

International Key Comparison of 24 keV Neutron Fluence Measurements (1993-2009) – CCRI(III)-K1

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ABSTRACT

A comparison of 24.5 keV neutron fluence standards was organised by Section III (Neutron Measurements) of the Comité Consultatif des Rayonnements Ionisants, (CCRI). The exercise involved the circulation of a set of three different-diameter Bonner spheres for calibration in fields with energies around 24.5 keV. The fields were produced using four different methods of neutron production.

The responses (counts per unit neutron fluence) of the individual spheres were initially determined for the neutron energy of the production method, or methods, employed. To derive the 24.5 keV responses, it was necessary to make corrections for spectral effects, and these were achieved by using response functions for the spheres calculated using the code MCNP. The results demonstrate good consistency within the estimated uncertainties (ranging from about 5% to 10% at the 95% confidence level) between the results reported by all the participants.

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1 INTRODUCTION

One of the main activities of Section III of CCRI is the sponsorship of comparisons of neutron metrology standards in order to achieve a consistent international measurement system, to improve neutron metrology worldwide, and to evaluate the state-of-the-art in measurement. A series of comparisons of measurements of fast neutron fluences has been carried out under the auspices of Section III, starting in 1973⁽¹⁾. Up until 1992, the lowest neutron energy used for a fluence measurement comparison was 144 keV^(2,3). In view of the importance of the measurement of lower energy neutron components, it was decided to extend the scope of these exercises to lower energies.

A Working Party was appointed by Section III to produce proposals for a comparison of neutron fluence measurements in the energy range from 20 keV to 50 keV. Six national metrology laboratories, NMIs, were interested in participating (see Section 2). Some indicated a preference for the measurements to be made at a neutron energy of 22.8 keV (as produced by an $^{124}\text{Sb-Be}(\gamma,n)$ source), some preferred an energy of about 24.5 keV (obtained with iron-filtered reactor beams), whilst others preferred energies of around 27.4 keV produced using the $^{45}\text{Sc}(p,n)^{45}\text{Ti}$ reaction (see Section 3). The use of the $^7\text{Li}(p,n)^7\text{Be}$ reaction, producing a neutron energy of about 30 keV, was suggested later.

A single reference energy of 24.5 keV was chosen by Section III for this comparison.

This energy corresponds to that obtained using iron-filtered reactor beams and lies about midway between the energies produced using an $^{124}\text{Sb-Be}$ source and the $^{45}\text{Sc}(p,n)^{45}\text{Ti}$ reaction.

Neither of the two techniques (indium foil activation⁽²⁾ or a ^{235}U fission counter⁽³⁾) which had been used in recent comparisons were considered to be sufficiently sensitive or convenient for the neutron fields that would be used. Alternatives, such as a ^3He spectrometer or a hydrogen-filled proportional counter were considered to be too sensitive to background neutrons or gamma rays. The Bonner sphere detector was advocated by the Working Party and chosen by Section III as the most suitable transfer detector in the chosen energy region. A set of three spheres with different diameters and employing a common central detector, used for a previous comparison, were available (see Section 4). The comparison involved the circulation of the Bonner spheres for participants to calibrate in neutron fields that were routinely in use at their laboratories.

The aim of the comparison was to measure the 24.5 keV neutron fluence responses of all three Bonner spheres.

Values obtained from measurements made at energies other than 24.5 keV would be corrected to the reference energy using computed response functions for the Bonner spheres (Section 5).

The exercise started in March 1993, and the measurements of five of the planned participants ended in April 1996. The schedule of measurements is shown in Appendix 1. A protocol for the comparison was drafted by the Working Party and approved by the participants. This provided guidance on the operation of the instrumentation and specified the various items of information to be sent to the Evaluator (see Appendix 2). All measurements were reported^(4,5,6,7,8) to the then Chairman of Section III (V.E. Lewis, NPL), who analysed the results and drafted a report⁽⁹⁾ (the Evaluator was not involved in the calibrations carried out at NPL.) An interim report covering the five sets of results reported here, but not disclosing absolute values, was presented at a meeting of Section III at the Bureau International des Poids et Mesures (BIPM) in April 1997.

The measurements of the sixth participant, NMIJ, Japan (previously known as the Electro-Technical Laboratory, ETL), were delayed until late 1997 due to problems at other facilities

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and the refurbishment of that facility. Unfortunately it was then discovered that the background neutron component was so large relative to the low intensity of the selected neutron source that accurate measurements were not possible. It was therefore decided to limit the exercise to the first five participating laboratories.

2 PARTICIPANTS

The establishments who expressed an interest in participating in the comparison were:

China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China
 National Metrology Institute, Japan (NMIJ) [then (ETL)]
 D.I. Mendeleev Institute for Metrology (VNIIM), St Petersburg, Russia
 National Institute of Standards and Technology (NIST), Gaithersberg, USA
 National Physical Laboratory (NPL), Teddington, United Kingdom
 Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany

The neutron fields used by each participant are given in Appendix 1.

3 RADIATION FIELDS

3.1 Antimony-beryllium source - ^{124}Sb -Be

The neutrons are produced by the reaction of 1691 keV and 2091 keV gamma rays from ^{124}Sb on beryllium. The ^{124}Sb is produced by irradiating a source containing natural antimony surrounded by a beryllium layer in a reactor. Since the half life is only 60 day the ^{124}Sb is usually produced immediately prior to any measurements. The source has a very high gamma radiation component. The main neutron group has an energy of 22.8 keV with a spread of ± 1.3 keV. The mean energy is lowered slightly by source scattering effects. There is also a higher energy group at 378 keV with an intensity of less than 3% that of the 22.8 keV group. The response values obtained must be corrected to give those at 24.5 keV. Two participants used ^{124}Sb -Be sources.

3.2 Reactor beam with iron filter

The iron absorption cross section has a narrow window at an energy of about 24.5 keV. Higher and lower energy neutrons may be present in the transmission spectrum and measured responses must be corrected accordingly to give values for 24.5 keV. Three participants used iron-filtered reactor beams. The diameters of these collimated beams were less than those of the Bonner spheres and scanning techniques were therefore employed.

3.3 The $^{45}\text{Sc}(p,n)^{45}\text{Ti}$ reaction

This reaction has a threshold energy of 2.908 MeV and has a resonance structure. The neutron energy therefore depends sensitively on the proton beam energy and also on the angle of neutron emission relative to the proton beam. A widely-used resonance yields neutrons with energies of 27.4 keV at 0° to the proton beam axis or 24.5 keV at 35° . To obtain neutrons from only one resonance it is necessary to use a target thickness corresponding to an energy loss of less than 2 keV. The resulting neutron field has a low intensity. Since the neutron field strength at 35° is lower than at 0° , measurements were normally made at 0° and the response corrected to give that at 24.5 keV. Three participants used neutron fields produced using the $^{45}\text{Sc}(p, n)^{45}\text{Ti}$ reaction.

3.4 The $^7\text{Li}(p,n)^7\text{Be}$ reaction

This reaction has a threshold energy of 1.881 MeV and is widely used to produce mono-energetic neutrons below 600 keV. With a proton beam energy of 1.942 MeV, 144 keV neutrons are emitted at zero degrees to the beam axis and 24 keV neutrons at 76.5° . A proton beam energy

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with a stability of about ± 0.1 keV is necessary. Only one participant used this reaction.

4 INSTRUMENTATION

4.1 Construction

The Bonner sphere detector system consisted of three spheres, designated A, B and H, made at NPL of high density polyethylene with diameters 63.5 mm, 88.9 mm and 241.3 mm (2.5, 3.5 and 9.5 inch respectively). These are shown in Figures 1 and 2 along with the central detector, a spherical ^3He proportional counter type SP9, provided by the BIPM. The two halves of sphere A are unscrewed and separated, the ^3He detector placed inside, and the two halves screwed together again. Sphere B is assembled in the same manner. To assemble sphere H, sphere A, containing the ^3He detector, was pushed into the central cavity and an end plug inserted to fill the remaining void.

The spheres were mounted on light-weight aluminium stands and oriented with the detector stem horizontal with connector diametrically opposite the sphere surface nearest to the neutron source.

4.2 Electronics and spectrum

A simple electronic system consisting of a pre-amplifier, main amplifier, single channel analyser (SCA) and scaler system could be used, along with an 850 V bias supply for the ^3He detector.

An example of a typical spectrum from the ^3He detector is shown in Figure 3. It has a main peak below which there is a plateau extending down to around 25% of the energy of the peak. Below this the events fall to almost background level until the noise level is reached. The SCA lower level discriminator was set at a pulse height 20% that of the main peak, at the position shown in the flat valley region. The upper level discriminator was set at least 40% higher than the main peak position. The position of the peak could vary slightly with count rate necessitating a small adjustment of amplifier gain or a small correction to the total number of recorded events.

5 BONNER SPHERE RESPONSE FUNCTIONS

The three Bonner spheres respond to neutrons over about nine decades of neutron energy with varying sensitivity. The smaller spheres are most sensitive to neutrons with energies below about 10 keV whilst the large sphere is most sensitive to MeV neutrons. Since the fields used in this exercise were not mono-energetic and/or did not have a principal energy of 24.5 keV, it was necessary to calculate spectral corrections for each sphere in each field.

Each sphere was modelled using the detailed design drawings of the polyethylene components and of the ^3He proportional counter detector. Care was taken to establish the density of the moderator material and the dimensions of any cavities between its parts. A Monte Carlo code was used to track neutrons of any given energy entering a sphere and being moderated by the polyethylene before either entering the central detector and producing an event or being lost elsewhere. Incident neutron energies ranging from 10^{-3} eV to 20 MeV were selected for the simulations; there was special emphasis on calculating the response in the region from 20 keV to 30 keV. These extensive computations were made by the PTB employing the code MCNP. The report from PTB describing this work more fully and giving calculated response values is attached as an Annex to this report.

The results are shown in a Figure within this Annex as response relative to that at 24.5 keV. Sphere A (63.5 mm) is five times more sensitive to eV neutrons than to 25 keV neutrons, but essentially insensitive to MeV neutrons. The situation for sphere H (241.3 mm) is the opposite to this. Both spheres have response characteristics that vary more markedly in the 10 keV to 40 keV region than that for sphere B (88.9 mm) which has an almost energy-independent

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response in this particular energy range.

