共鳴公式とパラメータ評価

原研リニアックとORELAでの経験

平成18年2月1日
核データ・チュートリアル
原子力機構先端基礎交流棟大会議室

原子力機構　水本　元治

講義内容

１．中性子反応断面積と中性子共鳴とは

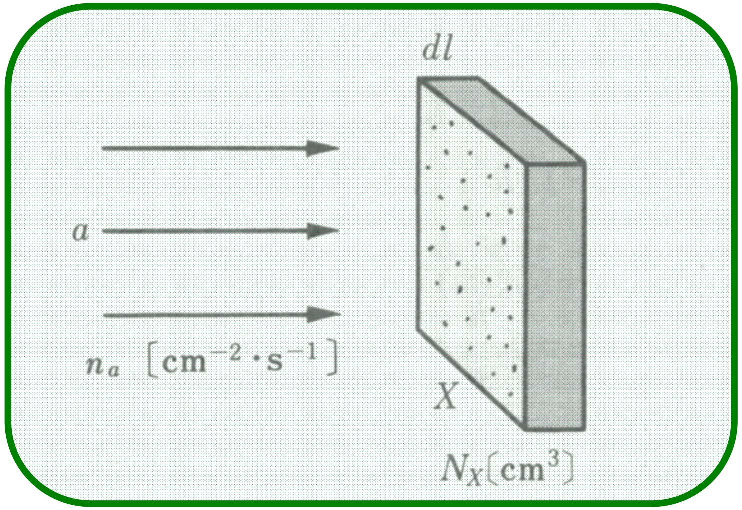
２．中性子共鳴断面積の測定実験

３．共鳴パラメータ（ブライト・ウィグナーの公式）

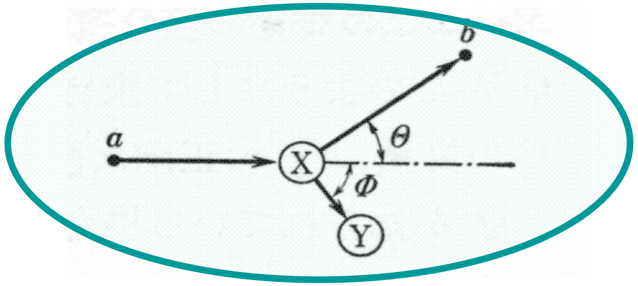
４．共鳴パラメータの解析例

５．まとめ

中性子反応と断面積



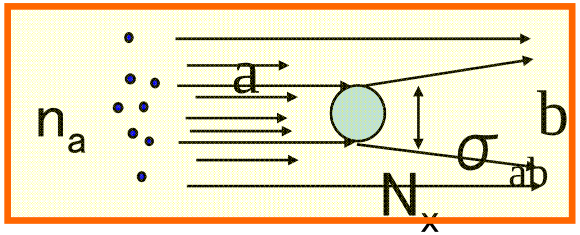
$$a + X \rightarrow Y + b$$



$$X\,(a,b)Y$$

a: 入射粒子
X:標的核
Y: 残留核
b: 放出粒子

弾性散乱、非弾性散乱
核変換(捕獲、吸収、分裂)



反応の収量

$$Y_{ab}\,d\ell = N_x\,d\ell \cdot n_a \cdot \sigma_{ab} \left[s^{-1} cm^{-2} \right]$$

$$\text{断面積}\ \sigma_{ab} = \frac{\text{毎秒標的核1個当たりに起こる反応の数}}{\text{毎秒1cm}^2\text{当たりに入射する粒子の数}}$$

面積の次元(cm^2)を持つ。通常10^{-24}cm^2(バーン)

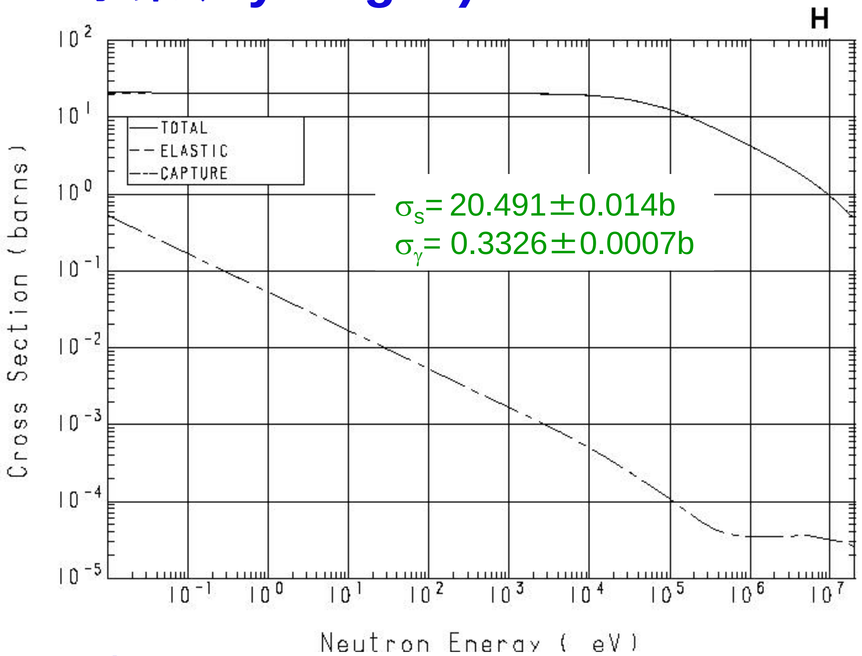
反応の前後で保存
エネルギー(質量を含む)、運動量、
角運動量、電荷、核子数、パリティー

2006.2.1

水素、炭素、鉄の中性子反応断面積
(JENDL3.3)

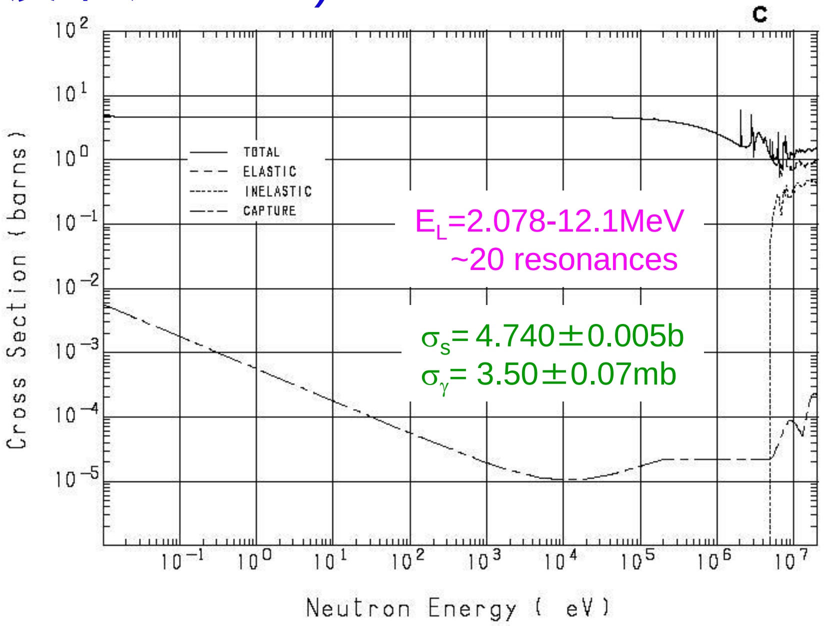
CPAF-JAEA

水素(Hydrogen)



σ_s= 20.491±0.014b
σ_γ= 0.3326±0.0007b

炭素(Carbon)

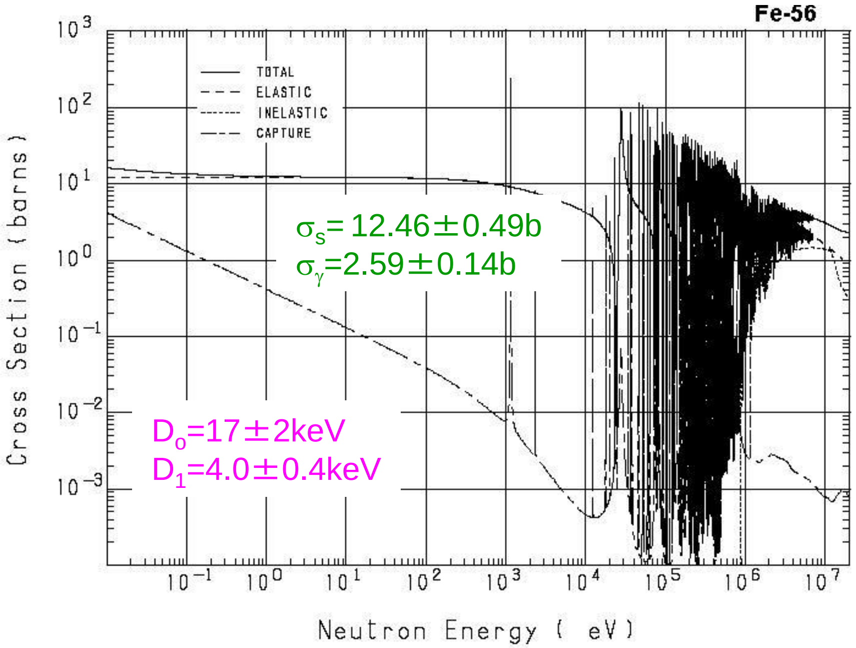


E_L=2.078-12.1MeV
~20 resonances

σ_s= 4.740±0.005b
σ_γ= 3.50±0.07mb

鉄(Ion)

E_H=850keV
t303 (s33,p142,d128)



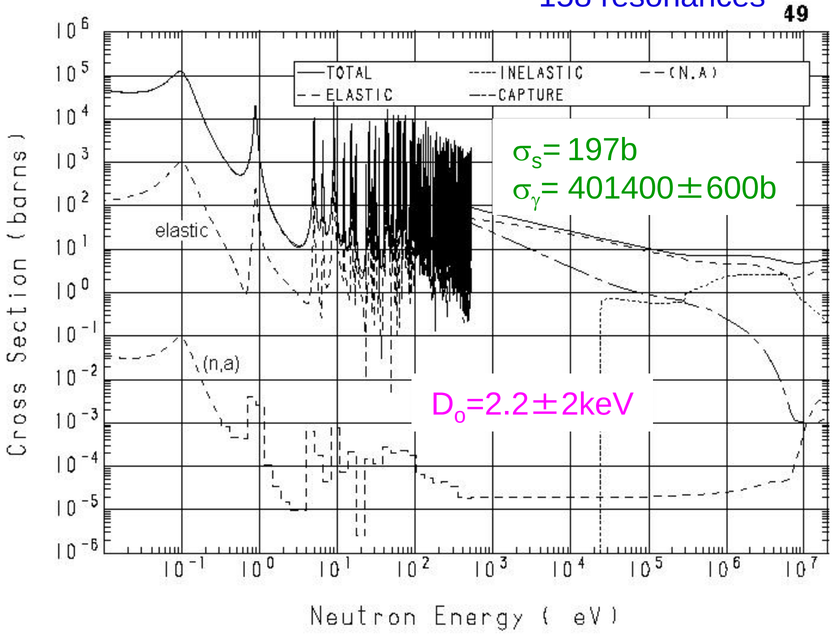
σ_s= 12.46±0.49b
σ_γ=2.59±0.14b

D_o=17±2keV
D_1=4.0±0.4keV

^{149}Smとウランの中性子断面積

^{149}Sm

E_H=520eV
158 resonances



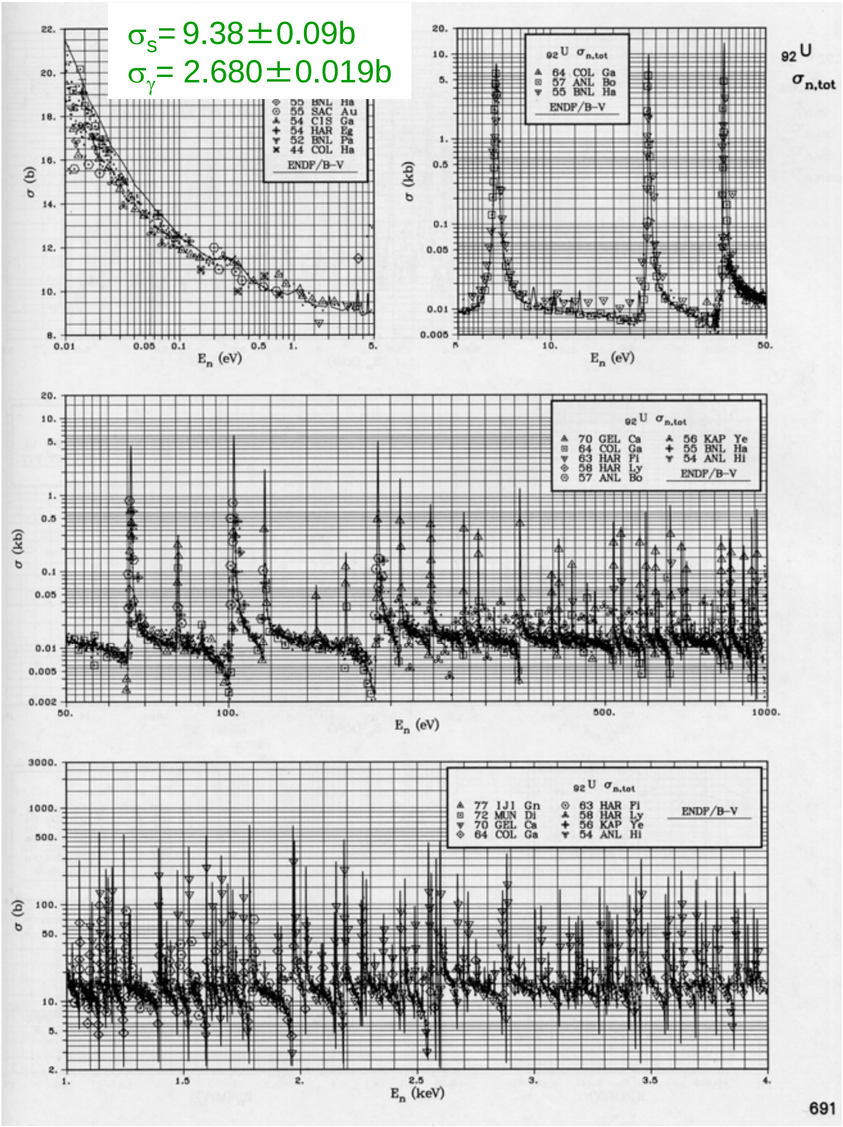
σ_s= 197b
σ_γ= 401400±600b

D_o=2.2±2keV

natU

^{235}U D_o=0.44±0.06eV E_H=2.25keV
3165 resonances

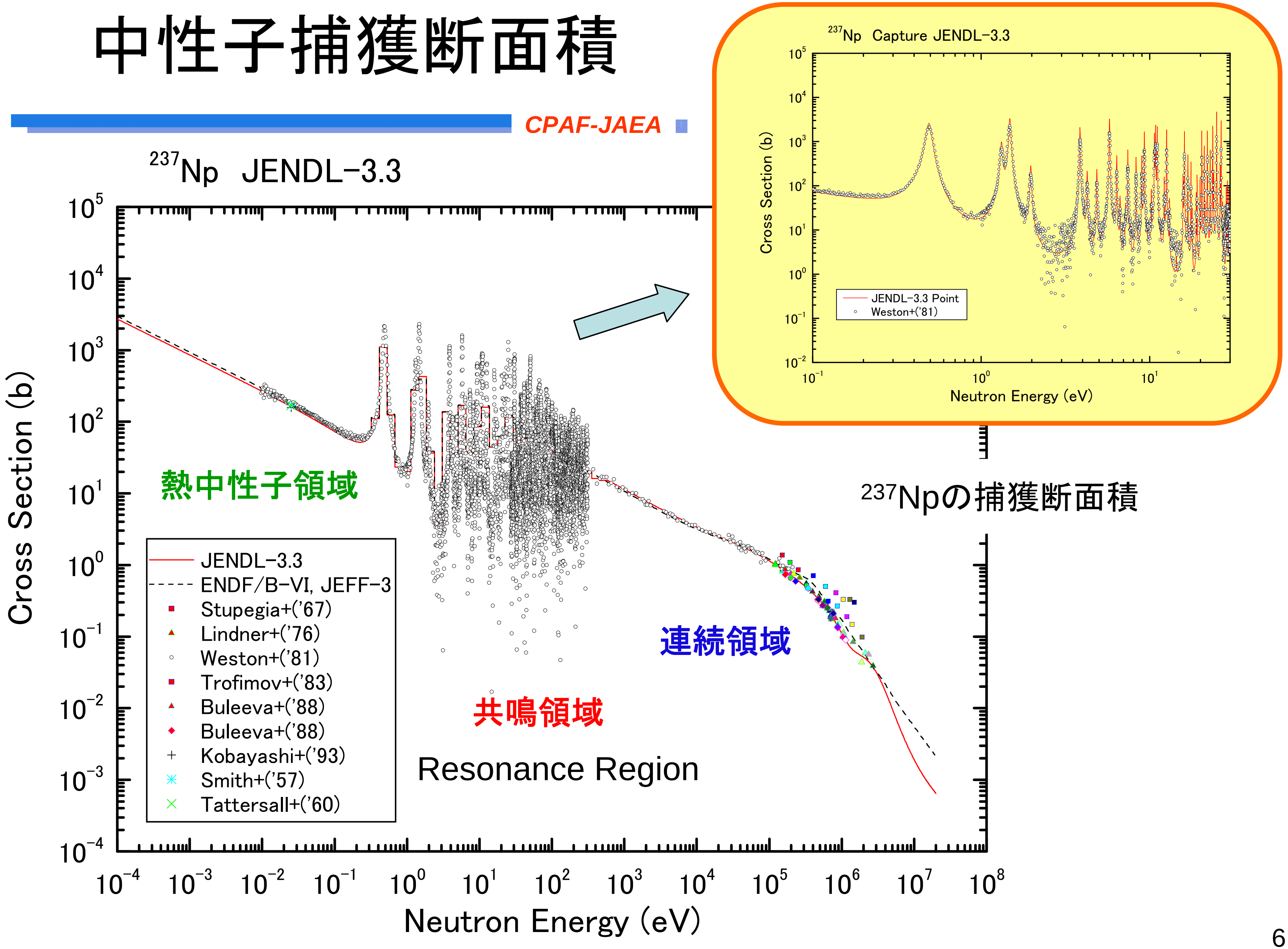
^{238}U D_o=20.9±1.16eV
D_1=7.2±0.4eV
E_H=10keV
s473,p1129 resonances



