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EVALUATION OF NEUTRON NUCLEAR DATA OF N-15

April 1989

Tokio FUKAHORI

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

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Evaluation of Neutron Nuclear Data of N-15

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Nuclear data of N-15 have been evaluated in the energy range from 0.01 meV to 20 MeV. The evaluated quantities are cross section, angular distributions and energy spectra of secondary neutrons, and γ-ray data. The evaluation was performed by fitting the multilevel Breit-Wigner formula to the experimental data of the total cross section below 5.5 MeV, and using the multistep statistical model above 5.5 MeV. For the calculation of the multistep statistical model, the optical model and the level density parameters were chosen so as to reproduce the experimental data of N-14. The results of present work are in good agreement with the experimental data of cross sections. They were compiled for JENDL-3 in the ENDF-5 format.

Keywords: Evaluation, N-15, Neutron Nuclear Data, MLBW, Optical Model
JENDL-3

^{15}Nの中性子核データの評価

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（1989年3月30日受理）

入射中性子エネルギー0.01 meVから20 MeVの範囲で^{15}Nの中性子核データの評価を行った。評価した量は断面積，放出中性子の角度分布及びエネルギー・スペクトル，放出γ線のデータである。入射中性子エネルギー5.5 MeV以下ではブライトーウィグナーの共鳴公式を用いて，5.5 MeV以上では多段階統計模型を使用して評価を行った。多段階統計模型の計算を行うに際して，光学模型パラメータ及び準位密度パラメータは^{14}Nの実験データを再現するように選んだ。評価結果は断面積の実験データとよい一致を示した。評価結果はENDF－5形式でJENDL－3に格納した。

東海研究所：〒319－11 茨城県那珂郡東海村白方字白根2－4

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1. Introduction

For the third version of the Japanese evaluated nuclear data library (JENDL-3), evaluation and compilation of the data have been continued. The evaluated nuclear data of N-15 are not included in JENDL-2. Since nitrogen-15 has a low activation cross section for fast neutrons, it is desirable to replace N-14 with N-15 in the air to decrease the radioactivity around the high conversion reactor core which has a high fluence neutron field. In this reason, the neutron nuclear data of N-15 are necessary to calculate neutron transport in the high conversion reactor, and were evaluated for the JENDL-3. A lot of experimental data of total cross section have been measured by several authors, but scarce measurements for the other quantities.

In this paper, the evaluation of neutron nuclear data of N-15 was performed in the neutron energy range from 0.01 meV to 20 MeV. The evaluated quantities, which are summarized in Table 1 with Q-values, were cross sections, angular distributions and energy spectra of secondary neutrons, and γ-ray data. The inelastic scattering cross sections were calculated for sixteen excited levels with the statistical model. The Q-values of the excited levels are shown in Table 2.

The evaluation of total, elastic scattering and capture cross sections was carried out by using the multilevel Breit-Wigner (MLBW) formula below the incident neutron energy of 5.5 MeV. Above 5.5 MeV, the evaluation was performed by using the multistep statistical model. The detail of evaluation is described in the following chapters.

2. Resonance Analysis

The total, elastic scattering and capture cross sections were evaluated with the MLBW formula below 5.5 MeV. The resonance parameters of Mughabghab et al./1/ and Ajzenberg-Selove/2/ did not reproduce the experiments, but were adopted as initial values. They were adjusted so as to reproduce the total cross section measured by Zeitnitz et al./3/. The resonance parameters thus obtained are shown in Table 3. For the total and elastic scattering, the cross sections calculated by using the resulted parameters tracked almost the experimental data, but a little discrepancy appeared in the energy range from 1 to 2 MeV.

Thus the background cross sections were given to reproduce the experimental data.

Above 5.5 MeV, the smooth curve of the total cross section was obtained by fitting it to the experimental data of Zeitnitz et al./3/. The elastic scattering cross section in the energy range from 5.5 MeV to 20 MeV was calculated by subtracting the reaction cross sections from the total cross section.

3. Statistical Model Calculation

The cross sections, angular distributions and energy spectra of secondary neutrons, and γ-ray data of inelastic scattering and reactions included in Table 1 were evaluated with the multistep statistical model. The angular distribution of elastically scattered neutrons was also calculated in the same way. The inelastic scattering and capture cross sections, and the angular distributions of inelastic scattering were calculated by using the statistical model code CASTHY/6/. Excited levels were assumed to be overlapping above 10 MeV. For the other reactions, the cross sections, angular distribution and energy spectra of secondary neutrons, and γ-ray data were evaluated with the multistep statistical model code GNASH/7/.

The adopted level scheme is shown in Table 2. The optical potential parameters used in the calculation were chosen to reproduce the experimental data of N-14 and shown in Table 4. Those for neutron, proton, and alpha particles were modified. The Perey-Perey's and Becchetti-Greenlees's parameters were adopted for deuteron and triton, respectively. The level density parameters were assumed to be the same as those of N-14/10/, and shown in Table 5.

For γ-ray data, the multiplicities of capture and inelastic scattering to the sixteen discrete levels were calculated by using the GNASH code below 11 MeV. Above 11 MeV, the γ-ray production cross section and spectra of non-elastic scattering including all reactions and inelastic scattering were also calculated by using the GNASH code.

4. Results and Discussion

The total cross section calculated with the MLBW formula below 6 MeV is shown in Fig.1(a). A slight discrepancy appears at about 2.8 MeV. However, the result reproduces almost the experimental data as illustrated in Fig.1(b). The elastic scattering and the capture cross sections are shown in Fig.2-3. The experimental data are only at the thermal energy, and are in good agreement with the present work.

Figures 4-5 show the charged particle emission and the neutron emission cross sections, respectively. There are no experimental data to be compared with the present work.

The inelastic scattering cross sections of the sixteen discrete levels and the overlapping level are illustrated in Fig.6. They also have no experimental data to be compared with them.

The angular distributions of elastically scattered neutrons at the incident energies of 6.0 and 14.0 MeV are shown in Fig.7 as examples of the present calculation.

5. Conclusion

The evaluation of neutron nuclear data of N-15 has been performed in the energy range from 0.01 meV to 20 MeV. The evaluation was carried out basically by using the MLBW formula and the statistical model. The evaluated neutron nuclear data of N-15 could contribute to the application of the high conversion reactors, because of the usableness to calculate the neutron transport in them. The present work was compiled in JENDL-3 in the ENDF-5 format.

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Table 1 The evaluated quantities. Symbol "0" means that the evaluation was performed.

