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Neutron Energy Response of a Modified Andersson-Braun Rem Counter

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Neutron Energy Response of a Modified Andersson-Braun Rem Counter

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Abstract

The energy response of four models of Andersson Braun (A-B) rem counters in different energy neutron radiation fields has been investigated. In three higher monoenergetic points and two high-energy stray radiation fields the energy response for modified A-B rem counters is better than that of conventional A-B rem counters. In the field of high-energy neutron radiation underestimations of the neutron dose equivalent will be unavoidable with the conventional A-B rem counter.

1 Introduction

The prompt radiation field around a high-energy accelerator is closely correlated with the primary beam energy. When the accelerated electron or proton energy is higher than a certain energy a secondary neutron (energy above 20 MeV) is produced. For a high-energy proton accelerator approximately 50% of the dose equivalent (D.E.) is contributed by neutrons with an energy greater than 50 MeV [1]. The measurement and evaluation of the high-energy neutron (above 20 MeV) dose equivalent is important for radiation protection.

The present commercial rem counter (conventional Andersson-Braun rem counter) is usually used to measure the neutron dose equivalent. However as is well known, the response of the conventional rem counter is underestimated in the energy interval from thermal to about 1 eV, and overestimated in the region from 1 eV to 100 keV. The adequate energy range is from 100 keV to 6 MeV. The response decreases with energy above 6 MeV, and diverges from the ICRP standard curve.

The carbon activation detector had been developed by a few high-energy physics laboratories to measure the neutron D.E. at an energy above 20 MeV. It is a passive-type detector which can not be used as an on-line monitor.

According to the parameters provided by R.K.Sun, a modified A-B rem counter was developed by Radiation Protection Division of IHEP. According to a theoretical calculation

[2], it could extend the energy response range to a high-energy region.

The purpose of this experiment was to investigate the neutron energy response of the modified A-B rem counter in the high-energy region. A few monoenergetic neutron source facilities, the ^{252}Cf radioactive neutron source and the radiation field outside the shielding in the east counter hall of the 12 GeV proton synchrotron at KEK (E-hall of KEK-PS), were used for this experiment. Four types of A-B rem counters were used in this energy response calibration (Table 1).

2 Modified A-B rem counter

The conventional A-B rem counter consists of a BF_3 proportional counter, an inner polyethylene moderator, a boron plastic attenuator and an outer polyethylene moderator (Fig.1).

The modified A-B rem counter has a similar construction to that of a conventional A-B rem counter (Fig.2). The unique point is adding a layer of 10mm lead (Pb) around the boron plastic attenuator. This Pb layer plays an important role in extending the energy response range of the A-B rem counter.

The moderation effect in a conventional rem counter is not sufficient to allow the high-energy neutrons to be recorded by a BF_3 counter. Therefore the response in high-energy region decreases. After passing through the outer polyethylene layer of a modified A-B rem counter, the low-energy neutrons interact with Pb nuclei, and cause elastic scattering. This process doesn't produce moderation. Therefore, this Pb layer of a modified A-B rem counter doesn't affect the correct response in the low-energy region, as does the conventional A-B rem counter.

When high-energy neutrons interact with Pb nuclei, inelastic scattering takes place. The high-energy neutrons give up a part of the initial energy to Pb nuclei and are moderated. They can then be detected by a BF_3 proportional counter.

The construction parameters of the A-B rem counter used in the energy response calibration are given in Table 2.

3 Low-energy response calibration (< 20 MeV)

3.1 Thermal neutron calibration

A calibration with thermal neutrons was carried out in the standard field at the Radiation Dosimetry Division of Department of Health Physics, Tokai Research Establishment, Japan Atomic Energy Research Institute. A-B rem counters were placed 40 cm from the surface of graphite pile which contains a ^{235}Cf neutron source. The cadmium cover was used to subtract the over-cadmium neutron. The measured data and results are listed in the Tables 3 and 4. The uncertainty in the measurements is on the order of 12%.

3.2 8 keV semi-monoenergetic neutron calibration

This energy calibration was carried out using the Dynamitron facility at the Fast Neutron Laboratory (FNL) of the Department of Nuclear Engineering, Tohoku University [3].

