative (lower) to the weighted mean $\overline{C}$.

Table: A.1.2: Degree of equivalence for 144 keV fluence measurements
The degree of equivalence (DoE) of each laboratory with respect to the KCRV is given by a pair of terms:
The deviation $D_\mathrm{i} = (x_\mathrm{i} - x_\mathrm{r})$ of the value reported by the laboratory i from the weighted mean value and the associated expanded uncertainty U_i, calculated as
$U_\mathrm{i} = 2(u_\mathrm{i}^2 - u_\mathrm{r}^2)^{1/2}$ according to equ. 5 of procedure A in Ref. [43].
The degree of equivalence between two laboratories is given by a pair of terms:
The difference $Dij = (x_i - x_j)$ between the values reported by the laboratories *i* and *j* and the expanded uncertainty U_{ij}, approximated by
$U_{ij} = 2(u_i^2 + u_\mathrm{j}^2)^{1/2}$ according to procedure A in [43].

				Lab .											
Lab *i*				**PTB**		**VNIIM**		**NMIJ**		**NPL**		**NIST**		**CIAE**	
	D_i	U_i		D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ cm^{-2}			/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}	
PTB	**-0.070**	0.065				**-0.047**	0.124	**-0.071**	0.121	**-0.138**	0.118	**-0.277**	0.329	**-0.097**	0.113
VNIIM	**-0.023**	0.090		**0.047**	0.124			**-0.024**	0.136	**-0.091**	0.133	**-0.230**	0.335	**-0.050**	0.129
NMIJ	**0.001**	0.086		**0.071**	0.121	**0.024**	0.136			**-0.067**	0.130	**-0.206**	0.334	**-0.026**	0.126
NPL	**0.068**	0.081		**0.138**	0.118	**0.091**	0.133	**0.067**	0.130			**-0.139**	0.332	**0.041**	0.123
NIST	**0.207**	0.318		**0.277**	0.329	**0.230**	0.335	**0.206**	0.334	**0.139**	0.332			**0.180**	0.331
CIAE	**0.027**	0.075		**0.097**	0.113	**0.050**	0.129	**0.026**	0.126	**-0.041**	0.123	**-0.180**	0.331		

Table A.2.1: Results for 1.2 MeV neutron fluence measurements (final data until 19/11/02)

Laboratory	Calibration coefficient *C* / cm^{-2}	Abs. Uncert. / cm^{-2}	Rel. Uncert.	Deviation from w.m. / cm^{-2}	Deviation uncertainty ($k = 2$) / cm^{-2}
PTB-1	1.873	0.039	2.08%		
VNIIM	1.740	0.052	3.01%	-0.119	0.097
IRMM	1.890	0.051	2.70%	0.031	0.095
PTB-2	1.859	0.038	2.07%		
PTB-3	1.861	0.039	2.08%		
NPL	1.826	0.044	2.40%	-0.033	0.080
CIAE	1.915	0.036	1.90%	0.056	0.062
NIST	1.870	0.086	4.60%	0.011	0.168
PTB-4	1.863	0.039	2.07%		
<PTB> (1-4)	1.864	0.037	2.01%	0.005	0.064
unweighted mean (u.m.)	1.851	0.023	1.24%		
weighted mean * (w.m.)	1.859	0.019	1.00%		
median	1.867				
χ^2-value for w.m.	1.700				
w.m. (without VNIIM)	1.876	0.020	1.06%		
χ^2-value for w.m. (without VNIIM)	0.658				

* adopted as key comparison reference value KCRV

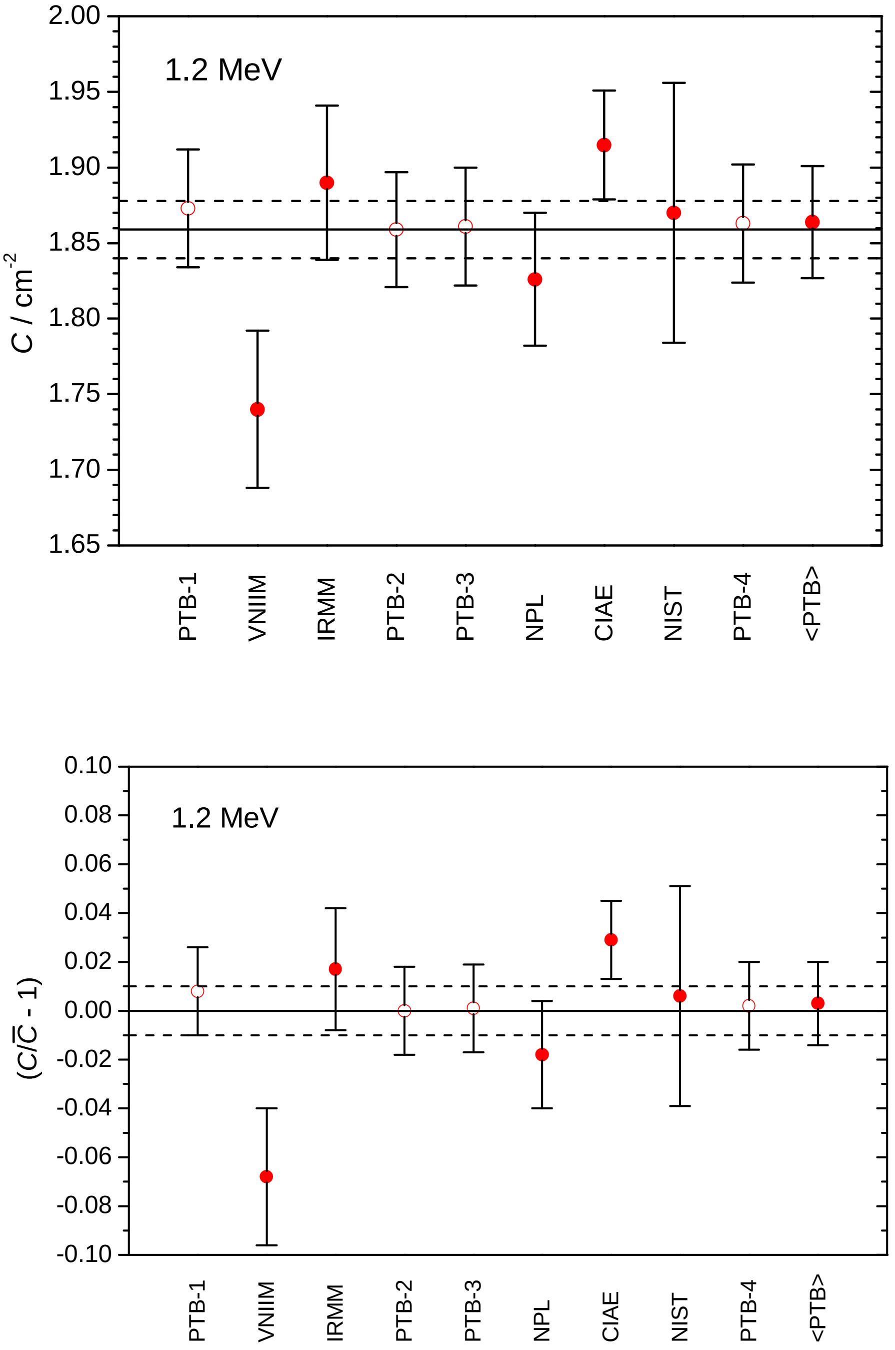


Figure A.2 Calibration coefficient C of a neutron monitor positioned at 17.5 deg and 606 cm to the target defined as the fluence of 1.2 MeV neutrons from the T(p,n)-reaction at 0 deg and 100 cm distance (in vacuum) per monitor count, absolute (upper) and relative (lower) to the weighted mean $\bar{C}$.