σ_s= 9.38±0.09b
σ_γ= 2.680±0.019b

中性子捕獲断面積

CPAF-JAEA

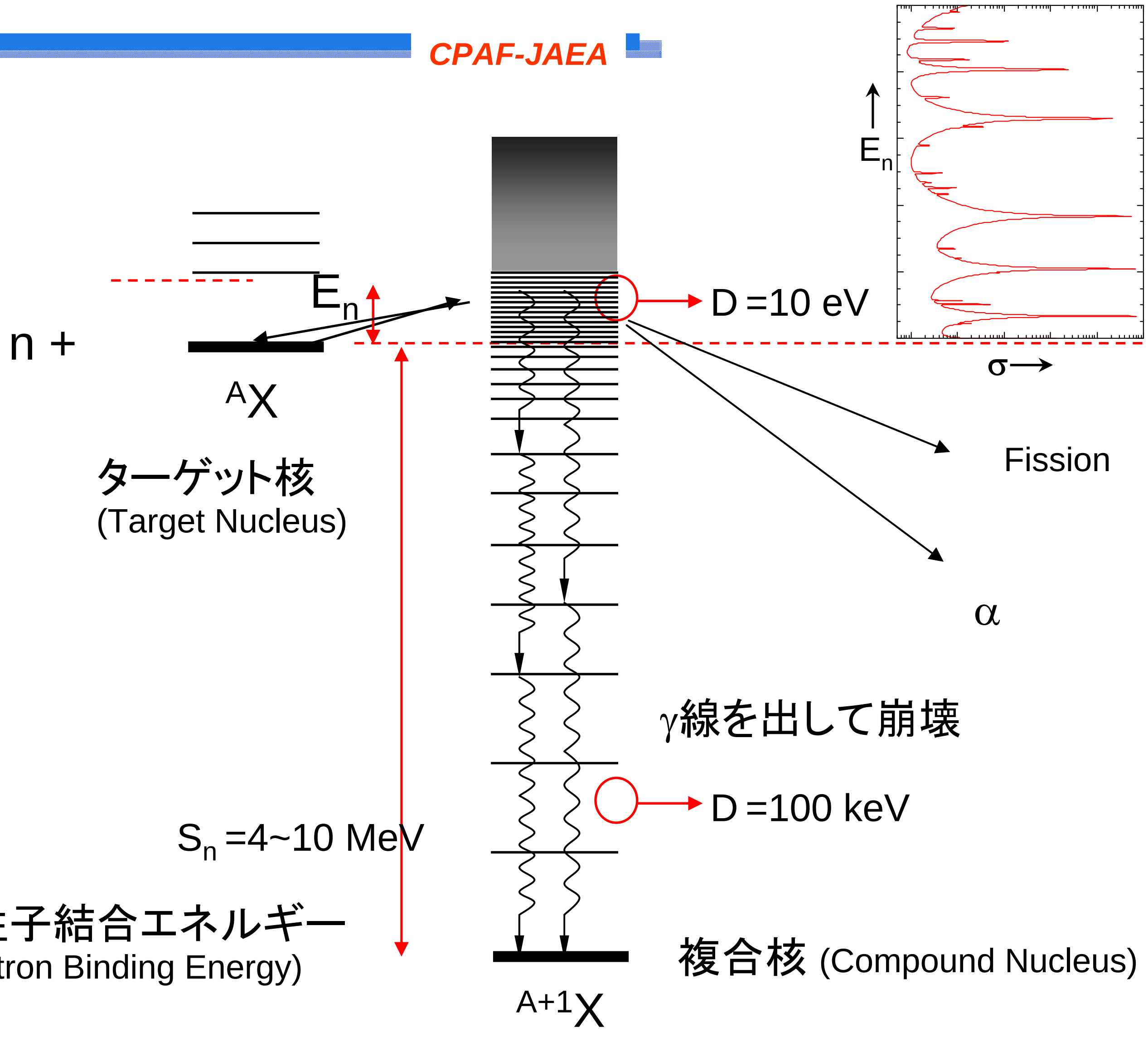


^{237}Npの捕獲断面積

中性子反応

CPAF-JAEA

Sn	
H:	2.225MeV
^{12}C:	4.946MeV
^{56}Fe:	7.646MeV
^{149}Sm:	7.985MeV
^{235}U:	6.546MeV
^{238}U:	4.806MeV



共鳴理論

- Breit-Wigner 公式
  G. Breit and E.P. Wigner Phys. Rev., 49, 519 (1936).

$$\sigma_{n,x}(E) = \frac{\pi}{k^2}\sum_{l}\sum_{J} g_J \sum_{r} \frac{\Gamma_{nr}\Gamma_{xr}}{(E - E_r')^2 + \frac{1}{4}\Gamma_r^2}$$

- 共鳴パラメータ
  J とLごとにE', Γ_n, Γ_x を評価

Eugene Paul Wigner (November 17, 1902 – January 1, 1995) was a Hungarian physicist and mathematician who received the Nobel Prize in Physics in 1963 "for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles". In 1939 and 1940, Dr. Wigner played a major role for a Manhattan Project. In 1946, Wigner accepted a job as director of research and development at Clinton Laboratory (now Oak Ridge National Laboratory) in Oak Ridge, Tennessee. Wigner returned to teaching and research at Princeton University.

Eugene Wigner

Gregory Breit

Gregory Breit (July 14, 1899 – September 11, 1981) was an Russian-born American physicist, professor at universities in New York, Wisconsin, Yale, and Buffalo. Together with Eugene Wigner he gave a description of particle resonant states. During the early stages of the war, Breit was chosen to supervise the early design of the first atomic bomb during an early phase in what would later become the Manhattan Project.

http://en.wikipedia.org/wiki/Eugene_Wigner Gregory_Breit

複合核準位λが形成される確率振幅　$F_\lambda(E)$

全系の波動関数

$$\exp(-iEt/\hbar)\Psi(E)$$

準位λの波動関数

$$\exp(-iWt/\hbar)X_\lambda$$

波動関数の時間によらない部分　$X_\lambda, \Psi(E)$

確率振幅

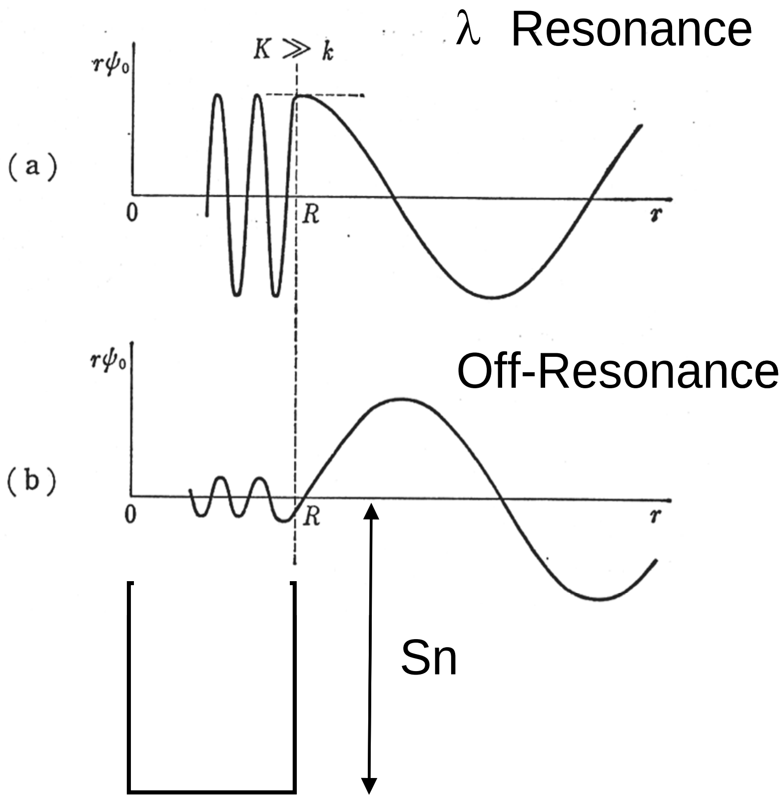
$$F_\lambda(E) \propto \int_0^\infty e^{iEt/h} e^{-iW_\lambda t/h} dt = \frac{\hbar}{i} \frac{1}{E - W_\lambda}$$

複合核過程の断面積

$$= \frac{\pi}{k_\alpha^2} \left| S_{\beta\alpha,res}(E) \right|^2 \propto \frac{1}{k_\alpha^2} \frac{1}{(E - E_\lambda)^2 + \Gamma_\lambda^2 / 4}$$

$$S_{\beta\alpha,res}(E) \propto F_\lambda(E) \propto \frac{1}{E - W_\lambda}$$

$$\boldsymbol{W_\lambda = E_\lambda - i\Gamma_\lambda \quad (\Gamma_\lambda > 0)}$$



JENDL3.3の共鳴順位のデータの例

（^{nat}Feの全断面積）

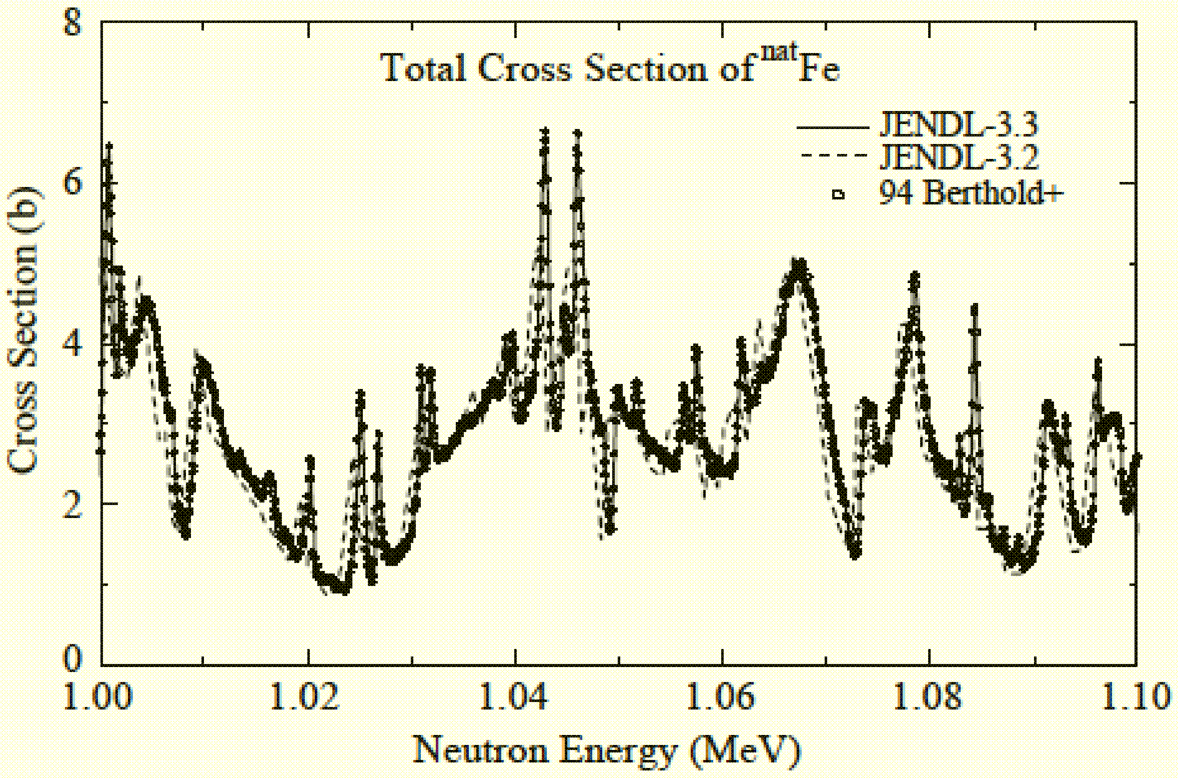
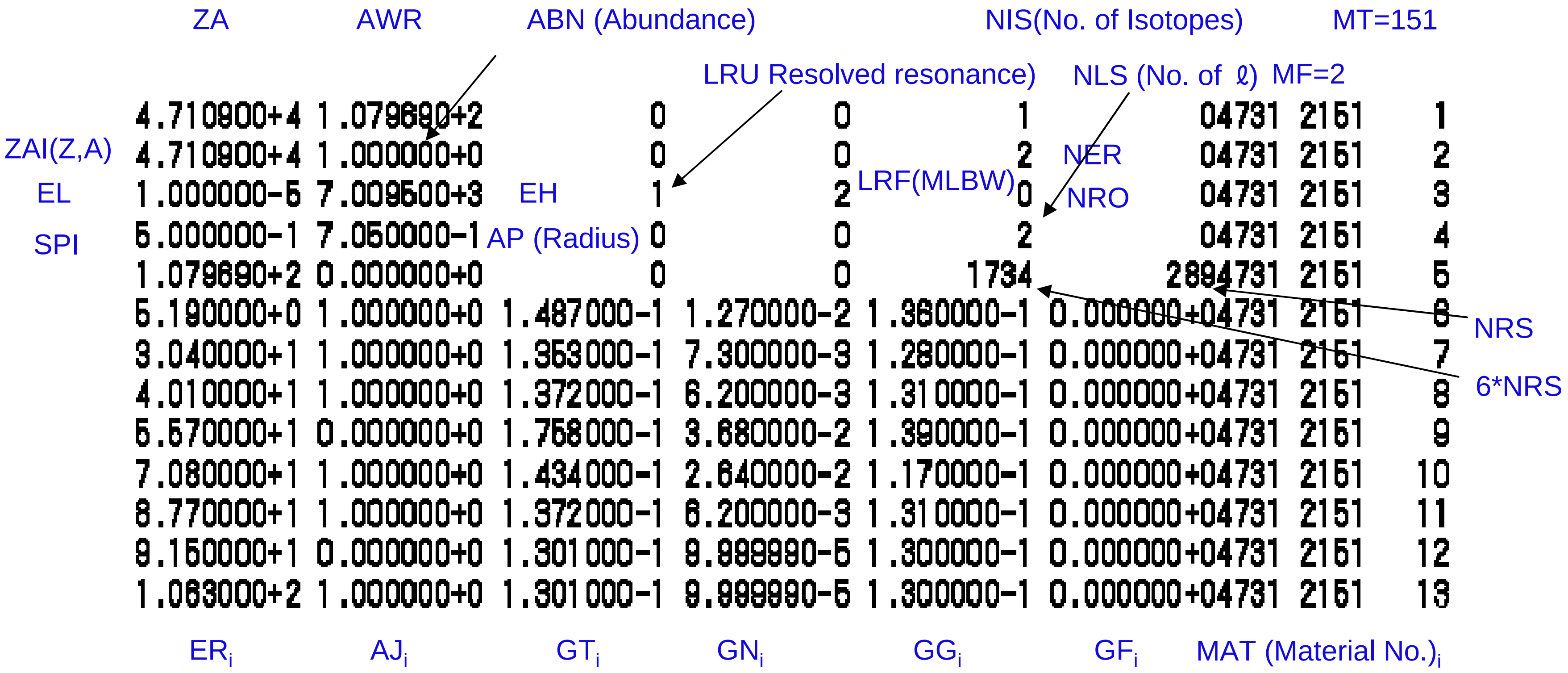


Fig. 3 Total cross section of elemental iron in the energy region from 1.0 to 1.1 MeV