An 8 keV neutron field was set up at the 30^0 port of the Dynamitron accelerator located at the center of the experimental room (Fig.3). The rem counters to be calibrated were placed 1 meter from the target on the 0^0 beam line.

A BF_3 counter (monitor 1) and the proton beam current (monitor 2) were used for monitoring. Monitor 2 was used for normalizing the measured data. The effect of scattering neutrons was corrected by means of a shadow bar. The absolute fluence conversion factor is $5.27 \times 10^3 \text{ n/cm}^2/\mu\text{c}$ at 1.27cm, and 100 counts of monitor 2 equals $1\mu\text{c}$. The measured data and results are given in Tables 5 and 6. The uncertainty of this measurement is on the order of 20%.

3.3 Calibration using a ^{252}Cf ($\bar{E}_n=2.5 \text{ MeV}$) neutron source

The calibration was carried out in the calibration room at the Cyclotron and Radioisotope Center (CYRIC), Tohoku University. The ^{252}Cf standard source was evaluated in the national standard field at the Electron Technical Laboratory (ETL). Its neutron emission

rate was $1.7218 \times 10^6 \text{ n}/(\text{s} \cdot 4\pi)$ on 24 th of May, 1995. Rem counters were placed 1 meter and 1.5 meters from the ^{252}Cf neutron source.

The same method as that for 8 keV was used to correct for the neutron scattering effect. The measured data and results are given in Tables 7 and 8. The uncertainty in these measurements is on the order of 16%.

4 High-energy response calibration

A high-energy response calibration was carried out using semi-monoenergetic neutron source facilities.

4.1 22.0 and 32.5 MeV semi-monoenergetic neutron calibration

The monoenergetic neutron field in the cyclotron facility at CYRIC was used in the calibration (Fig.4). Protons of 25 and 35 MeV were injected into a Li target to produce semi-monoenergetic neutrons of 22.0 and 32.5 MeV [4].

The neutrons emitted within 10° of the forward direction were used for the calibration after passing through two collimators, while proton beams penetrating through the Li-target were injected into a Faraday cup (Fig.5).

Since the A-B rem counters were located in the time of flight room, which is a long corridor, the neutron scattering effect could be neglected. The absolute values of the neutron fluences had been measured with a proton recoil counter telescope. Three monitors were used for monitoring: a ^{232}Th fission chamber (monitor 1), an NE213 liquid scintillator (monitor 2), and a proton current monitor (monitor 3). The fission chamber was used for normalization of the measured data.

The neutron energy spectra had been measured using the time of flight method (Fig.6 and Fig.7). The peak fluence conversion factors are given in Table 9. As can be seen in the above figures, the neutron energy distribution contains a continued spectrum below the

peak. At 22.0 MeV the neutron fluence of the peak part is 43.3%; the rest is 56.7%. At 32.5 MeV, the neutron fluence of the peak part is 40.1%; the rest is 59.9%. The A-B rem counters are sensitive to this part of the neutrons as well as the peak neutrons, though the sensitivities are different for these two parts. In the data process, the low energy counts of neutrons were subtracted using the calculated response curves of the conventional rem counter.

The measurement data and results are shown in the Tables 10,11,12 and 13. The total uncertainty of this measurement is on the order of 9%.

4.2 45.4 MeV semi-monoenergetic neutron calibration

The 45.4 MeV monoenergetic neutrons were provided by the 90 MV cyclotron facility of The Takasaki Ion Accelerators for Advanced Radiation Application (TIARA), Takasaki Radiation Chemistry Research Establishment, Japan Atomic Energy Research Institute (JAERI) (Fig.8) [5]. Fig.9 shows a vertical view of the semi-monoenergetic neutron source facility.

The proton beam bombard a Li-target so as to produce neutrons; the penetrating protons are bent downward by a clearing magnet so as to convey them into a Faraday cup. During the experiments the neutron source was monitored using the proton current of the Faraday cup (monitor 1), the ^{238}U (monitor 2) and the ^{232}Th (monitor 3) fission chamber. The rem counters were placed 885cm far from the exit of the collimator. The measured data and results are given in the Tables 14 and 15.