Quantities	σ	$d\sigma/d\Omega$	$d\sigma/dE$	γ-ray data	Q-values [MeV]
total	0	-	-	-	-
elastic	0	0	-	-	0.0
non-elastic	-	-	-	0	-10.12
capture	0	-	-	0	2.492
inelastic	0	0	0	0	-5.27
(n,2n)	0	0	0	-	-10.83
(n,p)	0	-	-	-	-8.99
(n,d)	0	-	-	-	-7.98
(n,t)	0	-	-	-	-9.90
(n,α)	0	-	-	-	-7.62
(n,np)	0	0	0	-	-10.21
(n,nd)	0	0	0	-	-16.16
(n,nt)	0	0	0	-	-14.85
(n,nα)	0	0	0	-	-10.99

Table 2 The level scheme (energy (MeV), spin and parity) /2,4,5/

	N-14		N-15		N-16		C-12		C-13	
gs	0.0	1+	0.0	1/2-	0.0	2-	0.0	0+	0.0	1/2-
1	2.313	0+	5.270	5/2+	0.120	0-			3.089	1/2+
2	3.948	1+	5.299	1/2+					3.685	3/2-
3	4.915	0-	6.324	3/2-					3.854	5/2+
4	5.106	2-	7.155	5/2+						
5	5.691	1-	7.301	3/2+						
6	5.834	3-	7.567	7/2+						
7	6.204	1+	8.313	1/2+						
8	6.446	3+	8.571	3/2+						
9	7.029	2+	9.050	1/2+						
10			9.152	3/2-						
11			9.155	5/2+						
12			9.225	1/2-						
13			9.758	5/2-						
14			9.829	7/2-						
15			9.928	3/2-						
16			10.070	3/2+						

	C-14		C-15		B-11		B-12	
gs	0.0	0+	0.0	1/2+	0.0	3/2-	0.0	1+
1	6.094	1-	0.740	5/2+	2.125	1/2-	0.953	2+
2	6.589	0-			4.445	5/2-	1.674	2-
3	6.728	3-			5.020	3/2-	2.620	1-
4	6.903	0-			6.743	7/2-	2.720	0+
5	7.012	2+			6.793	1/2+		
6	7.341	2-			7.286	5/2+		

Table 3 The evaluated resonance parameters

SCATTERING RADIUS = 3.1 fm SPIN OF ISOTOPE = 1/2

En(MeV)	J	l	Γ (keV)	Γn (keV)	Γγ (eV)
-2.369	0.0	0	6.50000E+03	6.50E+03	2.40E-03
-2.093	1.0	0	1.80000E+03	1.800+03	2.40E-03
9.210	1.0	1	2.00002E+01	2.00E+01	2.34E-01
1.095	1.0	1	3.00023E+00	3.00E+00	2.34E-01
1.563	2.0	3	2.00023E+00	2.00E+00	2.34E-01
1.948	1.0	1	2.20002E+01	2.20E+01	2.34E-01
2.060	1.0	0	1.20000E+02	1.20E+02	2.34E-01
2.390	1.0	2	4.00000E+02	4.00E+02	2.34E-01
2.425	2.0	1	5.50002E+01	5.50E+01	2.34E-01
2.640	1.0	2	4.50000E+02	4.50E+02	2.34E-01
2.755	1.0	0	5.50002E+01	5.50E+01	2.34E-01
2.815	2.0	3	7.00023E+00	7.00E+00	2.34E-01
2.837	3.0	2	7.00023E+00	7.00E+00	2.34E-01
2.915	1.0	1	2.00023E+00	2.00E+00	2.34E-01
2.943	2.0	2	6.00000E+02	6.00E+02	2.34E-01
3.000	1.0	1	1.50000E+02	1.50E+02	2.34E-01
3.225	2.0	3	3.00023E+00	3.00E+00	2.34E-01
3.454	1.0	1	2.40002E+01	2.40E+01	2.34E-01
3.760	1.0	3	3.50000E+02	3.50E+02	2.34E-01
3.997	1.0	1	8.80002E+01	8.80E+01	2.34E-01
4.142	3.0	2	1.00000E+02	1.00E+02	2.34E-01
4.270	2.0	2	1.10000E+02	1.10E+02	2.34E-01
4.610	2.0	1	3.50000E+02	3.50E+02	2.34E-01
4.790	1.0	1	3.00002E+01	3.00E+01	2.34E-01
5.055	3.0	2	2.50002E+01	2.50E+01	2.34E-01
5.430	3.0	3	2.50002E+01	2.50E+01	2.34E-01
5.534	1.0	0	7.00023E+00	7.00E+00	2.34E-01

Table 3 (continued)

En(MeV)	J	l	Γ (keV)	Γn (keV)	Γγ (eV)
5.730	4.0	3	1.60000E+02	1.60E+02	2.34E-01
5.880	2.0	1	7.00002E+01	7.00E+01	2.34E-01
6.280	1.0	2	2.00002E+01	2.00E+01	2.34E-01
6.420	1.0	1	5.30002E+01	5.30E+01	2.34E-01
6.650	1.0	1	4.50002E+01	4.50E+01	2.34E-01
7.100	2.0	1	1.10000E+02	1.10E+02	2.34E-01
7.400	2.0	1	1.05000E+02	1.05E+02	2.34E-01
7.680	2.0	1	1.50000E+02	1.50E+02	2.34E-01
8.070	3.0	2	3.00002E+01	3.00E+01	2.34E-01
8.200	2.0	1	1.75000E+02	1.75E+02	2.34E-01
8.730	2.0	1	1.30000E+02	1.30E+02	2.34E-01

Table 4 The optical potential parameters

neutron	V = 50.08-0.012E MeV	r0 = 1.22 fm	a0 = 0.66 fm
	Ws = 8.91+0.618E MeV	rI = 1.45 fm	aI = 0.13 fm
	Vsys= 5.50 MeV	r0 = 1.15 fm	a0 = 0.50 fm
proton	V = 51.30-0.220E MeV	r0 = 1.21 fm	a0 = 0.61 fm
	Ws = 6.40-0.050E MeV	rI = 1.03 fm	aI = 0.53 fm
	Vsym= 6.00 MeV	r0 = 1.06 fm	a0 = 0.53 fm
deuteron	Perey-Perey's potential /8/		
triton	Becchetti-Greenlees's potential /9/		
alpha	V = 43.9 MeV	r0 = 1.91 fm	a0 = 0.45 fm
	Ws = 3.85 MeV	rI = 1.91 fm	aI = 0.45 fm

Table 5 The Level Density Parameters

	a(1/MeV)	T(MeV)	Pair.(MeV)	Ex(MeV)
B-11	1.431	6.149	2.67	25.58
B-12	1.491	6.201	0.0	26.78
C-12	1.700	5.971	5.60	37.91
C-13	1.846	5.382	2.80	30.57
C-14	1.988	4.887	5.00	28.94
C-15	1.988	4.600	0.0	19.28
N-14	1.600	5.000	0.0	10.00
N-15	2.130	3.758	2.20	10.07
N-16	2.130	4.547	0.0	22.11