K.Shibata et al.,J.Nucl.Sci.Technol.,39(2002)1125

JENDL3.3 Resonance Parameters of ^{109}Ag (Example)



```
 4.710900+4 1.079690+2          0          0          1          04731 2151    1
 4.710900+4 1.000000+0          0          0          2          04731 2151    2
 1.000000-5 7.009500+3          1          2          0          04731 2151    3
 5.000000-1 7.050000-1          0          0          2          04731 2151    4
 1.079690+2 0.000000+0          0          0       1734        2894731 2151    5
 5.190000+0 1.000000+0 1.487000-1 1.270000-2 1.360000-1 0.000000+04731 2151    6
 3.040000+1 1.000000+0 1.353000-1 7.300000-3 1.280000-1 0.000000+04731 2151    7
 4.010000+1 1.000000+0 1.372000-1 6.200000-3 1.310000-1 0.000000+04731 2151    8
 5.570000+1 0.000000+0 1.758000-1 3.680000-2 1.390000-1 0.000000+04731 2151    9
 7.080000+1 1.000000+0 1.434000-1 2.640000-2 1.170000-1 0.000000+04731 2151   10
 8.770000+1 1.000000+0 1.372000-1 6.200000-3 1.310000-1 0.000000+04731 2151   11
 9.150000+1 0.000000+0 1.301000-1 9.999990-5 1.300000-1 0.000000+04731 2151   12
 1.063000+2 1.000000+0 1.301000-1 9.999990-5 1.300000-1 0.000000+04731 2151   13
```

ZA AWR ABN (Abundance) NIS(No. of Isotopes) MT=151

LRU Resolved resonance) NLS (No. of ℓ) MF=2

ZAI(Z,A)

EL

SPI

EH

AP (Radius)

LRF(MLBW)

NER

NRO

NRS

6*NRS

ER_i AJ_i GT_i GN_i GG_i GF_i MAT (Material No.)$_i$

以下略

Breit Wigner の一準位公式

（共鳴間・反応間のInterference(干渉)がない場合）

散乱断面積

$$\sigma_{n,n}(E)=\pi\bar{\lambda}^2\left\{4\sin^2 kR+\Gamma_{\lambda n}\frac{2(E-E_\lambda)\sin 2kR-\Gamma_\lambda(1-\cos 2kR)}{(E-E_\lambda)^2+1/4\Gamma_\lambda{}^2}+\frac{(\Gamma_{\lambda n})^2}{(E-E_\lambda)^2+1/4\Gamma_\lambda{}^2}\right\}$$

捕獲断面積

$$\sigma_{n,x}(E)=\pi\bar{\lambda}^2\frac{\Gamma_{\lambda n}\Gamma_{\lambda x}}{(E-E_\lambda)^2+1/4\Gamma_\lambda{}^2}$$

全断面積

$$\sigma_{n,T}(E)=\sigma_{n,n}(E)+\sigma_{n,\gamma}(E)$$

ピーク断面積

散乱 $\sigma_{0n}=\sigma_0\dfrac{\Gamma_n}{\Gamma}$ 捕獲 $\sigma_{0\gamma}=\sigma_0\dfrac{\Gamma_\lambda}{\Gamma}$

$$\sigma_0=4\pi\bar{\lambda}^2\frac{g\Gamma_n}{\Gamma}=\frac{2.608*10^6}{E_0(eV)}\left(\frac{A+1}{A}\right)^2\frac{g\Gamma_n}{\Gamma}$$

中性子強度関数

$$S_l = \frac{\langle g\Gamma_n^l \rangle}{(2l+1)D_l} = \frac{1}{(2l+1)\Delta E}\sum_j g_j \Gamma_{nj}^l$$

Reduced Neutron Width

$$\Gamma_{nj}^l = \sqrt{\frac{1eV}{E}}\,\frac{\Gamma_{nj}}{V_l}$$

Average level spacing D_l

Spin statistical weight factor

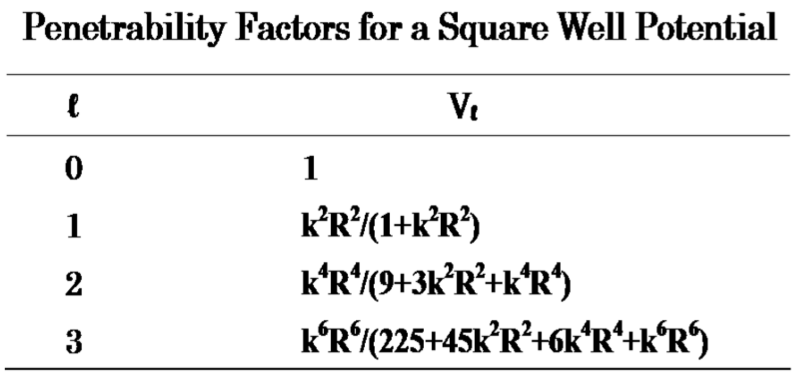
$$g_J = \frac{2J+1}{(2i+1)(2I+1)} = \frac{2J+1}{2(2I+1)}$$

S-wave

$$S_0 = \frac{\langle g\Gamma_n^0 \rangle}{D_0}$$

$$\Gamma_{nj}^0 = \sqrt{\frac{1eV}{E}}\,\Gamma_{nj}$$

$$\langle g_j \Gamma_{nj} \rangle = \sqrt{E}\,\langle g_j \Gamma_{nj}^0 \rangle = \sqrt{E}\,S_0 D_0$$



Penetrability Factors for a Square Well Potential

ℓ	V_ℓ
0	1
1	$k^2R^2/(1+k^2R^2)$
2	$k^4R^4/(9+3k^2R^2+k^4R^4)$
3	$k^6R^6/(225+45k^2R^2+6k^4R^4+k^6R^6)$

共鳴パラメータのコンピレーション

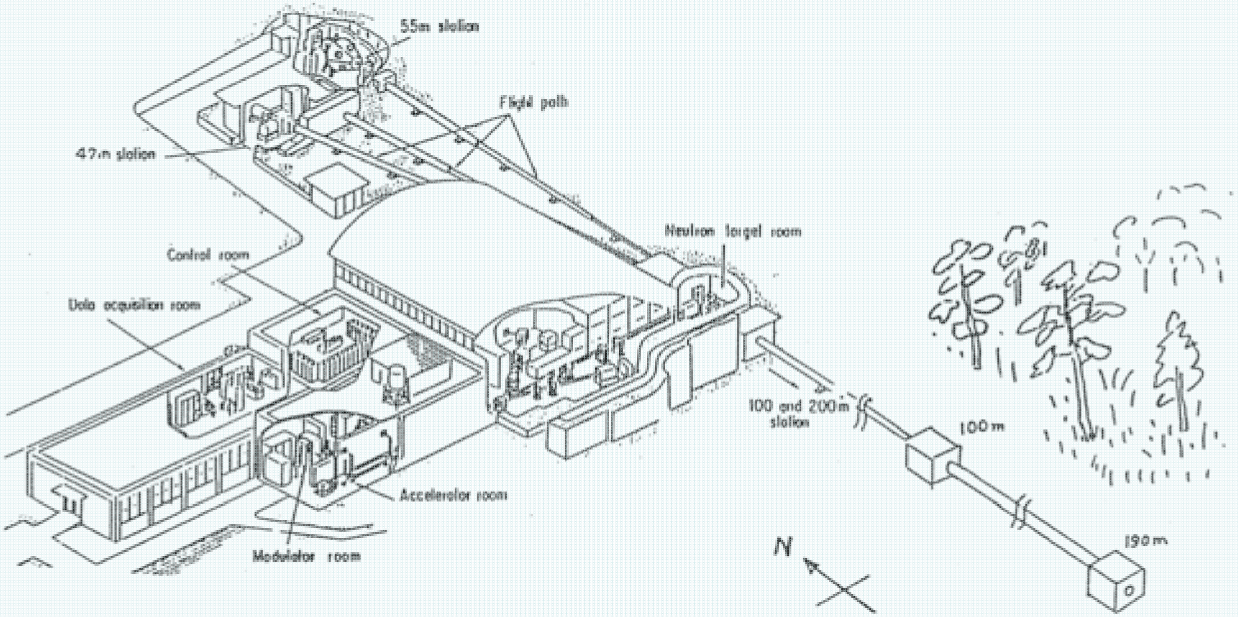
1. Said. F. Mughabghab et al.: “Neutron Cross Sections, Vol. 1, Part A, Z=1-60”, Academic Press (1981). “Neutron Cross Sections, Vol. 1, Part B, Z=61-100”, Academic Press (1984)
2. S.I. Sukhoruchkin et al.: “Low Energy Neutron Physics”, Landolt-Börnstein (1998)
3. Said F. Mughabghab : ”Atlas of Neutron Resonances : Resonance Parameters and Thermal Cross Sections. Part A: Z=1-50. Part B: Z=51-100(HRD)” /Publisher:Elsevier Published 2006/03 (出版予定) US$314.00

参考書

J.A.Harvey ed.,”Experimental Neutron Resonance Spectroscopy”, Publisher: Academic Press 1970

JAERI LINAC Resonance Experiments

Energy=120MeV Flight path =40m, 55m, 190m Rep=10-600pps
Pulse width=20ns-20us



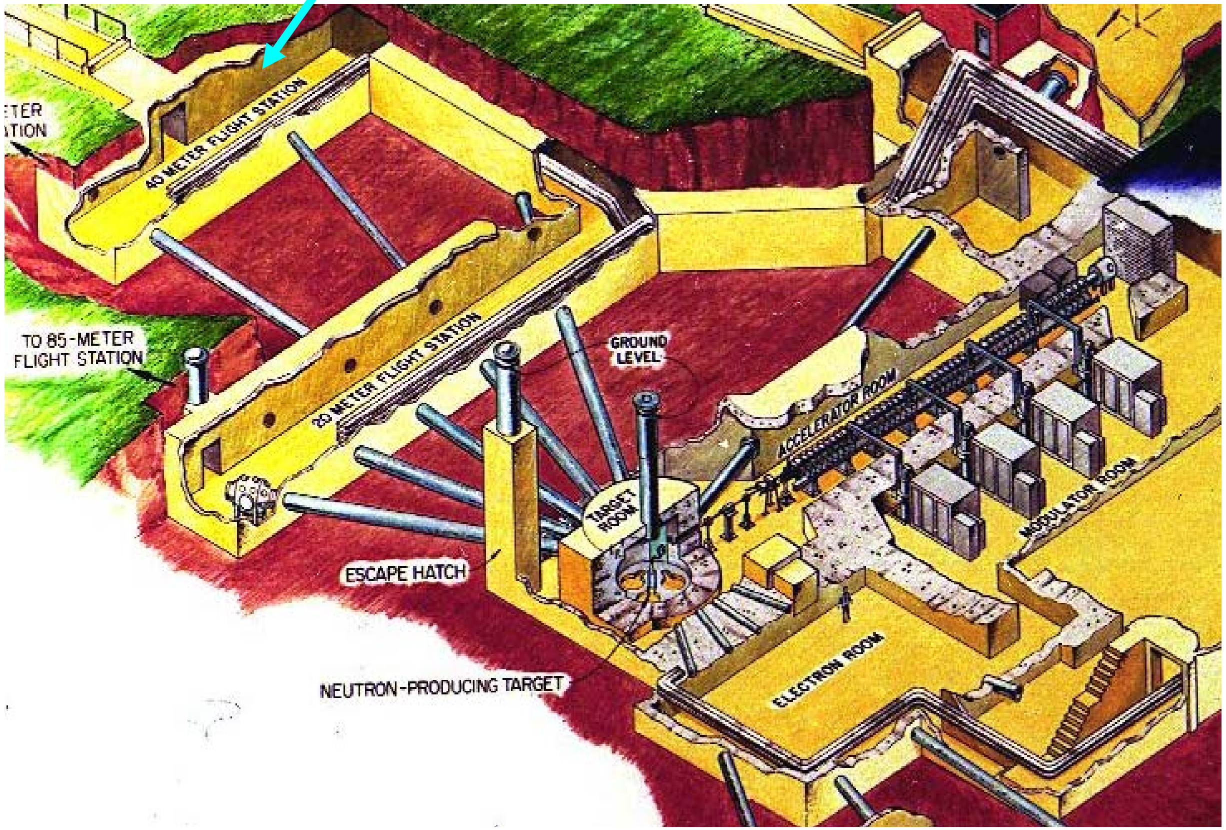
第５．１．１図　増力リニアックの鳥瞰図

FP（Ag,Eu,Nd,Sm,Cs・・・,^{238}U

The Oak Ridge Electron Linear Accelerator (ORELA)

(n.γ)
40 station

Flight path #7



150 MeV e$^-$ linac.

Δt = 2 – 30 ns.

P < 60 kW.

Rate = 1 – 1000 Hz.

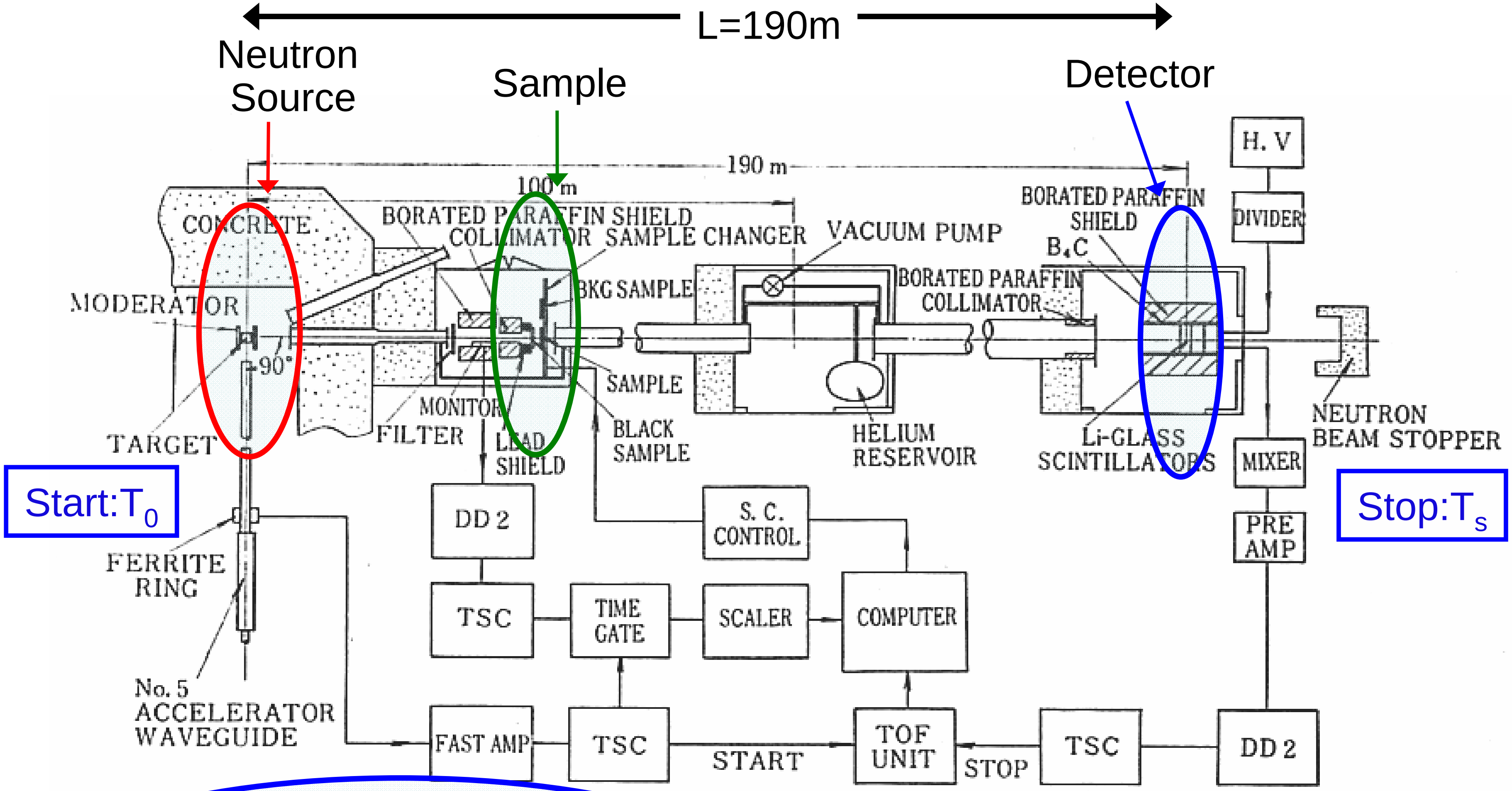
11 Flight Paths.

8-18, 20, 35, 40, 85, 150, and 200 m flight stations.