In the case that proton current was more than $300\text{ }\mu\text{A}$, there was a dark current for the monitor 1. So the fission chamber (monitor 2) was used for normalization of the measured data. The neutron energy spectra had been measured using the time of flight method (Fig.10). The peak absolute fluence conversion factor is $2.71 \times 10^9\text{ n/sr/}\mu\text{c}$ and 100 counts of monitor 1 equals $1\text{ }\mu\text{c}$. The ratio of counts of monitor 2 to monitor 1 equals 17.19. As can be seen in the above figures, the neutron energy distribution contains a continued spectrum below the peak. The neutron fluence of the peak is 46%; the rest is 54%. The

A-B rem counters are sensitive to both parts of the neutrons. In the data process, the low energy counts of neutrons were subtracted using the measured sensitivities for 22.0 MeV neutrons.

5 Measurements in the E-hall of the KEK-PS

The characteristics of the neutron radiation field and neutron spectrum had been measured in the E-hall of the KEK-PS [2]. Based on the above mentioned radiation field information, the response experiment of A-B rem counters was completed.

The beam comprises of 12 GeV protons with a beam intensity 4×10^{12} protons/spill. The long-pulse mode of the beam structure was used in this experiment. The repetition was 4.0 sec and the spill 2.0 sec.

As shown in Fig. 11, the slow extracted beam line (EP2) and the target assembly were shielded on the top and sides by concrete blocks. Two different positions were chosen for an intercomparison: one was outside the shielding configuration (No.1); the another was on the top of the shielding configuration (No.2).

One A-B rem counter was located at a fixed point near to the measurement position as a monitor. All of the measured data were normalized by the monitor. The carbon activation detector was used for measuring the neutron fluence rate with an energy above 20 MeV. The ratio of the neutron fluence measured by the carbon activation detector to the neutron fluence rate measured by the conventional A-B rem counter which is called as the ratio of ^{11}C to rem, was used to evaluate the hardness of the neutron spectra in the stray radiation field. The measurement data and results are presented in Tables 16 and 17.

6 Results and discussion

6.1 Energy response in monoenergetic neutron fields

Five neutron energy calibrations have been completed. The energy response of the absolute fluence sensitivities is given in Table 18. Because the four rem counters used in this experiment have parameters different from those of the BF_3 proportional counters and the circuits, the sensitivities of the rem counters are different.

In order to compare the energy response, the sensitivities of all the rem counters were normalized to the sensitivity of the model 2202D rem counter for ^{252}Cf . In this case, the sensitivities of all the rem counters at ^{252}Cf neutron energy have the same value. The normalizing process is reasonable because the ^{252}Cf energy is just in the energy range from 100 keV to 6MeV. In this range the energy response curves of conventional and modified A-B rem counters agree with the ICRP standard curve [2].

The dependence of the normalized fluence sensitivity on the neutron energy is shown in Table 19, Figs.13 and 14. As shown in the above table and the figure, the sensitivity of the M95-2 at 8 keV is not affected by the added lead layer in its construction. At a neutron energy of 22.0 MeV, the sensitivity of the M95-2 is 28% higher than that of the 2202D, and for the 6060 it is 22% higher than that of 2202D. At a neutron energy of 32.5 MeV the sensitivity of the M95-2 is 30% higher than that of the 2202D and for the 6060 it is 19% higher than that of the 2202D. At a neutron energy of 45.4 MeV, the sensitivity of the M95-2 is 148% higher than that of the 2202D, and for 6060 it is 135% higher than that of the 2202D.

6.2 Response in high-energy stray radiation fields

For the same reason as mentioned in section 6.1, the measurement results in the E-hall of the KEK-PS were normalized to sensitivity of the 2202D in the energy of Californium neutron source. (see Table 20).

From the $^{11}\text{C}/\text{rem}$ ratio value it is clear that the neutron spectrum at position No.2 is harder than at No.1. At position No.1 the normalized counting response of the M95-2 and the 6060 are 42.7% and 32.2% higher than that of the 2202D. At position No.2 the normalized counting response of the M95-2 and the Model 6060 are 84.5% and 53.0% higher than that of the 2202D (see Table 21).