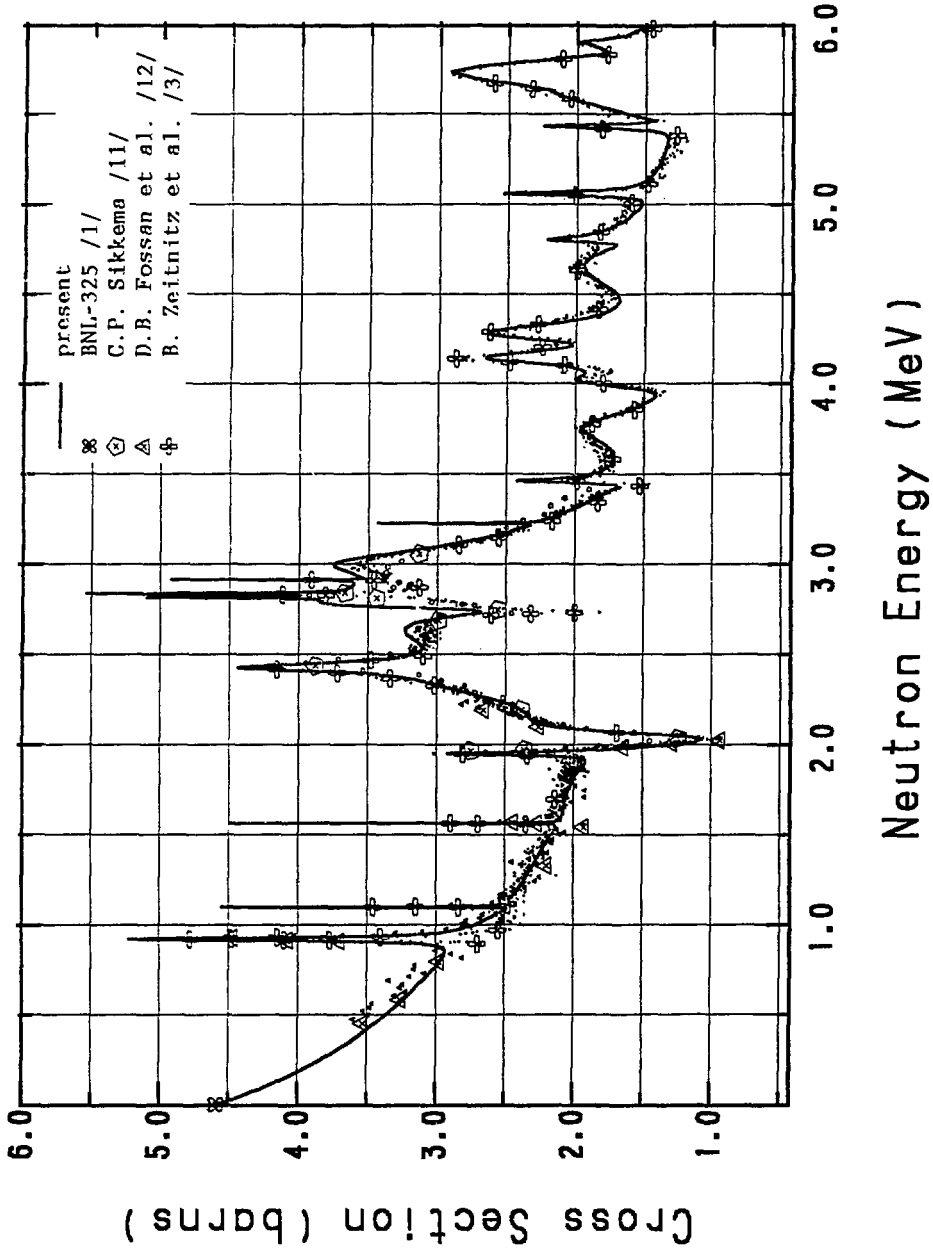


Fig.1(a) Total cross section below 6 MeV

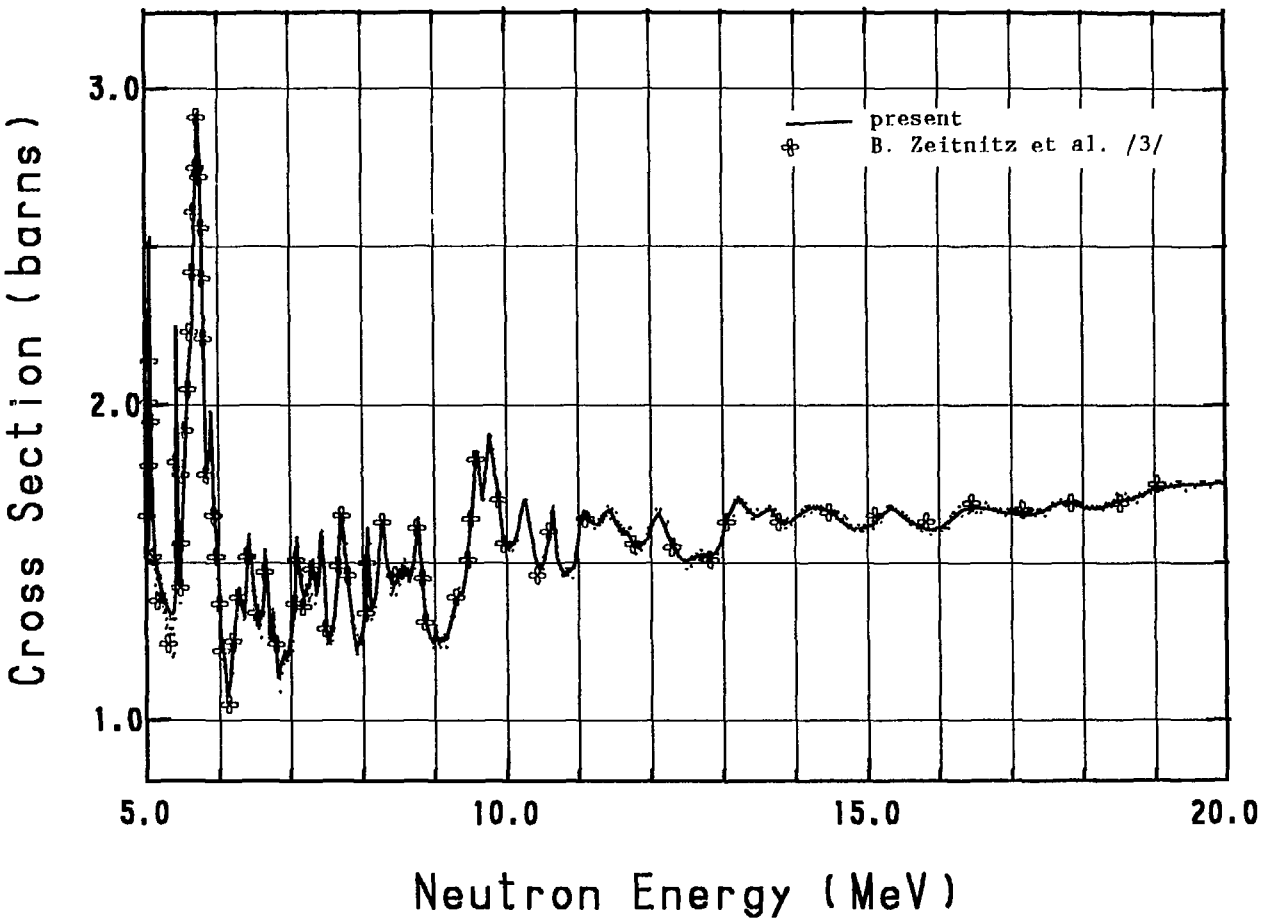


Fig.1(b) Total cross section (5-20 MeV)