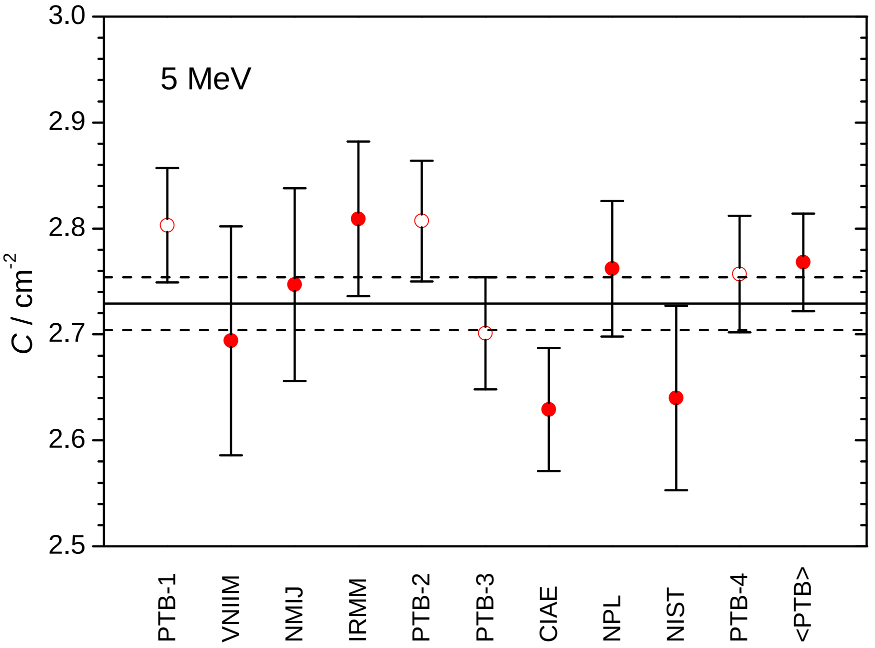
Table: A.2.2: Degree of equivalence for 1.2 MeV fluence measurements
The degree of equivalence (DoE) of each laboratory with respect to the KCRV is given by a pair of terms:
The deviation $D_i = (x_i - x_r)$ of the value reported by the laboratory *i* from the weighted mean value and the associated expanded uncertainty U_i, calculated as $U_i = 2(u_i^2 - u_r^2)^{1/2}$ according to equ. 5 of procedure A in [43].
The degree of equivalence between two laboratories is given by a pair of terms:
The difference $Dij = (x_i - x_j)$ between the values reported by the laboratories *i* and *j a*nd the expanded uncertainty U_{ij}, approximated by $U_{ij} = 2(u_i^2 + u_j^2)^{1/2}$ according to procedure A in [43].

			Lab *j*											
Lab *i*			**PTB**		**VNIIM**		**IRMM**		**NPL**		**CIAE**		**NIST**	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}	
PTB	**0.005**	0.064			**0.124**	0.128	**-0.026**	0.126	**0.038**	0.115	**-0.051**	0.103	**-0.006**	0.187
VNIIM	**-0.119**	0.097	**-0.124**	0.128			**-0.150**	0.146	**-0.086**	0.136	**-0.175**	0.126	**-0.130**	0.201
IRMM	**0.031**	0.095	**0.026**	0.126	**0.150**	0.146			**0.064**	0.135	**-0.025**	0.125	**0.020**	0.200
NPL	**-0.033**	0.080	**-0.038**	0.115	**0.086**	0.136	**-0.064**	0.135			**-0.089**	0.114	**-0.044**	0.193
CIAE	**0.056**	0.062	**0.051**	0.103	**0.175**	0.126	**0.025**	0.125	**0.089**	0.114			**0.045**	0.186
NIST	**0.011**	0.168	**0.006**	0.187	**0.130**	0.201	**-0.020**	0.200	**0.044**	0.193	**-0.045**	0.186		

Table A.3.1. Results for 5.0 MeV neutron fluence measurements (final data until 19/11/02)

Laboratory	Calibration coefficient *C* / cm^{-2}	Abs. Uncert. / cm^{-2}	Rel. Uncert.	Deviation from w.m. / cm^{-2}	Deviation uncertainty (k = 2) / cm^{-2}
PTB-1	2.803	0.054	1.93%		
VNIIM	2.694	0.108	4.01%	-0.034	0.210
NMIJ	2.747	0.091	3.30%	0.019	0.175
IRMM	2.809	0.073	2.60%	0.081	0.137
PTB-2	2.807	0.057	2.04%		
PTB-3	2.701	0.053	1.97%		
CIAE	2.629	0.058	2.20%	-0.099	0.104
NPL	2.762	0.064	2.30%	0.034	0.117
NIST	2.640	0.087	3.30%	-0.088	0.166
PTB-4	2.757	0.055	1.99%		
<PTB> (1-4)	2.768	0.046	1.65%	0.040	0.077
unweighted mean (u.m.)	2.721	0.024	0.88%		
weighted mean (w.m.) *	2.729	0.025	0.93%		
median	2.721				
χ^2-value for w.m.	1.063				

* adopted as key comparison reference value KCRV



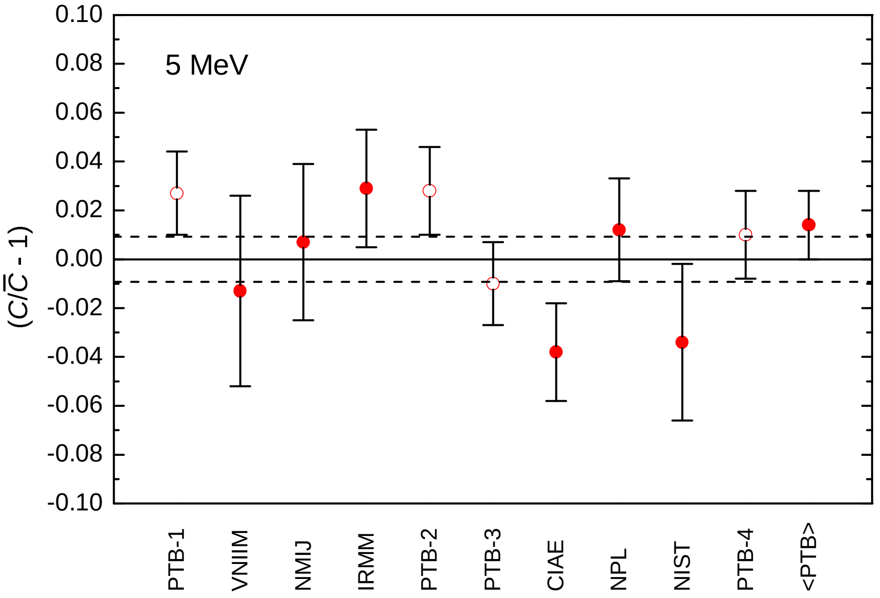


Figure A.3 Calibration coefficient *C* of a neutron monitor positioned at 17.5 deg and 606 cm to the target defined as the fluence of 5.0 MeV neutrons from the D(d,n)-reaction at 0 deg and 100 cm distance (in vacuum) per monitor count, absolute (upper) and relative (lower) to the weighted mean $\overline{C}$.

