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資料紹介（そのII）

中性子源のスペクトル
― ISO規格案から ―

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今年(1986年) 6月5日付でISO専門部会（ISO/TC85）加盟国に配布され，賛否を求められた国際規格案に「中性子モニター校正用基準中性子線」という文書*がある。

この規格案は放射線防護の目的で作られた中性子測定器（指示値は"線量当量"で表わされる）向けに使用されるものであって，エネルギーが20MeV以下，フルエンス率（1MeV中性子で）$1 \times 10^5\ cm^{-2} \cdot s^{-1}$ 以下（線量当量率で $100\ mSv \cdot h^{-1}$ 以下）の中性子場に適用される。

線量当量率校正用線源として勧告されているものは，

- 30 cmの球状重水槽の中心に置かれた ^{252}Cf
- ^{252}Cf
- $^{241}Am-B$
- $^{241}Am-Be$

の各線源である。（表5及びその注記参照）

又，エネルギー・レスポンスの測定用として，

- 原子炉熱中性子及びフィルターされた原子炉中性子
- Sb−Be，及び水減速材付Sb−Be
- $^{45}Sc(p,n)$，及びフィルター付 $^{45}Sc(p,n)$
- T(p，n)，及びフィルター付T(p,n)
- $^{7}Li(p,n)$，及びフィルター付 $^{7}Li(p,n)$
- D(p，n)，及びD(d，n)
- T(d，n)

の各線源が，それぞれ対応する中性子エネルギー値とともに掲げられている。（表6）

中性子スペクトル：線量当量率校正の基礎となる中性子スペクトルは ^{252}Cf 及び $^{241}Am-Be$（又はB）の放射性核種線源に対して，同規格案の付録として付けられているので，図1～4及び表1～4にそれを示す。このうち ^{252}Cf からの中性子スペクトルは線源強度をBとして，式：

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*正式な英文タイトルは，Neutron reference radiations for calibrating neutron measuring devices used for radiation protection purposes and for determining their response as a function of neutron energy，ISO/DIS 8529である。
規格案の投票〆切は1986年12月5日となっている。

$$\frac{dB}{dE}=\frac{2}{\sqrt{\pi\ E_0^{3/2}}}\times\sqrt{E}\times e^{-E/E_0}\times B,$$

$E_0=1.42$ MeV[4)]から計算されたものである。又減速材付 ^{252}Cf はモンテカルロ計算[1)]による。なおこの場合，重水層から流出する中性子は重水容器をかこむカドミウム壁で吸収（11.5%）されるため，全積分中性子強度は 0.885 になる。^{241}Am－Be ，^{241}Am－B 線源からの中性子スペクトルは実験値である。

なお，これらのＲＩ線源は，IAEAのTechnical Report Series No.252 "Neutron Monitoring for Radiological Protection (1985)" にも使用されている。

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Table 1—Values of group source strength per logarithmic energy interval for a ^{252}Cf spontaneous fission source

Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$	Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$
MeV	s^{-1}	MeV	s^{-1}
4,14 × 10^{-7}		2,80	4,42 × 10^{-1}
0,01	4,40 × 10^{-5}	3,00	4,27 × 10^{-1}
0,05	2,74 × 10^{-3}	3,40	4,01 × 10^{-1}
0,10	1,24 × 10^{-2}	3,70	3,66 × 10^{-1}
0,20	3,33 × 10^{-2}	4,20	3,25 × 10^{-1}
0,25	6,04 × 10^{-2}	4,60	2,78 × 10^{-1}
0,30	7,90 × 10^{-2}	5,00	2,39 × 10^{-1}
0,40	1,07 × 10^{-1}	5,50	1,99 × 10^{-1}
0,50	1,46 × 10^{-1}	6,00	1,61 × 10^{-1}
0,60	1,84 × 10^{-1}	6,50	1,28 × 10^{-1}
0,70	2,21 × 10^{-1}	7,00	1,01 × 10^{-1}
0,80	2,55 × 10^{-1}	7,50	7,92 × 10^{-2}
1,00	3,01 × 10^{-1}	8,00	6,16 × 10^{-2}
1,20	3,53 × 10^{-1}	8,50	4,76 × 10^{-2}
1,40	3,95 × 10^{-1}	9,00	3,65 × 10^{-2}
1,50	4,19 × 10^{-1}	9,50	2,79 × 10^{-2}
1,60	4,32 × 10^{-1}	10,00	2,13 × 10^{-2}
1,80	4,46 × 10^{-1}	11,00	1,42 × 10^{-2}
2,00	4,58 × 10^{-1}	12,00	8,04 × 10^{-3}
2,20	4,62 × 10^{-1}	13,00	4,51 × 10^{-3}
2,30	4,61 × 10^{-1}	14,00	2,50 × 10^{-3}
2,40	4,59 × 10^{-1}	16,00	1,08 × 10^{-3}
2,60	4,53 × 10^{-1}	18,00	3,20 × 10^{-4}

