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Measurement of Neutron Slowing Down Time in Hydrogeneous Moderators

Summary

The neutron slowing down times in light water, ice, paraffin, and santowax-R were obtained by measuring filter transmission rates as a function of time after injections of neutron bursts. The large flight time effects were taken into account experimentally. The results of the measurements of the slowing down times were as follows,

Moderator	Cut-off energy (eV)	Slowing down time (μsec)
Light water	0.63	1.7 ± 0.4
	0.43	1.9 ± 0.4
	0.20	3.9 ± 0.8
Ice	0.63	1.8 ± 0.4
	0.43	2.0 ± 0.4
	0.20	3.9 ± 0.8
Paraffin	0.63	1.1 ± 0.2
	0.43	1.3 ± 0.3
	0.20	4.0 ± 0.7
Santowax-R	0.63	2.5 ± 0.5
	0.43	3.0 ± 0.6
	0.20	6.8 ± 0.9

The measured slowing down times below 0.63 and 0.43 eV agreed well with theoretical values on the 0°K free gas model, However, the measured values below 0.20 eV are longer than the theoretical ones, which indicates the effect of the thermal agitation and chemical binding in the range of this energy.

July 1968

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水素を含む減速材中の減速時間測定

要　旨

軽水，氷，パラフィンおよびサントワックス中における中性子の減速時間を，パルス中性子源を使ったフィルタ法により測定した。測定にあたっては，とくに中性子飛行時間の効果を実験的に調べ補正することにより，系統誤差を小さくすることができた．測定結果はつぎのとおり．

減速材	切断エネルギー (eV)	減速時間 (μsec)
軽　水	0.63	1.7 ± 0.4
	0.43	1.9 ± 0.4
	0.20	3.9 ± 0.8
氷	0.63	1.8 ± 0.4
	0.43	2.0 ± 0.4
	0.20	3.9 ± 0.8
パラフィン	0.63	1.1 ± 0.2
	0.43	1.3 ± 0.3
	0.20	4.0 ± 0.7
サントワックス	0.63	2.5 ± 0.5
	0.43	3.0 ± 0.6
	0.20	6.8 ± 0.9

0.63 eV と 0.43 eV における減速時間は，0°K 自由ガスモデルによる理論値によく一致することがわかった．しかしながら，0.2 eV における測定値は上記モデルによる理論値より大きく，このエネルギー近くから熱運動や化学結合の効果がききはじめることがわかった．

1968 年 7 月

日本原子力研究所　東海研究所　原子炉工学部

金子　義彦　　秋濃　藤義　　黒川　良右
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1. Introduction

One of the most important porblems in nuclear reactor physics is determination of the neutron slowing down characteristic of reactor moderators.

For the past several years, experiments have been made on the slowing down times of fast neutrons in various moderators. CROUCH[1] measured the slowing down time in light water using a Po-Be constant source. Then, DARDEL[2], HIRAKAWA[3], KANEKO[4] and TAKAHASHI[5] have tried to determine the slowing down time in light water and other moderators by the use of pulsed neutron sources. They employed 1/v counters with filters having different cut-off energies for neutron detection. In recent years, capture gamma method initiated by MÖLLER[6] has been successful for the measurement in light water, due mainly to essentially zero flight time.

In the present paper, are reported the results of measurements of neutron slowing down times in light water, ice, paraffin and santowax by the filter transmission method, using pulsed neuron sources. The slowing down times are very short in these hydrogenous moderators. Therefore, the flight time effect requests large corrections. To cope with this problem, the flight time effect was taken into account experimentally.

2. Principle of the experiment

Several different definitions have so far been given for the slowing down time.
The slowing down time of fast neutrons below a definite energy E_c is usually defined as the first time moment of the slowing down density at energy E_c [6] $q\ (E_c.t)$

$$t_c=\frac{\int_0^\infty t\cdot q(E_c,t)dt}{\int_0^\infty q(E_c,t)dt} \tag{1}$$

Another definition in addition to the above t_c is adapted in the present paper, which is the slowing down time at a definite energy $E_{1/2}$, $t_{1/2}$. This definition is that at the instant of slowing down time $t_{1/2}$, the number of the neutrons above $E_{1/2}$ is equal to the number of those below.