7 Conclusions

The uncertainties of all the measurements for each A-B rem counter are given in Table 22.

At the three higher monoenergetic points and two measurement positions of the high-energy stray radiation fields the responses of the modified A-B rem counters are higher than those of the conventional rem counters. The difference between the two types of A-B rem counters is the larger, the higher neutron energy or the harder neutron spectrum. The effect of the lead layer in rem construction is clearly visible. Since the radiation field outside of the shielding of a high energy accelerator presents rich high-energy neutrons, any underestimation of the neutron dose equivalent is unavoidable with a conventional rem counter. In this experiment the two types of conventional rem counters show similarly low values in the high-energy region.

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Table 1. A-B rem counters used in the energy response calibration

Model	Type	Production establishment	Participated establishment
M95-2	Modified	IHEP	IHEP
C92-11	Conventional	IHEP	IHEP
6060	Modified	H.P.I.*	KEK
2202D	Conventional	ALNOR	TIARA

* Health Physics Instruments

Table 2. Construction parameters of the A-B rem counters used in the energy response calibration

Model	BF ₃ Counter (mm)	Inner moderator thickness (mm)	Outer moderator (mm)	Boron plastic
M95-2	25 ϕ $\times$ 100(L) 600mmHg	18	254 ϕ 79(thick.)	5mm thickness 28% of boron contain 22% of ϕ 10mm holes
C92-11	25 ϕ $\times$ 100(L) 500mmHg	16	216 ϕ 70(thick.)	
6060			236 ϕ	
2202D			210 ϕ	

Table 3. Thermal neutron measurement data

Model	Time(min.)	Counts (without Cd)	Time(min.)	Counts (with Cd)
M95-2 (IHEP)	5	732, 639	5	148
C92-11(IHEP)	30	2001	5	90
6060 (KEK)	5	638, 607	5	129
2202D(TIARA)	5	733, 682	5	173

Table 4. Calibration results of thermal neutron (2.5×10^{-8} MeV)

Model	Fluence ($\text{n}/\text{cm}^2 \cdot \text{s}$)	Fluence sensitivity ($\text{cps}/\text{n}/\text{cm}^2 \cdot \text{s}$)
M95-2 (IHEP)	2.86×10^2	6.226×10^{-3}
C92-11(IHEP)	2.87×10^2	2.829×10^{-3}
6060 (KEK)	2.87×10^2	6.098×10^{-3}
2202D(TIARA)	2.87×10^2	6.206×10^{-3}

Table 5. 8 keV measurement data

Model	Distance (cm)	Time (s)	Shadow bar	Counts of rem counter	Counts of monitor 1	Counts of monitor 2
M95-2 (IHEP)	100	300	without	191	7310	180119
	100	300	without	173	7495	179716
	100	300	without	206	7165	173715
	100	300	with	56	10554	177277
	100	300	with	38	10489	178021
2202D(TIARA)	100	300	without	207	7461	167632
	100	300	without	199	7373	171984
	100	300	without	186	7457	170514
	100	300	with	33	4807	164442
	100	300	with	32	4918	163448
C92-11(IHEP)	100	300	without	91	3810	163802
	100	300	without	121	4110	179375
	100	300	without	104	4131	175686
	100	300	with	26	4874	178877
	100	300	with	21	4868	168315
6060 (KEK)	100	300	without	182	4115	185724
	100	300	without	179	3903	193152
	100	300	without	199	3720	188204
	100	300	with	24	4607	183687
	100	300	with	20	4591	180136

Table 6. Calibration results of the rem counters using 8 keV neutron

Model	Normalized counts (rem counts/monitor)	Conversion factor (n/cm ² /monitor)	Fluence sensitivity (cps·(n/cm ²) ⁻¹ ·s ⁻¹)
M95-2	0.8054×10^{-3}	8.5×10^{-3}	0.09475
C92-11	0.4723×10^{-3}	8.5×10^{-3}	0.05556
6060	0.8672×10^{-3}	8.5×10^{-3}	0.1020
2202D	0.9625×10^{-3}	8.5×10^{-3}	0.1132