Table 2—Values of group source strength per logarithmic energy interval for a ^{241}Am—Be (α, n) source

Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$	Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$
MeV	s^{-1}	MeV	s^{-1}
4,14 × 10^{-7}		5,68	6,19 × 10^{-1}
0,11	1,15 × 10^{-3}	5,89	5,67 × 10^{-1}
0,33	3,04 × 10^{-2}	6,11	4,95 × 10^{-1}
0,54	6,35 × 10^{-2}	6,32	5,23 × 10^{-1}
0,75	8,56 × 10^{-2}	6,54	5,96 × 10^{-1}
0,97	9,72 × 10^{-2}	6,75	5,79 × 10^{-1}
1,18	1,09 × 10^{-1}	6,96	5,32 × 10^{-1}
1,40	1,16 × 10^{-1}	7,18	5,39 × 10^{-1}
1,61	1,25 × 10^{-1}	7,39	5,83 × 10^{-1}
1,82	1,57 × 10^{-1}	7,61	6,42 × 10^{-1}
2,04	1,95 × 10^{-1}	7,82	6,75 × 10^{-1}
2,25	2,19 × 10^{-1}	8,03	6,37 × 10^{-1}
2,47	2,41 × 10^{-1}	8,25	5,31 × 10^{-1}
2,68	2,79 × 10^{-1}	8,46	3,85 × 10^{-1}
2,90	3,74 × 10^{-1}	8,68	2,54 × 10^{-1}
3,11	5,09 × 10^{-1}	8,89	1,78 × 10^{-1}
3,32	5,64 × 10^{-1}	9,11	1,50 × 10^{-1}
3,54	5,39 × 10^{-1}	9,32	1,67 × 10^{-1}
3,75	5,32 × 10^{-1}	9,53	2,27 × 10^{-1}
3,97	5,26 × 10^{-1}	9,75	2,74 × 10^{-1}
4,18	5,22 × 10^{-1}	9,96	2,59 × 10^{-1}
4,39	5,84 × 10^{-1}	10,18	2,14 × 10^{-1}
4,61	6,50 × 10^{-1}	10,39	1,81 × 10^{-1}
4,82	6,90 × 10^{-1}	10,60	1,39 × 10^{-1}
5,04	7,47 × 10^{-1}	10,82	7,37 × 10^{-2}
5,25	7,45 × 10^{-1}	11,03	1,89 × 10^{-2}
5,47	6,67 × 10^{-1}	11,09	0

Table 3—Values of a group source strength per logarithmic energy interval for a ^{252}Cf spontaneous fission source in the centre of a D_2O sphere with a radius of 150 mm

Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$
MeV	s^{-1}
$4,14 \times 10^{-7}$	
$1,0 \times 10^{-6}$	$2,15 \times 10^{-2}$
$1,0 \times 10^{-5}$	$2,74 \times 10^{-2}$
$5,0 \times 10^{-5}$	$3,75 \times 10^{-2}$
$1,0 \times 10^{-4}$	$4,57 \times 10^{-2}$
$2,0 \times 10^{-4}$	$4,92 \times 10^{-2}$
$4,0 \times 10^{-4}$	$5,51 \times 10^{-2}$
$7,0 \times 10^{-4}$	$5,86 \times 10^{-2}$
$1,0 \times 10^{-3}$	$6,29 \times 10^{-2}$
$3,0 \times 10^{-3}$	$6,88 \times 10^{-2}$
$6,0 \times 10^{-3}$	$7,34 \times 10^{-2}$
$1,0 \times 10^{-2}$	$7,42 \times 10^{-2}$
$2,0 \times 10^{-2}$	$7,89 \times 10^{-2}$
$4,0 \times 10^{-2}$	$7,38 \times 10^{-2}$
$6,0 \times 10^{-2}$	$7,30 \times 10^{-2}$
$8,0 \times 10^{-2}$	$6,95 \times 10^{-2}$
$1,0 \times 10^{-1}$	$6,52 \times 10^{-2}$
$1,5 \times 10^{-1}$	$6,10 \times 10^{-2}$
$2,0 \times 10^{-1}$	$5,54 \times 10^{-2}$
$2,5 \times 10^{-1}$	$5,12 \times 10^{-2}$
$3,0 \times 10^{-1}$	$4,88 \times 10^{-2}$
$3,5 \times 10^{-1}$	$4,26 \times 10^{-2}$
$4,0 \times 10^{-1}$	$3,66 \times 10^{-2}$
$4,5 \times 10^{-1}$	$2,25 \times 10^{-2}$
$5,0 \times 10^{-1}$	$2,98 \times 10^{-2}$
$5,5 \times 10^{-1}$	$4,41 \times 10^{-2}$
$6,0 \times 10^{-1}$	$4,73 \times 10^{-2}$
$7,0 \times 10^{-1}$	$5,08 \times 10^{-2}$
$8,0 \times 10^{-1}$	$5,08 \times 10^{-2}$
$9,0 \times 10^{-1}$	$4,88 \times 10^{-2}$
1,0	$3,39 \times 10^{-2}$
1,2	$4,10 \times 10^{-2}$
1,4	$5,47 \times 10^{-2}$
1,6	$6,84 \times 10^{-2}$
1,8	$7,26 \times 10^{-2}$
2,0	$7,66 \times 10^{-2}$
2,3	$9,57 \times 10^{-2}$
2,6	$1,18 \times 10^{-1}$
3,0	$1,04 \times 10^{-1}$
3,5	$8,01 \times 10^{-2}$
4,0	$6,13 \times 10^{-2}$
4,5	$6,88 \times 10^{-2}$
5,0	$6,21 \times 10^{-2}$
6,0	$4,77 \times 10^{-2}$
7,0	$3,20 \times 10^{-2}$
8,0	$1,81 \times 10^{-2}$
9,0	$1,10 \times 10^{-2}$
10,0	$7,27 \times 10^{-3}$
11,0	$4,65 \times 10^{-3}$
12,0	$1,86 \times 10^{-3}$
13,0	$1,55 \times 10^{-3}$
14,0	$8,00 \times 10^{-4}$
15,0	$4,10 \times 10^{-4}$

Table 4 — Values of group source strength per logarithmic energy interval for a $^{241}Am-B(\alpha, n)$ source

Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$
MeV	s^{-1}
$4,14 \times 10^{-7}$	
0,82	$1,21 \times 10^{-3}$
1,09	$3,97 \times 10^{-2}$
1,34	$3,91 \times 10^{-2}$
1,56	$1,38 \times 10^{-1}$
1,78	$3,44 \times 10^{-1}$
1,98	$5,93 \times 10^{-1}$
2,17	$8,72 \times 10^{-1}$
2,36	1,06
2,54	1,26
2,72	1,41
2,89	1,37
3,05	1,31
3,22	1,23
3,38	1,03
3,53	$9,26 \times 10^{-1}$
3,68	$7,62 \times 10^{-1}$
3,83	$7,59 \times 10^{-1}$
3,98	$6,57 \times 10^{-1}$
4,13	$5,35 \times 10^{-1}$
4,27	$5,17 \times 10^{-1}$
4,41	$4,49 \times 10^{-1}$
4,55	$3,19 \times 10^{-1}$
4,69	$2,46 \times 10^{-1}$
4,83	$1,16 \times 10^{-1}$
4,96	$8,26 \times 10^{-2}$
5,09	$4,49 \times 10^{-2}$
5,22	$1,20 \times 10^{-2}$
5,35	$1,09 \times 10^{-2}$
5,48	$9,83 \times 10^{-3}$
5,61	$4,92 \times 10^{-3}$
5,74	$6,34 \times 10^{-3}$
5,86	$6,74 \times 10^{-3}$
5,98	$1,37 \times 10^{-2}$
6,11	$8,28 \times 10^{-3}$
6,19	$2,24 \times 10^{-2}$
6,25	0