In the experiment, the method was employed, which one of the authors had used in the experiment for graphite. But, a resonance type filter was not used in the case of hydrogeneous moderators, because it was difficult to obtain the exact values by the use of this type filter, due to a larger variation in the slowing down time distribution.

After injection of a burst of 14 MeV D–T fast neutrons, a bare BF_3 counter and a BF_3 counter covered with a filter located in the resulting neutron field of density $n(E,t)$, will show the following responses.

The counting rate of the bare BF_3 counter

$$(\mathrm{CR})_{\mathrm{bare}}=\int_0^\infty S(E)n(E,t)vdE \tag{2}$$

and that of the one covered with a filter.

$$(\mathrm{CR})_{\mathrm{filter}}=\int_0^\infty T(E)S(E)n(E,t)vdE \tag{3}$$

where $T(E)$ is the transmission of the filter, and $S(E)$, the counting efficiency of the BF_3 counter.

If the transmission of the filter is approximately of a sharp cut off, the slowing down density $q(E,t)$ can be evaluated by

$$q(E,t) \propto \frac{d}{dt}[(CR)_{bare} - (CR)_{filter}] \quad (4)$$

By substituting Eq. (4) into Eq. (1) the slowing down time t_c can be given by,

$$t_c = \frac{\int_0^\infty t\frac{d}{dt}[(CR)_{bare} - (CR)_{filter}]dt}{\int_0^\infty \frac{d}{dt}[(CR)_{bare} - (CR)_{filter}]dt} \quad (5)$$

The another slowing down time $t_{1/2}$ can be determined as the time when the counting rate of the counter with filter becomes half the value of the counting rate of the counter without it.

3. The experimental arrangement

In the experiment, bursts of neutrons were injected near the center of the moderator assembly. The time-dependent neutron transmission was measured by the use of BF_3 counters with and without filter. A block diagram for the neutron detection is shown in Fig. 1.

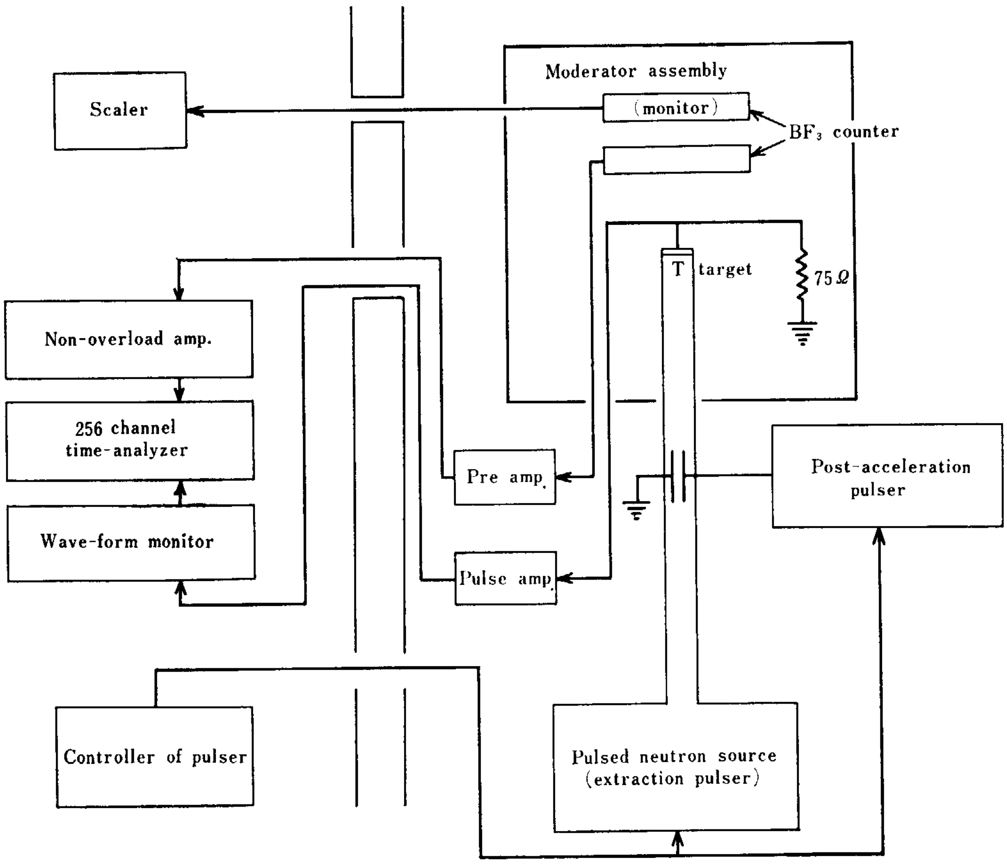

Fig. 1 Block diagram for the experiment.