Table 7. ²⁵²Cf source calibration data

Model	Distance(cm)	Time (s)	Shadow bar	Counts of rem counter
M95-2 (IHEP)	100	60	without	444, 382, 368, 401, 365
	100	60	with	47, 41, 54, 47, 42
	150	60	without	212, 191, 164, 186, 172
	150	60	with	32, 42, 46, 30, 35
C92-11(IHEP)	100	60	without	250, 261, 258, 251, 244
	100	60	with	25, 37, 28, 26, 23
	150	60	without	144, 120, 148, 128, 111
	150	60	with	31, 19, 30, 24, 17
2202D(TIARA)	100	60	without	436, 392, 464, 430, 479
	100	60	with	51, 48, 47, 46, 56
	150	60	without	204, 201, 192, 225, 208
	150	60	with	42, 43, 41, 38, 46
2202D (KEK)	100	60	without	632, 560, 557, 573, 635
	100	60	with	57, 70, 75, 74, 72
	150	60	without	242, 306, 281, 253, 244
	150	60	with	55, 52, 59, 64, 49

Table 7. ^{252}Cf source calibration data
(continue)

Model	Distance(cm)	Time (s)	Shadow bar	Counts of rem counter
2202D(CYRIC)	100	60	without	413, 443, 450, 470, 407
	100	60	with	44, 44, 51, 63, 59
	150	60	without	223, 201, 208, 228, 211
	150	60	with	52, 46, 49, 41, 39
6060 (KEK)	100	60	without	239, 258, 263, 279, 279
	100	60	with	26, 22, 22, 17, 35
	150	60	without	133, 107, 100, 123, 120
	150	60	with	27, 21, 33, 28, 25

Table 8. Calibration results of the rem counter using the ^{252}Cf source at Tohoku University

Detector	1 meter		1.5 meter		
	cps	$\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$	cps	$\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$	
M95-2	5.763	0.4207	2.467	0.4052	IHEP
C92-11	3.750	0.2737	1.767	0.2902	IHEP
6060	3.987	0.2910	1.497	0.2459	KEK
2202D	6.510	0.4752	2.733	0.4488	TIARA
2202D	8.683	0.6338	4.157	0.6827	KEK
2202D	6.407	0.4677	2.813	0.4620	CYRIC

Table 9. Fluence conversion factor

Proton energy	^{232}Th Fission chamber n/Sr/monitor
$E_p = 25 \text{ MeV}$	2.01×10^8
$E_p = 35 \text{ MeV}$	1.34×10^8

Table 10. 22.0 MeV neutron measurement data

Model	Distance (cm)	Time (s)	Counts of rem counter	Counts of monitor 1	Counts of monitor 2	Current of monitor 3 (μc)
M95-2 (IHEP)	1724.2	60	9368	149	32615	36.3474
		60	10912	177	38214	42.3947
		60	10588	175	36983	41.1993
C92-11(IHEP)	1722.3	60	5619	194	39877	43.5085
		60	5435	172	38362	42.0943
		60	5664	164	40968	44.7121
6060 (KEK)	1723	60	6037	148	35215	38.1915
		60	5538	128	31975	35.0178
		60	5472	145	31685	34.8735
2202D(TIARA)	1722.3	60	9640	189	37178	40.6322
		60	9722	177	38006	41.5815
		60	9733	170	37828	41.2824

Table 11. Calibration results of the rem counter using 22.0 MeV neutrons

Model	Normalized counts (rem counts/monitor)	Normalized factor (n/Sr/monitor)	Fluence sensitivity $\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$
M95-2	61.67	2.01×10^8	0.3437
C92-11	31.70	2.01×10^8	0.1763
6060	40.60	2.01×10^8	0.2260
2202D	54.40	2.01×10^8	0.3026