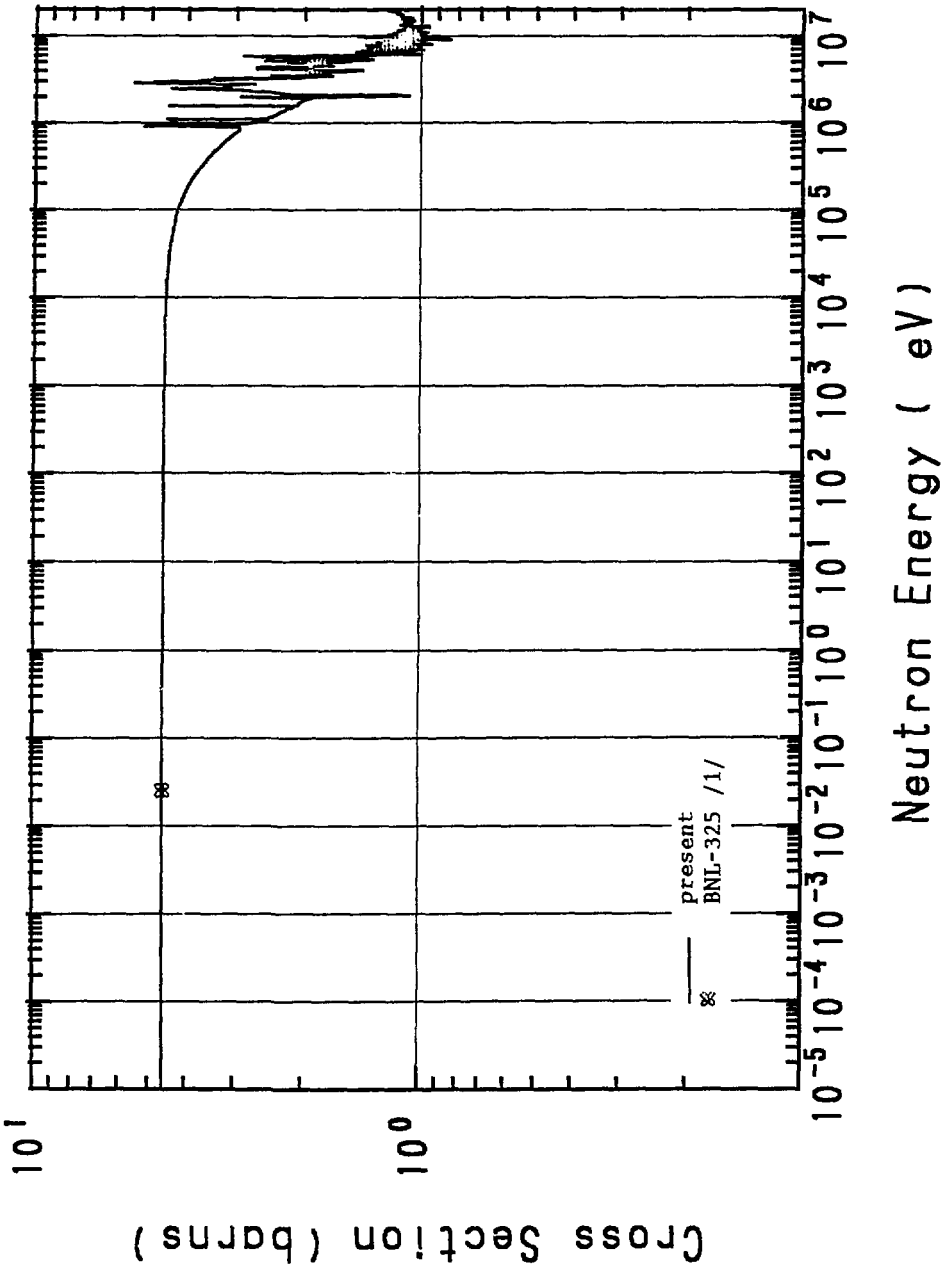


Fig.2 Elastic scattering cross section

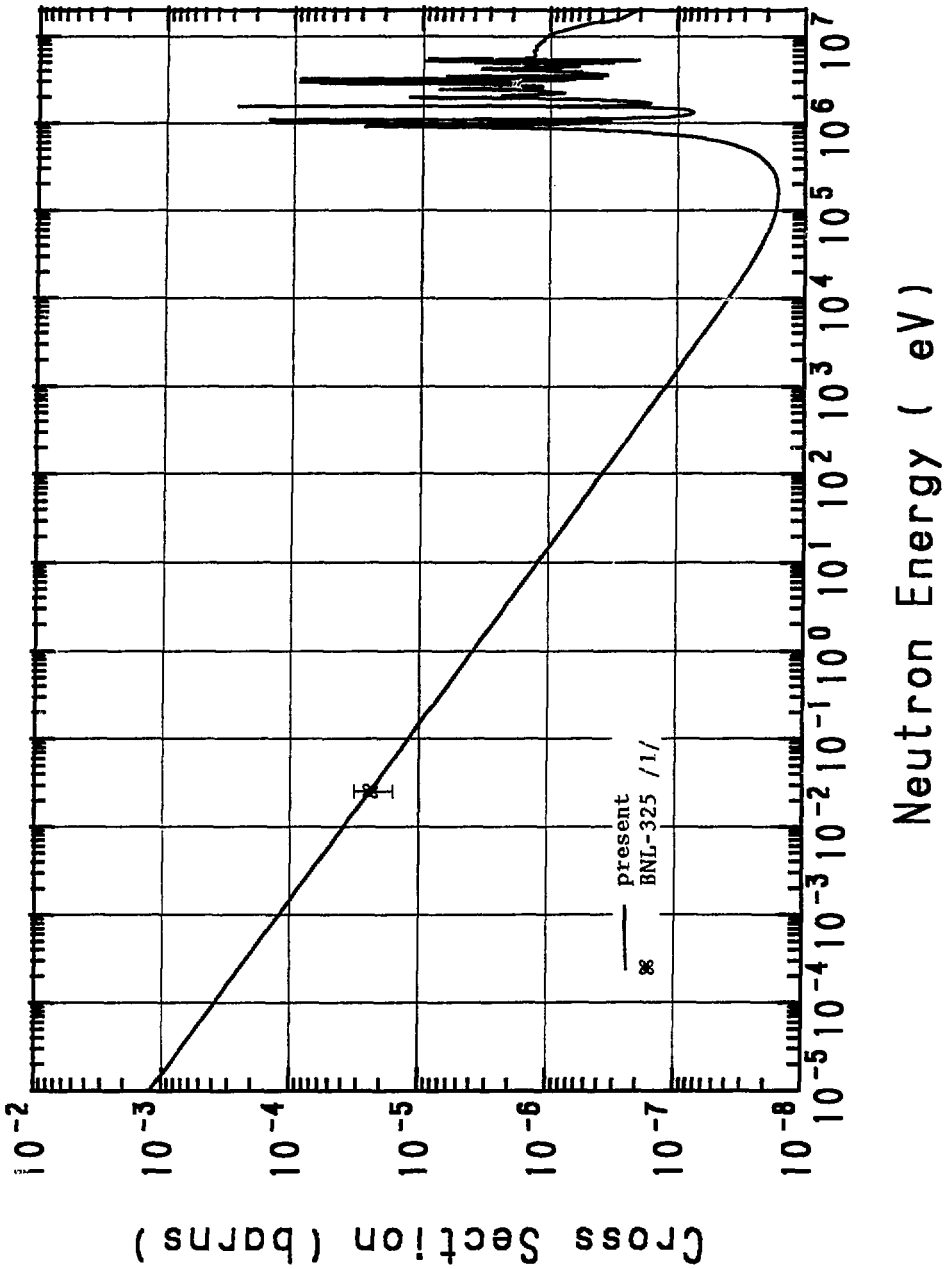