3.1 Pulsed neutron source

A 200 kV Cockcroft-type compact pulsed neutron source was used in the experiment. The slowing down time experiment was undertaken with the use of a thin tritium target, bursts of 14 MeV neutrons supplied with a pulse width of 0.1 μsec. A couple of pulsing systems operating synchronously was used for this purpose. One was an extraction pulser, and the other a post-accelerating deflection type pulser. The wave-form of deuteron pulse is shown in Photo 1.

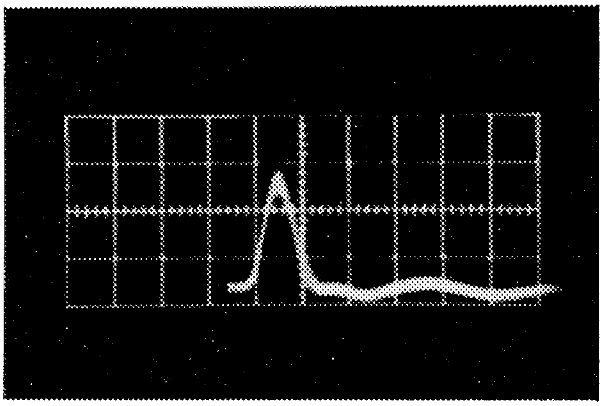

Photo 1 A waveform of deuteron pulse. (0.1 μsec/div.)

3.2 Moderator assembly

The moderator assemblies are schematically shown in Fig. 2. The water, ice and santowax-R assemblies were 40 cm cubes, while the paraffin one a 46 cm cube. In order to introduce the deuteron beam into the moderator assemblies, a target tube of aluminum with an outer diameter of 40 mm was provided. The moderator assemblies were shielded against neutrons scattered from out-

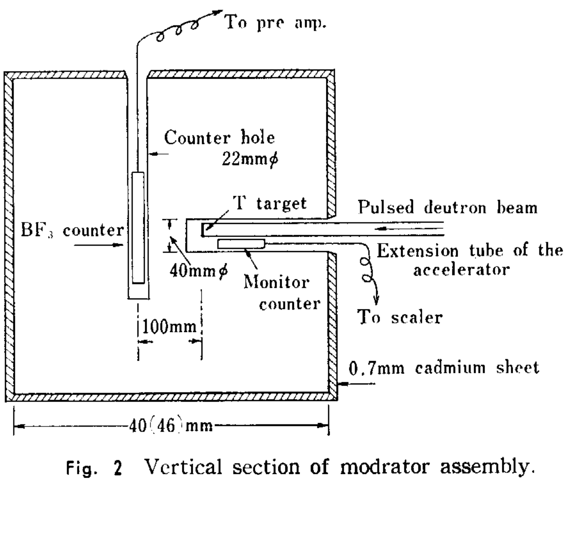

Fig. 2 Vertical section of modrator assembly.

TABLE 1 Point of assemblies

Moderator	Density g/cm³	Hydrogen number density	Size
Light water H_2O	1.00	$6.69\times10^{22}/cm^3$	40×40×40 cm
Ice H_2O	0.92	$6.16\times10^{22}/cm^3$	40×40×40 cm
Paraffin $C_{25}H_{52}$	0.92	$8.14\times10^{22}/cm^3$	46×46×46 cm
Santowax $C_{18}H_{14}$	0.13	$4.10\times10^{22}/cm^3$	40×40×40 cm