Table: A.3.2: Degree of equivalence for 5.0 MeV fluence measurements

The degree of equivalence (DoE) of each laboratory with respect to the KCRV is given by a pair of terms:

The deviation $D_i = (x_i - x_r)$ of the value reported by the laboratory *i* from the weighted mean value and the associated expanded uncertainty U_i, calculated as $U_i = 2(u_i^2 - u_r^2)^{1/2}$ according to equ. 5 of procedure A in [43].

The degree of equivalence between two laboratories is given by a pair of terms:

The difference $D_{ij} = (x_i - x_j)$ between the values reported by the laboratories *i* and *j* and the expanded uncertainty U_{ij}, approximated by $U_{ij} = 2(u_i^2 + u_j^2)^{1/2}$ according to procedure A in [43].

			Lab *j*													
Lab *i*			**PTB**		**VNIIM**		**NMIJ**		**IRMM**		**CIAE**		**NPL**		**NIST**	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}	
PTB	**0.040**	0.077			**0.074**	0.235	**0.021**	0.204	**-0.041**	0.173	**0.139**	0.148	**0.006**	0.158	**0.128**	0.197
VNIIM	**-0.034**	0.210	**-0.074**	0.235			**-0.053**	0.282	**-0.115**	0.261	**0.065**	0.245	**-0.068**	0.251	**0.054**	0.277
NMIJ	**0.019**	0.175	**-0.021**	0.204	**0.053**	0.282			**-0.062**	0.233	**0.118**	0.216	**-0.015**	0.223	**0.107**	0.252
IRMM	**0.081**	0.137	**0.041**	0.173	**0.115**	0.261	**0.062**	0.233			**0.180**	0.186	**0.047**	0.194	**0.169**	0.227
CIAE	**-0.099**	0.104	**-0.139**	0.148	**-0.065**	0.245	**-0.118**	0.216	**-0.180**	0.186			**-0.133**	0.173	**-0.011**	0.209
NPL	**0.034**	0.117	**-0.006**	0.158	**0.068**	0.251	**0.015**	0.223	**-0.047**	0.194	**0.133**	0.173			**0.122**	0.216
NIST	**-0.088**	0.166	**-0.128**	0.197	**-0.054**	0.277	**-0.107**	0.252	**-0.169**	0.227	**0.011**	0.209	**-0.122**	0.216		

Table A.4.1. Results for 14.8 MeV neutron fluence measurements (final data until 19/11/02)

Laboratory	Calibration coefficient *C* / cm^{-2}	Abs. Uncert. / cm^{-2}	Rel. Uncert.	Deviation from w.m. / cm^{-2}	Deviation uncertainty ($k = 2$) / cm^{-2}
PTB-1	2.290	0.068	2.96%		
IRMM	2.370	0.062	2.60%	0.121	0.119
NMIJ	2.183	0.043	1.97%	-0.066	0.078
VNIIM	3.138	0.158	5.02%	0.889	0.318
PTB-2	2.293	0.067	2.94%		
PTB-3	2.297	0.067	2.92%		
NPL - Foils	2.278	0.030	1.30%	0.029	0.048
CIAE	2.158	0.037	1.70%	-0.091	0.065
NIST	2.180	0.089	4.10%	-0.069	0.174
PTB-4	2.284	0.069	3.02%		
<PTB> (1-4)	2.290	0.057	2.47%	0.041	0.108
unweighted mean (u.m)	2.371	0.121	5.12%		
weighted mean (w.m.)	2.249	0.018	0.79%		
median	2.231				
χ^2-value for w.m.	7.714				
w.m.(2)* (without VNIIM)	2.238	0.018	0.80%		
χ^2-value for w.m.(2)	2.812				

* adopted as key comparison reference value KCRV

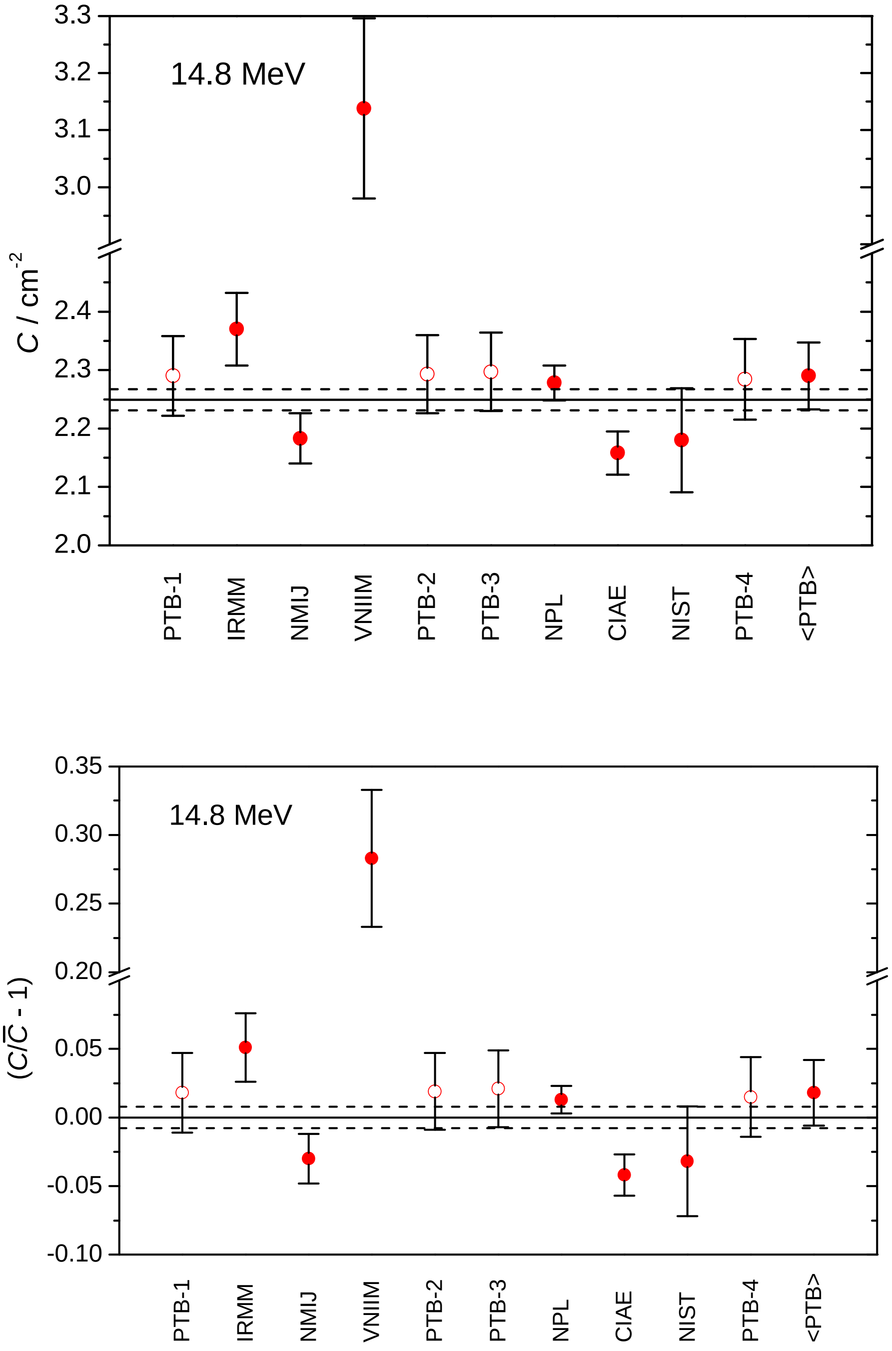


Figure A.4. Calibration coefficient C of a neutron monitor positioned at 17.5 deg and 606 cm to the target defined as the fluence of 14.8 MeV neutrons from the T(d,n)-reaction at 0 deg and 100 cm distance (in vacuum) per monitor count, absolute (upper) and relative (lower) to the weighted mean $\bar{C}$.