Fig.3 Capture cross section

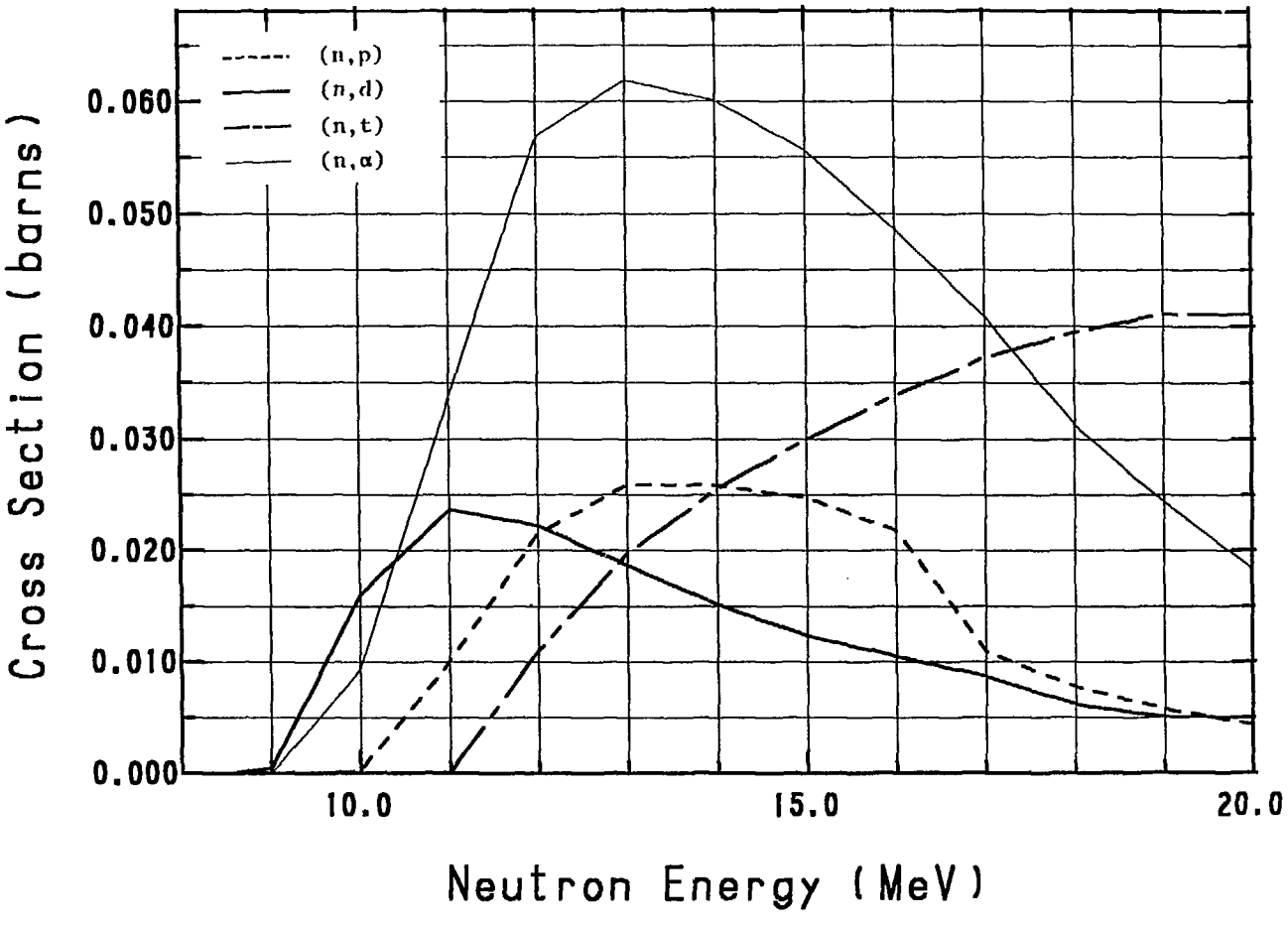


Fig.4 Charged particle emission cross sections