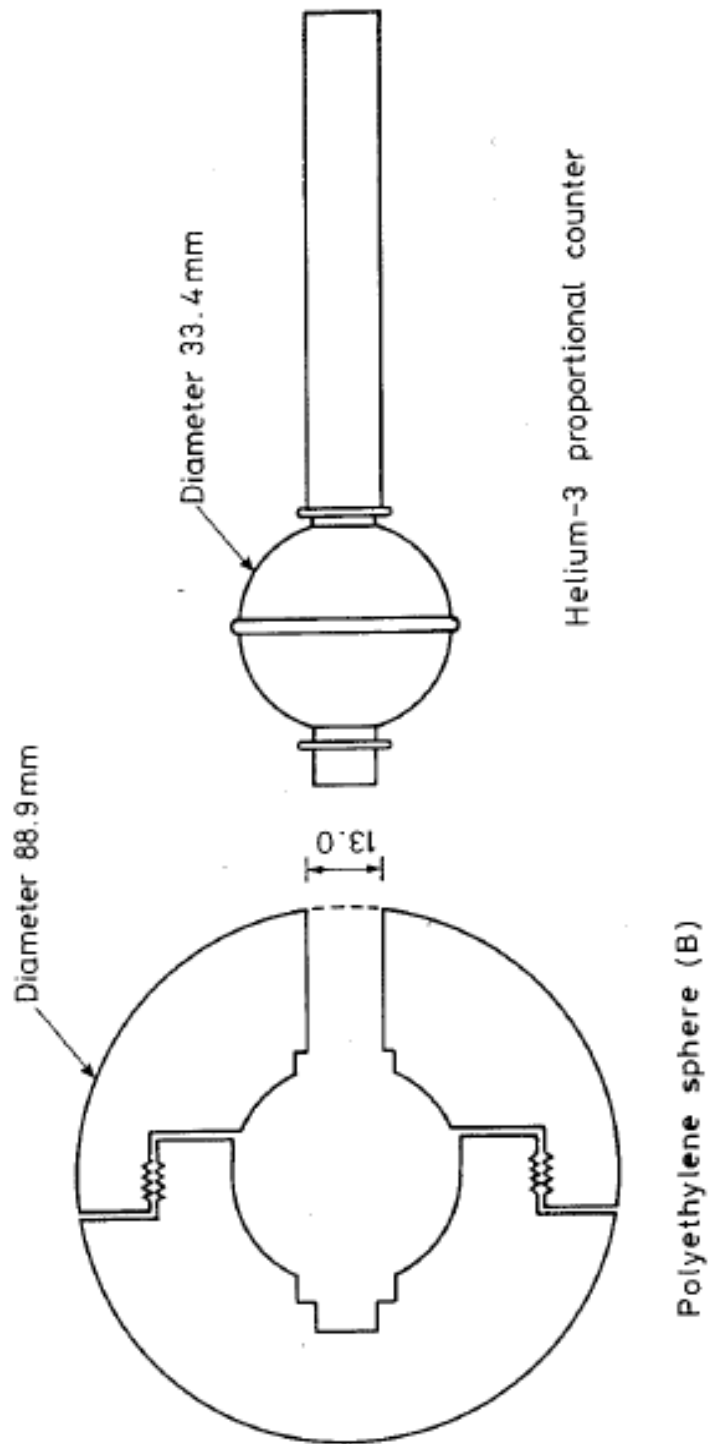


Figure 1. Bonner sphere B and central ^3He proportional counter detector

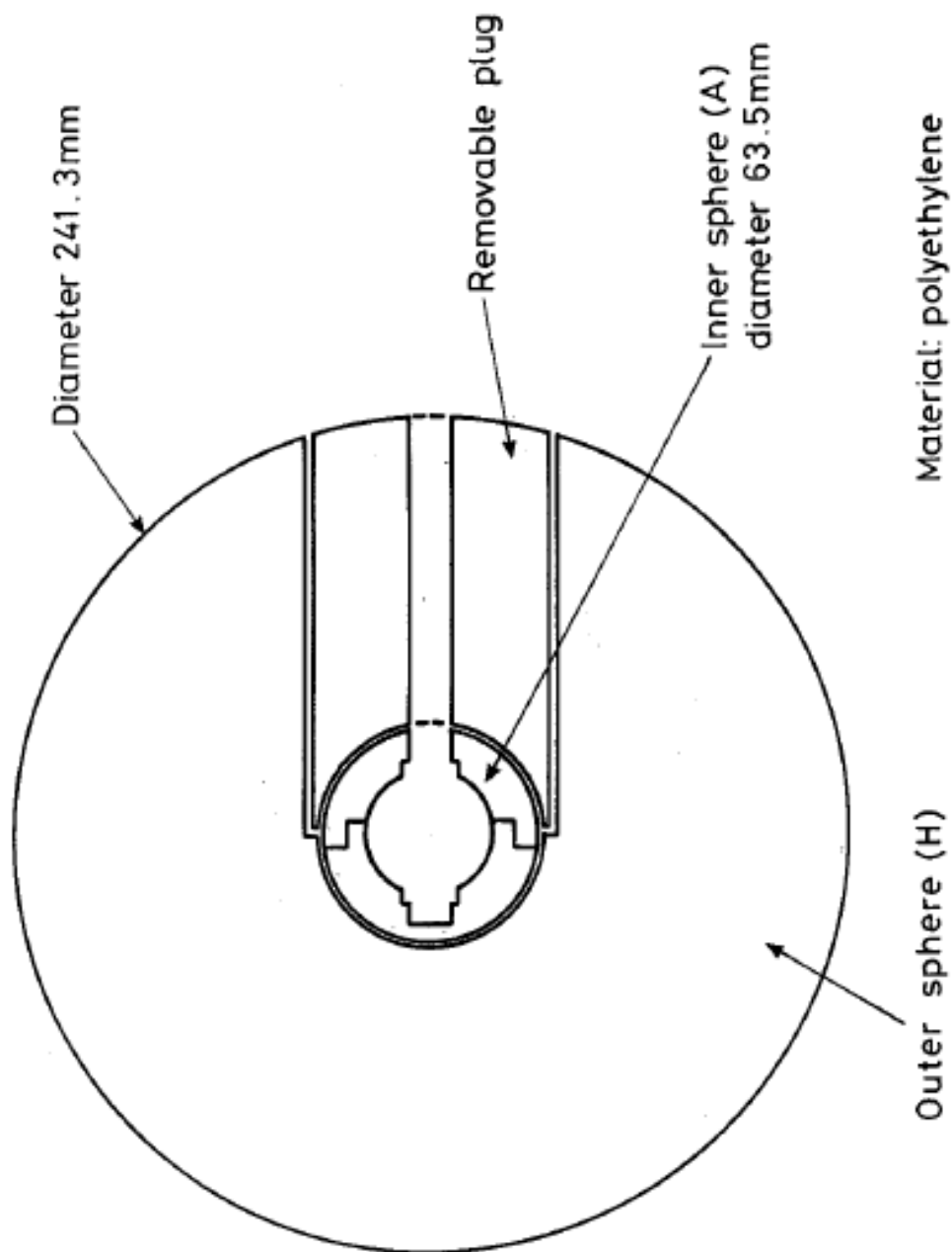


Figure 2. Bonner sphere H with small sphere A at the centre

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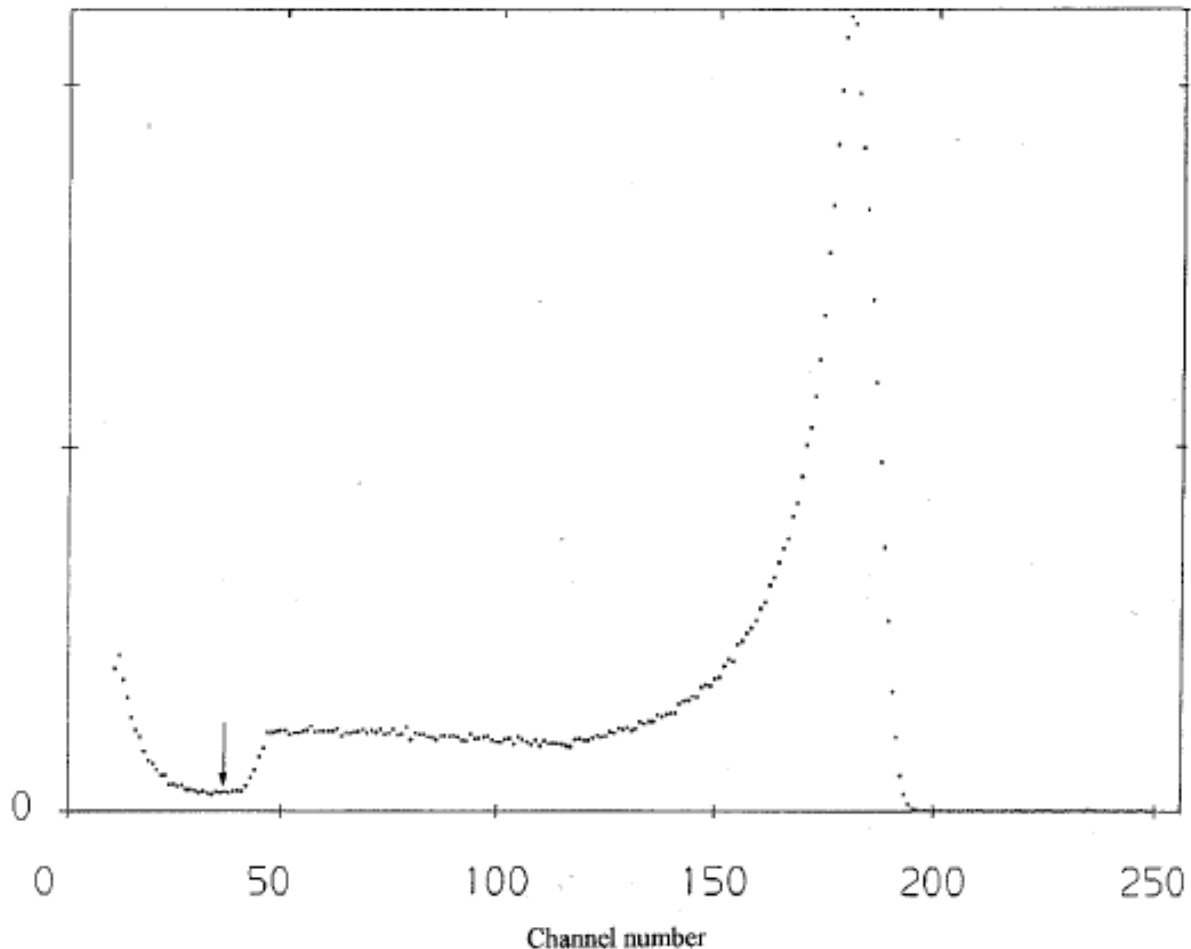


Figure 3. Pulse height distribution for ³He proportional counter. The arrow indicates the discriminator setting

6 MEASUREMENTS BY PARTICIPANTS

The Bonner sphere set was circulated to participating laboratories by the BIPM. In between the periods spent at the participants' laboratories the Bonner spheres were returned to the BIPM for checks of the response of the ³He proportional counter detector using an ²⁴¹Am-Be source in a fixed geometry arrangement. These check results are described in Section 7.

The participants measured the response of each sphere in each of their fields available for calibration in the 25 keV energy region. The choice of field and of the technique for the determination and monitoring of neutron fluence was left to participants.

Where necessary, the contributions to the sphere response due to air- and room-scattered neutrons were determined using an appropriate method such as the shadow cone technique.

Spectral corrections were required as appropriate for:

- effects of lower energy neutrons produced by interactions of the primary neutrons with the neutron-producing target or the material of the source;
- the presence of lower and higher energy neutron groups due to competing reactions;
- the presence of contaminant neutrons from other sources;
- the difference between the energy of the principal neutron group and the reference energy.

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These corrections were calculated by folding the sphere response functions with the measured or derived spectra. The experimental details are summarized in Appendix 3.

Reports were sent to the Evaluator for analysis at the NPL. Participants were asked to provide the various items of information listed in Appendix 2. These included details of the neutron spectrum at the point of measurement, stating how it was measured or derived.

7 RESULTS OF INSTRUMENTATION CHECKS

7.1 Arrangement for checking stability of instrumentation

The BIPM designed and constructed a polyethylene sphere, 200 mm in diameter, into which a 3.7 GBq Am-Be source could be inserted. This provided a stable neutron field into which the ^3He proportional counter detector could be placed at a reference position and the count rate measured as a check on the detector's stability.

7.2 Use of detector SP9-BIPM1

The stability of the ^3He proportional counter detector chosen for the comparison, designated SP9-BIPM1, was checked several times in the test rig at BIPM in 1992. A mean count rate of $(979.9 \pm 1.0) \text{ s}^{-1}$ was observed. Subsequent checks just before the instrumentation was sent to the NIST and on its return from the NIST yielded respective values of $(979.9 \pm 1.0) \text{ s}^{-1}$ and $(980.1 \pm 1.0) \text{ s}^{-1}$. It was concluded that the detector was stable over this period.

7.3 Use of detector SP9-BIPM2

When the instrumentation was received at the CIAE the detector did not work satisfactorily. It was then replaced by a similar detector, SP9-BIPM2. This also had been checked for stability in 1992 and was again checked on its return from the CIAE. The measured count rates were $(1009.6 \pm 0.7) \text{ s}^{-1}$ and $(1007.3 \pm 1.5) \text{ s}^{-1}$ respectively. It was concluded that the detector was stable over the period of the measurements at the CIAE.