Table: A.4.2: Degree of equivalence for 14.8 MeV fluence measurements

The degree of equivalence (DoE) of each laboratory with respect to the KCRV is given by a pair of terms:

The deviation $D_i = (x_i - x_r)$ of the value reported by the laboratory *i* from the weighted mean value and the associated expanded uncertainty U_i, calculated as $U_i = 2(u_i^2 - u_r^2)^{1/2}$ according to equ. 5 of procedure A in [43].

The degree of equivalence between two laboratories is given by a pair of terms:

The difference $Dij = (x_i - x_j)$ between the values reported by the laboratories *i* and *j* and the expanded uncertainty U_{ij}, approximated by $U_{ij} = 2(u_i^2 + u_j^2)^{1/2}$ according to procedure A in [43].

			Lab *j*											
Lab *i*			**PTB**		**IRMM**		**NMIJ**		**NPL**		**CIAE**		**NIST**	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}		/ cm^{-2}	
PTB	**0.052**	0.108			**-0.080**	0.168	**0.107**	0.143	**0.012**	0.129	**0.132**	0.136	**0.110**	0.211
IRMM	**0.132**	0.119	**0.080**	0.168			**0.187**	0.151	**0.092**	0.138	**0.212**	0.144	**0.190**	0.217
NMIJ	**-0.055**	0.078	**-0.107**	0.143	**-0.187**	0.151			**-0.095**	0.105	**0.025**	0.113	**0.003**	0.198
NPL	**0.040**	0.048	**-0.012**	0.129	**-0.092**	0.138	**0.095**	0.105			**0.120**	0.095	**0.098**	0.188
CIAE	**-0.080**	0.065	**-0.132**	0.136	**-0.212**	0.144	**-0.025**	0.113	**-0.120**	0.095			**-0.022**	0.193
NIST	**-0.058**	0.174	**-0.110**	0.211	**-0.190**	0.217	**-0.003**	0.198	**-0.098**	0.188	**0.022**	0.193		

9.2. Appendix B: Uncertainty Budgets Reported by the Participants

B.1 Uncertainties reported by VNIIM [17]

Table B.1.1. The uncertainty budget for the neutron fluence rate

E_n / MeV	U_R / %	u_A / %			$u_{c\varphi}$ / %		
		LC	*NM*	*Ch*	*LC*	*NM*	*Ch*
0.144	2.5	0.186	0.250	0.251	2.51	2.51	2.51
1.2	3.0	0.176	0.199	0.184	3.01	3.01	3.01
5.0	4.0	0.175	0.245	0.178	4.00	4.01	4.00
14.8	5.0	0.469	0.410	0.466	5.02	5.02	5.02

From Appendix:

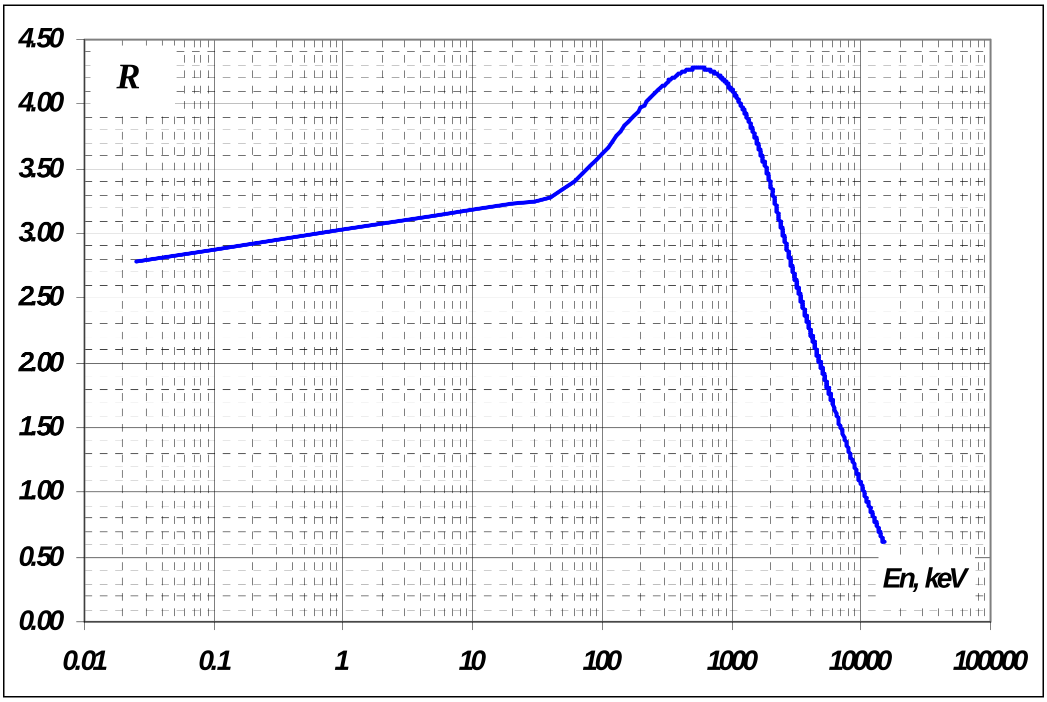


Figure B.1 Energy dependence of radiometer's sensitivity.

Table B.1.2. Calculated and experimentally determined values of detectors response.

Source	R_{exp} / cm^2	R_{calc} / cm^2
Sb-Be(γ,n)	3.17	3.11
Ra-Be(γ,n)	3.33	3.36
^{252}Cf	3.27	3.23
D(d,n)^{3}He, E_{n}=2.72 MeV	2.84	2.86
D(d,n)^{3}He, E_{n}=2.77 MeV	2.84	2.83
Am-Be(α,n)	2.41	2.43
T(d,n)^{4}He, E_{n}=14.55 MeV	0.657	0.645

B.2. Uncertainties reported by NMIJ/AIST [18]
(for details see Budget Sheets 1 to 3 in Ref. 18)

Table B.2.1 : Uncertainty budget for the calibration coefficient *C* for 0.144 MeV

Items	E_n = 0.144 MeV Uncertainties / %	Type of uncertainty
(1) Statistical uncertainty	0.52	A
(2) Various correction processes	0.95	A, B
(3) Simulation process (including nuclear data)	1.68	A, B
(4) Number of hydrogen atoms per cm^3	0.31	B
(5) Sensitive volume of proportional counter	1.19	B
(6) Distance between source and detector	0.39	A, B
Combined Standard Uncertainty / %	2.38	

Table B.2.2 : Uncertainty budget for the calibration coefficient *C* for 5.0 MeV

Items	E_n = 5.0 MeV Uncertainties / %	Type of uncertainty
(1) Statistical uncertainty	0.91	A
(2) Various correction processes	1.07	A, B
(3) Simulation process	1.52	A, B
(4) Nuclear data	2.09	B
(5) Number of hydrogen atoms per cm^3 radiator	1.43	B
(6) Distance between source and detector	0.40	A, B
Combined Standard Uncertainty / %	3.30	

Table B.2.3 : Uncertainty budget for the calibration coefficient *C* for 14.8 MeV

Items	E_n = 14.8 MeV Uncertainties / %	Type of uncertainty
(1) Statistical uncertainty	0.41	A
(2) Various correction processes	1.59	A, B
(3) Nuclear data	0.83	B
(4) Detection efficiency of associated particle detector (solid angle)	0.57	B
(5) Distance between source and detector	0.40	A, B
Combined Standard Uncertainty / %	1.97	