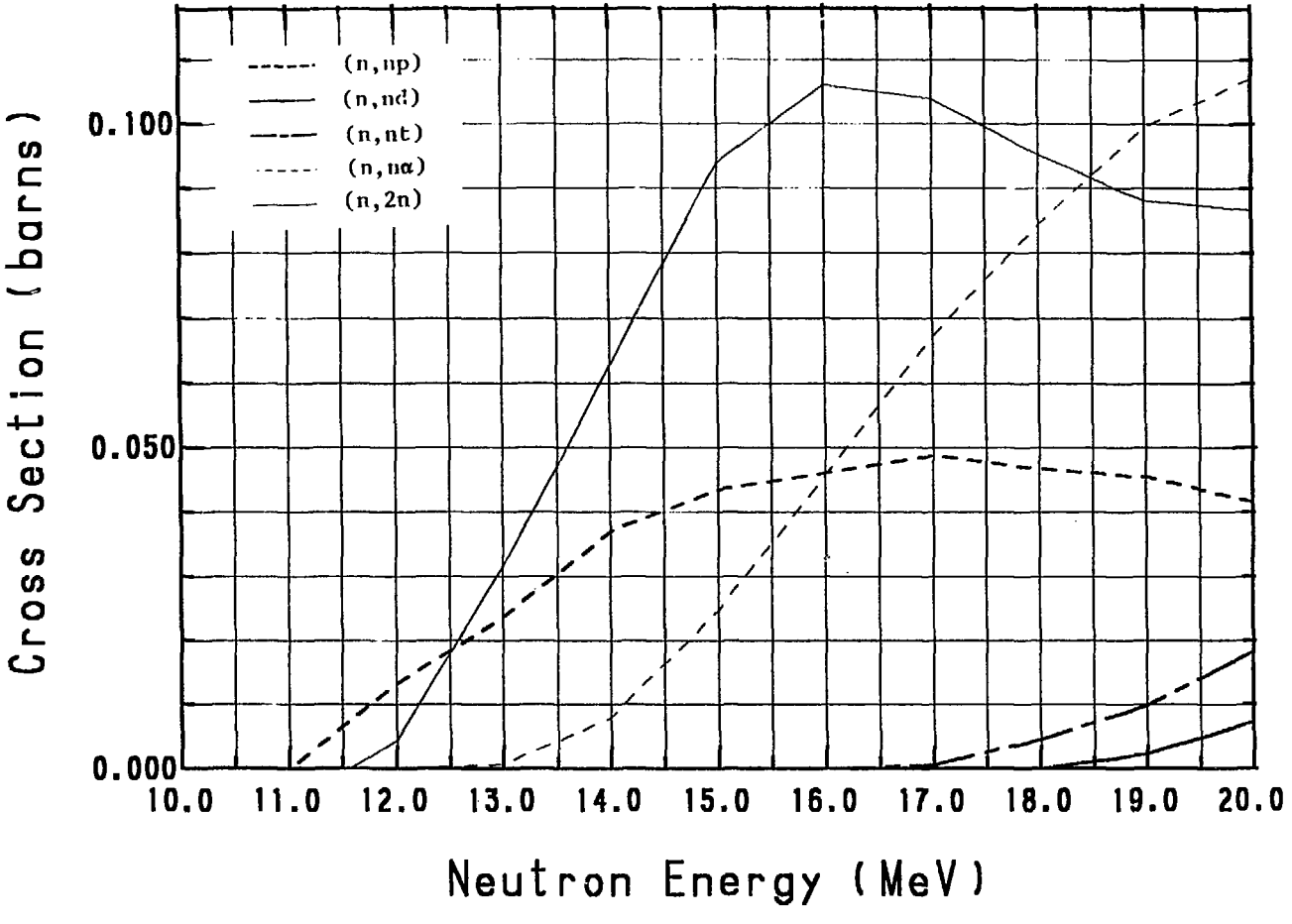


Fig.5 Neutron emission cross sections

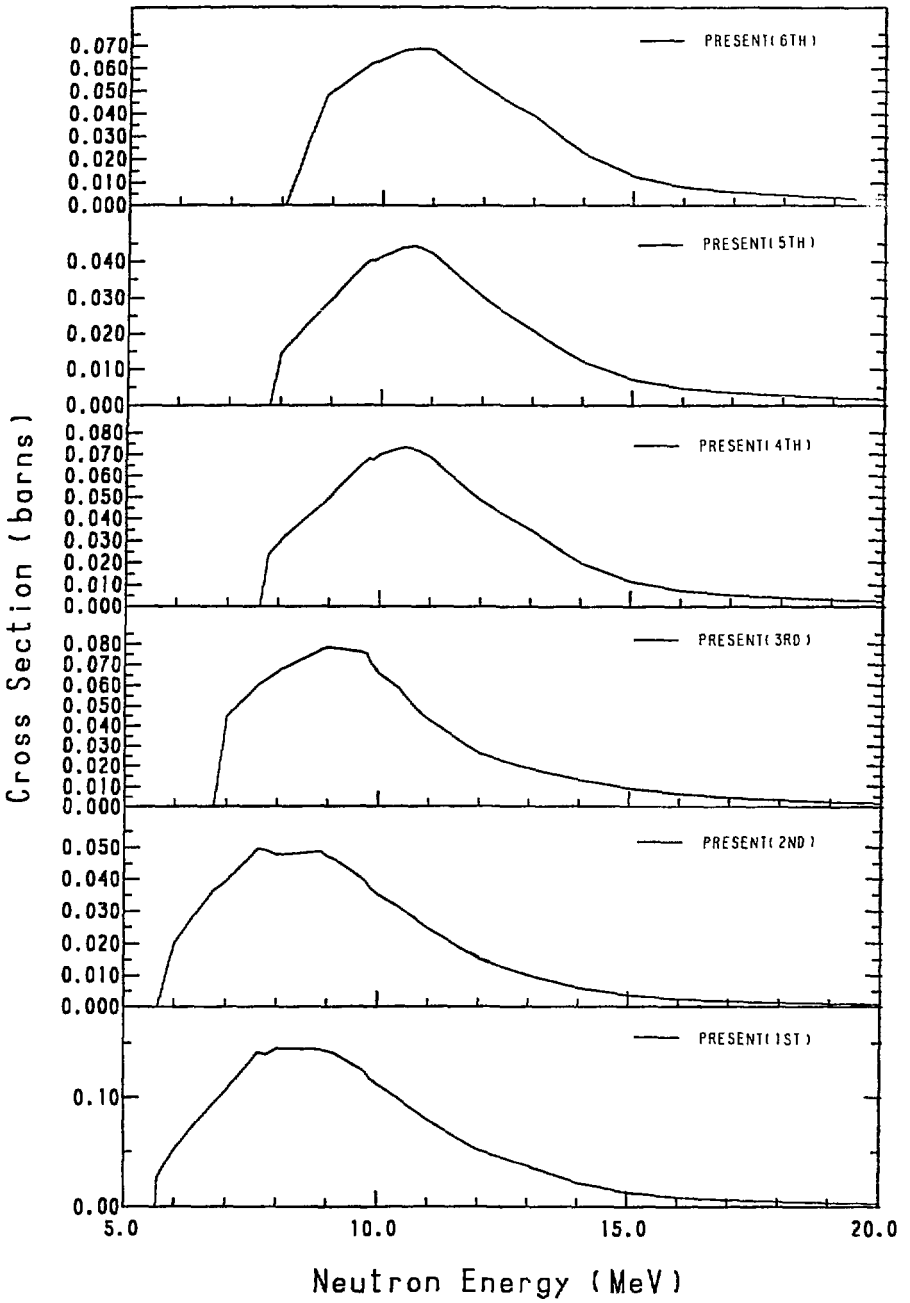