Table 5 — Reference radioactive neutron sources for calibrating neutron measuring devices

Source[1)]	Half-life	Dose equivalent average energy[2)]	Specific source strength[3)]	Specific neutron dose equivalent rate at 1 m distance[4)]	Specific photon dose equivalent rate[5)] at 1 m distance[4)]
	a[6)]	MeV	$s^{-1}\cdot kg^{-1}$	$Sv\cdot s^{-1}\cdot kg^{-1}$	$Sv\cdot s^{-1}\cdot kg^{-1}$
^{252}Cf (D_2O moderated)[7)] (sphere 300 mm in diameter)	2,65	2,2	$2,1 \times 10^{15}$	1,5	0,25
^{252}Cf	2,65	2,4	$2,4 \times 10^{15}$	6,5	0,31[8)]
	a	MeV	$s^{-1}\cdot Bq^{-1}$	$Sv\cdot s^{-1}\cdot Bq^{-1}$	$Sv\cdot s^{-1}\cdot Bq^{-1}$
$^{241}Am\text{-}B_{(\alpha,n)}$	432	2,8	$1,6 \times 10^{-5}$	$5,0 \times 10^{-20}$	$1,9 \times 10^{-19}$
$^{241}Am\text{-}Be_{(\alpha,n)}$	432	4,4	$6,6 \times 10^{-5}$	$2,0 \times 10^{-19}$	$1,9 \times 10^{-19}$

1) In addition to the sources listed, $^{238}Pu\text{-}Be_{(\alpha,n)}$ is also used. However, it is recommended that laboratories should not start using plutonium-beryllium sources if they are not already doing so.

2) Neutron spectra of sources are given in figures 2 to 5. Definition of the dose equivalent average energy is given in 3.19.

3) The specific source strength *B* related to the mass of 1 kg or the source activity of 1 Bq. Information on the sources is given for mederated ^{252}Cf in references [1, 2 and 3], for ^{252}Cf in [4], for $^{241}Am\text{-}B$ in [5], and for $^{241}Am\text{-}Be$ in [6].

4) For ^{252}Cf-sources, this is related to the mass of californium contained in the source; for the other sources, this is related to the activity of the ^{241}Am contained in the source.

5) Conversion of exposure to dose equivalent was performed using the factor of 0,01 $Sv\cdot R^{-1}$.

6) 1 a = 1 mean solar year = 31 556 926 s or 365,242 20 days.

7) Yields of neutrons for 300 mm diameter heavy-water sphere covered with cadmium shell of thickness approximately 1 mm.

8) For approximately 2,5 mm thick steel encapsulation.

Table 6 — Neutron radiations for determining the response of neutron measuring devices as a function of neutron energy[1)]