Transmission

ORELA
^{206,207,208}Pb, Capt., Trans.
^{159}Tb, Capt.
^{136}Xe,Capt, Trans

全断面積の測定



Start:T_0

Stop:T_s

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{L}{t}\right)^2 = \left(\frac{72.3\times L}{t_s - t_0}\right)^2$$

L：Flight Path Length
T: Flight time (T_s-T_0)

全断面積（透過率測定Transmission）

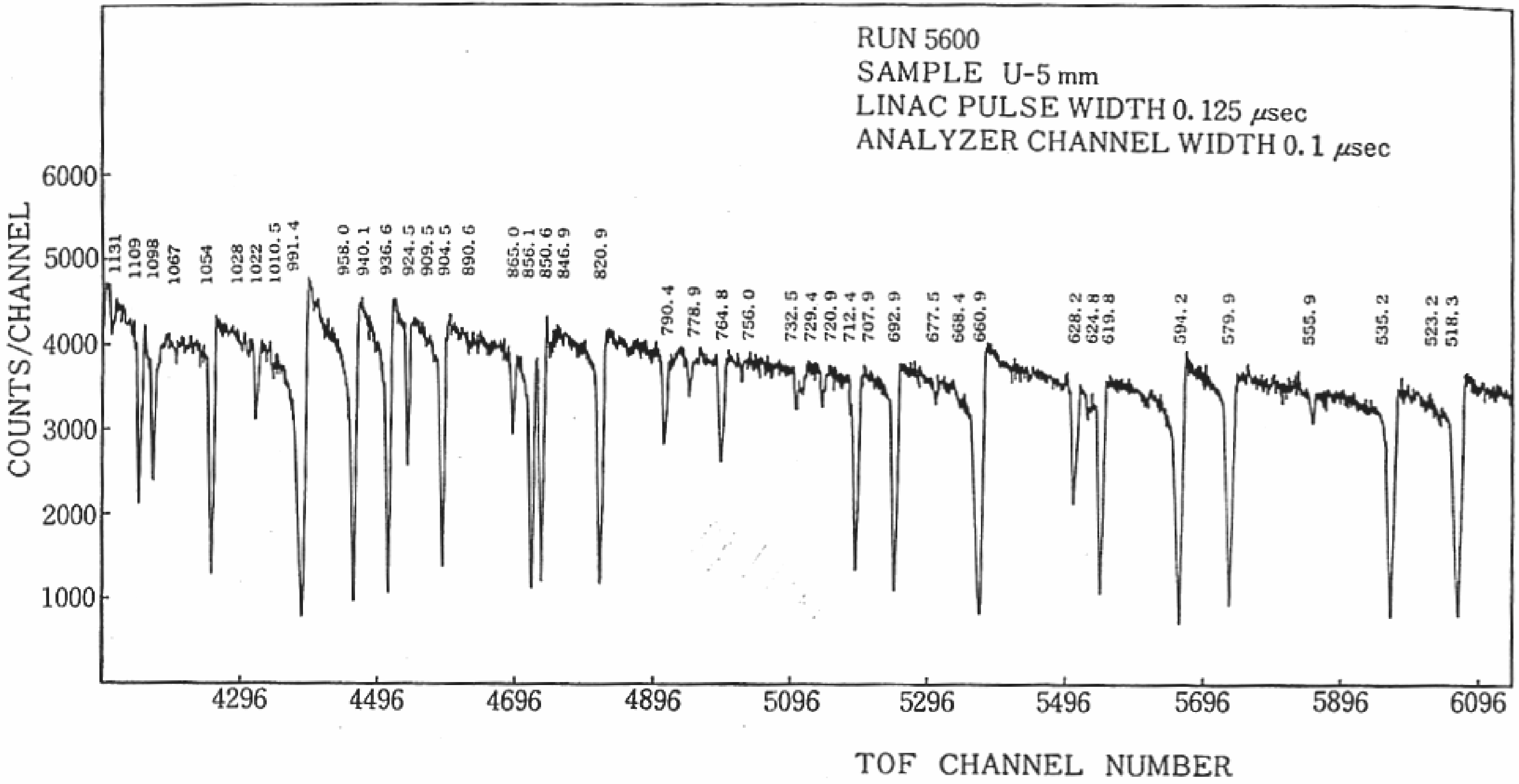


Fig. 16.10 Neutron transmission spectrum for a natural uranium sample. Numbers associated with the absorption dips in the spectrum are resonance energies in electron volt.

Transmission Experiment

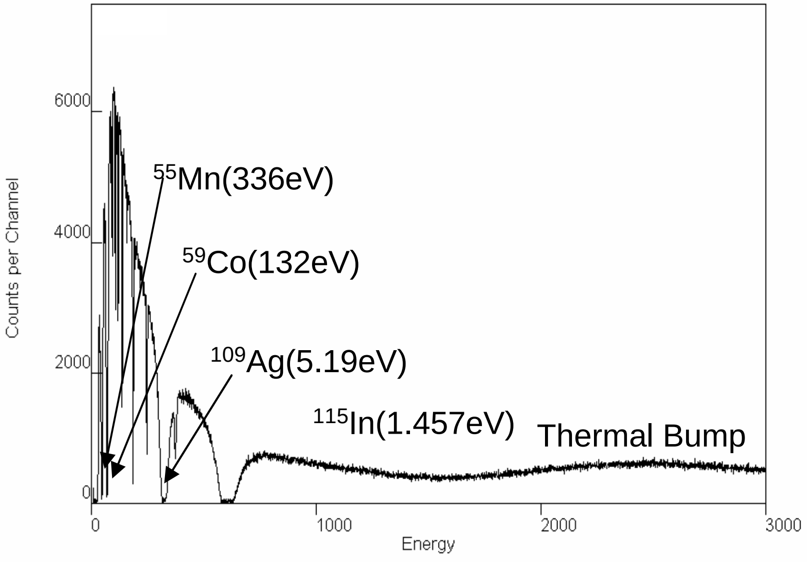
$$T_{trans} = \frac{(I_{in} - Bkg_{in})/mon_{in}}{(I_{out} - Bkg_{out})/mon_{out}} = \exp(-n\sigma_t)$$

$$\sigma_t = -\frac{1}{n}\log(T_{trans})$$

T_{trans}: Transmission
σ_t: total cross section
n:sample thickness

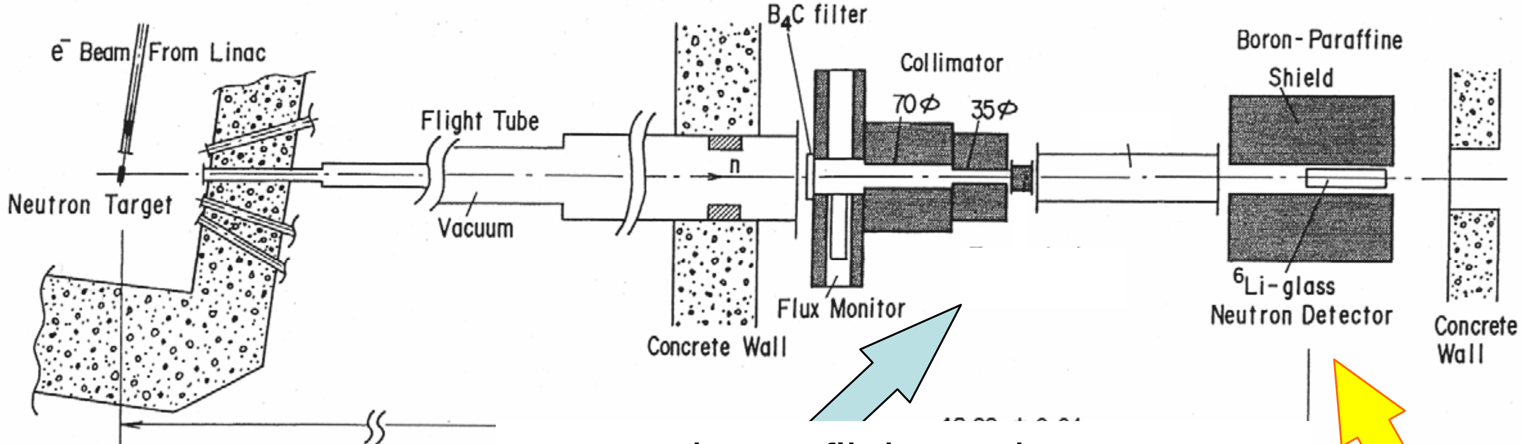
I_{in}: sample in counts
I_{out}:sample out counts
Bkg_{in}: Background (to sample in)
Bkg_{out}:Background (to sample out)
mon: monitor counts

Sample Changer to compensate the neutron fluctuation



Black Resonance Filter Method for Background Determination

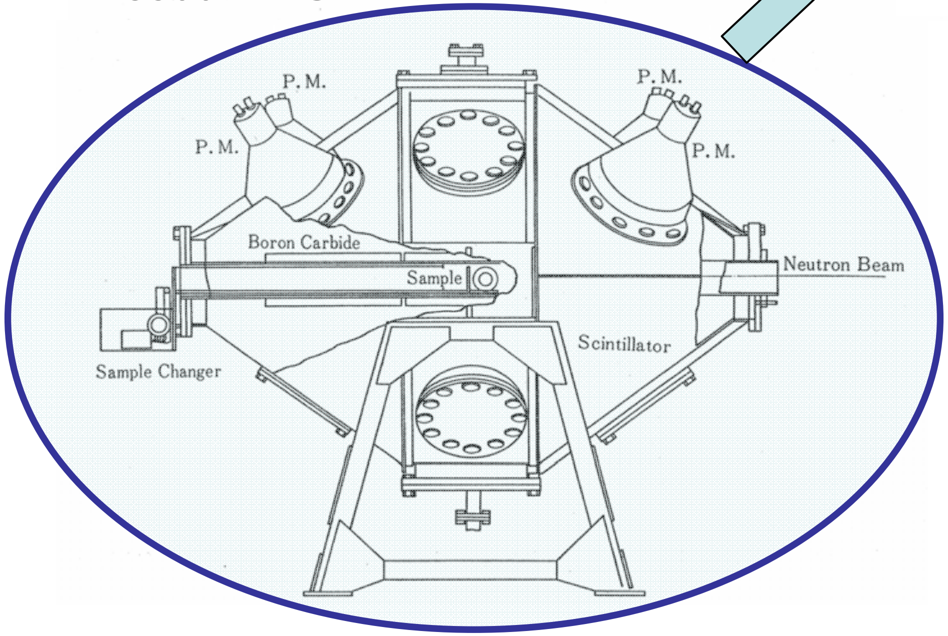
捕獲･散乱断面積測定

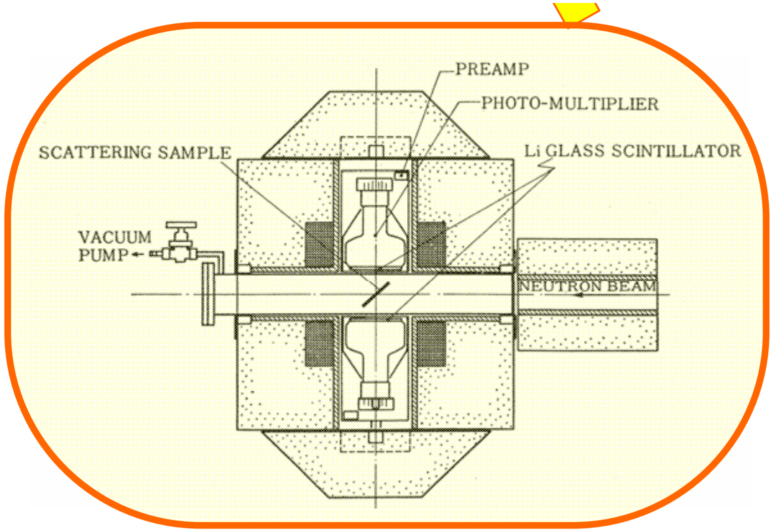


55m 捕獲断面積測定装置
3500l LLSD

47m and 55m flight station

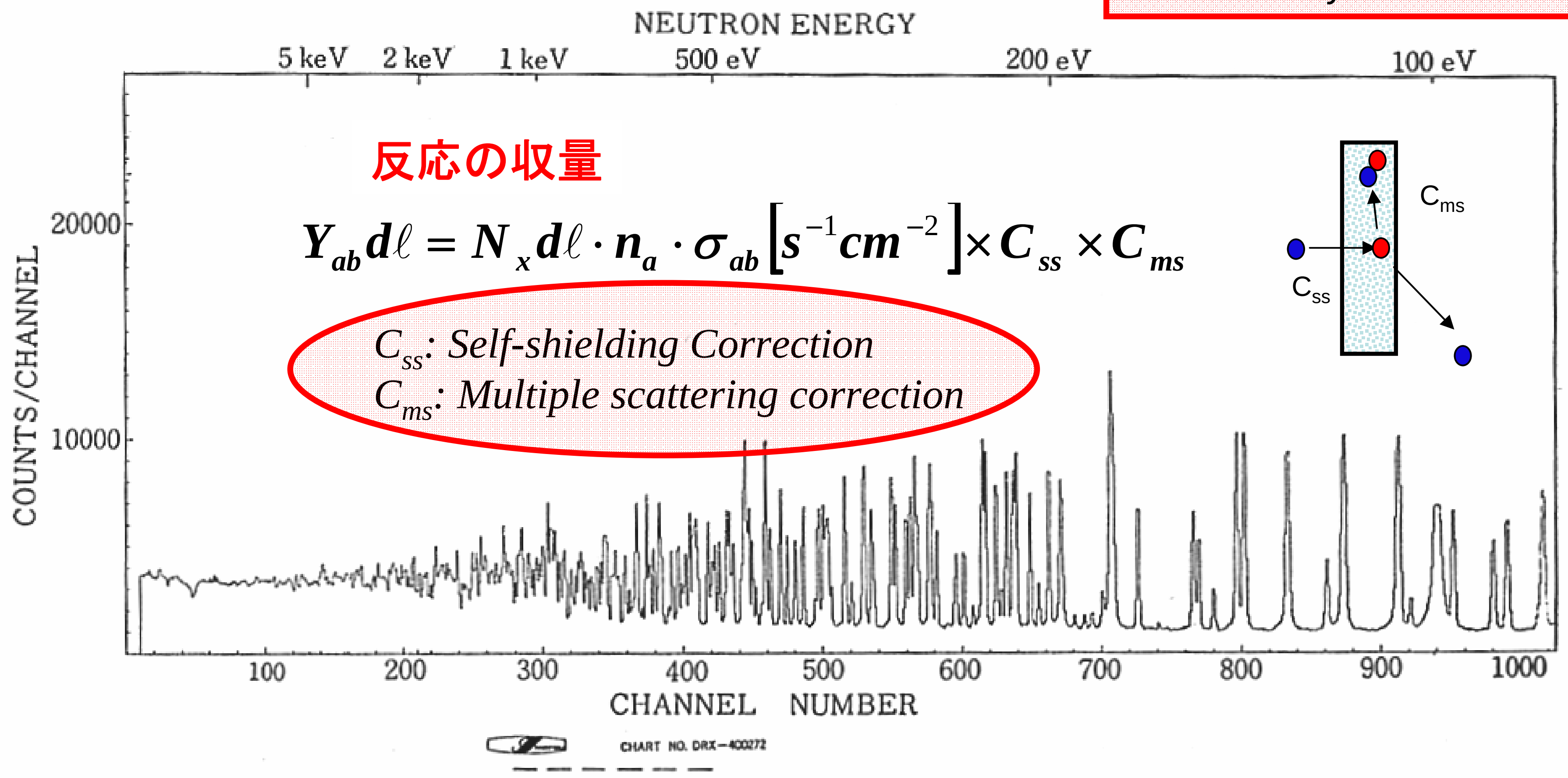
47m 散乱断面積測定装置
^{6}Li 検出器





捕獲断面積測定

Sample thickness correction is necessary



反応の収量

$$Y_{ab}d\ell = N_x d\ell \cdot n_a \cdot \sigma_{ab}\left[s^{-1}cm^{-2}\right]\times C_{ss}\times C_{ms}$$

C_{ss}: *Self-shielding Correction*

C_{ms}: *Multiple scattering correction*

Fig. 16.11 The number of capture counts per channel for a 0.8 mm thick tantalum sample plotted aginst neutron time-of-flight. (Electron pulse width 0.5 μsec, Channel width 0.5 μsec, Flight path length 52 m).

散乱断面積測定

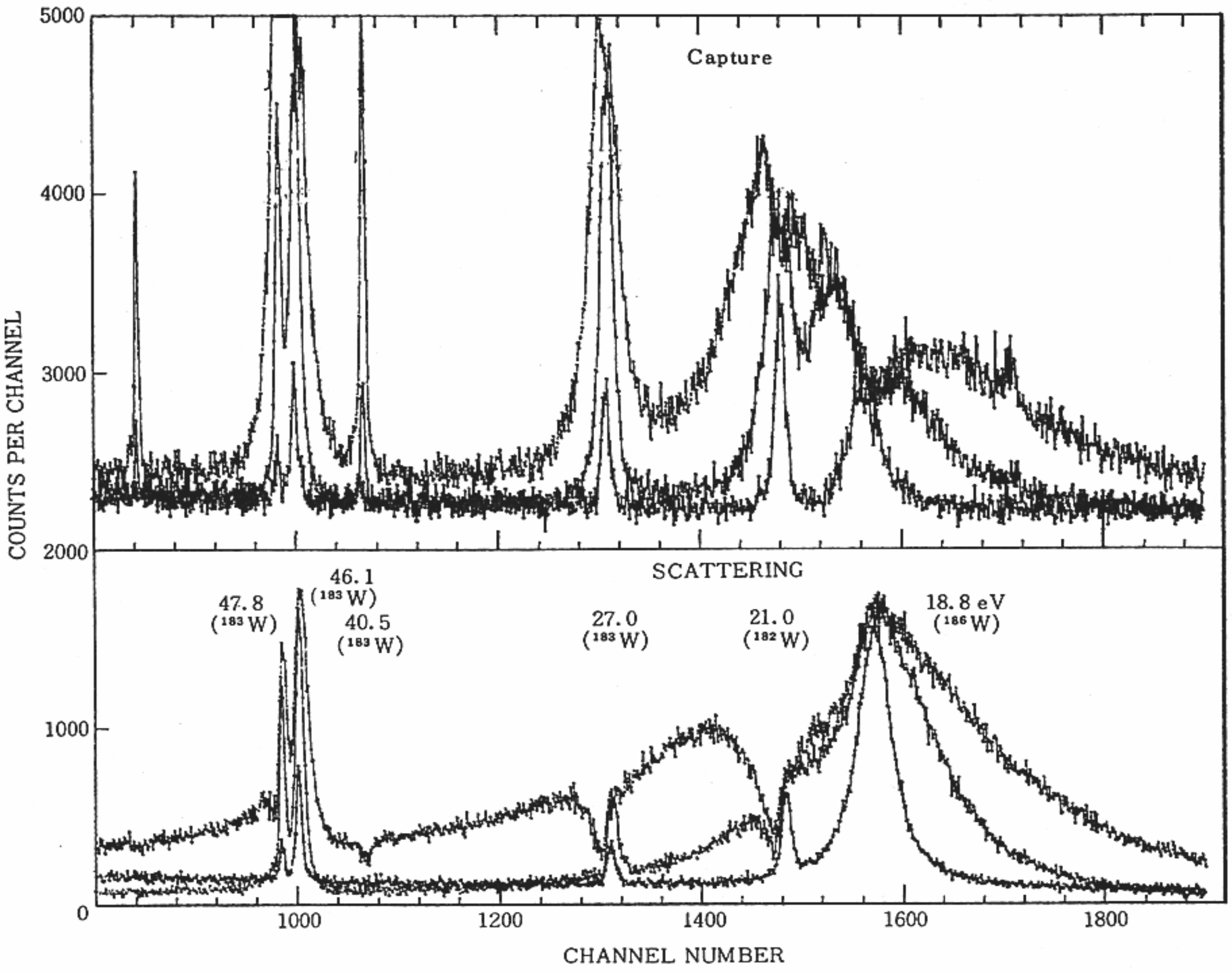


Fig. 16.12 The number of scattering (below) and capture (above) counts per channel versus neutron time-of-flight for 0.026, 0.39 and 1.9 mm thick samples of tungsten. Resonance energies and the isotopes responsible for the resonances are shown.