On the return of the instrumentation from the PTB, a count rate of $(981.4 \pm 1.3) \text{ s}^{-1}$ was observed. Because it could not be determined when and why this apparent decrease in response took place, a mean value of $(995 \pm 14) \text{ s}^{-1}$ was assumed for the effective count rate.

On the return of the instrumentation from NPL, a count rate of $(978.6 \pm 1.0) \text{ s}^{-1}$ was observed. Due to the transfer of the test rig to another room at the BIPM, the count rate was re-measured in a new location before the instrumentation was sent to the VNIIM. The observed count rate was higher at $(1140.0 \pm 0.4) \text{ s}^{-1}$ due to increased background. On the return of the instrumentation from Russia, a count rate of $(1140.5 \pm 0.4) \text{ s}^{-1}$ was observed and therefore it was concluded that the response had remained stable since the return of the instrumentation from the PTB.

7.4 Normalization

It was decided to normalize the measured responses to a count rate of 979 s^{-1} in the BIPM arrangement. The reported sensitivities would be multiplied by the correction factors below.

NIST	980 s^{-1}	Normalization factor:	0.999
CIAE	1008.5 s^{-1}		0.970
PTB	$995 \pm 14 \text{ s}^{-1}$		0.985 ± 0.014
NPL	979 s^{-1}		1.000
VNIIM	979 s^{-1}		1.000

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8 ANALYSIS

The 24.5 keV response values reported initially to the Evaluator are shown in Table 1, denoted by $R(d)$, where d is the sphere diameter in inches. The units are cm^2 throughout. All corrections had been made by the participants, although not all had corrected the values to the reference energy. (The order of participants is not chronological, but has been arranged for easier comparison of results in similar neutron fields.) The uncertainties are those estimated by the participants. The values obtained from the MCNP computations are also given in Table 1.

These response values were multiplied by the factors given in Section 7 above to correct for changes in the response of the ^3He detector. The corrected values, denoted by $R'(d)$, are also shown in Table 1. In general the estimated uncertainties are better than 5% at the 1σ 66.7% confidence level. However, due to observed inconsistencies in the beam calibration, NIST assigned a non-random uncertainty of 20% (at the 1σ confidence level) to their values.

When the newly-calculated relative response functions became available from PTB, the spectral corrections discussed in Section 5 were re-calculated by the participants as necessary. Corrections varied between -10% to about +1%, generally being less than 5% in magnitude.

In 1998, a year after these results were initially collated, but before it was decided that no further results would be included, the PTB reported an error in the corrections for the measurements performed using the accelerator⁽¹⁰⁾. The values for the $^{45}\text{Sc}(p,n)$ and $^7\text{Li}(p,n)$ fields were revised by about 4% and 6% respectively, and the filtered beam results were also modified (by 1.3%) due to a change in the common fluence reference value. The revised values represent the present state-of-the-art at PTB. The changes, which slightly worsen the general consensus, do not affect the overall conclusions drawn from this exercise. The final values for all participants, including the PTB corrections, and also corrected by the Evaluator for the changes in the response of the ^3He detector are denoted by $R''(d)$ and are shown in Table 2. The ratios of the sensitivities of pairs of spheres are also given. Table 2 is the definitive set of values for the blind comparison exercise.

9 RESULTS

9.1 Results for 2.5 inch sphere A

The measured results in Table 2 consist of a band of seven values from four participants with upper and lower limits (both from CIAE) 11% apart, with an isolated value (NIST) about 16% lower than the un-weighted mean of the others. The uncertainty for the NIST value is, however, greater than the deviation from the un-weighted mean and the value is thus not at this stage an outlier. The other values are consistent within the estimated uncertainties which are all less than 5% (at 66.7% confidence level). The calculated (MCNP) value is 8% lower than the un-weighted mean of the values from the four groups.

9.2 Results for 3.5 inch sphere B

In a similar way to the above results for the smallest sphere, these results consist of a band of seven values from four participants with upper and lower limits 9% apart, with an isolated value (NIST) about 23% lower than the un-weighted mean of the others. The deviation of the NIST value from the un-weighted mean is greater than the quoted uncertainty at $k = 1$ but not for $k = 2$ so cannot be classed as an outlier relative to the un-weighted mean. The other values are consistent within the estimated uncertainties which are all less than about 5% (at 66.7% confidence level). The calculated (MCNP) value is 5.5% lower than the un-weighted mean of the values from the four groups.

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Table 1. Values and (uncertainties) initially submitted to the evaluator for the 24.5 keV neutron fluence responses, and the same values corrected for the variation of the ^3He proportional counter response during the exercise

Participant		$R(2.5)$ (cm^2)	Corrected $R'(2.5)$ (cm^2)	$R(3.5)$ (cm^2)	Corrected $R'(3.5)$ (cm^2)	$R(9.5)$ (cm^2)	Corrected $R'(9.5)$ (cm^2)
VNIIM:	$^{124}\text{Sb-Be}$	0.500 (0.011)	0.500 (0.011)	1.760 (0.034)	1.760 (0.034)	0.566 (0.010)	0.566 (0.010)
CIAE	$^{124}\text{Sb-Be}$	0.548 (0.019)	0.548 (0.019)	1.882 (0.063)	1.826 (0.063)	0.600 (0.020)	0.582 (0.020)
	Filtered beam	0.493 (0.022)	0.478 (0.022)	1.738 (0.078)	1.686 (0.078)	0.587 (0.026)	0.569 (0.026)
NIST	Filtered beam	0.422 (0.085)	0.422 (0.085)	1.342 (0.268)	1.342 (0.268)	0.493 (0.098)	0.493 (0.098)
PTB	Filtered beam	0.520 (0.023)	0.512 (0.023)	1.824 (0.078)	1.797 (0.086)	0.621 (0.024)	0.612 (0.028)
	$^7\text{Li(p,n)}$	0.492 (0.021)	0.485 (0.021)	1.783 (0.078)	1.756 (0.075)	0.583 (0.026)	0.574 (0.024)
	$^{45}\text{Sc(p,n)}$	0.497 (0.023)	0.490 (0.023)	1.738 (0.075)	1.712 (0.078)	0.559 (0.026)	0.551 (0.025)
NPL	$^{45}\text{Sc(p,n)}$	0.506 (0.025)	0.506 (0.025)	1.791 (0.083)	1.791 (0.083)	0.608 (0.027)	0.608 (0.027)
Calculated (MCNP)		0.468	0.468	1.684	1.684	0.610	0.610

Participants have applied their own corrections to adjust values to a mean energy of 24.5 keV

Uncertainties are standard uncertainties, i.e. are quoted at $k = 1$.

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Table 2. Values and (uncertainties) for the neutron fluence responses, corrected for the variation of the ^3He proportional counter response during the exercise and for the differences between the energies at which the measurements were made and the reference energy of 24.5 keV.

Participant		$R''(2.5)$ (cm^2)	$R''(3.5)$ (cm^2)	$R''(9.5)$ (cm^2)	Ratio (2.5/3.5)	Ratio (9.5/3.5)	Ratio (2.5/9.5)
VNIIM:	$^{124}\text{Sb-Be}$	0.500 (0.011)	1.755 (0.034)	0.567 (0.010)	0.285 (0.008)	0.323 (0.008)	0.882 (0.024)
CIAE	$^{124}\text{Sb-Be}$	0.534 (0.019)	1.832 (0.063)	0.583 (0.020)	0.291 (0.014)	0.318 (0.015)	0.916 (0.044)
	Filtered beam	0.478 (0.022)	1.686 (0.078)	0.569 (0.026)	0.284 (0.018)	0.337 (0.022)	0.840 (0.054)
NIST	Filtered beam	0.422 (0.085)	1.341 (0.268)	0.493 (0.098)	0.315 (0.089)	0.368 (0.103)	0.856 (0.242)
PTB	Filtered beam	0.519 (0.023)	1.820 (0.078)	0.620 (0.024)	0.285 (0.018)	0.341 (0.020)	0.837 (0.049)
	$^7\text{Li(p,n)}$	0.516 (0.022)	1.838 (0.078)	0.614 (0.024)	0.281 (0.017)	0.334 (0.020)	0.840 (0.050)
	$^{45}\text{Sc(p,n)}$	0.511 (0.024)	1.772 (0.075)	0.574 (0.026)	0.288 (0.018)	0.324 (0.020)	0.890 (0.058)
NPL	$^{45}\text{Sc(p,n)}$	0.513 (0.025)	1.797 (0.083)	0.600 (0.027)	0.285 (0.019)	0.334 (0.021)	0.855 (0.056)
Un-weighted mean and standard error of mean		0.499 (0.012) (2.5%)	1.730 (0.058) (3.4%)	0.578 (0.014) (2.4%)	0.289 (0.004) (1.3%)	0.335 (0.005) (1.6%)	0.865 (0.010) (1.2%)
Calculated (MCNP)		0.468	1.684	0.610	0.278	0.362	0.767

Corrections to the reference energy have been performed using response functions calculated by Wiegel at PTB

Uncertainties are standard uncertainties, i.e. are quoted at $k = 1$. Note, however, that the uncertainties in the ratios have been calculated from the individual response values and their uncertainties without considering correlations and are thus probably larger than they should be.

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9.3 Results for 9.5 inch sphere H

These results also consist of a band of seven values from four participants with upper and lower limits 9% apart, with an isolated value (NIST) about 16% lower than the un-weighted mean of the others, but is nevertheless within one standard error of the un-weighted mean. The other values are consistent within the estimated uncertainties which are all less than 5% (at 66.7% confidence level). The calculated (MCNP) value is about 3% higher than the un-weighted mean of the values from the four groups.

9.4 Overall trends

- a) The NIST values are consistently around 18% lower than the un-weighted mean of the other values.
- b) The values obtained from the CIAE ^{124}Sb -Be field are consistently higher than those for the VNIIM ^{124}Sb -Be field. These differences are, however, within the estimated uncertainties and the difference for the 9.5" sphere H is not significant.
- c) The PTB results for the filtered beam are about 8% higher than those for the CIAE filtered beam for all three spheres. These differences are also within the uncertainties.
- d) The NPL values are higher than those obtained using the PTB $^{45}\text{Sc}(p,n)$ field but the differences, averaging about 2%, are not significant.
- e) The values obtained from the CIAE ^{124}Sb -Be field are consistently higher than those for the CIAE filtered beam. The difference is 11% for the 2.5" sphere A but is not significant for the 9.5" sphere H. These differences are, however, within the estimated uncertainties.
- f) There are no marked internal trends for the results for the three fields used at the PTB.

9.5 Ratios of sensitivities for pairs of spheres

Three ratios of results for the three spheres in each field for each participant were calculated in order to cancel out possible systematic errors, for example, in fluence monitoring. From the values, shown in Table 3, it is clear that the variation of the ratios is less than that for the sets of responses of individual spheres, in spite of the fact that the random uncertainty components for each pair of spheres are additive, thus indicating some degree of correlation. This is reflected in the values for the standard error in the mean for the un-weighted values which are 1.3%, 1.6% and 1.2% for the ratios and 2.5%, 3.4% and 2.4% for the responses. The NIST values are the highest for the (2.5/3.5) and the (9.5/3.5) ratios but not for the (2.5/9.5) ratio possibly indicating that the 3.5" sphere result is low. For the (2.5/3.5) ratio the standard error of the mean, excluding the NIST result, is only 0.5%

10 DISCUSSION OF RESULTS

When the results outlined above were made known to all the participants in 1999 several questions arose.

- a) The uncertainty information provided was very variable, ranging from full uncertainty budgets to a simple statement of the final uncertainty. Although this comparison had been organized prior to the formalities of the Mutual Recognition Arrangement of the Comité International des Poids et Mesures (CIPM MRA)⁽¹¹⁾, a full uncertainty budget was requested from all the participants. Some additional data were subsequently received from the CIAE⁽¹²⁾.