Fig.6 Inelastic scattering cross sections

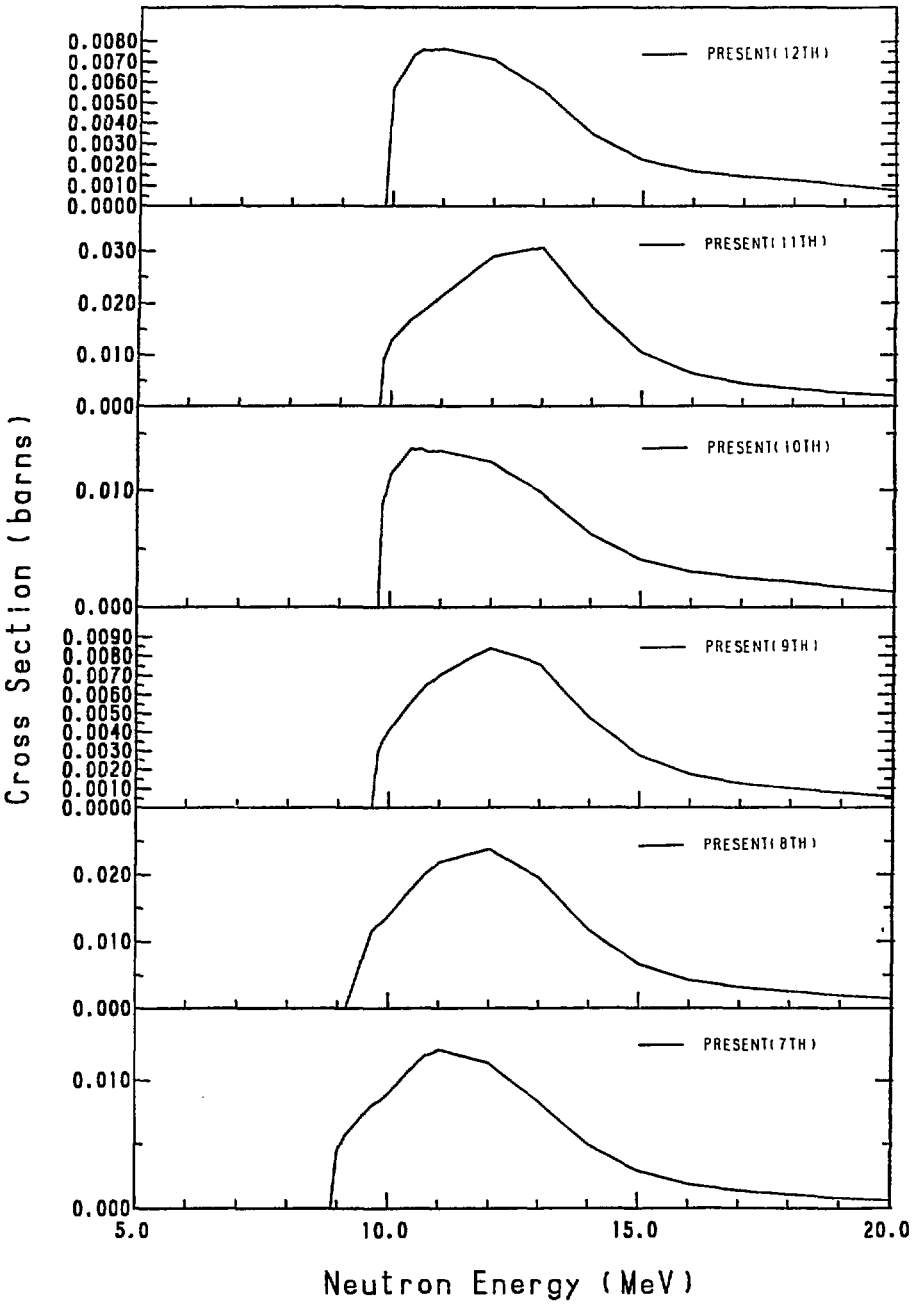
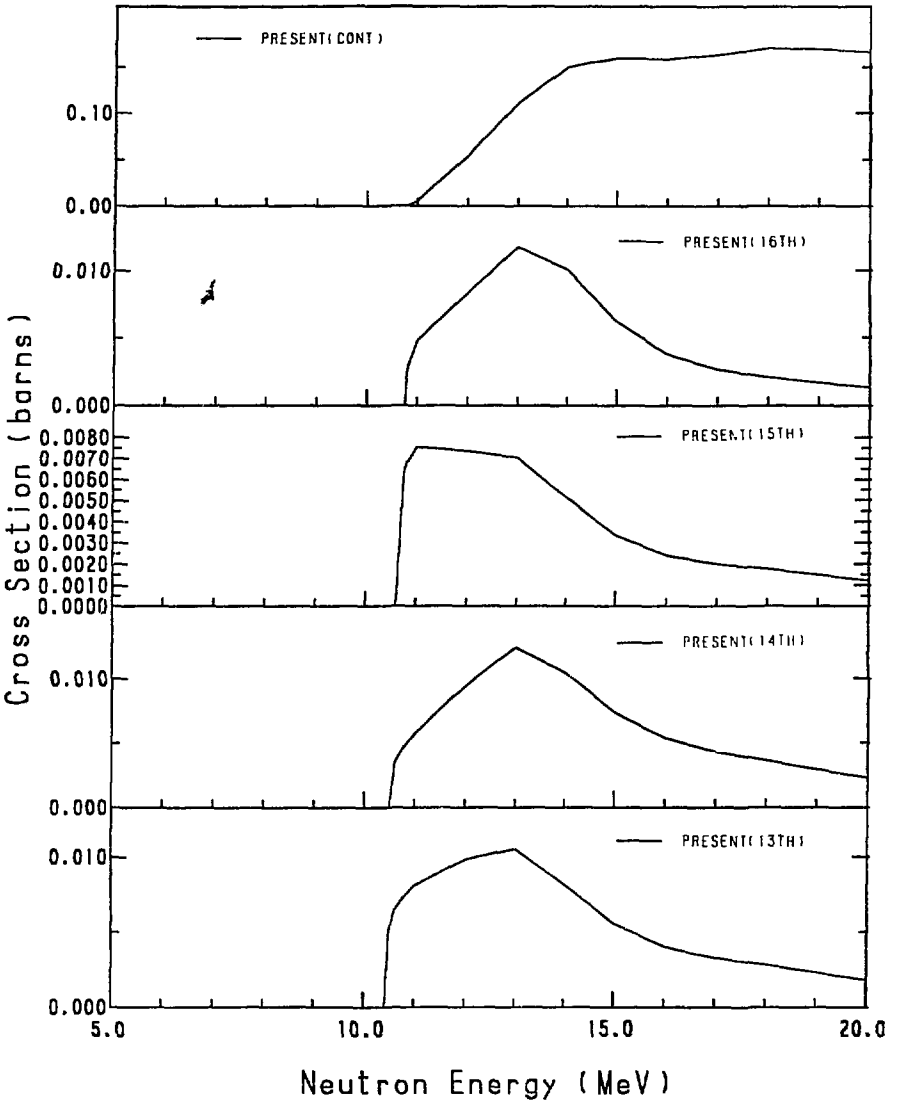