核分裂断面積測定

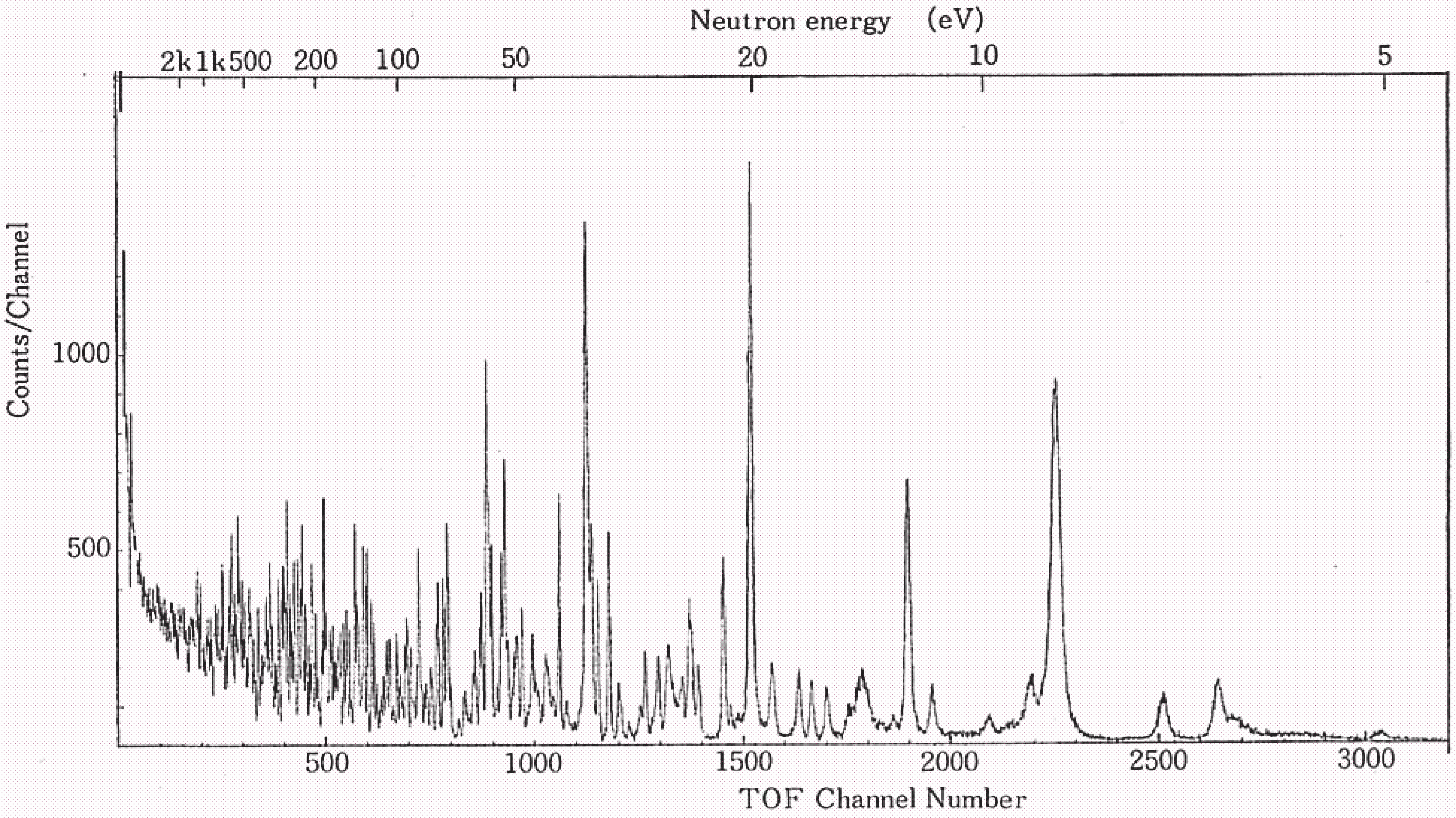


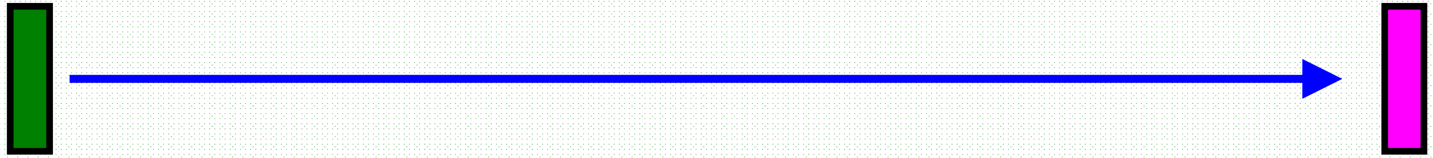
Fig. 16.13 The number of fission counts per channel plotted against neutron time-of-flight for a ^{235}U sample.

Resolution Broadening

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{L}{t}\right)^2 = \left(\frac{72.3\times L}{t}\right)^2$$

$$m = 938(MeV)/(2{,}9979\times10^8(m/s))^2$$

$$= 938\times10^6\times1.602\times10^{-13}/(2{,}9979\times10^8(m/s))^2\,kg = 1.675\times10^{-27}\,kg$$



$$dE/E = \left((2dt/t)^2 + (2dL/L)^2\right)^{1/2}$$

$$= \left((2dt/(72.3*L)*\sqrt{E_n})^2 + (2dL/L)^2\right)^{1/2}$$

$$f_{Lc}(E) \approx \frac{1}{\Delta_{Lc}\sqrt{\pi}}\int_{-\infty}^{\infty} dE''\, exp\left\{-\frac{(E''-E)^2}{\Delta_{Lc}^2}\right\} f(E'')$$

$$\Delta_{Lc}^2 = \frac{2}{3}E^2\left[(\Delta t_c/t)^2 + (\Delta L/L)^2\right]$$

Doppler Broadening

$$\sigma_D(E) \approx \frac{1}{\Delta_D\sqrt{\pi}}\int_{-\infty}^{\infty} dE'' \exp\left\{-\frac{(E''-E)^2}{\Delta_D^2}\right\}\sigma(E'')$$

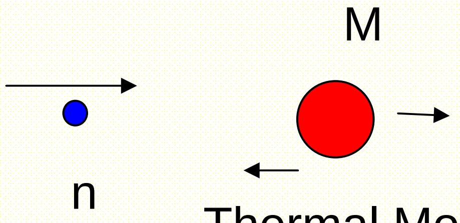
$$\Delta_D^2 = \frac{4mEkT}{M}$$

m : mass of neutron,

M : target mass,

k : Boltzmann's constant,

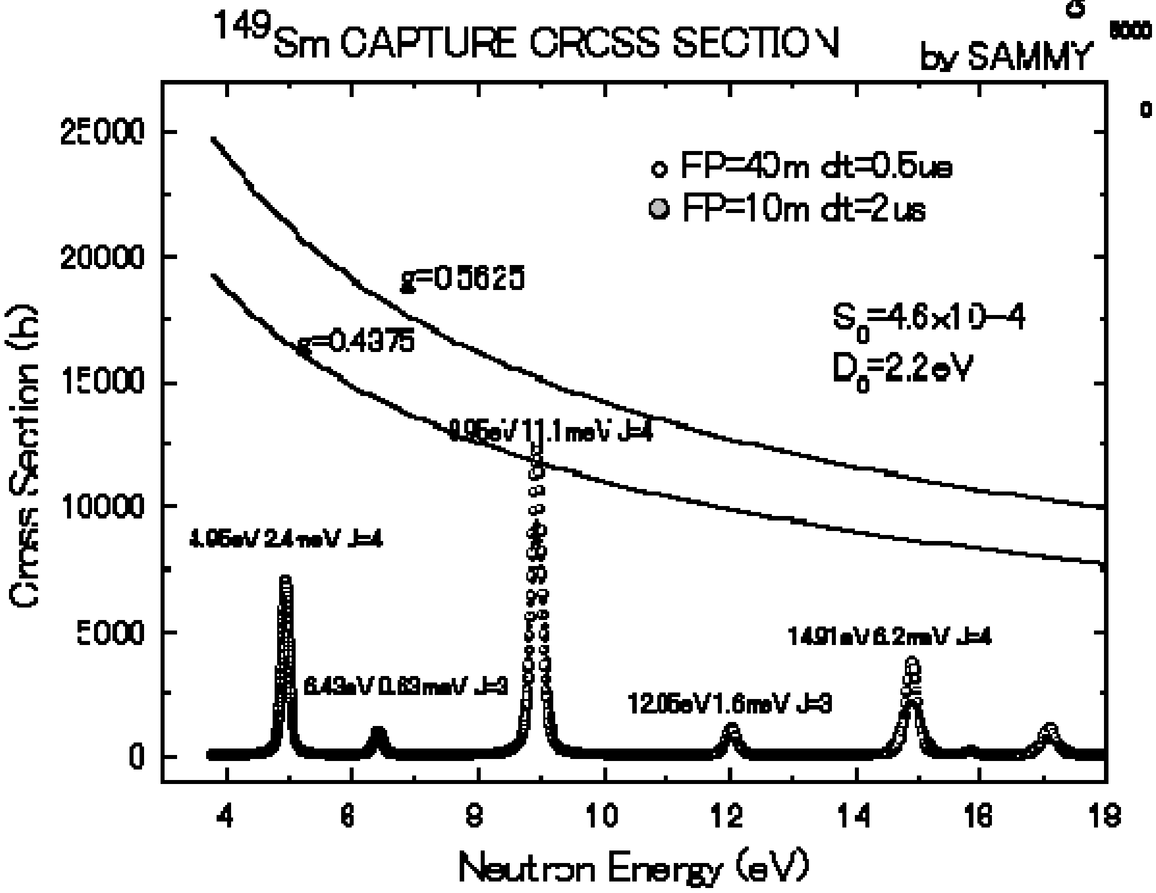
T : effective temperature of sample material

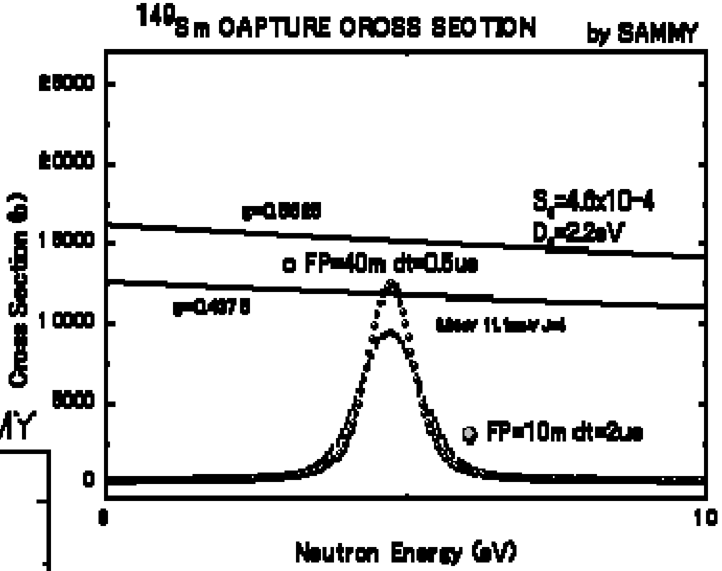


Thermal Motion

コード（SAMMY）によって再現された^{149}Sm 共鳴

CPAF-JAEA





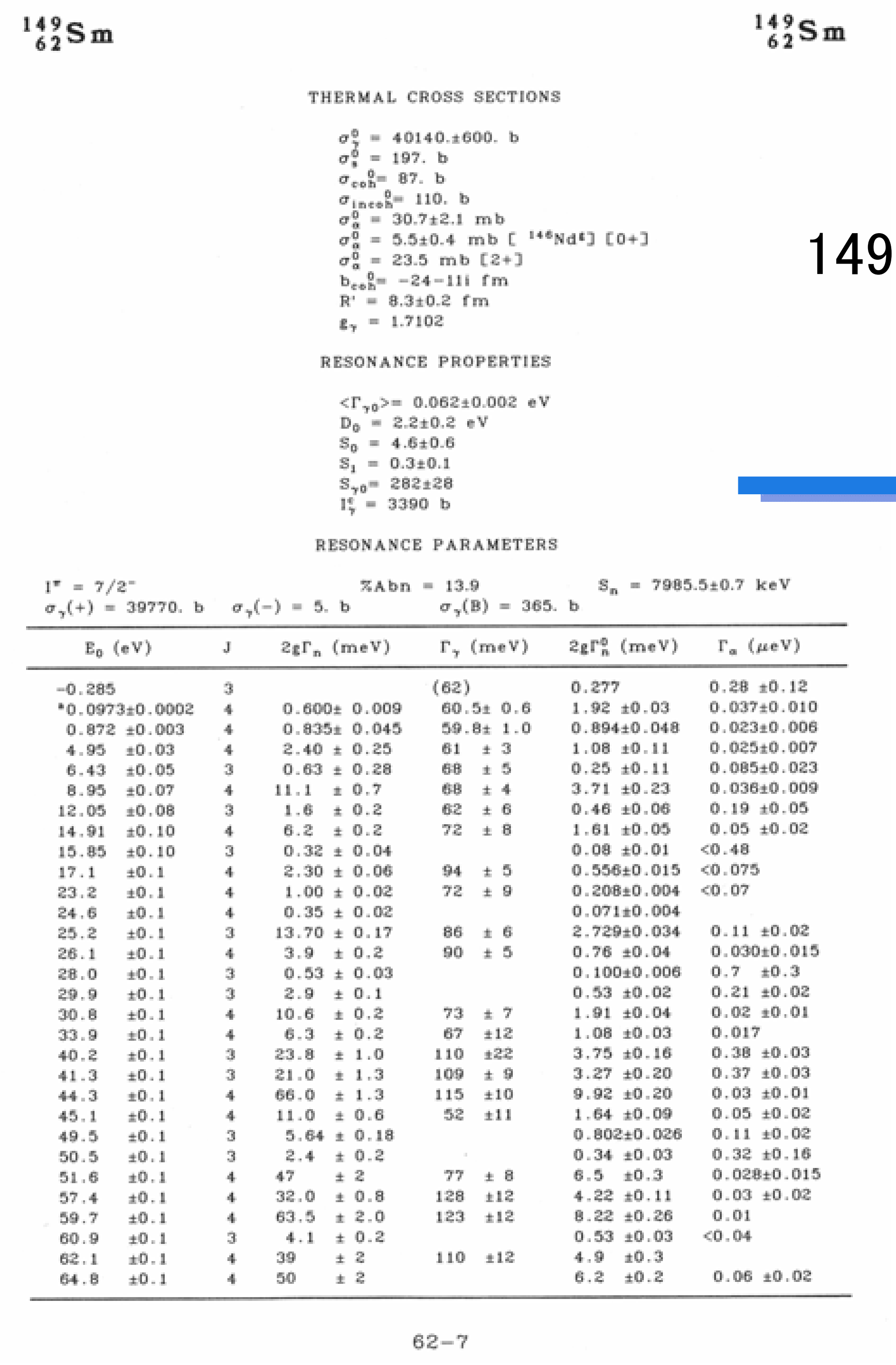
$$\sigma_{0\gamma} = \sigma_0 \frac{\Gamma_\lambda}{\Gamma}$$

$$\sigma_0 = 4\pi\lambda\!\!\!^{-}{}^2 \frac{g\Gamma_n}{\Gamma} = \frac{2.608*10^6}{E_0(eV)} \left(\frac{A+1}{A}\right)^2 \frac{g\Gamma_n}{\Gamma}$$

$$\langle g_j \Gamma_{nj} \rangle = \sqrt{E}\, \langle g_j \Gamma_{nj}^0 \rangle = \sqrt{E}\, S_0 D_0$$