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- b) The total uncertainty quoted by the VNIIM is roughly half the value quoted by most of the other participants. The VNIIM were asked to review their uncertainties but came to the conclusion that they were confident in their values and did not want to change them⁽¹³⁾ and these are the values used in deriving the reference values.
- c) Although the CIAE ¹²⁴Sb-Be source is similar to the corresponding VNIIM source, the spectrum and mean energy dependent corrections are only 2% compared to 11% for the 2.5" sphere when used with the VNIIM source. It was suggested that VNIIM could calculate the spectrum for the CIAE source. This was done and the data sent to CIAE who reviewed their results on the basis of this new data. Their conclusion was⁽¹⁴⁾: "According to the ¹²⁴Sb-Be neutron source spectrum calculated by VNIIM, the mean energy of the part of low energy is 19.8 keV (98.3%). The difference between the results of VNIIM and CIAE is 1.7 keV (21.5 keV, 97%). The mean energy is 24.7 keV, it is very close to 24.5 keV. Because the Kr* is about 98%, we suggest that the results do not be revised, but the uncertainty is expanded, adding the neutron source spectrum correction item 2.0%. So the combined uncertainty is 3.9%, the expanded uncertainty is 7.8% ($k = 2$) for ¹²⁴Sb-Be neutron source." The increase in the expanded uncertainty is not large, changing from 3.4% to 3.9%, and in the interests of getting the best possible reference values the revised uncertainties were used in their derivation.

11 EXPRESSION OF THE DEGREE OF EQUIVALENCE

In a key comparison the degree of equivalence of a laboratory's measurement standard is the degree to which this standard is consistent with the key comparison reference value, KCRV⁽¹¹⁾. This is expressed quantitatively in terms of the deviation of the comparison result from the KCRV and the expanded uncertainty of this deviation (coverage factor $k = 2$).

The degree of equivalence between any pair of national measurement standards is the degree to which the two standards are consistent. It is expressed in terms of the difference in the two comparison results and the expanded uncertainty of this difference.

In the present comparison the derivation of the KCRV and the calculation of the degrees of equivalence were complicated by the fact that two laboratories used more than one method to produce their neutron fields, and the fact that three transfer instruments with different responses were used. The various data values must be combined in order to derive the final results, however, in the first instance the data for individual transfer devices and all neutron production methods are compared to investigate in detail the consistency with the reference value for particular transfer devices.

11.1 Comparison of NMI results with the reference values for individual spheres

For each individual sphere, m , ($m = A, B, \text{ or } H$) a reference value, x_{refm} , can be derived from the n measured values, x_{nm} , reported by the laboratories ($n = 1$ to 8), and for each measured value an experimental difference, δ_{nm} can be calculated from:

$$\delta_{nm} = x_{nm} - x_{refm} \quad (1)$$

* The correction factor for the response at the reference energy

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The standard uncertainty, $u(\delta_{nm})$ in δ_{nm} is given⁽¹⁵⁾ by:

$$u^2(\delta_{nm}) = u^2(x_{nm}) - u^2(x_{refm}) \quad (2)$$

where $u(x_{nm})$ and $u(x_{refm})$ are the uncertainties in x_{nm} and x_{refm} respectively, and the expanded uncertainty (coverage factor $k = 2$) of this difference, $U(\delta_{nm})$, is given by:

$$U(\delta_{nm}) = 2 \cdot u(\delta_{nm}) \quad (3)$$

Values for x_{nm} and $u(x_{nm})$ were taken from Table 2 (with the exception of the slight increase in the CIAE value for the uncertainty of the $^{124}\text{Sb-Be}$ measurements – see section 10) and were used to calculate δ_{nm} , $U(\delta_{nm})$, and E values. The E -value, another measure of the deviation from the reference value, is defined as $\delta_{nm}/u(\delta_{nm})$. Table 3 to Table 5 give the values for each NMI, and for each transfer instrument in turn. The data are presented graphically in Figure 4 and Figure 5.

Table 3. The responses and experimental differences as determined using the 2.5" sphere A as a transfer standard

Laboratory	Technique	Response x_{nA} (cm ²)	Uncertainty $u(x_{nA})$	Differences and expanded uncertainties*		E -value
				δ_{nA}	$U(\delta_{nA})$	
VNIIM	$^{124}\text{Sb-Be}$	0.500	0.011	-0.005	0.015	-0.71
CIAE	$^{124}\text{Sb-Be}$	0.534	0.021	0.029	0.039	1.46
CIAE	Filt. beam	0.478	0.022	-0.027	0.041	-1.32
NIST	Filt. beam	0.422	0.085	-0.083	0.169	-0.98
PTB	Filt. beam	0.519	0.023	0.014	0.044	0.63
PTB	$^7\text{Li(p,n)}$	0.516	0.022	0.011	0.041	0.51
PTB	$^{45}\text{Sc(p,n)}$	0.511	0.024	0.006	0.046	0.25
NPL	$^{45}\text{Sc(p,n)}$	0.513	0.025	0.008	0.048	0.32
	Un-weighted mean	0.499	0.012			
	Weighted mean	0.505	0.007 [¶]	$\chi^2/\nu = 1.0$		
	Median	0.512				

* Calculated relative to the weighted mean

[¶] Calculated from $\sqrt{(1/\sum w_{nA})}$ where w_{nA} is the weight for value x_{nA} .

The reference values used to calculate the experimental differences in Table 3 to Table 5 were weighted means. Use of the weighted mean requires some justification, and the way in which appropriate weighting factors were derived to allow for possible correlations in the results from individual labs which used more than one technique requires explanation.

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Table 4. The responses and experimental differences as determined using the 3.5" sphere B as a transfer standard

Laboratory	Technique	Response x_{nB} (cm ²)	Uncertainty $u(x_{nB})$	Differences and expanded uncertainties*		E -value
				δ_{nB}	$U(\delta_{nB})$	
VNIIM	¹²⁴ Sb-Be	1.755	0.034	-0.013	0.045	-0.56
CIAE	¹²⁴ Sb-Be	1.832	0.072	0.064	0.134	0.96
CIAE	Filt. beam	1.686	0.078	-0.082	0.147	-1.11
NIST	Filt. beam	1.341	0.268	-0.427	0.533	-1.60
PTB	Filt. beam	1.820	0.078	0.052	0.148	0.71
PTB	Li(p,n)	1.838	0.078	0.070	0.148	0.95
PTB	⁴⁵ Sc(p,n)	1.772	0.075	0.004	0.142	0.06
NPL	⁴⁵ Sc(p,n)	1.797	0.083	0.029	0.157	0.37
Un-weighted mean		1.730	0.058			
Weighted mean		1.768	0.024 [¶]	$\chi^2/\nu = 1.1$		
Median		1.776				

* Calculated relative to the weighted mean

[¶] Calculated from $\sqrt{(1/\sum w_{nB})}$ where w_{nB} is the weight for value x_{nB} .

Table 5. The responses and experimental differences as determined using the 9.5" sphere H as a transfer standard

Laboratory	Technique	Response x_{nH} (cm ²)	Uncertainty $u(x_{nH})$	Differences and expanded uncertainties*		E -value
				δ_{nH}	$U(\delta_{nH})$	
VNIIM	¹²⁴ Sb-Be	0.567	0.010	-0.010	0.013	-1.52
CIAE	¹²⁴ Sb-Be	0.583	0.023	0.006	0.044	0.27
CIAE	Filt. beam	0.569	0.026	-0.008	0.050	-0.33
NIST	Filt. beam	0.493	0.098	-0.084	0.194	-0.87
PTB	Filt. beam	0.620	0.024	0.043	0.046	1.88
PTB	⁷ Li(p,n)	0.614	0.026	0.037	0.050	1.48
PTB	⁴⁵ Sc(p,n)	0.574	0.026	-0.003	0.050	-0.13
NPL	⁴⁵ Sc(p,n)	0.600	0.027	0.023	0.051	0.90
Un-weighted mean		0.578	0.014			
Weighted mean		0.577	0.008 [¶]	$\chi^2/\nu = 0.9$		
Median		0.587				

* Calculated relative to the weighted mean

[¶] Calculated from $\sqrt{(1/\sum w_{nH})}$ where w_{nH} is the weight for value x_{nH} .

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In view of the large differences in the uncertainties quoted, those from VNIIM being particularly small and those from NIST large, a weighted mean should be used rather than an un-weighted one, provided the uncertainties are reliable. After the results had been made known to the participants they were all asked to review their uncertainties. On the basis of new information about the ^{124}Sb -Be spectrum the CIAE changed their uncertainties for using this source, but the overall effect was small (an increase from 3.4% to 3.9%). No other participant changed their uncertainties so it would appear that the participants believed their uncertainties to be correct. Weighted means were therefore used as reference values.

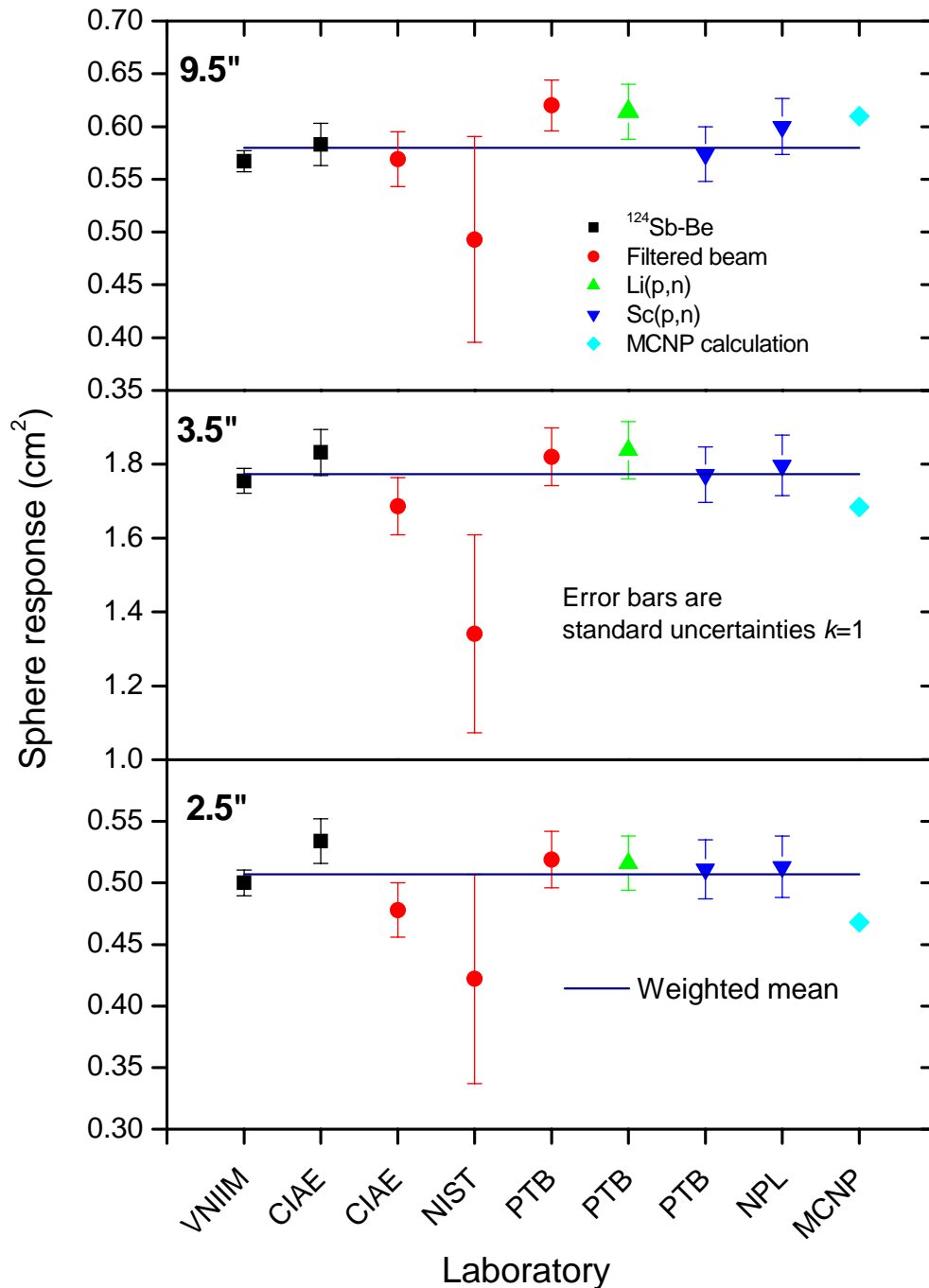


Figure 4. Measured sphere responses

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The use of more than one datum from a lab when calculating the reference value can be justified if the measurements are independent, use different techniques, and provided any correlations are negligible. The CIAE used both the iron filtered beam technique and an ^{124}Sb -Be source⁽⁴⁾. For the source the fluence was derived from a manganese bath measurement, whereas for the filtered beam the fluence was derived from a long counter measurement. The long counter had been calibrated at higher energies and a flat response was assumed to extrapolate the response down to 24.5 keV. The degree of correlation is thus believed to be negligible.