Neutron energy MeV	Method of production	Reference (see bibliography)
$2,5 \times 10^{-8}$ (thermal)[1)]	Moderated-reactor or accelerator-produced neutrons	[10]; [7]
0,000 5	$Sb\text{-}Be_{(\gamma,n)}$, radionuclide source, water-moderated	[8]
0,002	Scandium-filtered reactor neutron beam or accelerator-produced neutrons from reaction $^{45}Sc_{(p,n)}\,^{45}Ti$	[9]; [10]
0,021	$Sb\text{-}Be_{(\gamma,n)}$ radionuclide source	[11]; [12]
0,024	Iron/aluminium-filtered reactor neutron beam or accelerator-produced neutrons from reaction $^{45}Sc_{(p,n)}\,^{45}Ti$	[9]; [10]; [13]
0,144[1)]	Silicon-filtered reactor neutron beam or accelerator-produced neutrons from reactions $T_{(p,n)}\,^{3}He$ and $^{7}Li_{(p,n)}\,^{7}Be$	[9]; [14]; [15]; [16]
0,25[1)]	Accelerator-produced neutrons from reactions $T_{(p,n)}\,^{3}He$ and $^{7}Li_{(p,n)}\,^{7}Be$	[14]; [15]; [16]
0,565[1)]	Accelerator-produced neutrons from reactions $T_{(p,n)}\,^{3}He$ and $^{7}Li_{(p,n)}\,^{7}Be$	[14]; [15]; [16]
1,2	Accelerator-produced neutrons from reaction $T_{(p,n)}\,^{3}He$	[14]; [15]; [16]
2,5[1)]	Accelerator-produced neutrons from reaction $T_{(p,n)}\,^{3}He$	[14]; [15]; [16]
2,8[2)]	Accelerator-produced neutrons from reaction $D_{(d,n)}\,^{3}He$	[14]; [15]; [16]
5,0	Accelerator-produced neutrons from reaction $D_{(d,n)}\,^{3}He$	[14]; [15]; [16]
14,8[1) 2)]	Accelerator-produced neutrons from reaction $T_{(d,n)}\,^{4}He$	[14]; [15]; [16]
19,0	Accelerator-produced neutrons from reaction $T_{(d,n)}\,^{4}He$	[14]; [15]; [16]

1) Energies at which international intercomparisons of neutron fluence measurements were performed [17].

2) Accelerator-produced neutrons, with a deuteron energy of a few hundred kiloelectronvolts.

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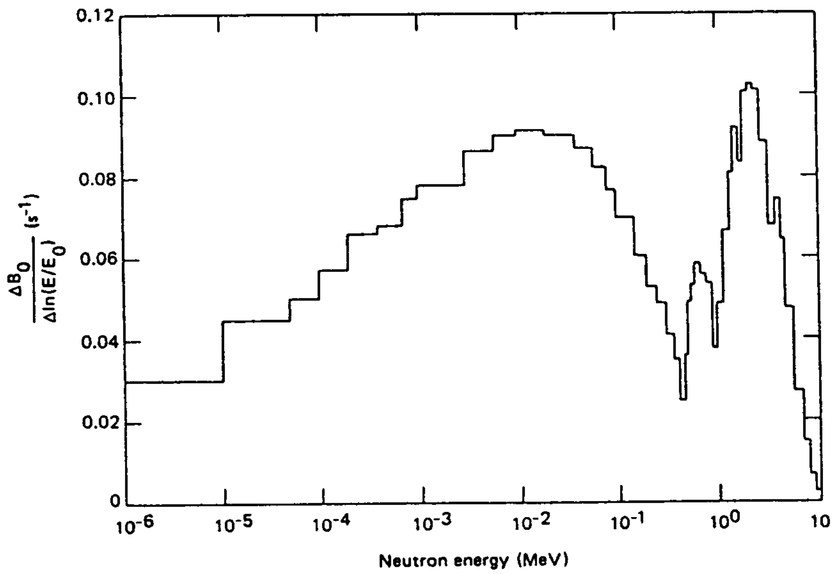


FIG. 1 Neutron spectrum from a ^{252}Cf spontaneous fission source in the centre of a D_2O sphere with a radius of 15 cm [2,3]