^{149}Sm 共鳴パラメータ
BNL-325

CPAF-JAEA



$^{149}_{62}$Sm $^{149}_{62}$Sm

THERMAL CROSS SECTIONS

σ_{γ}^{0} = 40140.±600. b
σ_{s}^{0} = 197. b
σ_{coh}^{0}= 87. b
σ_{incoh}^{0}= 110. b
σ_{α}^{0} = 30.7±2.1 mb
σ_{α}^{0} = 5.5±0.4 mb [^{146}Nd^{g}] [0+]
σ_{α}^{0} = 23.5 mb [2+]
b_{coh}^{0}= -24-11i fm
R' = 8.3±0.2 fm
g_{γ} = 1.7102

RESONANCE PROPERTIES

$<\Gamma_{\gamma 0}>$= 0.062±0.002 eV
D_0 = 2.2±0.2 eV
S_0 = 4.6±0.6
S_1 = 0.3±0.1
$S_{\gamma 0}$= 282±28
I_{γ}^{c} = 3390 b

RESONANCE PARAMETERS

I^{π} = 7/2^{-} %Abn = 13.9 S_n = 7985.5±0.7 keV
$\sigma_{\gamma}(+)$ = 39770. b $\sigma_{\gamma}(-)$ = 5. b $\sigma_{\gamma}(B)$ = 365. b

E_0 (eV)	J	$2g\Gamma_n$ (meV)	Γ_{γ} (meV)	$2g\Gamma_n^0$ (meV)	Γ_{α} (μeV)
-0.285	3		(62)	0.277	0.28 ±0.12
*0.0973±0.0002	4	0.600± 0.009	60.5± 0.6	1.92 ±0.03	0.037±0.010
0.872 ±0.003	4	0.835± 0.045	59.8± 1.0	0.894±0.048	0.023±0.006
4.95 ±0.03	4	2.40 ± 0.25	61 ± 3	1.08 ±0.11	0.025±0.007
6.43 ±0.05	3	0.63 ± 0.28	68 ± 5	0.25 ±0.11	0.085±0.023
8.95 ±0.07	4	11.1 ± 0.7	68 ± 4	3.71 ±0.23	0.036±0.009
12.05 ±0.08	3	1.6 ± 0.2	62 ± 6	0.46 ±0.06	0.19 ±0.05
14.91 ±0.10	4	6.2 ± 0.2	72 ± 8	1.61 ±0.05	0.05 ±0.02
15.85 ±0.10	3	0.32 ± 0.04		0.08 ±0.01	<0.48
17.1 ±0.1	4	2.30 ± 0.06	94 ± 5	0.556±0.015	<0.075
23.2 ±0.1	4	1.00 ± 0.02	72 ± 9	0.208±0.004	<0.07
24.6 ±0.1	4	0.35 ± 0.02		0.071±0.004	
25.2 ±0.1	3	13.70 ± 0.17	86 ± 6	2.729±0.034	0.11 ±0.02
26.1 ±0.1	4	3.9 ± 0.2	90 ± 5	0.76 ±0.04	0.030±0.015
28.0 ±0.1	3	0.53 ± 0.03		0.100±0.006	0.7 ±0.3
29.9 ±0.1	3	2.9 ± 0.1		0.53 ±0.02	0.21 ±0.02
30.8 ±0.1	4	10.6 ± 0.2	73 ± 7	1.91 ±0.04	0.02 ±0.01
33.9 ±0.1	4	6.3 ± 0.2	67 ±12	1.08 ±0.03	0.017
40.2 ±0.1	3	23.8 ± 1.0	110 ±22	3.75 ±0.16	0.38 ±0.03
41.3 ±0.1	3	21.0 ± 1.3	109 ± 9	3.27 ±0.20	0.37 ±0.03
44.3 ±0.1	4	66.0 ± 1.3	115 ±10	9.92 ±0.20	0.03 ±0.01
45.1 ±0.1	4	11.0 ± 0.6	52 ±11	1.64 ±0.09	0.05 ±0.02
49.5 ±0.1	3	5.64 ± 0.18		0.802±0.026	0.11 ±0.02
50.5 ±0.1	3	2.4 ± 0.2		0.34 ±0.03	0.32 ±0.16
51.6 ±0.1	4	47 ± 2	77 ± 8	6.5 ±0.3	0.028±0.015
57.4 ±0.1	4	32.0 ± 0.8	128 ±12	4.22 ±0.11	0.03 ±0.02
59.7 ±0.1	4	63.5 ± 2.0	123 ±12	8.22 ±0.26	0.01
60.9 ±0.1	3	4.1 ± 0.2		0.53 ±0.03	<0.04
62.1 ±0.1	4	39 ± 2	110 ±12	4.9 ±0.3	
64.8 ±0.1	4	50 ± 2		6.2 ±0.2	0.06 ±0.02

62-7

Γ_{γ}: constant
Γ_{n} is proportional to Sqrt(En)

^{147}Sm and ^{149}Sm 共鳴解析

CPAF-JAEA

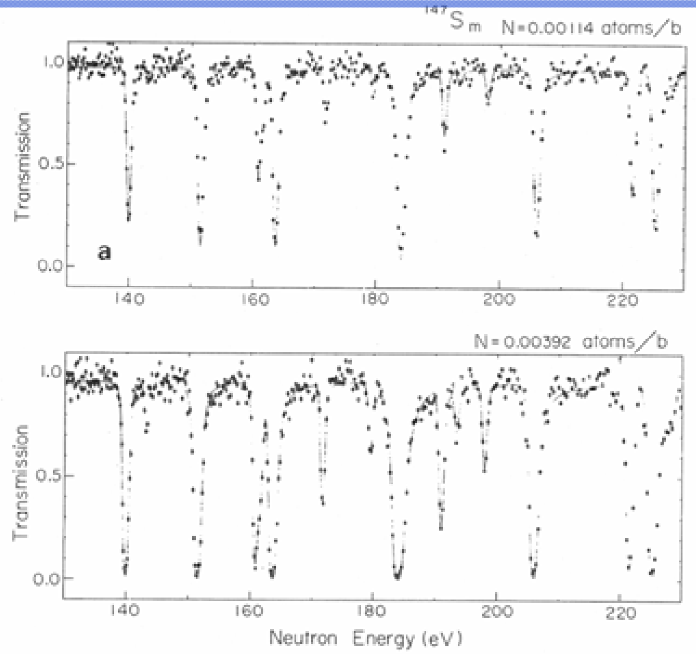


Fig. 1a. Example of resonance analysis of the transmission data for ^{147}Sm. The solid line is a multi-level Breit-Wigner fit.

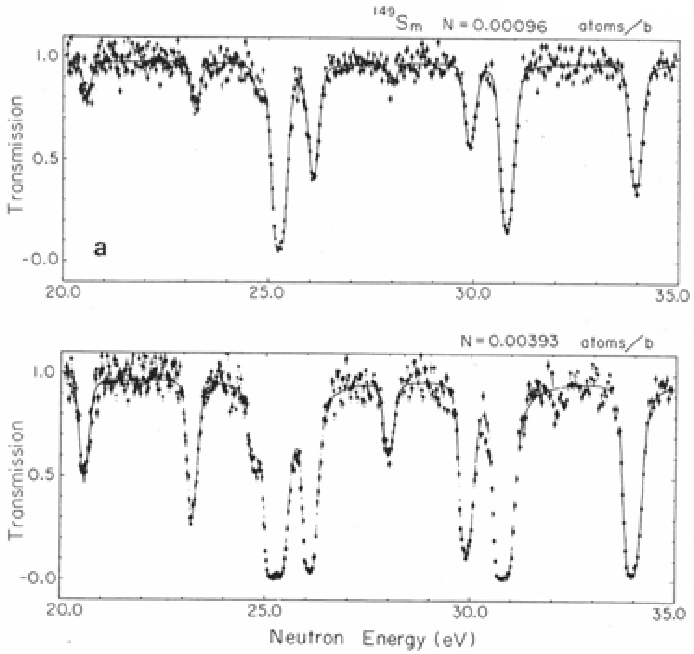


Fig. 2a. Example of resonance analysis of the transmission data for ^{149}Sm. The solid line is a multi-level Breit-Wigner fit.

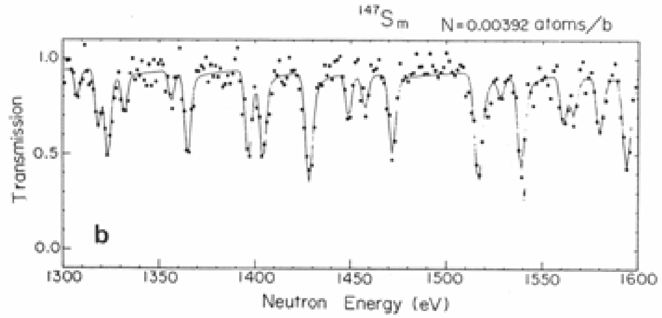


Fig. 1b. Example of resonance analysis of the transmission data for ^{147}Sm. The solid line is a multi-level Breit-Wigner fit.

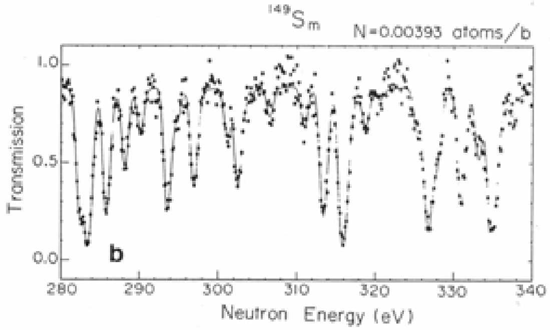


Fig. 2b. Example of resonance analysis of the transmission data for ^{149}Sm. The solid line is a multi-level Breit-Wigner fit.

Nuclear Physics A357(1981)90

^{206}Pb 全断面積と捕獲断面積

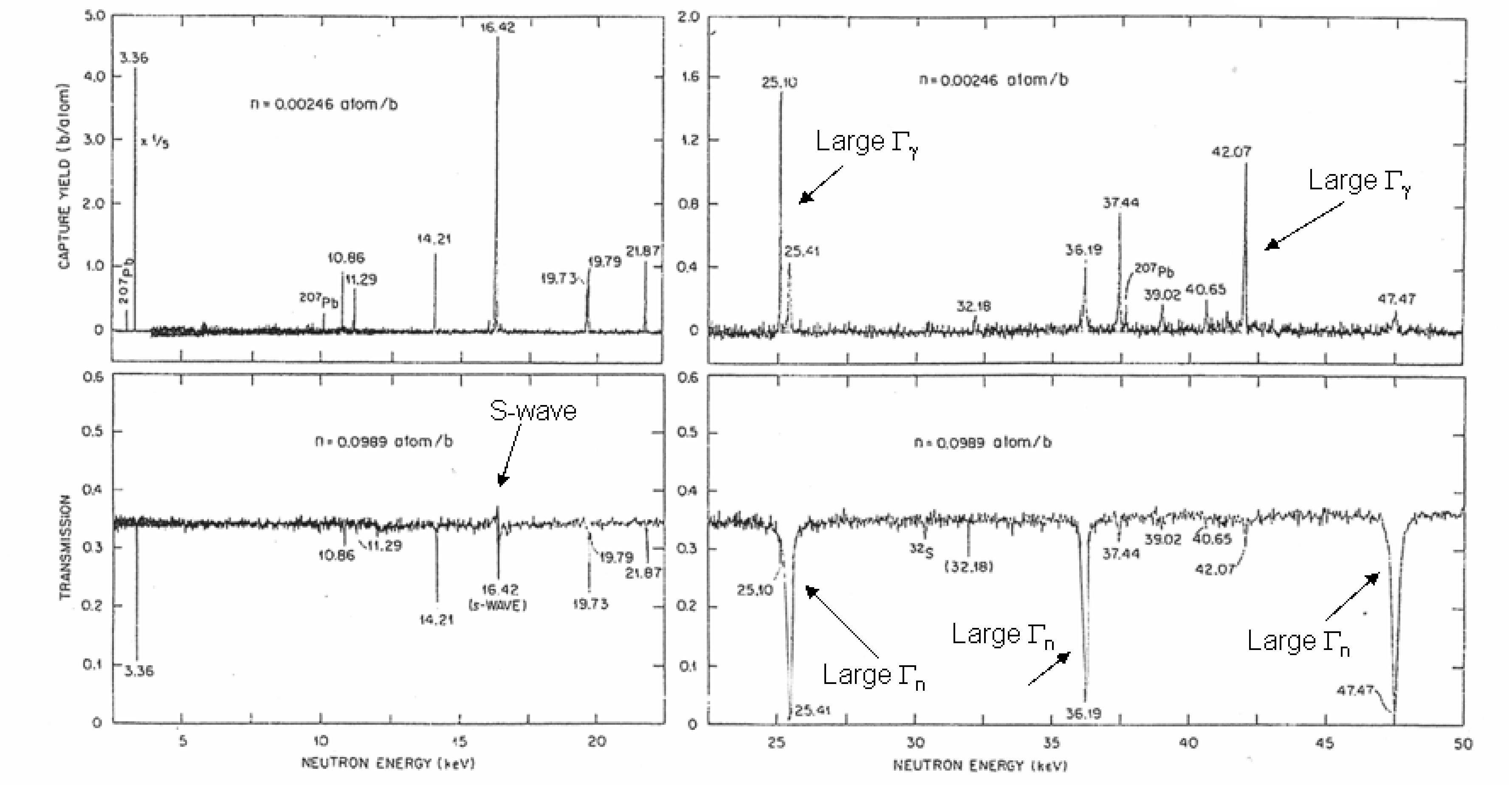


FIG. 1. Neutron capture yields (top part) and neutron transmission data (bottom part) obtained at flight paths of 40.12 m and 78.203 m, respectively.

ORELA Exp Phys. Rev. C19 (1979) 335

実験解析コード

Atta-Harvey：Trans. Single Level B-W, Area Analysis, Atta-Harvey
SIOB: Trans. Multi-Level B-W, Shape Analysis, de Saussure et al.
TACASI: Trans, Capt., Self Indication, Single Level B-W, Shape&Area, Frohner
LSFIT: Cap. Single Level B-W, Shape&Area, Macklin
SAMMY: Trans. Capt. Fission etc., Reich Moore, Larson

Resonance-resonance interference
Resonance self-shielding
Doppler broadening
Multiple scattering
Experimental resolution broadening

Normalization, Background Fitting

Sammy R–M、MLBW

Reich-Moore 公式

C.W. Reich and M.S. Moore Phys. Rev., 111, 929 (1958)

In the MLBW approximation, all off-diagonal elements of level matrix A are neglected.

In the RM approximation, only those off-diagonal elements arising from photon channels are neglected.

The MLBW formulation does not include level-level interference nor the multi channel features of RM

For isolated resonances of non-fissile nuclei, the values for these parameters would be equal in the two cases.