B.3. Uncertainties reported by IRMM [23]

Table B.3.1. Uncertainty budget

		Relative uncertainty / %						
		E_n = 1.2 MeV		E_n = 5.0 MeV			E_n = 14.8 MeV	
	Type	Distance						
		175 mm	275 mm	191 mm	291 mm	391 mm	275 mm	375 mm
Calculation of efficiency								
a) Hydrogen content of radiator	B	1.00	1.00	1.00	1.00	1.00	1.00	1.00
b) Distance target to PRT and angle of PRT	B	0.17	0.11	0.18	0.12	0.09	0.11	0.08
c) Internal PRT geometry, including scattering by aperture and proportional wires	B	1.30	1.30	1.30	1.30	1.30	1.30	1.30
d) Total H(n,p)n cross section	B	0.90	0.90	0.90	0.90	0.90	1.00	1.00
e) H(n,p)n angular cross section	B	0.05	0.05	0.17	0.17	0.17	0.60	0.60
f) Numerical solution of integrals	B	-	-	-	-	-	-	-
Analysis of measurements								
g) Energy (spectral fluence) of incident neutrons	B	0.18	0.21	0.09	0.11	0.25	0.38	0.35
h) Number of events in peak of measured distribution	A	1.04	1.27	0.80	0.92	1.04	0.45	0.82
i) NM monitor normalisation	A	0.03	0.02	0.06	0.04	0.04	0.04	0.05
j) Choice of limits for the proton peak	B	0.25	0.31	0.34	0.45	0.51	0.34	0.26
k) Background subtraction	B	1.50	1.50	1.50	1.50	1.50	1.50	1.50
l) Dead time and pile up effects	B	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
m) In/out scattering of neutrons to PRT	B	-	-	-	-	-	-	-
Combined relative uncertainty / %		2.64	2.74	2.57	2.62	2.68	2.61	2.68
Uncertainty for mean value / %		2.7		2.6			2.6	

B.4: Uncertainties reported by CIAE [27]

Table B.4.1 Uncertainty budget for 0.144 MeV and 1.2 MeV neutron fluence measurements

Items	E_n = 0.144 MeV	E_n = 1.2 MeV	Type of uncertainty
	Uncertainties / %	Uncertainties / %	
(1) Sensitive volume of counter	1.0	1.0	B
(2) Number of hydrogen atoms per cm^3	0.3	0.3	B
(3) Distance of source-to-detector	0.5	0.5	B
(4) Corrected factor	1.1	1.1	B
(5) Statistic error of the total counts	0.8	0.3	A
(6) Statistic error of the background's counts	0.3	0.1	A
(7) Theoretical recoil proton spectrum	0.7	0.7	B
(8) (n,p) elastic-scattering cross section[3]	0.5	0.5	B
Combined Standard Uncertainty / %	2.1	1.9	

Table B.4.2 Uncertainty budget for 5.0 MeV and 14.8 MeV neutron fluence measurements

Items	E_n = 5.0 MeV	E_n = 14.8 MeV	Type of uncertainty
	Uncertainties / %	Uncertainties / %	
(1) (n,p) scattering cross section	0.5	0.5	B
(2) Mass of sample	0.06	0.01	A
(3) Diameter of radiator	0.24	0.3	A
(4) Distance of radiator-to-diaphragm	1.0	0.49	B
(5) Diameter of diaphragm	0.03	0.04	A
(6) Background	0.3	0.3	B
(7) Distance of radiator-to-target	1.7	1.3	B
(8) Statistic error of counts	0.46	0.5	A
(9) calculation of *m*	0.1	0.1	B
(10) Corrected factor	0.02	0.12	B
Combined Standard Uncertainty / %	**2.2**	**1.7**	

B.5. Uncertainties reported by NIST [29]

Table B.5.1. Uncertainty budget summary - 144 keV comparison

Uncertainty Factor	Type A Uncertainty / %	Type B Uncertainty / %	Combined Uncertainty / %
Californium Reference Source Emission Rate		1.5	1.5
^{252}Cf Rotation-Averaged, Room-return-corrected Neutron Count Rate at 1 m	0.26	0.25	0.36
NM Scattering and Dead Time for 0.144 MeV (u)		0.3	0.3
FC and NM Statistical Uncertainties for 0.144 MeV (u)	2.86		2.86
Estimated FC-SC Interaction at 37 cm separation		3.9	3.9
Target Scattering Correction		0.5	0.5
FC Scattering Response Corrections by MC Calculations		4.2	4.2
Cf-Spectrum-Averaged / 0.144 MeV (u) Cross Sections		2.0	2.0
MCA Correction of SCA Data		1.1	1.1
Air Out-Scattering Correction and In-Scatter by SC		2.1	2.1
Combined Uncertainty	2.87	6.72	7.3

Table B.5.2. Uncertainty budget summary - 1.2 MeV comparison

Uncertainty Factor	Type A Uncertainty / %	Type B Uncertainty / %	Combined Uncertainty / %
Californium Reference Source Emission Rate		1.5	1.5
^{252}Cf Rotation-Averaged, Room-return-corrected Neutron Count Rate at 1 m	0.26	0.25	0.36
NM Scattering and Dead Time for 1.2 MeV (u)		0.2	0.2
FC and NM Statistical Uncertainties for 1.2 MeV (u)	1.47		1.47
Estimated FC-SC Interaction at 37 cm separation		3.1	3.1
Target Scattering Correction		0.9	0.9
FC Scattering Response Corrections by MC Calculations		0.5	0.5
Cf-Spectrum-Averaged / 1.2 MeV (u) Cross Sections		2.0	2.0
MCA Correction of SCA Data		1.1	1.1
Air Out-Scattering Correction and In-Scatter by SC		0.9	0.9
Combined Uncertainty	1.49	4.37	4.6

Table B.5.3. Uncertainty budget summary - 5.0 MeV comparison

Uncertainty Factor	Type A Uncertainty / %	Type B Uncertainty / %	Combined Uncertainty / %
Californium Reference Source Emission Rate		1.5	1.5
^{252}Cf Rotation-Averaged, Room-return-corrected Neutron Count Rate at 1 m	0.26	0.25	0.36
NM Scattering and Dead Time for 5.0 MeV (u)		0.7	0.7
FC and NM Statistical Uncertainties for 5.0 MeV (u)	1.16		1.16
Target Scattering Correction		0.5	0.5
FC Scattering Response Corrections by MC Calculations		1.0	1.0
Cf-Spectrum-Averaged / 5.0 MeV (u) Cross Sections		2.0	2.0
MCA Correction of SCA Data		1.1	1.1
Air Out-Scattering Correction and In-Scatter by SC		0.6	0.6
Combined Uncertainty	1.19	3.11	3.3

Table B.5.4. Uncertainty budget summary - 14.8 MeV comparison

Uncertainty Factor	Type A Uncertainty / %	Type B Uncertainty / %	Combined Uncertainty / %
Californium Reference Source Emission Rate		1.5	1.5
^{252}Cf Rotation-Averaged, Room-return-corrected Neutron Count Rate at 1 m	0.26	0.25	0.36
NM Scattering and Dead Time for 14.8 MeV (u)		0.7	0.7
FC and NM Statistical Uncertainties for 14.8 MeV (u)	0.73		0.73
Target Scattering Correction		0.5	0.5
FC Scattering Response Corrections by MC Calculations		2.6	2.6
Cf-Spectrum-Averaged / 14.8 MeV (u) Cross Sections		2.0	2.0
MCA Correction of SCA Data		1.1	1.1
Air Out-Scattering Correction and In-Scatter by SC		0.9	0.9
Combined Uncertainty	0.77	3.99	4.1

B.6. Uncertainties reported by NPL [31]

The fluence is derived from the measured De Pangher long counter data using eq.(1).

$$\Phi = M \cdot (1 - f) \cdot \mathrm{e}^{l\Sigma} \cdot \frac{(l + r)^2}{100^2} \cdot \frac{1}{\varepsilon} \tag{1}$$

where:

M	is the long counter count rate for direct neutrons,
f	is the target scatter correction factor,
l	is the target to long counter moderator distance in cm,
Σ	is the macroscopic cross section for attenuation in air averaged over the direct spectrum,
r	is the De Pangher effective centre, in cm, averaged over the direct spectrum,
$\frac{(l+r)^2}{100^2}$	corrects the measured fluence to the value at 1 m (100 cm), and
ε	is the efficiency of the De Pangher averaged over the direct spectrum.