Table 12. 32.5 MeV neutron measurement data

Model	Distance (cm)	Time (s)	Counts of rem counter	Counts of monitor 1	Counts of monitor 2	Current of monitor 3 (μc)
M95-2 (IHEP)	1197	60	26200	278	35194	35.4525
		60	22995	240	30482	30.7940
	1724.2	60	12320	268	35108	34.7132
		60	11876	279	32652	32.5147
	2166.2	60	7976	285	36471	36.1579
		60	6943	248	31136	31.1533
C92-11(IHEP)	1722.3	60	4777	244	30477	30.6372
		06	4933	245	31137	31.9081
		60	4547	221	28669	28.8288
6060 (KEK)	1723	60	6388	218	29770	30.0941
		60	6234	239	29048	29.5106
		60	6657	235	30860	31.4980
2202D(TIARA)	1722.3	60	9724	238	33424	34.3525
		60	8994	260	30846	31.8806
		60	8492	192	29298	30.1302
		60	8681	254	30028	30.8891

Table 13. Calibration results of the rem counter using 32.5 MeV neutrons

Model	Normalized counts (rem counts/monitor)	Normalized factor (n/Sr/monitor)	Fluence sensitivity $\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$
M95-2	44.27	1.34×10^8	0.2807
C92-11	20.09	1.34×10^8	0.1271
6060	27.90	1.34×10^8	0.1767
2202D	38.47	1.34×10^8	0.2434

Table 14. 45.4 MeV neutron measurement data

Model	Distance (cm)	Time (s)	Counts of rem counter	Counts of monitor 1	Counts of monitor 2	Counts of monitor 3
M95-2 (IHEP)	601	60	8792	605	10736	1434
		60	8891	607	10643	1473
	883.5	60	6597	612	10865	1565
		60	6310	612	10910	1524
C92-11(IHEP)	887	60	2821	615	10780	1580
		60	2762	613	10748	1468
6060 (KEK)	886	60	4198	612	10973	1479
		60	4315	614	10892	1500
2202D(TIARA)	888	60	4698	631	10997	1541
		60	4431	629	11163	1548

Table 15. Calibration results of the rem counter using 45.4 MeV neutrons

Model	Normalized counts (rem counts/monitor)	Normalized factor (n/Sr/monitor)	Fluence sensitivity $\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$
M95-2	10.19	2.71×10^7	0.3124
C92-11	4.458	2.71×10^7	0.1063
6060	6.693	2.71×10^7	0.2049
2202D	7.082	2.71×10^7	0.1424

Table 16. Measurement data in the E-Hall of the KEK-PS
at position No.1 at position No.2

Model	Time (s)	Counts of rem counter	Counts of monitor	Time (s)	Counts of rem counter	Counts of monitor
Carbon	1800		19447	1440		5405
M95-2 (IHEP)	107	1039	1000	294	1051	1000
	108	1093	1000	300	1056	1000
	118	1122	1000	273	1068	1000
	106	1060	1000	253	1007	1000
	117	1099	1000	260	1014	1000
C92-11(IHEP)	106	523	1000	321	450	1000
	100	485	1000	268	436	1000
	105	499	1000	278	423	1000
	96	486	1000	257	323	1000
	97	458	1000	269	369	1000
2202D(TIARA)	94	874	1000	270	662	1000
	98	848	1000	270	638	1000
	98	870	1000	274	666	1000
	98	866	1000	267	615	1000
	94	842	1000	244	600	1000
6060 (KEK)	96	735	1000	256	637	1000
	93	723	1000	268	603	1000
	94	717	1000	257	563	1000
	95	639	1000		554	952
	90	668	1000			
2202D (KEK)	94	1106	1000	277	1011	1000
	98	1136	1000	254	918	1000
	89	1105	1000	258	1009	1000
	95	1118	1000	267	911	1000
	91	1107	1000	277	1060	1000

Table 17. Measurement results in the E - Hall of the KEK - PS

Model	No.1		No.2	
	$^{11}\text{C}/\text{rem}$	Normalized counts (rem counts/monitor)	$^{11}\text{C}/\text{rem}$	Normalized counts (rem counts/monitor)
M95-2	2.720	1.0826	4.645	1.0390
C92-11	2.720	0.4902	4.645	0.4002
6060	2.720	0.6964	4.645	0.5963
2202D	2.720	0.8600	4.645	0.6362