Area Analysis

^{238}U　66.01eV

(a) 薄い試料による中性子透過面積

$$A_{t1} = 2\pi^2 ƛ^2 n g \Gamma_n$$

(b) 厚い試料による中性子透過面積

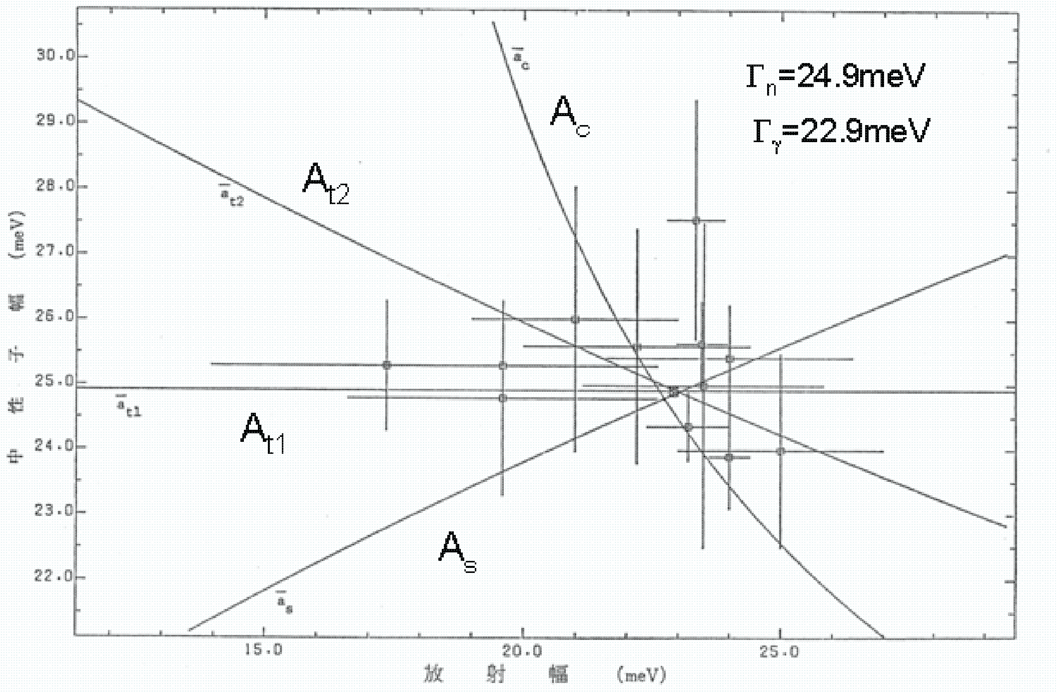
$$A_{t2} = 2\pi ƛ \sqrt{n g \Gamma_n (\Gamma_n + \Gamma_\gamma)}$$

(c) 薄い試料による中性子捕獲面積

$$A_c = 2\pi^2 ƛ^2 n g \Gamma_n \Gamma_\gamma / (\Gamma_n + \Gamma_\gamma)$$

(d) 薄い試料による中性子散乱面積

$$A_s = 2\pi^2 ƛ^2 n g \Gamma_n^2 / (\Gamma_n + \Gamma_\gamma)$$



66.01 eV にある ^{238}U の s 波共鳴である。□は測定値，4 本の曲線 ($\bar{a}_{t1}$, $\bar{a}_{t2}$, $\bar{a}_c$, $\bar{a}_s$) は共鳴面積から求まる Γ_n と Γ_γ の関係を示す。最小自乗法で求めた交点の位置は Γ_n=24.9 meV, Γ_γ=22.9 meV となった。

第 2 図　面積解析法の 1 例

原子力学会誌Vol.23　(1981) 709　中川等

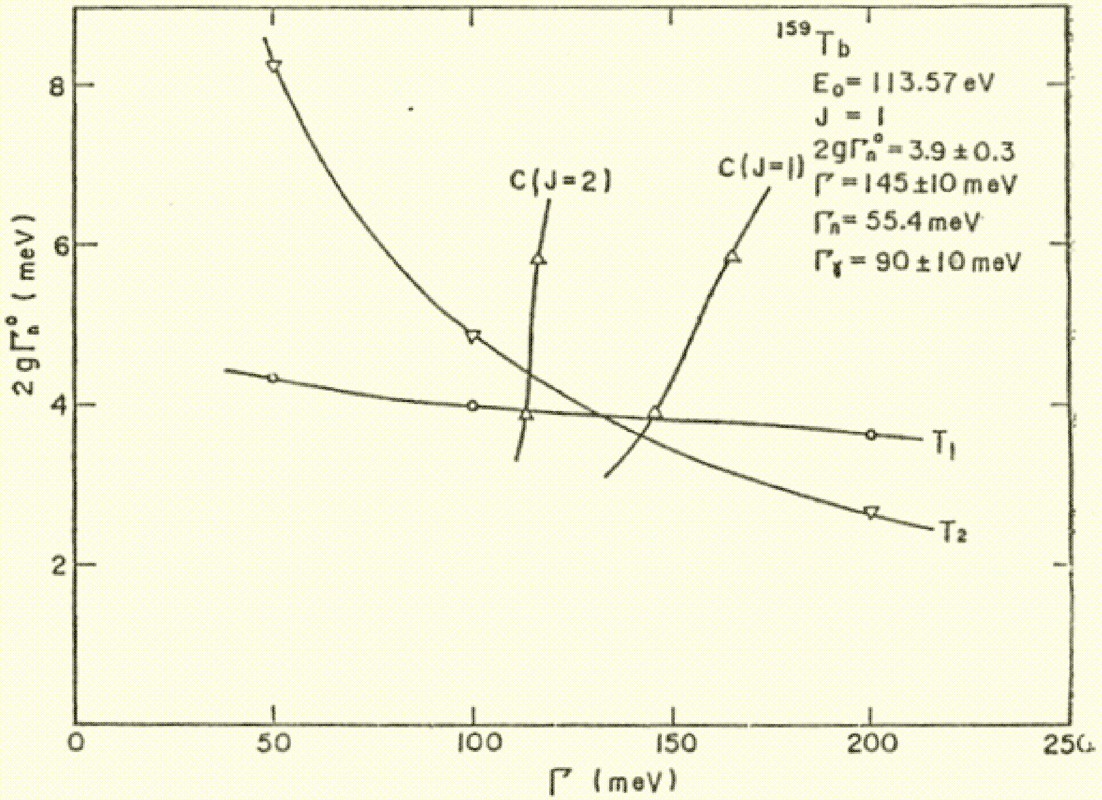
注意

$$\textit{Capture kernel}\quad A_\gamma = g\Gamma_n\Gamma_\gamma /(\Gamma_n + \Gamma_\gamma)$$

$$A_\gamma = g\Gamma_\gamma /(1 + g\Gamma_\gamma /(g\Gamma_n))$$

$$A_\gamma < g\Gamma_\gamma$$

Area Analysisの例

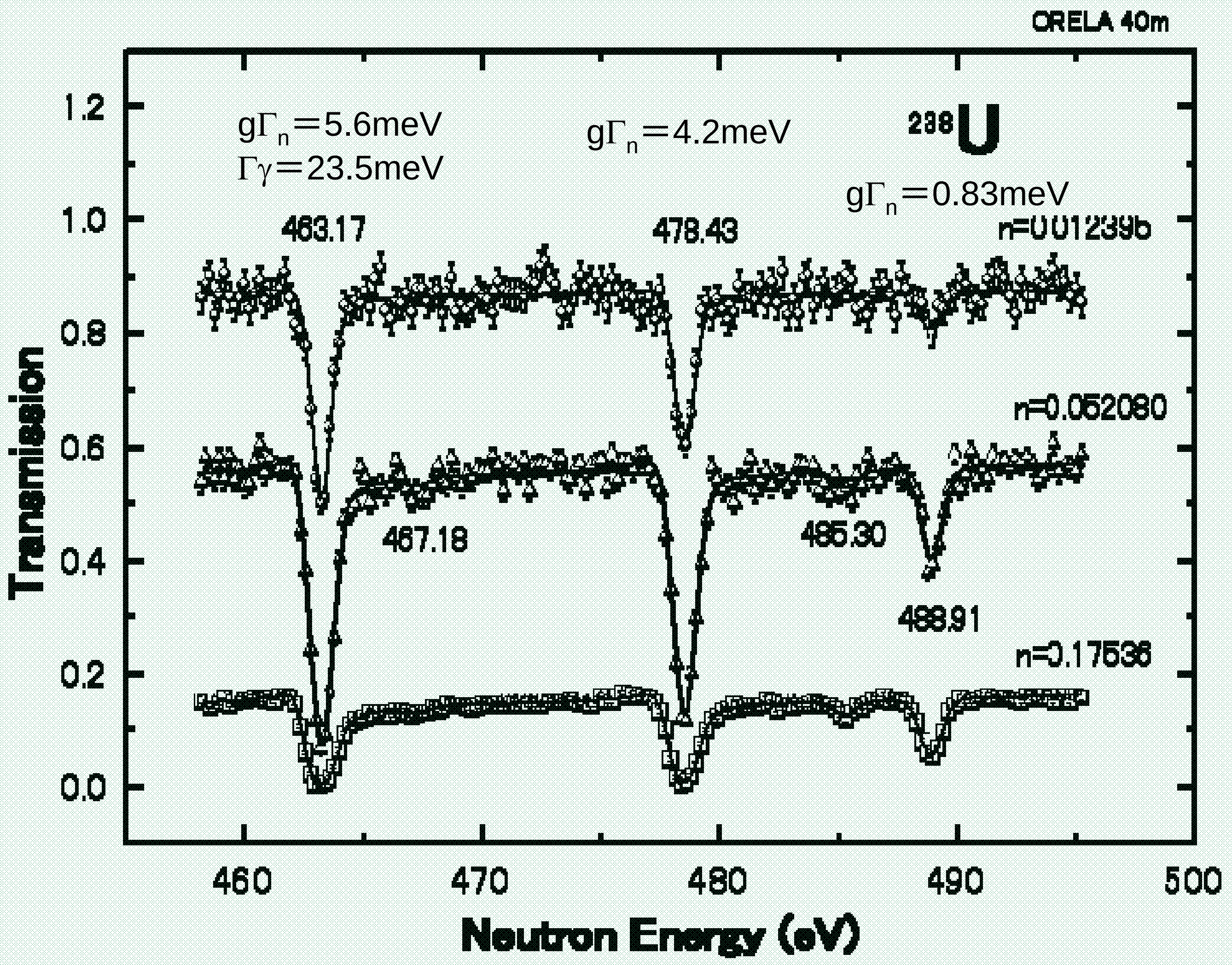


T_1, T_2 は厚さの異なる全断面積の解析，Cは捕獲断面積の解析から得られた関係を示す。

第3図 面積法から得られたΓと$2g\Gamma_n^0$との関係

M.Ohkubo J.Nucl.Sci.Technol.16(1979)701

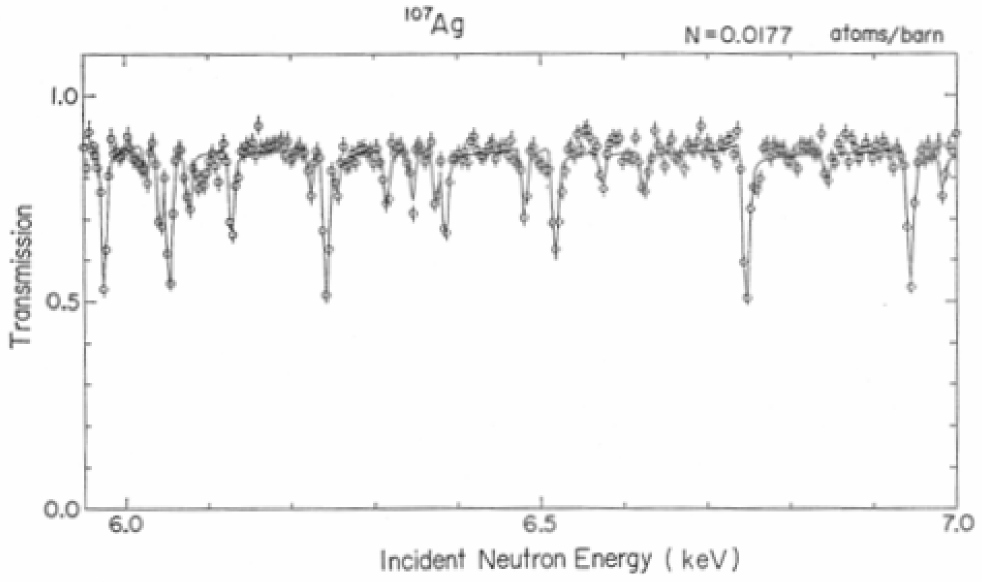
SIOB Analysis(サンプルの厚さによる効果）



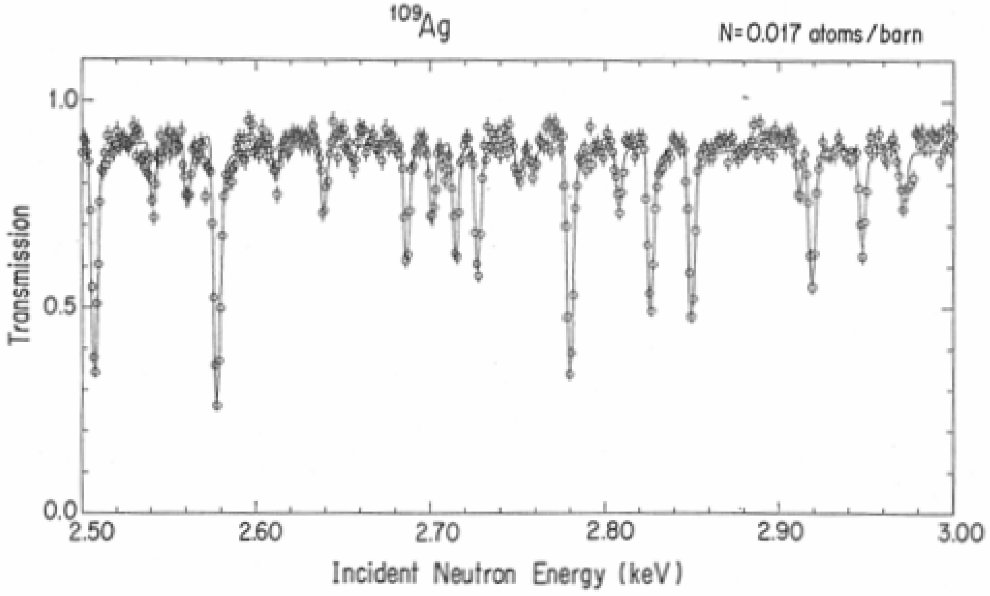
SIOB Analysis for ^{107}Ag and ^{109}Ag

CPAF-JAEA

For analyses,
$\Gamma\gamma$=130meV for ^{107}Ag
$\Gamma\gamma$=140meV for ^{109}Ag
are assumed



(a) ^{107}Ag



(b) ^{109}Ag

The solid line is a multi-level Breit-Wigner fit.

Fig. 2(a),(b) Example of resonance analysis of high resolution transmission data for ^{107}Ag and ^{109}Ag

Cumulative Level

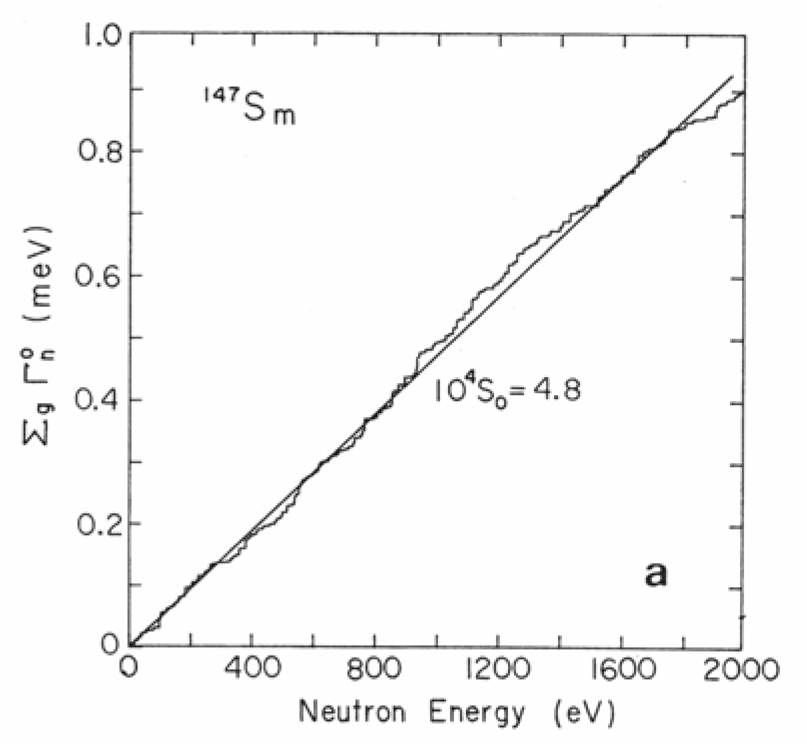


Fig. 4a. $g\Gamma_n^0$ versus energy for levels in ^{147}Sm. The slope gives the s-wave strength function.

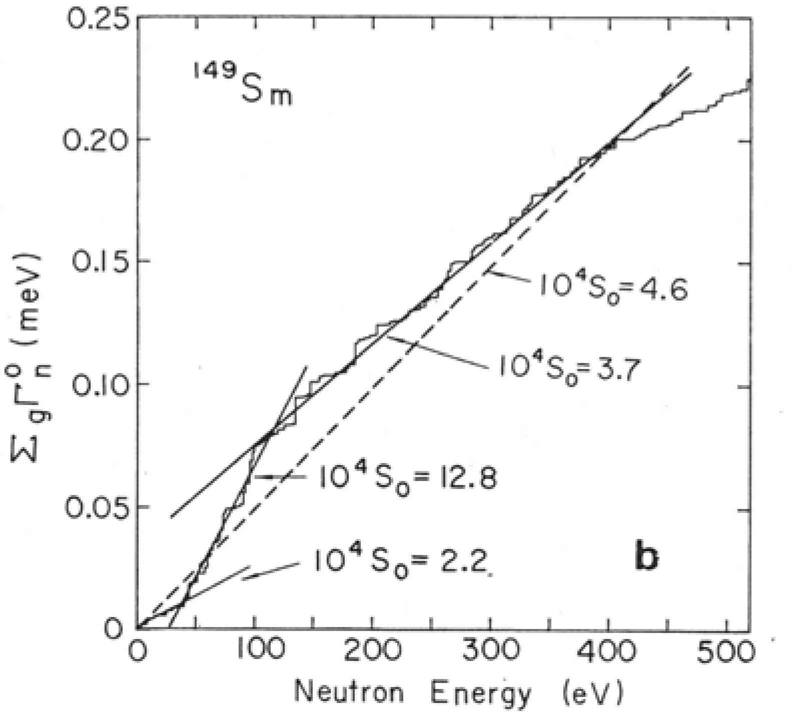


Fig. 4b. $g\Gamma_n^0$ versus energy for levels in ^{149}Sm. The slope gives the s-wave strength function. The dotted line shows a simple average.