If the reasonable assumption is made that in the above equation the effect of the uncertainty in l on $\mathrm{e}^{l\Sigma}$ is negligible compared to the uncertainty in Σ, then all the input parameters can be treated as if they occur only once in eq. (1), and the combined variance, $u_c^2(\Phi)$, for a fluence measurement at a single target to long counter distance is given in terms of the standard uncertainties in the individual quantities, *u(M), u(f),* etc., by:

$$\begin{aligned} u_c^2(\Phi) = {} & \left(\frac{\partial \Phi}{\partial M}\right)^2 \cdot u^2(M) + \left(\frac{\partial \Phi}{\partial f}\right)^2 \cdot u^2(f) + \left(\frac{\partial \Phi}{\partial \Sigma}\right)^2 \cdot u^2(\Sigma) \\ & + \left(\frac{\partial \Phi}{\partial l}\right)^2 \cdot u^2(l) + \left(\frac{\partial \Phi}{\partial r}\right)^2 \cdot u^2(r) + \left(\frac{\partial \Phi}{\partial \varepsilon}\right)^2 \cdot u^2(\varepsilon) \end{aligned} \tag{2}$$

Inserting the values for the derivatives eq. (3) is derived for the final uncertainty.

$$\begin{aligned} \left(\frac{u_c(\Phi)}{\Phi}\right)^2 = {} & \left(\frac{u(M)}{M}\right)^2 + \left(\frac{f}{(1-f)} \cdot \frac{u(f)}{f}\right)^2 + \left(l\Sigma \cdot \frac{u(\Sigma)}{\Sigma}\right)^2 \\ & + \left(2 \cdot \frac{u(l)}{(l+r)}\right)^2 + \left(2 \cdot \frac{u(r)}{(l+r)}\right)^2 + \left(\frac{u(\varepsilon)}{\varepsilon}\right)^2 \end{aligned} \tag{3}$$

and this can be written as:

$$\left(\frac{u_c(\Phi)}{\Phi}\right)^2 = \left(c_M \frac{u(M)}{M}\right)^2 + \left(c_f \cdot \frac{u(f)}{f}\right)^2 + \left(c_\Sigma \cdot \frac{u(\Sigma)}{\Sigma}\right)^2 + \left(c_l \cdot u(l)\right)^2 + \left(c_r \cdot u(r)\right)^2 + \left(c_\varepsilon \cdot \frac{u(\varepsilon)}{\varepsilon}\right)^2 \tag{4}$$

where the c_i values are sensitivity coefficients.

Table B.6.1. Component uncertainties for the NPL De Pangher long counter measurements at 144 keV.

Source of uncertainty			Uncertainty[¶] (u_i)	Sensitivity coefficient		Component $u_i \cdot c_i$
Parameter	Symbol	Value		Expression	Value (c_i)	
Uncertainties in the fluence						
Long counter direct counts	M* / %	0.8096	0.50%	1	1	0.50%
Target scatter factor	f / %	0.0201	10%	$f/(1-f)$	0.0206	0.21%
Air attenuation cross section	Σ / %	1.9×10^{-4}	10%	$l\cdot\Sigma$	0.0379	0.38%
Source to detector distance	l / cm	199.6	0.2	$2/(l+r)$	0.00992	0.20%
Effective centre value	r / cm	2.08	0.5	$2/(l+r)$	0.00992	0.50%
Long counter efficiency	ε / %	3.194	2%	1	1	2.0%
Combined uncertainty for the fluence =						2.1%
Uncertainties in the monitor counts						
New monitor statistics			0.2%	1	1	0.20%
New monitor stability			0.4%	1	1	0.40%
Combined uncertainty for fluence per new monitor count =						**2.2%**

[¶] All uncertainties are assumed to have a normal probability distribution

* The uncertainty in the long counter direct counts is made up of components for: statistics (0.2%), the in-scatter correction (0.2%), and the De Pangher stability correction (0.4%).

Table B.6.2. Component uncertainties for the NPL De Pangher long counter measurements at 1.2 MeV.

Source of uncertainty			Uncertainty[¶] (u_i)	Sensitivity coefficient		Component $u_i \cdot c_i$
Parameter	Symbol	Value		Expression	Value (c_i)	
Uncertainties in the fluence						
Long counter direct counts	M* / %	0.6356	0.70%	1	1	0.70%
Target scatter factor	f / %	0.0315	10%	$f/(1-f)$	0.0325	0.33%
Air attenuation cross section	Σ /%	9.9×10^{-5}	10%	$l\cdot\Sigma$	0.0397	0.40%
Source to detector distance	l / cm	400.5	0.3	$2/(l+r)$	0.00499	0.15%
Effective centre value	r / cm	0.47	2.0	$2/(l+r)$	0.00499	1.0%
Long counter efficiency	ε / %	3.459	2%	1	1	2.0%
Combined uncertainty for the fluence =						2.4%
Uncertainties in the monitor counts						
New monitor statistics			0.2%	1	1	0.20%
New monitor stability			0.4%	1	1	0.40%
Combined uncertainty for fluence per new monitor count =						**2.4%**

[¶] All uncertainties are assumed to have a normal probability distribution

* The uncertainty in the long counter direct counts is made up of components for: statistics (0.2%), the in-scatter correction (0.5%), and the De Pangher stability correction (0.4%).

Table B.6.3. Component uncertainties for the NPL De Pangher long counter measurements at 5.0 MeV.

Source of uncertainty			Uncertainty[¶] (u_i)	Sensitivity coefficient		Component $u_i \cdot c_i$
Parameter	Symbol	Value		Expression	Value (c_i)	
Uncertainties in the fluence						
Long counter direct counts	M* / %	5.465	0.50%	1	1	0.50%
Target scatter factor	f / %	0.0	10%	$f/(1-f)$	0.0	0.0%
Air attenuation cross section	Σ / %	6.7×10^{-5}	10%	$l\cdot\Sigma$	0.0206	0.21%
Source to detector distance	l / cm	306.9	0.2	$2/(l+r)$	0.00638	0.13%
Effective centre value	r / cm	6.85	1.0	$2/(l+r)$	0.00638	0.64%
Long counter efficiency	ε / %	3.334	2%	1	1	2.0%
Combined uncertainty for the fluence =						2.2%
Uncertainties in the monitor counts						
New monitor statistics			0.2%	1	1	0.20%
New monitor stability			0.4%	1	1	0.80%
Combined uncertainty for fluence per new monitor count =						**2.3%**

[¶] All uncertainties are assumed to have a normal probability distribution

* The uncertainty in the long counter direct counts is made up of components for: statistics (0.3%), the in-scatter correction (0.2%), and the De Pangher stability correction (0.4%).