Fig.6 (continued)



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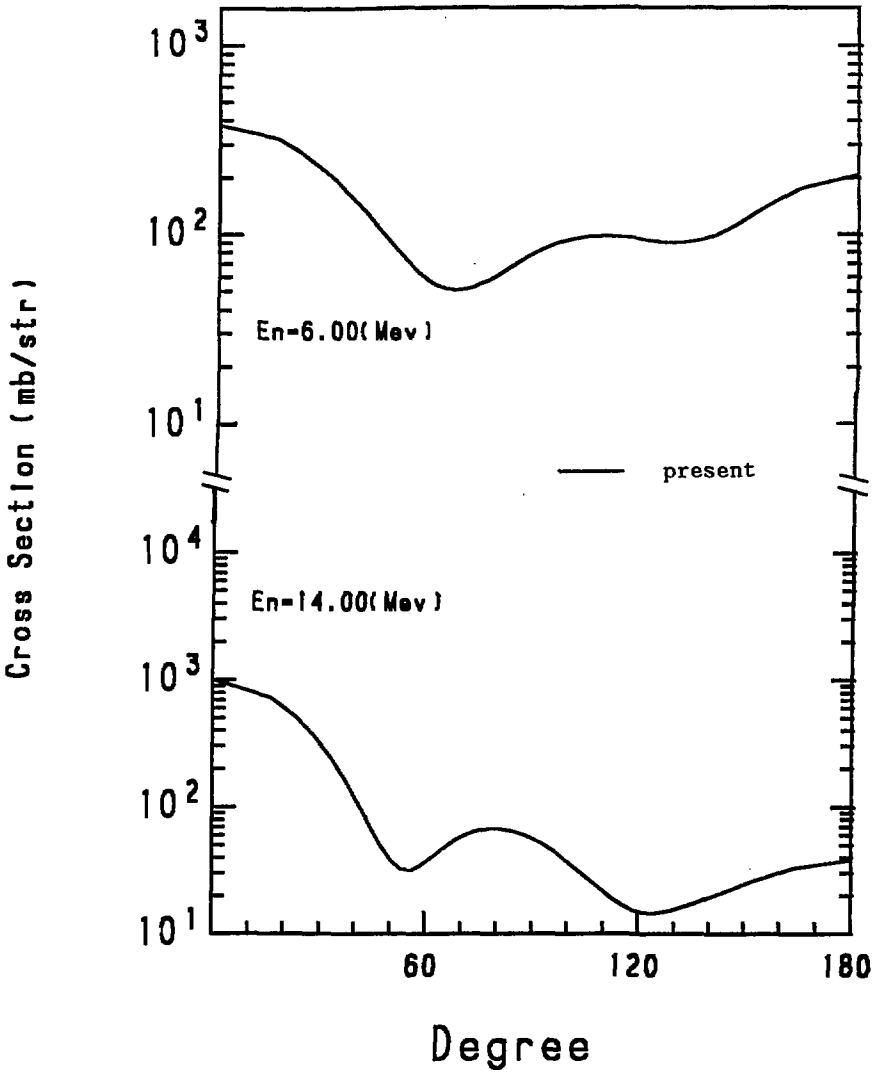

Fig. 7 Angular distributions of elastically scattered neutrons

国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SI と併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ \mathrm{eV} = 1.60218 \times 10^{-19}\ \mathrm{J}$

$1\ \mathrm{u} = 1.66054 \times 10^{-27}\ \mathrm{kg}$

表 5　SI 接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表 3　固有の名称をもつ SI 組立単位

量	名称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SI と共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \mathrm{Å} = 0.1\ \mathrm{nm} = 10^{-10}\ \mathrm{m}$

$1\ \mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$

$1\ \mathrm{bar} = 0.1\ \mathrm{MPa} = 10^5\ \mathrm{Pa}$

$1\ \mathrm{Gal} = 1\ \mathrm{cm/s}^2 = 10^{-2}\ \mathrm{m/s}^2$

$1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}$

$1\ \mathrm{rad} = 1\ \mathrm{cGy} = 10^{-2}\ \mathrm{Gy}$

$1\ \mathrm{rem} = 1\ \mathrm{cSv} = 10^{-2}\ \mathrm{Sv}$

(注)

1. 表1　5は「国際単位系」第5版，国際度量衡局　1985年刊行による．ただし，1 eV および 1 u の値は CODATA の 1986 年推奨値によった．
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した．
3. bar は，JIS では流体の圧力を表わす場合に限り表2のカテゴリーに分類されている．
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている．

換　算　表

力	N(=10^5 dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m²)=10 P(ポアズ)(g/(cm·s))

動粘度　1 m²/s=10⁴St(ストークス)(cm²/s)

圧力	MPa(=10 bar)	kgf/cm²	atm	mmHg(Torr)	lbf/in²(psi)
	1	10.1972	9.86923	7.50062×10^{3}	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^{6}	3.67098×10^{5}	1	8.59999×10^{5}	3412.13	2.65522×10^{6}	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)
= 4.184 J　(熱化学)
= 4.1855 J　(15 °C)
= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)