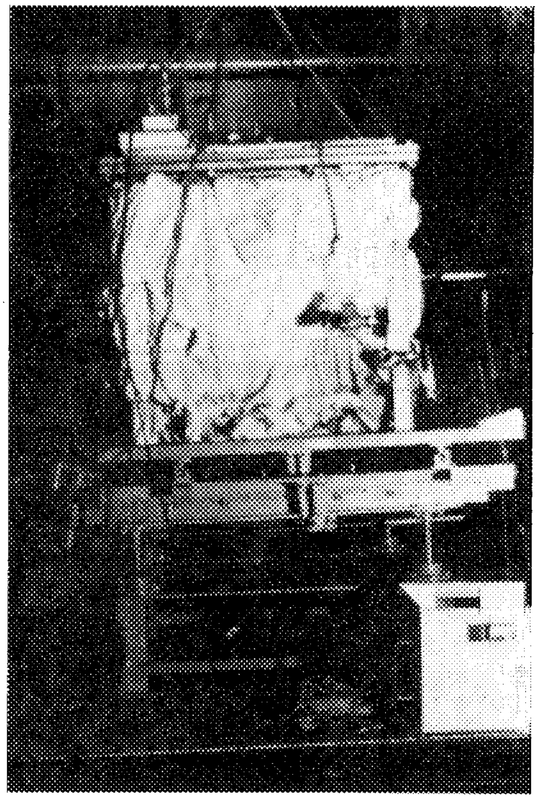

Photo 2 The ice assembly cooled down with dry ice.

side of the assembly by the use of 0.7 mm cadmium sheets. The moderator temperatures were 22°, 16°, 16° and −30°C in the water, paraffin, santowax and ice assembly, respectively. The ice assembly which was cooled down with dry ice is shown in Photo 2.

3.3 Neutron detector and time analyzer

The slowing down neutrons after injection of 14 MeV neutrons were detected first by a bare BF_3 counter and then by the counter with a filter. This counter is 13 mm in diameter, 50 mm in active length, having an inner pressure of 400 mmHg. Three cut off type filters, of which one was made of gadolinium metal and two of cadmium metal were used in the experiment. The physical characteristics of these filters are listed in Table 2. The effective cut-off energies mentioned in this table were obtained by assuming that the probable slowing down spectrum $n(E,t)$ is that of the 0°K free proton gas model and that neutron incident to counters is isotropic. Calculations were performed by using a computer code EC-5, which is a version of EC-4 developed by Takeda and Inoue [7] for the calculation of effective cut-off energies in static problems. Small errors due to the deviation of these assumed spectra from the true spectra to be investigated are within experimental error.

Neutron induced pulses in the detector were amplified by a pre-amplifier, and a non-overloading amplifier with 0.1 μsec rise time, and the output of a pulse height selector was fed to the time analyzer, TMC 256 channel analyzer and a Model 211 time of flight logic unit with 0.25 μsec channel width.

Trigger signals of the time analyzer were derived from amplifying target pulsed beam current by a pulse amplifier with rise time 0.01 μsec and amplitude about one hundred. A monitor channel was also provided to measure the total neutron yields in a run.

TABLE 2 Results of the experiments

Filter	Thickness (mm)	Outer diameter (mm)	Energy characteristic (eV)	Moderator	Experimental value (μsec)	Theoretical value (0°K free gas) (μsec)
Cadmium-I	1.36	17.9	E_c =0.63 $E_{1/2}$=0.68	light water	t_c =1.7±0.4	1.36
					$t^1/_2$=1.4±0.3	1.11
				ice	t_c =1.8±0.4	1.45
					$t^1/_2$=1.2±0.3	1.20
				paraffin	t_c =1.1±0.2	1.12
					$t^1/_2$=1.0±0.2	0.91
				santowax	t_c =2.5±0.5	2.22
					$t^1/_2$=2.2±0.4	1.80
Cadmium-II	0.31	13.6	E_c =0.43 $E_{1/2}$=0.50	light water	t_c =1.9±0.4	1.64
					$t^1/_2$=1.5±0.3	1.30
				ice	t_c =2.0±0.4	1.78
					$t^1/_2$=1.3±0.4	1.41
				paraffin	t_c =1.3±0.3	1.35
					$t^1/_2$=1.1±0.2	1.07
				santowax	t_c =3.0±0.6	2.68
					$t^1/_2$=2.8±0.5	2.13
Gadolinium	0.05	13.1	E_c =0.20 $E_{1/2}$=0.22	light water	t_c =3.9±0.8	2.43
					$t^1/_2$=3.5±0.6	1.96
				ice	t_c =3.9±0.8	2.64
					$t^1/_2$=3.3±0.6	2.12
				paraffin	t_c =4.0±0.7	2.00
					$t^1/_2$=3.0±0.6	1.61
				santowax	t_c =6.8±0.9	3.97
					$t^1/_2$=5.7±0.8	3.18