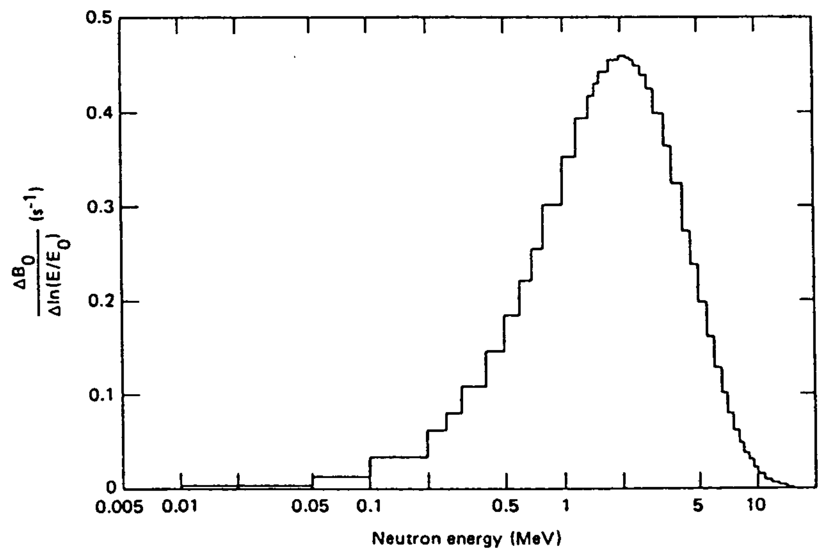
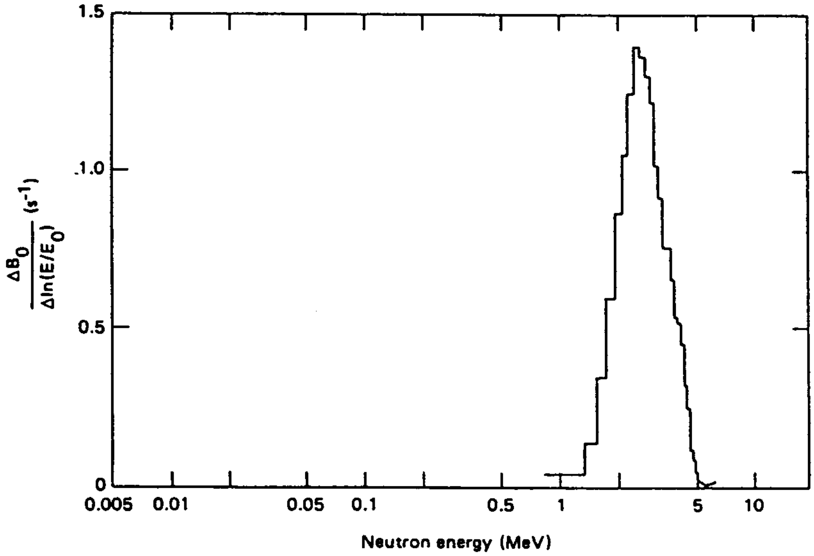
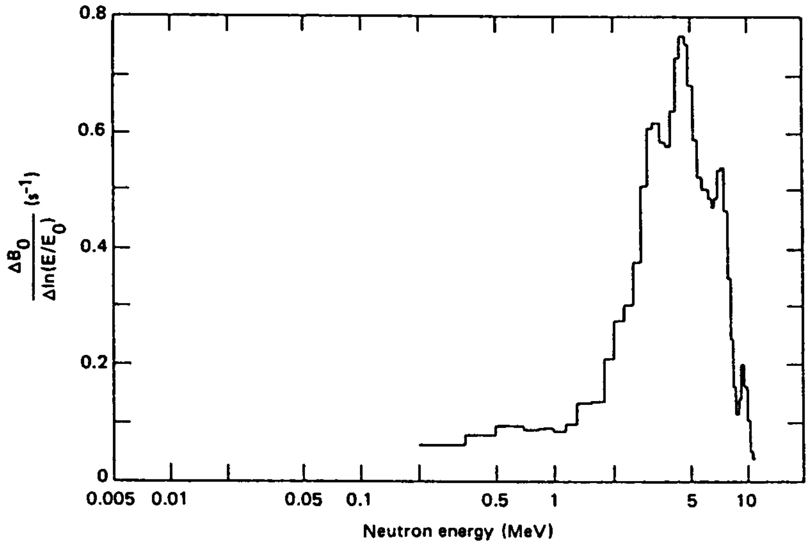


FIG. 2 Neutron spectrum from a ^{252}Cf spontaneous fission source [4]



F IG. 3 Neutron spectrum from a ^{241}Am−B (α, n) source〔5〕



F IG. 4 Neutron spectrum from a ^{241}Am−Be (α, n) source〔6〕