Table B.6.4. Component uncertainties for the aluminium foil measurements at 14.8 MeV.

Symbol	Source of uncertainty	Value / %	Probability distribution	Divisor	u_i / %
	Counting statistics	0.1	normal	1	0.1
F_T	Flux variations	0.005	normal	1	0.005
$\varepsilon_ß$	ß-counting efficiency	0.2	normal	1	0.2
K	K-correction	0.2	normal	1	0.2
$\sigma(E)$	Activation cross section	0.5	normal	1	0.5
E_n	Mean neutron energy (20 keV)	0.38	rectangular	√3	0.22
m	Foil mass	0.1	rectangular	√3	0.06
λ	Decay constant	0.01	normal	1	0.01
	Dead time correction	0.2	rectangular	√3	0.12
	Target – foil distance (0.7 mm)	1.5	rectangular	√3	0.89
f_s	Target scatter factor	0.05	normal	1	0.05
$u(\varphi)$	Combined uncertainty CI results	---	normal	---	1.1
	New Monitor statistics	0.02	normal	1	0.02
	New Monitor stability	0.6	normal	1	0.6
$u(\varphi)$	Combined uncertainty NM results	---	normal	---	1.3

B.7 Uncertainties reported by PTB [36]

Table B.7.1. Reduced uncertainty budget for 0.144 MeV and 1.2 MeV neutron fluence measurement.

Items	E_n = 0.144 MeV uncertainty / %	E_n = 1.2 MeV uncertainty / %	uncertainty divisor
(n,p) elastic cross section	0.5	0.5	1
Sensitive volume of counter	0.3	0.3	1
Number of hydrogen atoms	0.5	0.5	1
Source-detector distance	0.09	0.09	√3
Statistic of the net counts (TOTAL-BG)	0.2	0.2	1
Calculated response function	1.73	1.73	1
fraction of measured phd	1.0	1.0	√3
fraction of response function	1.0	1.0	√3
attenuation correction for iron window	0.08	0.04	1
attenuation correction for ambient air	0.06	0.06	1
Combined Standard Uncertainty / %	**2.2**	**2.2**	

Table B.7.2. Reduced uncertainty budget for 5.0 MeV and 14.8 MeV neutron fluence measurement.

Items	E_n = 5.0 MeV uncertainty / %	E_n = 14.8 MeV uncertainty / %	uncertainty divisor
(n,p) elastic cross section	0.5	0.5	1
Mass of tristearin radiator	0.03	0.03	1
Number of hydrogen atoms	0.03	0.03	1
Source-detector distance	0.26	0.26	√3
Statistic of the net counts (TOTAL-BG)	0.8	1.7	1
lower integration boundary of peak	1.0	1.0	√3
Calculated efficiency factor	1.4	2.2	1
attenuation correction for Al window and Ta backing	0.3	0.3	1
attenuation correction for ambient air	0.03	0.03	1
Combined Standard Uncertainty / %	**1.8**	**2.9**	

9.3 Appendix C: Extended Data Sets Reported by theParticipants including Results Obtained after 2003

Results reported by the laboratories (x_i) with corresponding uncertainties (u_i) until November 2002 and revised data received after May 2003 used for the calculation of unweighted and weighted mean values

Table C.1: Calibration coefficient *C*, determined as neutron fluence per NM monitor count, for 144 keV

Lab *i*	C_i	u_i
	/ cm^{-2}	**/ cm^{-2}**
PTB	1.913	0.038
VNIIM	1.960	0.049
NMIJ	1.984	0.047
NPL	2.051	0.045
NIST	2.190	0.160
CIAE	2.010	0.042
u.mean	2.018	0.036
w.mean	1.983	0.019
VNIIM	1.979	0.049
NPL	2.027	0.045
u.mean	2.017	0.035
w.mean	1.981	0.019

χ^2=1.594
χ^2=1.291

Table C.2: Calibration coefficient *C*, determined as neutron fluence per NM monitor count, for 1.2 MeV

Lab *i*	x_i	u_i
	/ cm^{-2}	**/ cm^{-2}**
PTB	1.864	0.037
VNIIM	1.740	0.052
IRMM	1.890	0.051
NPL	1.826	0.044
CIAE	1.915	0.036
NIST	1.870	0.086
u.mean	1.851	0.023
w.mean	1.859	0.019
VNIIM	1.840	0.052
NPL	1.853	0.044
u.mean	1.872	0.010
w.mean	1.876	0.019

χ^2=1.70
χ^2=0.416

Table C.3: Calibration coefficient *C*, determined as neutron fluence per NM monitor count, for 5.0 MeV

Lab *i*	**C_i**	**u_i**
	/ cm^{-2}	**/ cm^{-2}**
PTB	2.768	0.046
VNIIM	2.694	0.108
NMIJ	2.747	0.091
IRMM	2.809	0.073
CIAE	2.629	0.058
NPL	2.762	0.064
NIST	2.640	0.087
u.mean	2.721	0.024
w.mean	2.729	0.025
VNIIM	2.727	0.108
NPL	2.741	0.064
u.mean	2.723	0.023
w.mean	2.727	0.025

χ^2=1.063
χ^2=1.005

Table C.4 : Calibration coefficient *C*, determined as neutron fluence per NM monitor count, for 14.8 MeV

Lab *i*	**C_i**	**u_i**
	/ cm^{-2}	**/ cm^{-2}**
PTB	2.290	0.057
IRMM	2.370	0.062
NMIJ	2.183	0.043
VNIIM	3.138	0.158
NPL	2.278	0.030
CIAE	2.158	0.037
NIST	2.180	0.089
u.mean	2.371	0.121
w.mean*	2.238	0.018
CIAE	2.186	0.037
VNIIM	2.287	0.158
u.mean	2.253	0.025
w.mean**	2.246	0.018
NPL/PLC	2.237	0.059

χ^2=2.812
χ^2=1.873
* without VNIIM-result
** all data included except NPL/PLC

References

[1] ISO Standard 8529, parts 1-3, Geneva (1998 - 2001), Reference neutron radiation*:*
Part 1 (2001): Characteristics and methods of production
Part 2 (2000): Calibration fundamentals related to the basic quantities characterising the radiation field
Part 3 (1998): Calibration of area and personal dosimeters and determination of the response as a function of neutron energy and angle of incidence

[2] CIPM Mutual Recognition Arrangement, October 1999 (*see homepage of BIPM at* http://www.bipm.org, *CIPM MRA Appendices B and C*)

[3] ISO/IEC Standard 17025, Geneva (1999) General requirements for the competence of testing and calibration laboratories

[4] Huynh, V D 1980 International comparison of flux density measurements for mono-energetic fast neutrons *Metrologia* **16** 31-49

[5] Lewis V E 1984 International intercomparison of d+T neutron fluence and energy using niobium and zirconium activation *Metrologia* **20** 49-53

[6] Liskien H 1984 International fluence-rate intercomparison for 2.5 Mev and 5.0 MeV neutrons *Metrologia* **20** 55-59

[7] Ryves T B 1987 International fluence-rate intercomparison for 144 and 565 keV neutrons *Metrologia* **24** 27-37

[8] Gayther D B 1990 International intercomparison od fast neutron fluence-rate measurements using fission chamber transfer instruments *Metrologia* **27** 221-231