4. Results of the experiment

4.1 Determination of the time origin

The deuteron current pulses at the target was used as the trigger signals of the time analyzer. This pulses, however, were not used as the time origin of the neutron bursts, because each circuit shown in Fig.1, had a proper delay time, and so it was difficult to estimate the delay time resulting from all the circuits. Therefore, a convenient method of determining the time origin from the experimental data itself, was used in the experiment. The time response of a count rate of the cadmium filter covered counter should show a sharp rise at the time origin. The time origin was determined using this property.

4.2 The time dependence of the filter transmission

The counting rates of BF_3 counters with and without a fliter as a function of time for the experiment in the light water assembly are shown in Fig.3. In this case the time origin is placed at the 18 channel. The experimental data of time dependent counting rates were fitted to a polino-

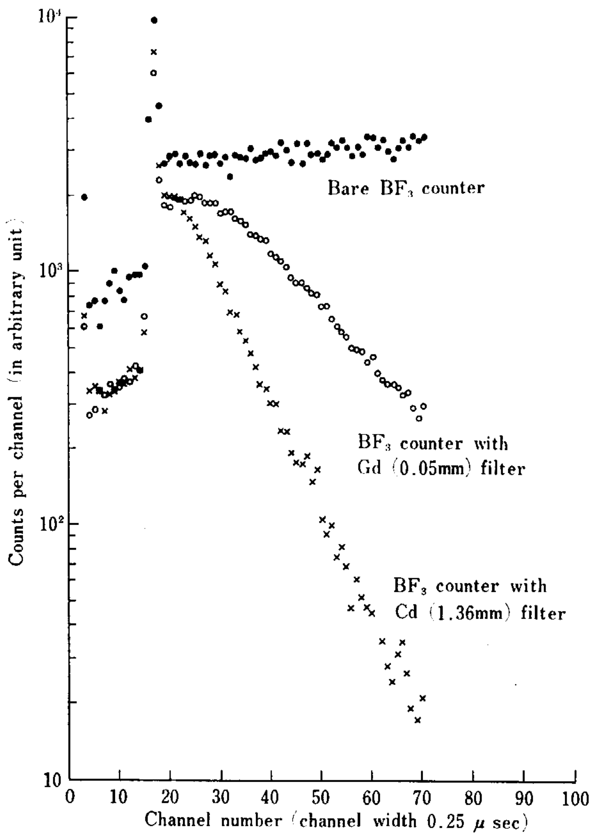

Fig. 3 Time response of the detector in light water.

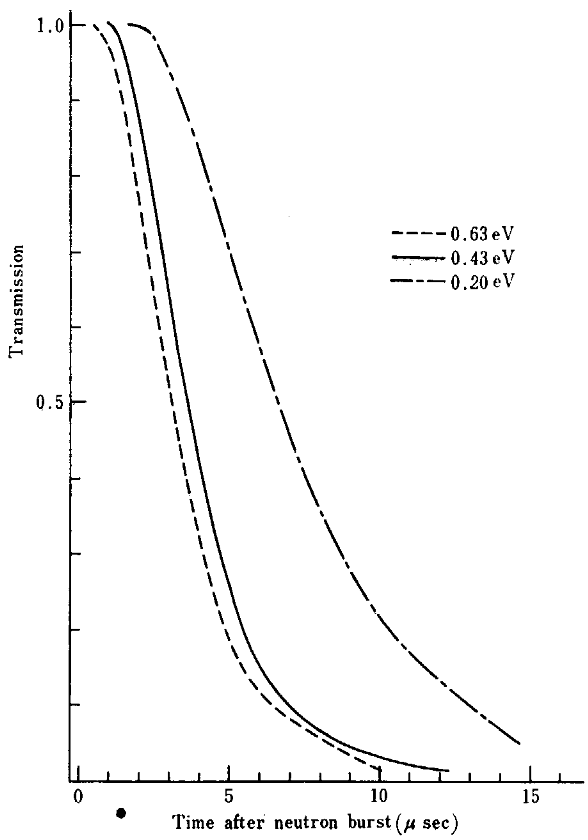

Fig. 4 Time dependent transmission in light water.