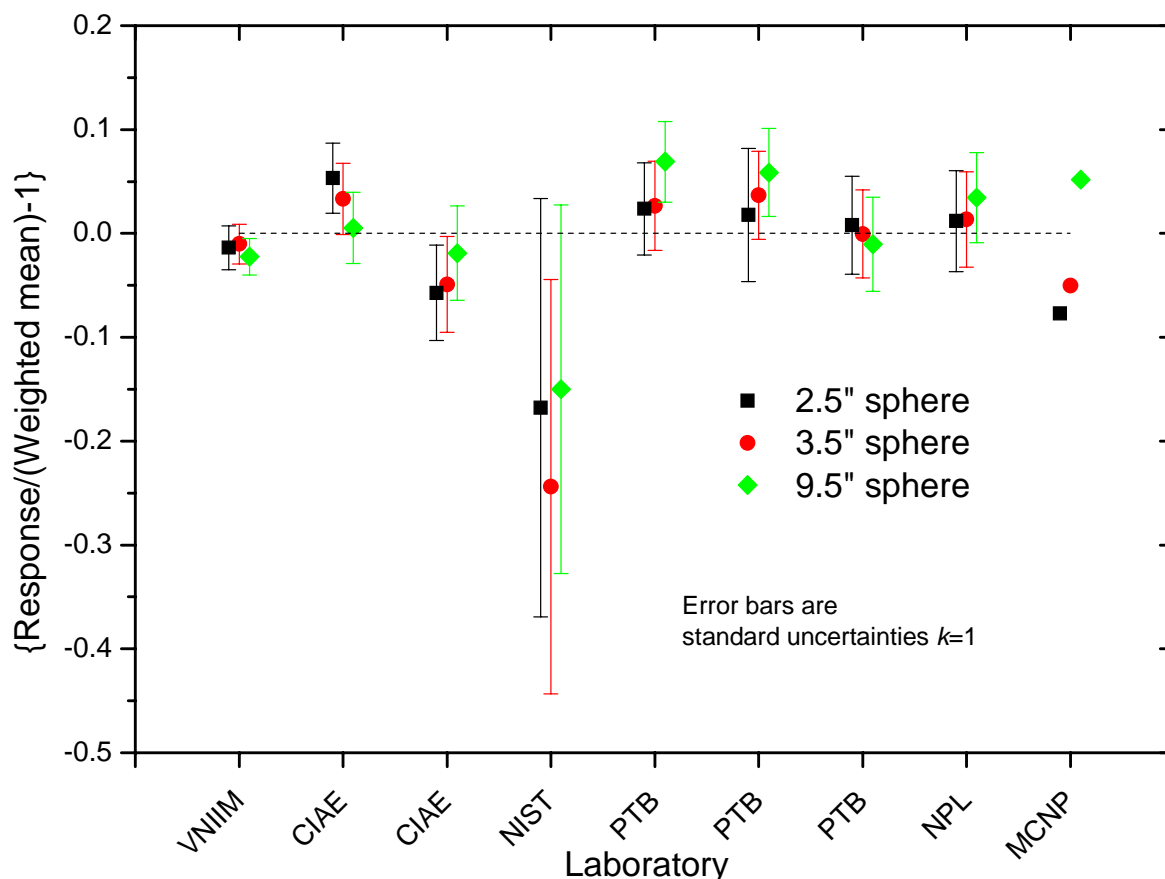


Figure 5. Measured responses displayed relative to the weighted mean value

The case of the three results from the PTB is, however, different. At their accelerator a recoil proton proportional counter, RPPC, was used to measure both the $^{45}\text{Sc}(p,n)$ and the $^7\text{Li}(p,n)$ neutron fluences. For the filtered beam this same RPPC was used together with a ^3He proportional counter as a check. Although there are several components in the uncertainty budgets for the three different techniques there is an obvious element of correlation present. In the PTB report⁽⁷⁾ a mean value of all three techniques is given for each sphere with an uncertainty which allows for these correlations. These values, after correction by the factor of 0.985 explained in section 7.4, are presented in Table 6, and these are the results used in deriving the reference values, presented as the weighted means, in Table 3 to Table 5. In practice the differences between the means derived by taking all data values as being independent and those obtained by taking a combined result in the case of the PTB measurements are very small. They are about 0.2% for the 2.5" and 3.5" spheres and about 0.4% for the 9.5" sphere.

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Table 6. PTB combined results for three techniques with uncertainty which allows for correlation.

	Neutron fluence response (cm ²)		
	2.5" sphere A	3.5" sphere B	9.5" sphere H
Mean value	0.515 ± 0.016	1.810 ± 0.055	0.603 ± 0.018

In Table 3 to Table 5 values are given for the chi-squared per degree of freedom, χ^2/ν , for each weighted mean. The no of degrees of freedom was taken to be 1 less than the number of independent measurements (i.e. 5). They indicate completely consistent sets of data.

11.2 Comparison of a given NMI with the KCRV

To enable a degree of equivalence to be calculated for each NMI, the data needed to be reduced to one value for each laboratory. This involved combining data from different measurement techniques when a lab used more than one. It also involved combining the data from the three transfer devices. For the PTB results mean values for the three neutron production techniques employed are presented in Table 6, and these were taken as the response values for that laboratory. For the CIAE data the uncertainties for the two measurement techniques were almost identical so a simple un-weighted mean was taken as the value for the laboratory. This process resulted in a set of values for the quantity, x_{im} , where the suffix i refers to a laboratory rather than a measurement. For VNIIM, NIST, and NPL $x_{im} = x_{nm}$ since only one neutron production technique was used by these labs, but for CIAE and PTB x_{im} is derived from two or more x_{nm} values. Values for the quantity, δ_{im} , i.e. differences between the laboratory values and the reference value for a sphere, can be derived from:

$$\delta_{im} = x_{im} - x_{refm} \quad (4)$$

Note that the value for x_{refm} is that derived from all the data for the reasons explained in section 11.1.

For VNIIM, NIST, and NPL the uncertainties, $u(x_{im})$, and $u(\delta_{im})$ are of course the same as $u(x_{nm})$, and $u(\delta_{nm})$. The uncertainties quoted in Table 6 for the PTB, although appropriate for calculating reference values, are not the best ones to use when deriving degrees of equivalence. This is because the result of any calibration performed would depend on the technique actually employed. Luckily all three techniques have very similar uncertainties so a mean of these was used to derive values for $u(x_{im})$ and hence, $u(\delta_{im})$. Similarly for the CIAE, the uncertainties for their two techniques were very similar, so the mean uncertainty was used.

To combine the results from the three transfer devices the response for each Bonner sphere relative to the weighted mean for that sphere, i.e. x_{im} / x_{refm} , was derived, and the results for the three Bonner spheres were combined for each lab simply by taking an un-weighted average to give a relative response, x_i , for each lab. The KCRV is thus defined as the value 1, and can be expressed in terms of cm²/cm². This approach results in the values shown in

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Table 7.

Table 7. Measured response values expressed as ratios to the reference values.

Laboratory	2.5" sphere A	3.5" sphere B	9.5" sphere H	$x_i = \text{mean of}$
	$\frac{x_{iA}}{x_{refA}}$	$\frac{x_{iB}}{x_{refB}}$	$\frac{x_{iH}}{x_{refH}}$	$\frac{x_{im}}{x_{refm}}$ values
VNIIM	0.990	0.993	0.982	0.988
CIAE	1.001	0.995	0.998	0.998
NIST	0.835	0.759	0.854	0.816
PTB	1.019	1.024	1.045	1.029
NPL	1.015	1.017	1.039	1.024

A unique value for the degree of equivalence d_i for each laboratory can then be defined as:

$$d_i = x_i - 1 \quad (5)$$

which is equivalent to the mean value of δ_{im}/x_{refm} for the three spheres. The uncertainty $u(x_i)$ is taken to be the average of the $u(x_{im})/x_{refm}$ values which, for a particular lab, were very similar for the three transfer devices. Similarly $U(d_i)$ is taken to be the average of the three individual, $U(\delta_{im})/x_{refm}$. The final results are presented in Table 8.

Table 8. Degrees of equivalence in relative terms for the three transfer devices and the mean value.

Laboratory	2.5" sphere A		3.5" sphere B		9.5" sphere H		$d_i =$	$U(d_i) =$
	δ_{iA}	$U(\delta_{iA})$	δ_{iB}	$U(\delta_{iB})$	δ_{iH}	$U(\delta_{iH})$	mean	mean
	$\frac{\delta_{iA}}{x_{refA}}$	$\frac{U(\delta_{iA})}{x_{refA}}$	$\frac{\delta_{iB}}{x_{refB}}$	$\frac{U(\delta_{iB})}{x_{refB}}$	$\frac{\delta_{iH}}{x_{refH}}$	$\frac{U(\delta_{iH})}{x_{refH}}$	$\frac{\delta_{im}}{x_{refm}}$	$\frac{U(\delta_{im})}{x_{refm}}$
VNIIM	-0.010	0.030	-0.007	0.026	-0.018	0.023	-0.012	0.026
CIAE	0.001	0.080	-0.005	0.080	-0.002	0.081	-0.002	0.080
NIST	-0.165	0.335	-0.241	0.301	-0.146	0.337	-0.184	0.324
PTB	0.019	0.086	0.024	0.083	0.044	0.084	0.029	0.084
NPL	0.015	0.095	0.017	0.089	0.040	0.088	0.024	0.091

11.3 Comparison of any pair of NMIs

The degree of equivalence, d_{ij} , between any pair of NMIs, i and j , is defined in terms of the difference:

$$d_{ij} = d_i - d_j = x_i - x_j \quad (6)$$

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and the expanded uncertainty (coverage factor $k = 2$) of this difference, $U(d_{ij})$, where:

$$U(d_{ij}) = 2 \cdot u(d_{ij}) \quad (7)$$

and

$$u^2(d_{ij}) = u^2(x_i) + u^2(x_j) \quad (8)$$

These values are presented in Table 9.