Table 18. Energy response of the absolute sensitivity ($\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$)

model	Thermal n^*	8 KeV	2.5 MeV	22.0 MeV	32.5 MeV	45.4 MeV
M95-2 (IHEP)	6.266×10^{-3}	0.09475	0.4207	0.3437	0.2807	0.3124
C92-11(IHEP)	2.829×10^{-3}	0.05556	0.2737	0.1763	0.1271	0.1063
6060 (KEK)	6.098×10^{-3}	0.1020	0.2910	0.2260	0.1767	0.2049
2202D(TIARA)	6.206×10^{-3}	0.1132	0.4752	0.3026	0.2434	0.1424

* $2.5 \times 10^{-8} \text{ MeV}$

Table 19. Dependence of the normalized fluence sensitivity
on neutron energy ($\text{cps} \cdot (\text{n}/\text{cm}^2)^{-1} \cdot \text{s}^{-1}$)

model	Thermal n^*	8 KeV	2.5 MeV	22.0 MeV	32.5 MeV	45.4 MeV
M95-2 (IHEP)	7.078×10^{-3}	0.1070	0.4752	0.3882	0.3171	0.3529
C92-11(IHEP)	4.911×10^{-3}	0.09646	0.4752	0.3061	0.2207	0.1846
6060 (KEK)	9.958×10^{-3}	0.1666	0.4752	0.3690	0.2885	0.3346
2202D(TIARA)	6.026×10^{-3}	0.1132	0.4752	0.3026	0.2434	0.1424

* $2.5 \times 10^{-8} \text{ MeV}$

Table 20. Measurement results normalized to the 2202D
in the E-Hall of the KEK-PS

model	No.1 ($^{11}\text{C}/\text{rem}=2.72$)	No.2 ($^{11}\text{C}/\text{rem}=4.645$)
M95-2 (IHEP)	1.223	1.174
C92-11(IHEP)	0.8510	0.6948
6060 (KEK)	1.137	0.9737
2202D(TIARA)	0.8600	0.6362

Table 21. Intercomparison results relative to the 2202D

model	Thermal n*	8 KeV	2.5MeV	22.0 MeV	32.5 MeV	45.4 MeV	No.1	No.2
M95-2	1.010	0.9452	1.000	1.283	1.303	2.478	1.422	1.845
C92-11	0.4558	0.8521	1.000	1.012	0.9067	1.296	0.9895	1.092
6060	0.9826	1.472	1.000	1.219	1.185	2.350	1.322	1.530
2202D	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

* $2.5 \times 10^{-8} \text{MeV}$

Table 22. Uncertainties of the A-B rem counter (%)

Model	Thermal n*	8 KeV	2.5 MeV	22.0 MeV	32.5 MeV	45.4 MeV	No.1	No.2
M95-2	12.0	19.2	15.7	8.87	7.44	6.50	8.34	10.3
C92-11	13.3	24.9	20.1	8.87	7.52	6.68	8.99	11.0
6060	11.8	24.6	21.3	8.87	7.48	6.58	8.65	10.7
2202D	10.9	21.4	15.2	8.87	7.45	6.58	8.49	10.6

* $2.5 \times 10^{-8} \text{MeV}$

- ① Polyethylene
- ② Borated Polyethylene
- ③ BF₃ Counter

Figure 1, Construction of the standard Andersson Braun rem counter

- ① Polyethylene
- ② Lead (pure)
- ③ Borated Polyethylene
- ④ BF₃ Counter

Figure 2, Construction of the modified Andersson Braun rem counter

Figure 3, 8 keV calibration arrangement

Figure 4, Cyclotron facility at CYRIC

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Figure 5, 22.0 MeV and 32.5 MeV calibration arrangement

Figure 6, 22.0 MeV neutron spectrum

Figure 7, 32.5 MeV neutron spectrum

Figure 8, 90 MV cyclotron facility at TIARA

Figure 10, 45.4 MeV neutron spectrum

Figure 11, Experimental arrangement at the E-hall of the KEK-PS

Figure 12, Energy response of the absolute fluence sensitivity

Figure 13, Dependence of the normalized fluence sensitivity on the neutron energy

Figure 14, Energy response of the normalized fluence sensitivity