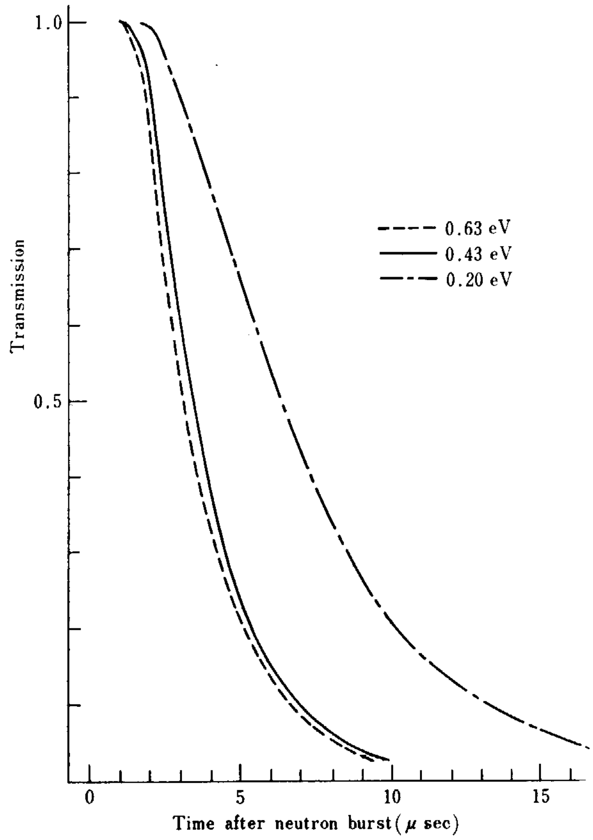

Fig. 5 Time dependent transmission in ice.

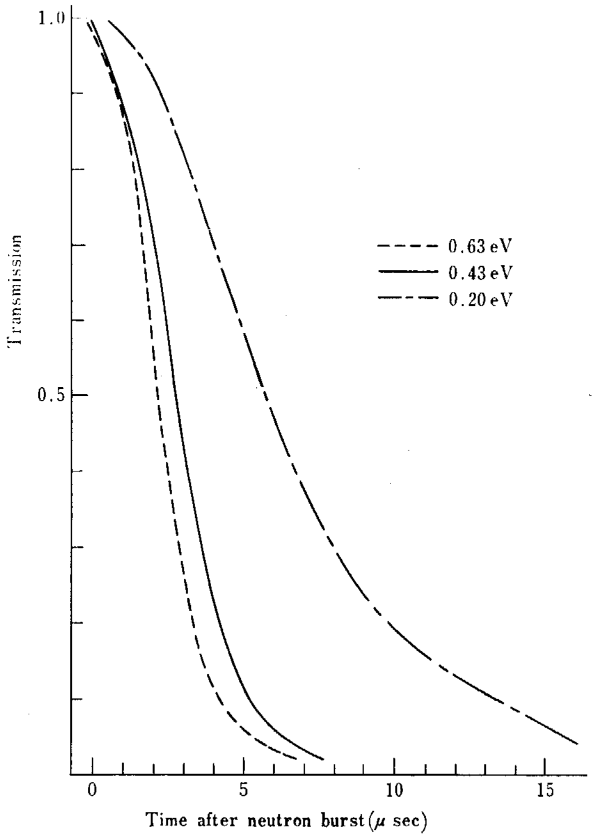

Fig. 6 Time dependent transmission in paraffin.