Table 9. Degrees of equivalence between pairs of participants

Lab i ↓	Lab j →		VNIIM		CIAE		NIST		PTB		NPL	
	d_i	$U(d_i)$	d_{ij}	$U(d_{ij})$	d_{ij}	$U(d_{ij})$	d_{ij}	$U(d_{ij})$	d_{ij}	$U(d_{ij})$	d_{ij}	$U(d_{ij})$
VNIIM	-0.012	0.026			-0.010	0.093	0.172	0.328	-0.041	0.096	-0.036	0.102
CIAE	-0.002	0.080	0.010	0.093			0.182	0.337	-0.031	0.123	-0.026	0.127
NIST	-0.184	0.324	-0.172	0.328	-0.182	0.337			-0.213	0.337	-0.208	0.339
PTB	0.029	0.084	0.041	0.096	0.031	0.123	0.213	0.337			0.006	0.130
NPL	0.024	0.091	0.036	0.102	0.026	0.127	0.208	0.339	-0.006	0.130		

12 COMMENTS ON FUTURE COMPARISONS

The CCRI(III) has agreed that comparisons should be repeated at least every ten years. However, the CIPM has concurred that the results of this comparison are valid until the comparison can be repeated. This is expected to be around 2012.

If an NMI makes a bilateral comparison of their primary standard with another NMI for this quantity, the results can be included in the database with the approval of the CCRI(III). Such approval requires that the comparison is declared in advance, that it follows an approved protocol, and that one of the NMIs already has a comparison result.

13 CONCLUSIONS

Low energies are important for instrument assessment as the IEC Standard 61005 on calibration and type testing of area survey instruments requires a calibration in each of the following energy ranges:

- thermal neutrons;
- at least one neutron energy in the range between 1 keV and 50 keV;
- at least one neutron energy in the range between 50 keV and 600 keV;
- at least one neutron energy in the range between 1 MeV and 5 MeV;
- at least one neutron energy in the range between 13.5 MeV and 16 MeV.

The present comparison exercise demonstrates that although there are significant difficulties in producing fields in the energy range 1 keV to 50 keV, standards can be produced albeit with

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rather low fluence rates and hence low dose equivalent rates.

Although four fundamentally different types of neutron field were used in this comparison, consistent values were obtained by participants for the fluence responses of the Bonner spheres with three different diameters. The accuracies achieved here suggest that uncertainties in neutron fluence determination in this energy region of better than 9% (at 95% confidence level) are generally possible. However, there are practical difficulties with the production of neutron fields in this energy region (e.g. low fluence rates with accelerator-produced fields, handling and half life problems with ^{124}Sb -Be sources).

With the limited number of laboratories using each type of field it is not possible to draw any conclusion regarding trends between the different techniques for producing neutrons in this energy region.

The Bonner sphere detector has now been successfully used in comparisons of fluence measurements from 25 keV to 15 MeV⁽¹⁶⁾. This represents the range of neutron energy that has so far been covered by CCRI comparisons (excluding measurements of thermal neutron fluence rate). No spheres used in the present exercise had optimum response function for this neutron energy region and therefore the corrections for spectral effects were not minimized.

There are a few trends and discrepancies in the results which could usefully be investigated.

ACKNOWLEDGEMENTS

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The contribution made by the participating laboratories to this exercise is gratefully acknowledged.

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¹ NMSPU is now within BIS, the Department for Business Innovation & Skills.

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APPENDIX 1. Schedule of measurements

Participant	Field	Instrumentation sent from BIPM	Completion of measurements	Comments
NIST	Filtered beam	March 1993	August 1993	Detector SP9-BIPM1 used
CIAE	$^{124}\text{Sb-Be}$ Filtered beam	October 1993	May 1994	Detector SP9-BIPM1 found to be defective; replaced by SP9-BIPM2.
PTB	Filtered beam $^7\text{Li(p,n)}$ $^{45}\text{Sc(p,n)}$	June 1994	November 1994	Calibration of SP9-BIPM2 changed between June and November
NPL	$^{45}\text{Sc(p,n)}$	December 1994	October 1995	Measurements in March 1995 stopped by failure of Van de Graaff beam deflection magnet. Six month delay to completion.
VNIM	$^{124}\text{Sb-Be}$	December 1995	April 1996	No comments
NMIJ	$^{45}\text{Sc(p,n)}$	June 1996	March 1998	Measurements delayed by refurbishment of accelerator facility. Background due to contaminant neutrons too high. Measurements postponed indefinitely.

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APPENDIX 2. Requested Experimental Data

The following information was requested for the report to the Evaluator.

Neutron fieldAntimony/beryllium source

Construction/encapsulation
 Neutron emission energy for the principal reaction
 Mean neutron energy after escape from source
 Energy of contaminant group
 Mean neutron energy after escape from source
 Proportions of principal and higher energy group (%).

Filtered reactor beam

Structure of filter
 Beam profile and/or description of scanning procedure
 Proportions of the principal and higher energy groups (%).

Scandium (p,n) reaction

Thickness of scandium layer
 Backing material and thickness
 Proton beam energy
 Energy loss in scandium layer and mean reaction energy
 Angles used for measurements with set of spheres
 Corresponding neutron energies and spreads at those angles.

Lithium (p,n) reaction

Thickness of lithium layer
 Backing material and thickness
 Proton beam energy
 Energy loss in lithium layer
 Mean neutron energy.

Spectra should be given for all fields used. State whether measured or derived by calculation.

Neutron monitoring system

Device used to monitor neutron fluence
 Dead time
 Monitor counts and times
 Data relating to stability

Neutron fluence measurement

Complete account of neutron fluence determination
 Corrections applied: their calculation or determination
 Values and associated uncertainties
 Spectrum obtained from detector used, if available
 Values for measured fluence per monitor unit

Measurements with Bonner spheres

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Details of electronics

Example of pulse height spectrum with indication of bias used.

Effective overall dead time of electronics circuit

Detailed description of determination of corrections due to air- and room scattered neutrons, and to target interaction effects.

Analysis of data

Value of response of each sphere in field(s) used

(for a bias of 0.20 of peak height in the ^3He detector spectrum)

Corrections applied for scattered neutrons, etc

Spectral correction

Value of response of each sphere for 24.5 keV neutron energy

Ratios of responses of pairs of spheres (2.5"/3.5", 9.5"/3.5", 2.5"/9.5") and associated uncertainties

Uncertainties

A complete statement of uncertainties is required for all values

Random uncertainties

Non-random uncertainties

Combined uncertainties

Method used to combine components

Correlation coefficients

Confidence level, preferably 95%.

APPENDIX 3. Experimental Details

A3.1 Antimony - beryllium sources

The VNIIM source consisted of a 6.3 mm diameter antimony ball in a 25 mm diameter sphere of beryllium, encapsulated in iron. The neutron emission (up to $5 \times 10^6 \text{ s}^{-1}$ at the time of the measurements with the Bonner spheres) was determined using the manganese bath method. The CIAE source consisted of a 15 mm diameter antimony ball in a 25 mm diameter beryllium shell. This was put into an aluminium cylinder, 25 mm diameter by 25 mm length, with a 0.5 mm wall. The neutron emission (up to $1.7 \times 10^6 \text{ s}^{-1}$ at the time of the measurements) was determined using the manganese bath method.

Both laboratories calculated the fluence rate at a given distance from the source emission rate, source anisotropy and the distance between source and detector effective centres. Corrections were applied for air and room scatter using the shadow-cone technique. For both sources the neutron spectrum was calculated in order to calculate the spectral corrections to the sphere responses. This type of source has a very high gamma radiation activity that necessitated a correction for the gamma pile-up effect in the ^3He detector of the Bonner spheres.

A3.2 Reactor beams with iron filter

The diameters of the filtered beams depended on collimator size, beam divergence and distance from the collimators. The collimator diameters were about (25, 30 and 50) mm for NIST, CIAE, and PTB respectively. The beam profile at the measurement positions depended on other geometrical parameters such as distance and beam divergence. Each laboratory employed a scanning technique to measure the effective uniform irradiation responses of the Bonner spheres.

The CIAE used a long counter, calibrated at 144 keV, 565 keV and higher energies, and a set of four Bonner spheres, with calibrations calculated employing MCNP, to determine the neutron beam fluence. The beam profile was measured using a cadmium-covered ^3He proportional counter. Measurements of the spectrum using a high-pressure, cylindrical ^3He proportional counter indicated that the higher energy contamination was less than 1% and therefore no spectral corrections were applied.

The NIST determined the neutron fluence using a cylindrical BF_3 proportional counter that had been calibrated using a thermal neutron beam to determine the number of ^{10}B atoms and an evaluated value for the $^{10}\text{B}(n,\alpha)$ cross section at 24.5 keV, and applying various corrections. Proton recoil counter measurements showed 97.1% of the fluence to be at 24.5 keV with 1.6% at 135 keV and 1% at 280 keV. The large uncertainty was essentially due to the beam calibration, assigned on the basis of inconsistent results obtained in this and previous work.

The PTB filtered beam was monitored with a fission chamber which was calibrated using a recoil proton proportional counter, RPPC. The same counter was used to measure the fluence in the accelerator-based measurements and details of its construction are given in the accelerator-based fields section below. The spectral distribution was obtained for two filter arrangements (iron filter and iron filter with titanium difference filter) using a transmission calculation with ENDF/B-VI cross sections, taking into account the reactor spectrum at the filter entrance. The ratio of the higher energy lines to the 24 keV line of 0.14 for the iron filter was reduced to 0.017 for the 'difference' beam. Difference spectra calibrations of detectors were made by taking the difference in responses obtained using the iron filter and the iron filter with difference filter.

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A3.3 Accelerator-based fields

At the PTB, a cylindrical proton recoil proportional counter, sensitive length 193 mm and diameter 55 mm, was used to determine the fluence of neutrons produced using the $^{45}\text{Sc}(p,n)^{45}\text{Ti}$ and $^7\text{Li}(p,n)^7\text{Be}$ reactions. The gas filling was 57.9 kPa hydrogen and 2.1 kPa methane. The response function was calculated for mono-energetic neutrons and folded with the neutron spectrum for a specified neutron-producing target for a specified measurement position, taking account of the neutron interactions with the target and counter materials. Special efforts were required to subtract the background due to the photon radiation in the accelerator-based neutron fields.

NPL measured the fluence of neutrons produced with the $^{45}\text{Sc}(p,n)^{45}\text{Ti}$ reaction using a precision long counter that had been calibrated using a range of radionuclide sources, including an ^{124}Sb -Be source. From earlier time-of-flight measurements the spectrum was believed to be mono-energetic. No corrections were applied for the effect of interactions in the neutron-producing target although an uncertainty component was included for this effect.

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APPENDIX 4. Reported uncertainties

The uncertainties presented by the various participants are listed below and are grouped according to the technique used to produce the neutrons. All values are standard uncertainties, i.e. are at a confidence level of about 66.7% ($k = 1$).

A4.1 Uncertainties when using an ^{124}Sb -Be source

Two participants used an ^{124}Sb -Be source and their quoted uncertainties are shown in Table A4. 1. The uncertainties have not been quoted in the same ways by both participants, but where an uncertainty has been quoted for the same parameter by both participants, e.g. for the source emission rate, the CIAE value is larger. There is a degree to which the uncertainty quoted by VNIIM for the source-detector characteristic constant is a combination of the distance and counting uncertainties quoted by CIAE.

Table A4. 1 Uncertainties quoted for neutron fluences produced by an ^{124}Sb -Be source

Parameter or effect	% uncertainty			
	2.5" sphere A	VNIIM 3.5" sphere B	9.5" sphere H	CIAE
Source emission rate	0.7	0.7	0.7	2.0
Source-detector characteristic constant	0.3	0.3	0.3	
Distance				0.2
Counting				1.5
Discriminator setting losses	0.01	0.01	0.01	
Gamma ray correction				2.0
Anisotropy	0.1	0.1	0.1	
Correction to reference energy	1.84	1.76	1.67	2.0
Other unspecified corrections				1.0
Total uncertainty – quadrature sum	2.0	1.9	1.8	3.9

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A4.2 Uncertainties when using filtered beams

Filtered beams were used by CIAE, NIST and PTB. The uncertainty budget provided by CIAE is presented in Table A4. 2.