[9] Axton E J 1991 Report on the intercomparison of neutron fluence using two Bonner spheres as transfer instruments *CCEMRI-document/91-4*

[10] Caswell R S , Lewis V E 1992 Neutron measurement intercomparisons sponsored by CCEMRI, section III (neutron measurements) *Radiat. Prot. Dosim.* **44** 105-110

[11] Lewis V E 1998 Comparison of 24.5 kV neutron fluence measurements 1993-1996 *NPL-report CIRM 16*

[12] Brede H J, Cosack M, Dietze G., Gumpert H, Guldbakke S, Jahr R, Kutscha M Schlegel-Bickmann D, Schölermann H 1980 The Braunschweig accelerator facility for fast neutron research – I. Building design and accelerators *Nucl. Instrum. Meth.* **169** 349-358

[13] Lesiecki H, Cosack M, Schölermann H 1988 Mono-energetic neutron fields for the calibration of neutron dosimeters at the accelerator of the PTB *PTB-Mitteilungen* **97**, 373-376

[14] Böttger R 2002 Energy calibration of the PTB VdG accelerator *Laboratory report* **PTB-6.41-02-2**

[15] Schlegel D 1998 TARGET user manual *Laboratory report* **PTB-6.41-98-1**

[16] Siebert B R L, Brede H J, Lesiecki H 1982 SINENA – A Monte Carlo program for transfering proton-recoil telescope neutron fluence measurements to detectors *PTB Report* **PTB-ND-23, ISSN 0572-7170**

[17] Moisseev N N, Kharitonov IA 2002 Fluence-rate measurement for 0.144, 1.2, 5.0 and 14.8 MeV neutrons *reports to the evaluator* (3/2002 and 11/2002)

[18] Kudo K, Uritani A, Takeda N 2002 (2002) NMIJ report for CCRI key comparison of neutron fluence measurements at energies 144 keV, 5.0 MeV and 14.8 MeV *report to the evaluator*

[19] Yoshizawa M, Saegusa J, Yoshida M, Sugita T 2000 **I** A Monte Carlo program for estimating characteristics of neutron calibration fields using a pelletron accelerator *Proc. P-3b-152 IRPA-10*

[20] Takeda N, Kudo K, Toyokawa H, Torii T, Hashimoto M, Sugita T, Dietze G, Yang X 1999 A development of NRESPG Monte Carlo code for the calculation of neutron response function for gas counters *Nucl. Instrum. Meth.* **A422** 69-74

[21] Biersack J P, Haggmark L G 1980 A Monte Carlo computer program for the transport of energetic ions in amorphous targets *Nucl. Instrum. Meth.* **174** 257-269

[22] Kudo K, Kinoshita T 1989 Standardisation of DT neutron field and its application to detector calibration for fusion diagnostics *Fusion Engineering & Design* **10** 145-149

[23] Lövestam G, Plompen A, Puglisi R 2001 IRMM participation in a CCRI key comparison of neutron fluence measurements in mono-energetic neutron fields *IRMM report* GE/R/NP/4/01

[24] Bame S J, Haddard E, Perry J E, Smith R K, Swartz B 1957 Absolute determination of mono-energetic neutron flux in the energy range 1 to 30 MeV *Rev. Scient. Instrum.* **28** 997-1006
see also:
Bame S J, Haddard E, Perry J E, Smith R K 1960 Counter telescope measurements of neutron flux *Rev. Scient. Instrum.* **31** 911-913

[25] Sloan D, Robertson J C 1982 The efficiency of a recoil proton monitor *Nucl. Instrum. Meth.* **198** 365-372

[26] Liskien H, Paulsen A 1969 Determination of 1 MeV neutron fluxes from the T(p,n)^{3}He reaction by the associated particle method *Nucl. Instrum. Meth.* **69** 70-76

[27] Chen J, Wang Z, Rong C 2002 The final report of key comparison of mono-energetic neutron fluence measurements *Reports to the evaluator* (3/2002 and 11/2002)

[28] Parker J B, White P H, Webster R J 1963 The interpretation of recoil proton spectra *Nucl. Instrum. Meth.* **23** 61-68

[29] Gilliam D M, Eisenhauer C M, Nico J S, Dewey M S 2002 Comparison of measurements in mono-energetic fast neutron fields – NIST results and estimated uncertainties *Reports to the evaluator*(4/2002 and 11/2002)

[30] Evaluated Nuclear Data Files ENDF/B-IV (IRMM and PTB for σ_{np}) or ENDF/B-VI (NIST for σ_{nf} and CIAE for σ_{np})

[31] Thomas D J, Roberts N J, Bennet A, Kolkowski P 2002 The NPL contribution to a CCRI international comparison of fast neutron fluence measurements performed at the PTB in March 2001 *NPL report* **CIRM 51**

[32] De Pangher J, Nichols L L 1966 A precision long counter for measuring fast neutron flux density *PNL report* **BNWL-260**

[33] Tagziria H, Thomas D J 1998 Re-calibration and Monte Carlo modelling of the NPL long counters *NPL report* **CIRM 19**
See also:
Tagziria H, Thomas D J 2000 Calibration and Monte Carlo modelling of neutron long counters *Nucl. Instrum. Meth.* **A452** 470-483

[34] Thomas D J, Lewis V E 1981 Standardisation of neutron fields produced by the ^{3}H(d,n)^{4}He reaction *Nucl. Instrum. Meth.* **179** 397-404

[35] Hunt J B 1976 The calibration and use of long counter for the accurate measurement of neutron flux density *NPL report* **RS(EXT) 5**

[36] Schlegel D, Guldbakke S 2002 Key comparison of neutron fluence measurements in mono-energetic neutron fields – Determination of neutron fluence and monitor calibration factors *Laboratory report* **PTB-6.41-2002-01**

[37] ISO Standard GUM, Geneva (1995) Guide to the expression of uncertainties in measurements

[38] Schlegel D R, Guldbakke S 2002 Neutron fluence measurement with the recoil proton proportional counter *Laboratory report* **PTB-6.41-02-03**

[39] Schlegel D R, Guldbakke S 2002 Neutron fluence measurement with the recoil proton telescope *Laboratory report* **PTB-6.41-02-04**

[40] Guldbakke S, Löb S, Schlegel D 2001 Key comparison of neutron fluence measurements in mono-energetic neutron fields – Monitoring and calculation of the spectral fluence *communication to the participants*

[41] Böttger R, Guldbakke S, Klein H, Schölermann H 1989 Problems associated with the production of mono-energetic neutrons *Nucl. Instrum. Meth.* **A282** 358-367

[42] Klein H, Brede H J, Siebert B R L 1982 Energy and angle straggling effects in a D(d,n)^{3}He neutron source using a gas target *Nucl. Instrum. Meth.* **A193** 635-644

[43] Cox M G 2002 The evaluation of key comparison data *Metrologia* **39** 589-595

[44] Rong C, Wang Z 2003 Revised result for 14.8 MeV fluence measurements *Report to the evaluator* (June 2003)

[45] Kharitonov I, Moisseev N 2004 Supplement to VNIIM's Report on fluence-rate measurement of 0.144, 1.2, 5.0 and 14.8 MeV neutrons according to CCRI(III)-K10 key-comparison *Report to the evaluator* (November 2004)

[46] Thomas D, Roberts N 2003 Recent improvements to NPL long counter effective centre values *Report to the evaluator* (July 2003)

[47] Roberts N, Tagziria H, Thomas D 2004 Determination of the effective centres of the NPL long counters *NPL report* DQL RN004 (November 2004)