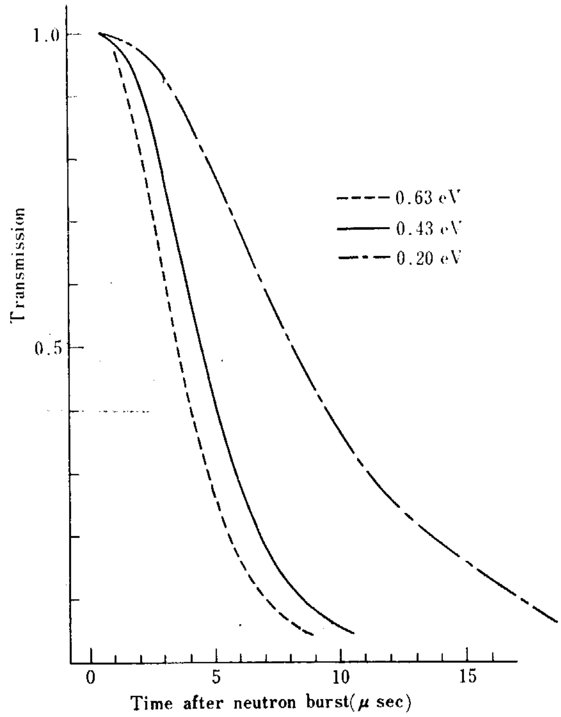

Fig. 7 Time dependent transmission in santowax.

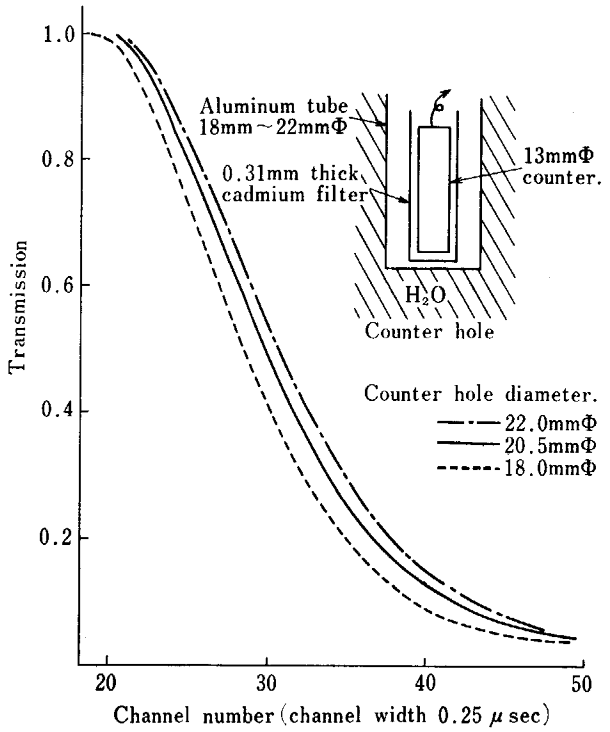

Fig. 8 Change of time dependent transmission with defferent counter hole diameters.

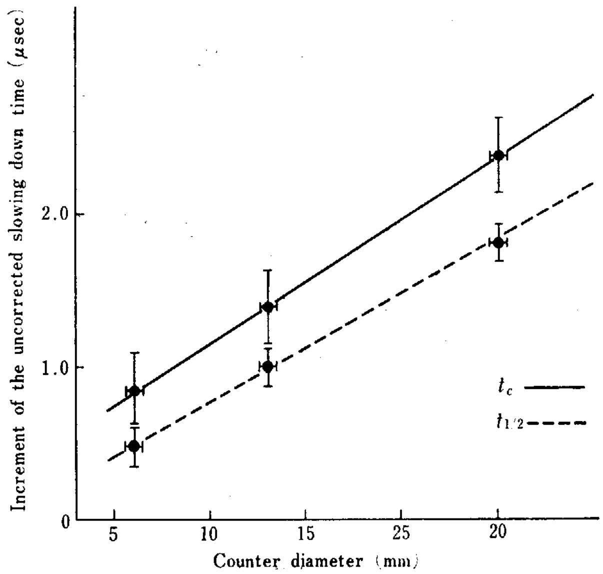

Fig. 9 Effect of neutron flight in a counter.