Table A4. 2 Uncertainties quoted by CIAE for their filtered beam measurements

Component	Value
Efficiency of detector	2.5%
Monitor	1.0%
Sweep integral (Vol.)	2.0%
Counting	0.5%
Background	2.0%
Correction for high energy neutrons	2.0%
Total	4.2%

Unfortunately the uncertainty information provided by NIST is rather sparse. A “non-random uncertainty of 20%, at the 1 σ level” was assigned with a covering statement saying: “This is essentially the uncertainty in the beam calibration, and is assigned on the basis of inconsistent results obtained over a period of a number of years in the use of these beams”. A random uncertainty of 8% was also applied to cover uncertainties in corrections which have to be applied. The net result was an over-all uncertainty of 22% at the 1 σ level.

The PTB report⁽⁷⁾ contains a detailed breakdown of the uncertainties in the quantities used to derive the measured responses. The beam neutron current was measured using a cylindrical recoil proton proportional counter, RPPC, in two different ways namely with the counter axis parallel to the beam and with the axis perpendicular to the beam. (A check measurement with a ³He counter agreed with the values obtained with the RPPC, but this measurement was not included in the final result.) A weighted mean value of the results with the RPPC in its two orientations was taken as the value for the current. The model equations for analysing data from the two orientations differed and involved some different quantities. A final uncertainty of 3% was assigned to the current and this component is common for all three spheres.

Several components were involved in the uncertainties in the measured sphere count rates. The final values quoted in the report ranged from 2.1% for the 9.5" sphere to 3.0% for the 3.5" sphere. One additional component is included in the uncertainty budget to cover the correction for neutrons of energies > 24 keV. The final values are listed in Table A4. 3.

Table A4. 3. Uncertainties quoted by PTB for their filtered beam measurements

Uncertainty component	Transfer instrument		
	2.5" sphere A	3.5" sphere B	9.5" sphere H
The sphere count rates	2.4%	3.0%	2.1%
Correction for neutrons with $E_n > 24$ keV	0.3%	0.4%	1.1%
The neutron current in the filtered beam	3.0%	3.0%	3.0%
Total	3.9%	4.2%	3.8%

A4.3 Uncertainties when using the ${}^7\text{Li}(p,n)$ reaction

The PTB was the only lab to use the ${}^7\text{Li}(p,n)$ reaction and the uncertainty budget for their measurements is presented in Table A4. 4. The components are divided up into type A uncertainties (evaluated by a statistical analysis of a series of observations) and type B uncertainties (evaluated by means other than analysis of a series of observations).

Table A4. 4 Uncertainty budget provided by PTB for measurements with the ${}^7\text{Li}(p,n)$ reaction

Source of uncertainties	Type A	Type B
Fluence measurement with the RPPC		
- active gas volume		0.8%
- gas filling (purity, p , T)		0.8%
- n,p cross section		0.7%
- fitting procedure MC-Exp.		1.8%
- external distance		0.1%
- in-out-scattering		1.0%
- target scattering correction		0.2%
- background subtraction		0.5%
- fluence attenuation in air		0.3%
quadratic sum		2.5%
- gamma attenuation in the shadow cone		2.7%
- counting statistics	1.0%	
quadratic sum	1.0%	3.7%
Measurement with the spheres		
- distance		0.3%
- counting statistics etc.	1.7%	
Overall uncertainties		4.2%

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A4.4 Uncertainties when using the $^{45}\text{Sc}(p,n)$ reaction

The $^{45}\text{Sc}(p,n)$ reaction was used by PTB and NPL. The instruments used to measure the fluence, a recoil proton proportional counter, RPPC, in the case of PTB and a long counter in the case of NPL, are different and it is thus not possible to compare corresponding uncertainty estimates. The uncertainty budgets of the two labs are therefore presented here separately in Table A4. 5 and Table A4. 5.

Table A4. 5 Uncertainty budget provided by PTB for measurements with the $^{45}\text{Sc}(p,n)$ reaction

Source of uncertainties	Type A	Type B
Fluence measurement with the RPPC		
- active gas volume		0.8%
- gas filling (purity, p , T)		0.8%
- n,p cross section		0.7%
- fitting procedure MC-Exp.		2.0%
- external distance		0.1%
- in-out-scattering		1.0%
- target scattering correction		0.2%
- background subtraction		0.5%
- fluence attenuation in air		0.3%
quadratic sum		2.68%
- gamma attenuation in the shadow cone		2.2%
- counting statistics	1.8%	
quadratic sum	1.8%	3.46%
Measurement with the spheres		
- distance		0.3%
- counting statistics etc.		
2.5" sphere A	2.4%	
3.5" sphere B	1.6%	
9.5" sphere H	2.3%	
Overall uncertainties		
2.5" sphere A		4.6%
3.5" sphere B		4.2%
9.5" sphere H		4.5%

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Table A4. 6 Uncertainty budget provided by NPL for measurements with the $^{45}\text{Sc}(p,n)$ reaction

Uncertainty component	% value
Type B uncertainties for fluence and sphere measurements	
Long counter efficiency	1.5%
Positioning the long counter	0.3%
Positioning the spheres	0.3%
Effective centre of the long counter	0.7%
Monitor calibration stability	0.5%
Air out scatter (10% of correction)	long counter spheres 0.4% 0.4%
In-scatter correction (6% of correction)	long counter 2½" sphere A 3½" sphere B 9½" sphere H 0.3% 1.3% 0.8% 0.7%
Absence of a correction for target scatter	2.0%
Absence of a correction for scatter into the monitor	2.0%
Systematic (type B) uncertainties added in quadrature:	
	2½" sphere A 3½" sphere B 9½" sphere H 3.6% 3.5% 3.5%
Type A uncertainties for fluence and sphere measurements	
	2½" sphere A 3½" sphere B 9½" sphere H 3.3% 2.9% 2.9%
Total uncertainty obtained by adding type A and B in quadrature	
	2½" sphere A 3½" sphere B 9½" sphere H 4.9% 4.6% 4.4%

Rounding errors in displaying the component uncertainties mean that they do not always appear to add in quadrature to the final total uncertainty

ANNEX BONNER SPHERE RESPONSE FUNCTIONS - DETAILED DATA

(B. Wiegel, PTB Braunschweig)

The response $R_d(E_n)$ for neutron energy E_n was calculated with the Monte Carlo code MCNP4A [A1]. In order to get consistent results between calculations and calibration measurements at different energies for a set of Bonner Spheres, e.g. the one used at PTB (called PTB-C), the geometry model used as input to MCNP needs to include a detailed description of the central ^3He -filled counter (Centronic Ltd., Model SP9). For details of the calculations for the PTB-C set see reference A2.

For the special set of Bonner Spheres used in this comparison (2.5", 3.5" and 9.5") the above mentioned model was used with some modifications. Figure A1 shows as an example the MCNP geometry plot of the NPL 2.5" sphere as a cross section along the symmetry axis (the stem on the right side of the counter is not shown completely). The technical drawing of the moderator sphere, as given in Figure 1, shows an extra gap between the counter and the polyethylene (PE) sphere - compared to the PTB hardware, labeled "air gap C-S" in Figure A1. The way the two PE half spheres are connected (see Figure 1) implies an additional volume which is not filled with PE. This complicated looking gap was approximated by a ring of rectangular cross section which is labeled "air gap S-S" in Figure A1. All shaded areas in Figure A1 are additional air gaps compared to the PTB design.

The polyethylene density ρ_{PE} is determined from the volumes of the PE shells calculated by

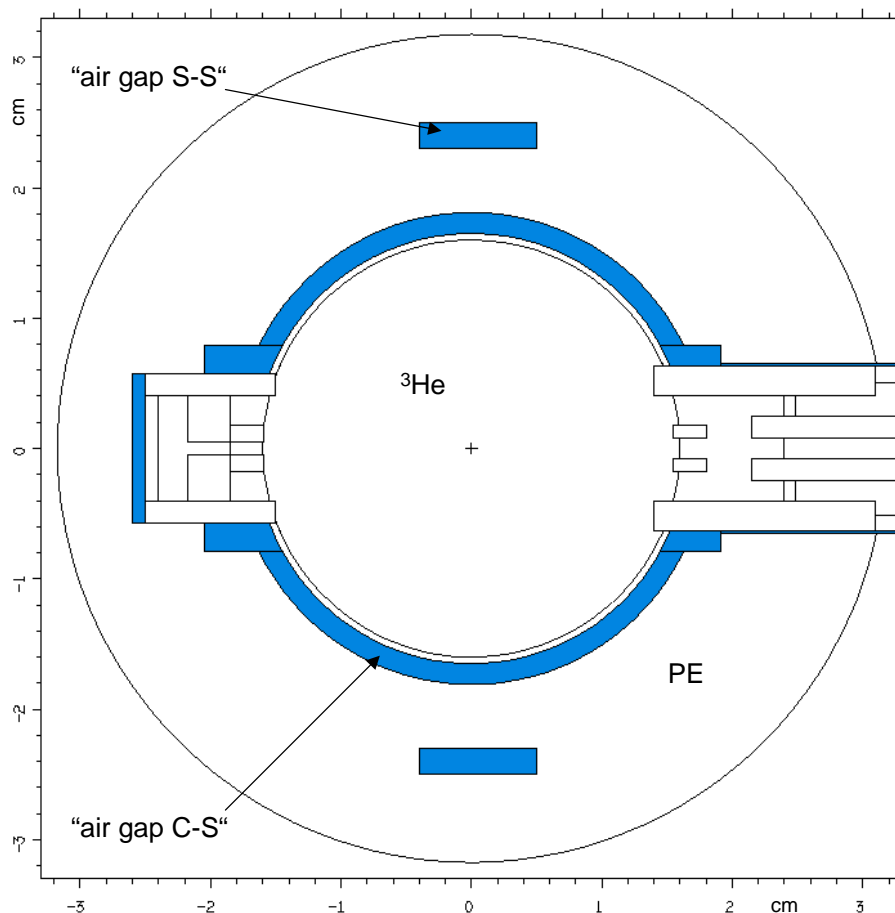


Figure A1: MCNP geometry plot of the NPL 2.5" sphere with additional air gaps.

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Table A1: Calculated volumes and densities of the polyethylene (PE) shells. The numbers in parentheses are the results without "air gap S-S".

d in inch	m in g	V_{MCNP} in cm^3	ρ_{PE} in g cm^{-3}
2.5	98	103.3 (106.0)	0.9487 (0.9245)
3.5	315	333.3 (338.1)	0.9451 (0.9317)
9.5	6988	7313.9 (7316.6)	0.9554 (0.9551)

MCNP and their measured masses (measurements were performed at NPL and at NIST). Since the three spheres were made from the same batch of polyethylene it is assumed that the densities are the same for all three spheres. With these constraints the dimensions of "air gap S-S" has been varied until the three calculated PE densities were comparable. Since the 2.5" sphere (A) is embedded in sphere shell H to become the 9.5" sphere (see Figure 2) the variation was always the same for those two spheres. Table A1 gives the final values for the MCNP-calculated volumes of the polyethylene shells and the corresponding PE densities.

The response functions $R_d(E_n)$ of the Bonner Sphere including the SP9 detector provided by

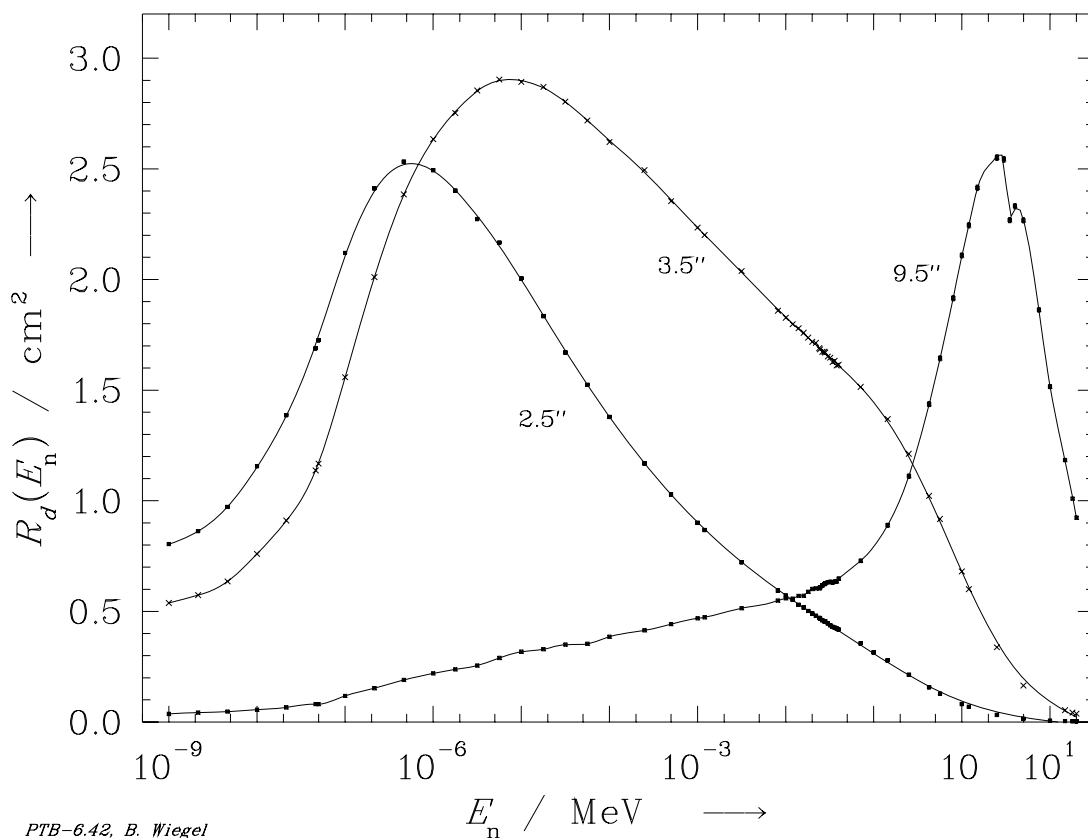


Figure A2: Response functions $R_d(E_n)$ for three diameters d . The responses were calculated at the energies marked by the symbols (uncertainties smaller than the symbol sizes), the lines are spline fits. Responses are valid only for the specified parameter values of ρ_{PE} and n_{He} .

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NPL were calculated with the following parameters:

- polyethylene density $\rho_{PE} = 0.95 \text{ g/cm}^3$ which is the average of the three values listed in Table A1
- ^3He number density $n_{He} = 4.9418 \cdot 10^{19} \text{ cm}^{-3}$ which is the value determined for the PTB detector "A".

It is important to note that the absolute responses shown in Figure A2 and listed in Table A2 are valid only for the parameter values given above. The energy grid is that used for the PTB set with special emphasis on energies between 10 keV and 40 keV.

Table A2: Absolute response values $R_d(E_n)$ and their relative statistical uncertainties u_d for three diameters d . Responses are valid only for the specified values of ρ_{PE} and n_{He} .

E_n MeV	$R_{2.5}(E_n)$ cm^2	$u_{2.5}$ %	$R_{3.5}(E_n)$ cm^2	$u_{3.5}$ %	$R_{9.5}(E_n)$ cm^2	$u_{2.5}$ %
1.000E-09	0.80400	0.32	0.53791	0.51	0.03640	3.27
2.150E-09	0.86258	0.32	0.57346	0.51	0.04280	3.09
4.640E-09	0.97201	0.32	0.63500	0.51	0.04720	2.95
1.000E-08	1.15600	0.33	0.75962	0.47	0.05582	3.16
2.150E-08	1.38670	0.31	0.91086	0.44	0.06616	2.84
4.640E-08	1.68880	0.30	1.13700	0.42	0.08072	2.58
5.000E-08	1.72490	0.30	1.16750	0.42	0.08070	2.54
1.000E-07	2.12020	0.29	1.55820	0.36	0.11819	2.15
2.150E-07	2.41160	0.27	2.01060	0.33	0.15289	1.95
4.640E-07	2.53210	0.26	2.38440	0.32	0.19001	2.01
1.000E-06	2.49370	0.26	2.63440	0.31	0.21973	1.87
1.780E-06	2.40130	0.25	2.75230	0.31	0.23759	1.82
3.160E-06	2.27340	0.25	2.85420	0.32	0.25510	1.76
5.620E-06	2.16620	0.25	2.90380	0.34	0.28944	1.64
1.000E-05	2.00450	0.26	2.89320	0.33	0.31742	1.68
1.780E-05	1.83440	0.27	2.87040	0.33	0.32862	1.66
3.160E-05	1.67020	0.28	2.80360	0.34	0.34990	1.59
5.620E-05	1.52400	0.29	2.71850	0.34	0.35340	1.56
1.000E-04	1.37870	0.31	2.62120	0.35	0.38555	1.52
2.500E-04	1.16850	0.32	2.49410	0.34	0.41400	1.46
5.000E-04	1.02820	0.31	2.35410	0.32	0.44252	1.40
1.000E-03	0.90015	0.33	2.23470	0.33	0.46873	1.37
1.200E-03	0.86747	0.34	2.20140	0.33	0.47326	1.37
3.160E-03	0.72156	0.37	2.03820	0.34	0.51431	1.31
8.150E-03	0.59413	0.38	1.85850	0.36	0.54860	1.27
1.000E-02	0.57130	0.37	1.82690	0.36	0.55867	1.26
1.200E-02	0.55212	0.38	1.79750	0.37	0.55720	1.24
1.400E-02	0.52966	0.39	1.77950	0.37	0.57034	1.24
1.600E-02	0.51743	0.39	1.75940	0.37	0.57046	1.23
1.800E-02	0.50185	0.40	1.73740	0.37	0.58881	1.21
2.000E-02	0.49020	0.41	1.71820	0.37	0.60138	1.21
2.200E-02	0.47962	0.41	1.71340	0.37	0.60365	1.21
2.400E-02	0.47051	0.19	1.68960	0.17	0.60411	0.54
2.450E-02	0.46777	0.19	1.68410	0.17	0.60966	0.54
2.600E-02	0.45998	0.42	1.67330	0.38	0.61783	1.20

Table A2: Absolute response values $R_d(E_n)$ and their relative statistical uncertainties u_d for three diameters d . Responses are valid only for the specified values of ρ_{PE} and n_{He} (continued).

CCRI(III)-K1 24 keV Neutron Fluence Comparison

E_n MeV	$R_{2.5}(E_n)$ cm^2	$u_{2.5}$ %	$R_{3.5}(E_n)$ cm^2	$u_{3.5}$ %	$R_{9.5}(E_n)$ cm^2	$u_{2.5}$ %
2.740E-02	0.45537	0.42	1.67360	0.38	0.62328	1.19
2.800E-02	0.45550	0.42	1.66960	0.38	0.62761	1.17
3.000E-02	0.44611	0.43	1.65180	0.38	0.63150	1.19
3.200E-02	0.43752	0.43	1.64640	0.38	0.63351	1.18
3.400E-02	0.43055	0.43	1.62640	0.38	0.63049	1.18
3.600E-02	0.42640	0.44	1.63210	0.38	0.63388	1.17
3.800E-02	0.42259	0.44	1.61120	0.39	0.63577	1.17
4.000E-02	0.41769	0.44	1.61480	0.39	0.64766	1.17
7.100E-02	0.35530	0.46	1.51490	0.38	0.72852	1.10
1.000E-01	0.31456	0.47				
1.440E-01	0.27878	0.49	1.36910	0.37	0.88973	0.99
2.500E-01	0.21357	0.54	1.21200	0.39	1.11130	0.89
4.250E-01	0.15686	0.60	1.02160	0.40	1.43660	0.78
5.650E-01	0.12777	0.63	0.91741	0.42	1.64400	0.71
8.000E-01					1.91540	0.60
1.000E+00	0.08120	0.71	0.68085	0.44	2.10880	0.54
1.200E+00	0.06880	0.76	0.60003	0.46	2.24450	0.53
1.500E+00					2.41460	0.51
2.500E+00	0.03180	0.98	0.33780	0.56	2.55060	0.50
3.000E+00					2.54300	0.50
3.500E+00					2.26830	0.52
4.000E+00					2.33180	0.52
5.000E+00	0.01400	1.27	0.16493	0.69	2.26700	0.52
7.500E+00					1.86210	0.55
1.000E+01	0.00563	1.89			1.51560	0.57
1.480E+01	0.00431	1.92	0.05352	1.09	1.18390	0.62
1.800E+01	0.00340	2.03	0.04243	1.22	1.00960	0.66
2.000E+01	0.00291	2.08	0.03774	1.31	0.92338	0.68

REFERENCES used in the Annex

- [A1] Briesmeister J.F. (Editor), *MCNP - A General Monte Carlo N - Particle Transport Code Version 4A*, LA-12625-M, Los Alamos National Laboratory, 1993.
- [A2] Wiegel B., Alevra A., Siebert B.R.L., *Calculations of the Response Functions of Bonner Spheres with a Spherical ^3He Proportional Counter Using a Realistic Detector Model*, PTB report PTB-N-21, Braunschweig 1994.

References

- 1 R.S. Caswell and V.E. Lewis, Neutron Measurement Intercomparisons sponsored by CCEMRI, Section III (Neutron Measurements), *Radiation Protection Dosimetry*, **44**, 105 - 110 1992.
- 2 T.B. Ryves, International Fluence-Rate Intercomparison for 144 and 565 keV Neutrons, *Metrologia* **24**, 27 - 37, 1987.
- 3 D.B. Gayther, International Intercomparison of Fast Neutron Fluence-Rate Measurements using Fission Chamber Transfer Instruments, *Metrologia* **27**, 221 - 231, 1990.
- 4 R.B. Schwartz, 1995 Measurement of 24.5 keV fluence, *Private communication* from D.M. Gilliam to V. E. Lewis.
- 5 Rong Chaofan, Zhai Guangnian, Bao Zongyu and Yang Xiaoyun. 1996, The comparison of 24.5 keV neutron fluence measurement, *Private communication* from Rong ChaoFan to V. E. Lewis.
- 6 D.J. Thomas, 1996, Sc(p,n) measurements for CCEMRI comparison Sept/Oct 1995, *Private communication* to V E Lewis. Later superseded by: David J. Thomas, NPL contribution to an international comparison of 24.5 keV neutron fluence measurements, *NPL Report CIRM 46*, June 2001.
- 7 E. Dietz, S. Guldbakke, and D. Schlegel, 1999, Comparison of 24.5 keV neutron fluence measurements at the PTB, *PTB Report PTB-N-37*, Braunschweig, January 1999
- 8 I. Kharitonov, 1997 Report on fluence-rate measurements for 24 keV neutrons, *Private communication* to V E Lewis
- 9 V.E. Lewis, Comparison of 24.5 keV Neutron Fluence Measurements 1993 – 1996, *NPL Report CIRM 16*, December 1998.
- 10 H. Klein 1998 *Private communication* to V.E. Lewis.
- 11 CIPM MRA: Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes, *International Committee for Weights and Measures*, 1999, 45 pp. <http://www.bipm.org/pdf/mra.pdf>.
- 12 R. Chaofan et al. 2001, *Private communication* from CIAE to H. Klein, 11/06/2001
- 13 N. Moiseev, *Private communication* from VNIIM to H. Klein
- 14 R. Chaofan, 2005, *Private communication* from CIAE to H. Klein 27/06/2005
- 15 M.G. Cox, The evaluation of key comparison data, *Metrologia* **39**, 589-596, 2002.
- 16 E.J. Axton, Report on intercomparison of neutron fluence measurements using two Bonner spheres as transfer instruments. *Report 93-2 to Section III*, CCEMRI, 1993. See also reference 1.