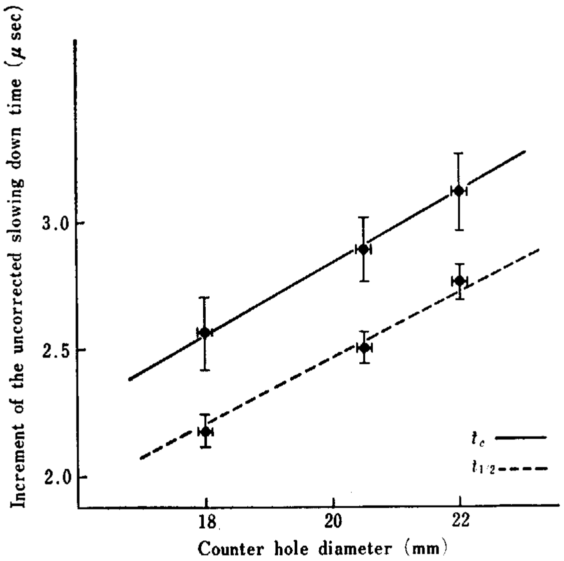

Fig. 10 Effect of neuron flight from the moderator surface to a counter.

mial of 4th degree by the least square method, then normalized, such that the maximum transmission would become 1.00 ; this was confirmed from the results of a complementary experiment. The results of the above mentioned treatment for the transmissions measured by the use of the three type filters for light water and other moderators are shown in Figs. 4, 5, 6, and 7.

4.3 Flight time effect.

Since the BF_3 counters had a radius of about 7 mm, and some space was needed for the filters, the distance from the center of the counter to the moderator surface was about 11 mm. This small distance was supposed to cause an apperciable flight time delay in the raw data. In order to investigate the effect, time dependent transmissions were measured in the case of light water with a 1.36 mm cadmium filter by the use of the three counters of different diameters for the three different distances from the counter to the moderator inner surface. The results of these measurement are shown in Figs. 8, 9, and 10. The effect for the inside of counter are determined as 0.161 μsec for t_c and 0.141 μsec for $t_{1/2}$ per 1 mm of counter radius at 0.43 eV. The effect for the outside of counter are determined as 0.288 μsec for t_c and 0.276 μsec for $t_{1/2}$ per 1 mm of counter hole radius at the same energy.

The same effects in the use of the other filter were estimated under tne assumption that the values of this effect was inversely proportional to the neutron velocity corresponding to the values of E_c and $E_{1/2}$.

4.4 Results of the measurement

The results of the measurements of the neutron slowing down times in which a correction has been made for the flight time effects are listed in Table 2.

The mean slowing down time t_c in light water, ice, paraffin and santwax-R below 0.63 eV were 1.7 μsec, 1.8 μsec, 1.1 μsec and 2.5 μsec, respectively ; below 0.43 eV, they were 1.9 μsec, 2.0 μsec, 1.3 μsec and 3.0 μsec ; below 0.20 eV, they were 3.9 μsec, 3.9 μsec, 4.0 μsec and 6.8 μsec in the four moderators. The slowing down times in the other definition $t_{1/2}$ at 0.68 eV were 1.4 μsec, 1.2 μsec, 1.0 μsec and 2.2 μsec, respectively ; at 0.50 eV, they were 1.5 μsec, 1.3 μsec, 1.1 μsec and 2.8 μsec ; at 0.22 eV, they were 3.5 μsec, 3.3 μsec, 3.0 μsec and 5.7 μsec, in the four moderators, respectively.

Experimental errors were also shown in TABLE 2. They were caused from the counting statistics and the ambiguity in the determination of the time origin, due to the fairly longer channel width 0.5 μsec compared to the value of the slowing down times.

5. Conclusion

The pulsed neutron source technique was applied to the measurements of the slowing down times to three different energy levels in the four different moderator systems. The experimental results were compared with the theoretical ones on the 0°K free gas model in TABLE 2. In the calculation of theoretical values, a simple experssion of the time spectrum of the slowing down density $q(E,t)$ is assumed as

$$q(E,t) \propto vte^{-\frac{vt}{l}} \qquad (6)$$

where l is the mean free path in the moderator. The transmission characteristics of the used filter is also used, which is the same with that used in the calculation of the cut-off energies of the filters.

The experimental results of the slowing down time below 0.63 and 0.43 eV agreed well with theoretical values on the 0°K free protons gas model. But, the slowing down times below and at 0.20 eV were larger than the theoretical values for this crude model, which seems to indicate the effects of the chemical binding and thermal agitation.

Acknowledgement

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