S-波強度関数

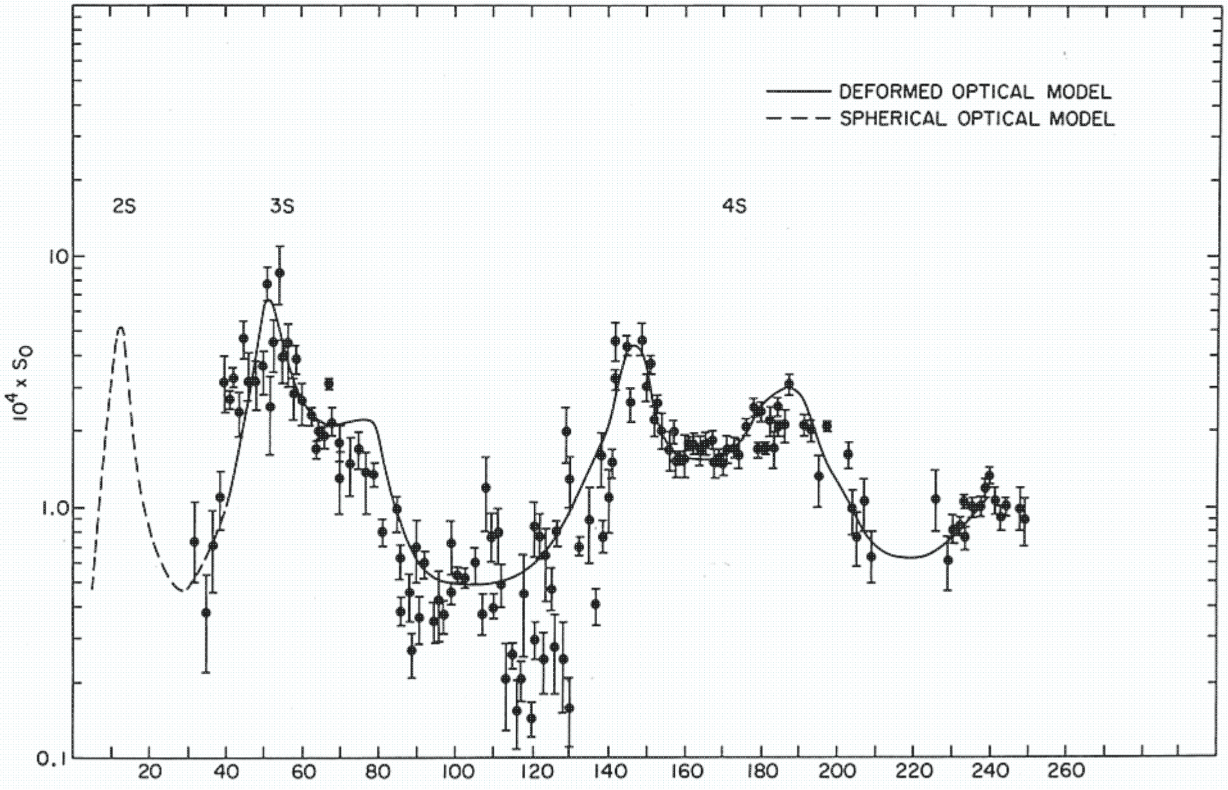


図 s-波中性子強度関数の実験と理論の比較。実験と波線はそれぞれ変形、球形核光学モデルの計算による

P-波強度関数

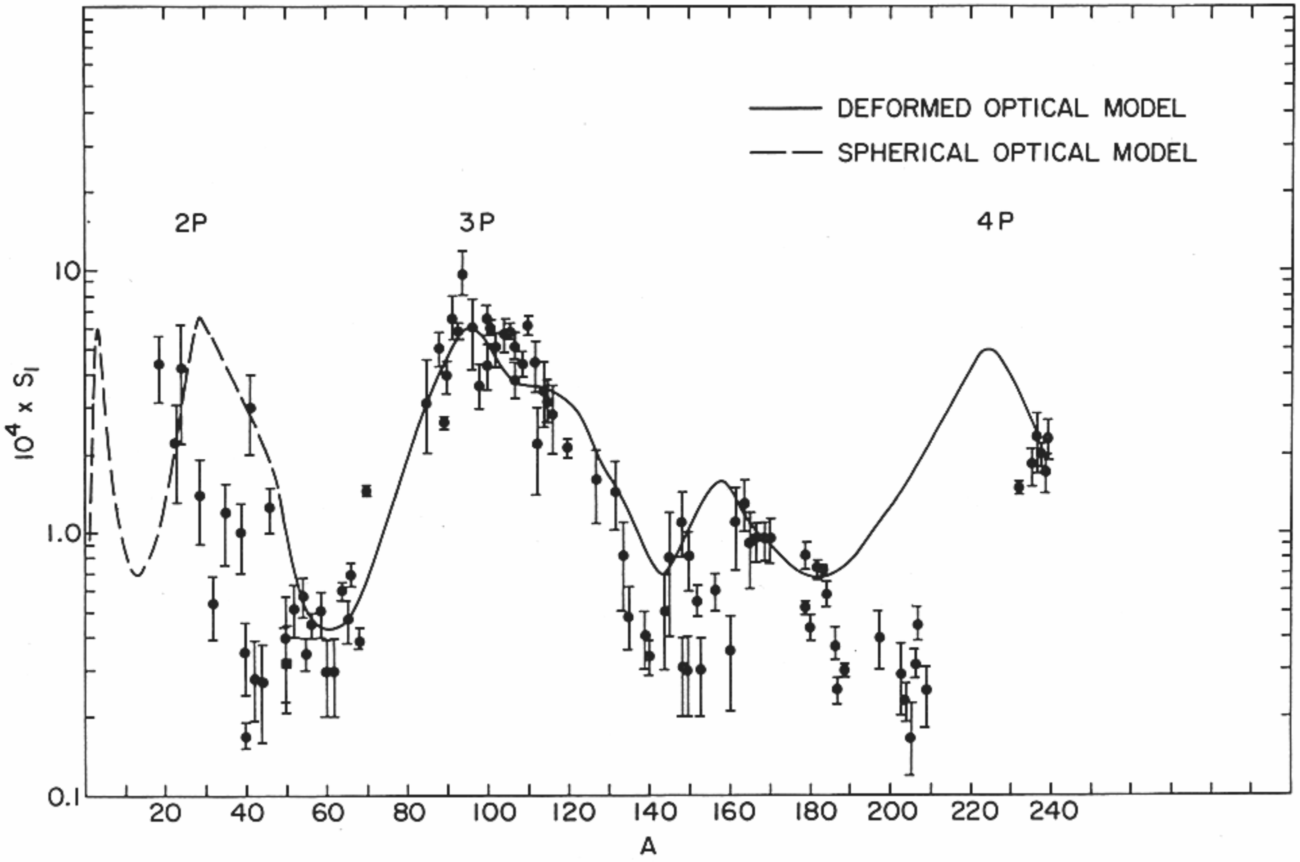
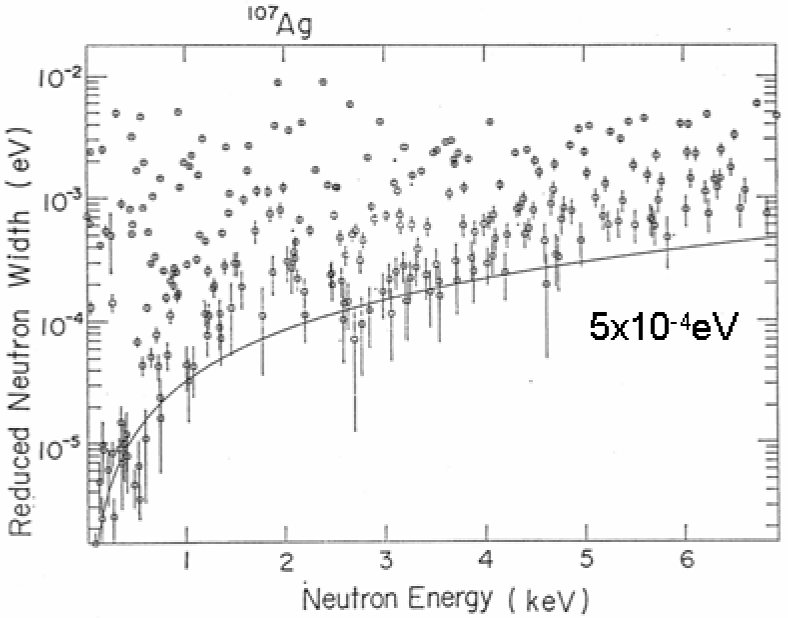


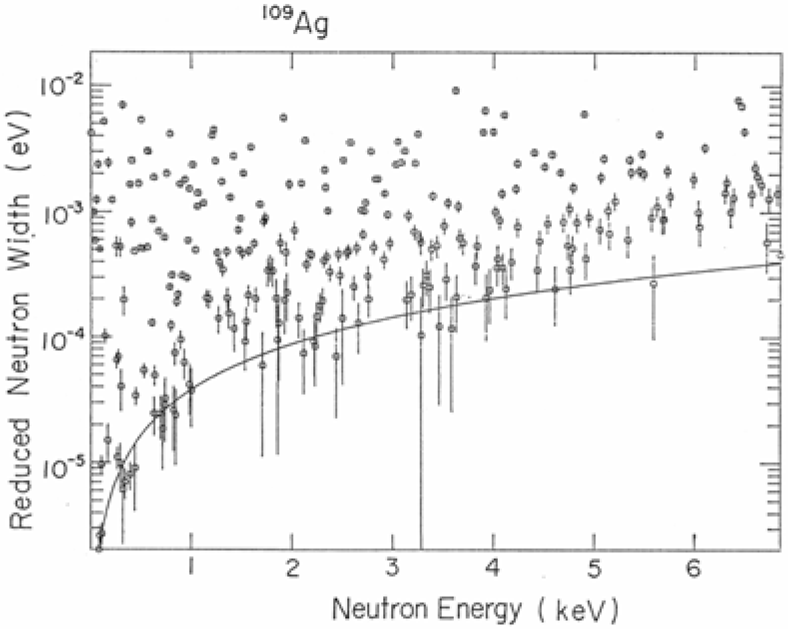
図 P-波中性子強度関数の実験と理論の比較。実験と波線はそれぞれ変形、球形核光学モデルの計算による。A=160近傍にある小さなピークはBuckとPereyによって予想された4P巨大共鳴の 回転分離による。

Level Missing for ^{107}Ag and ^{109}Ag

CPAF-JAEA



(a) ^{107}Ag



(b) ^{109}Ag

The curve indicates the detectability of small resonances.

Fig. 3(a),(b) Reduced neutron widths *vs.* neutron energy for ^{107}Ag and ^{109}Ag

Moore procedure for missing resonances using the moments of the reduced neutron width distribution. truncated Porter Thomas distribution

$$(\sum\omega_i)(\sum\omega_i g\Gamma_{ni}^0) / \left(\sum\omega_i\sqrt{g\Gamma_{ni}^0}\right)^2$$

Weight (ω_i) for -wave contribution is calculated by Bayes theorem

D=20eV for ^{107}Ag
D=20eV for ^{109}Ag

Porter Thomas Distribution

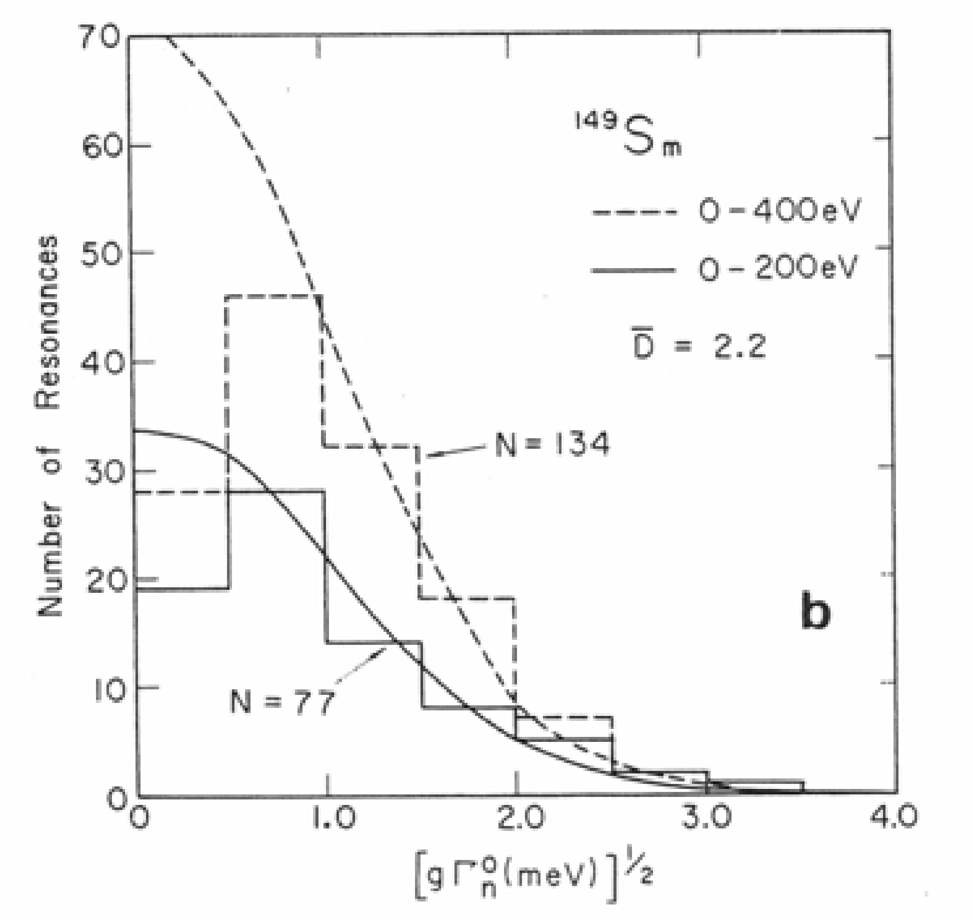


Fig. 5b. Histograms of observed $(g\Gamma_n^0 \text{ MeV})^{1/2}$ values for ^{149}Sm The results for two choices of upper limits are shown.

Measured at 55m flight path

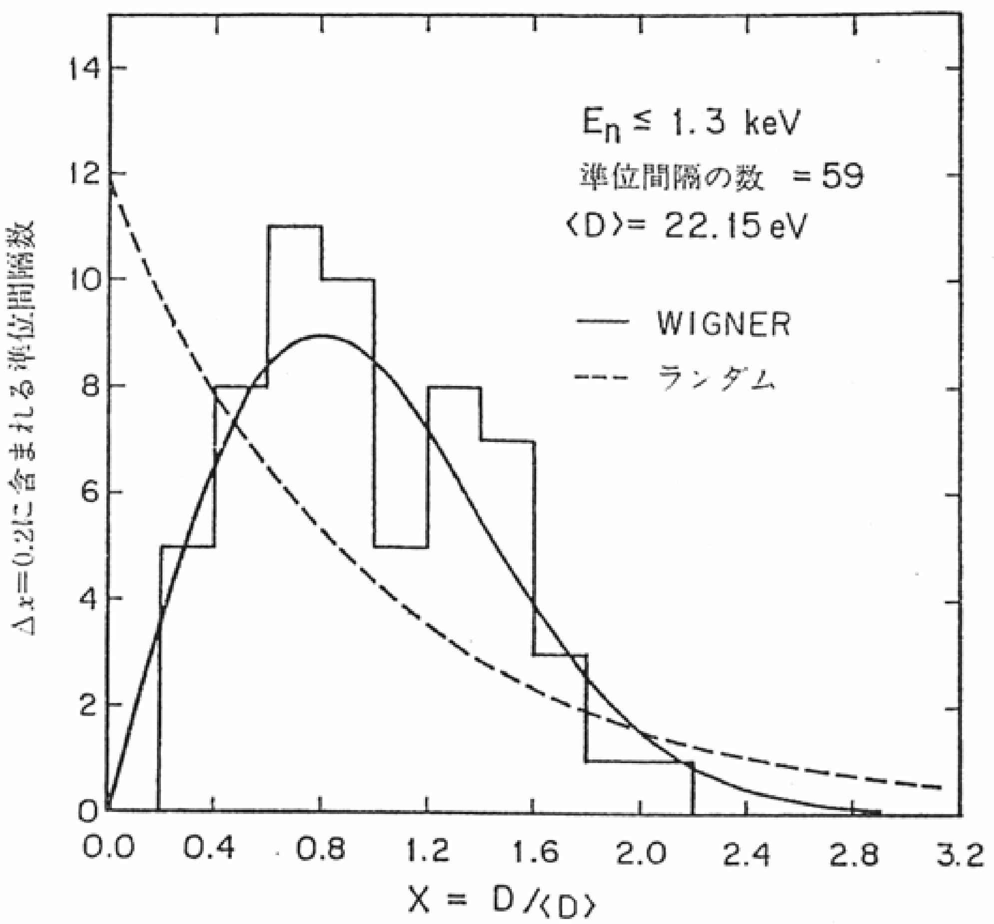
$$P(x) = \frac{1}{\sqrt{2\pi x}} e^{-\frac{x}{2}}$$

$$x = \Gamma_{n0} / \langle \Gamma_{n0} \rangle$$

Chi-squared distribution with the degree of freedom ν=1

NP, A357(1981)90

Wigner Distribution



第7図 Wigner 分布と実験値との比較(^{238}U の例)

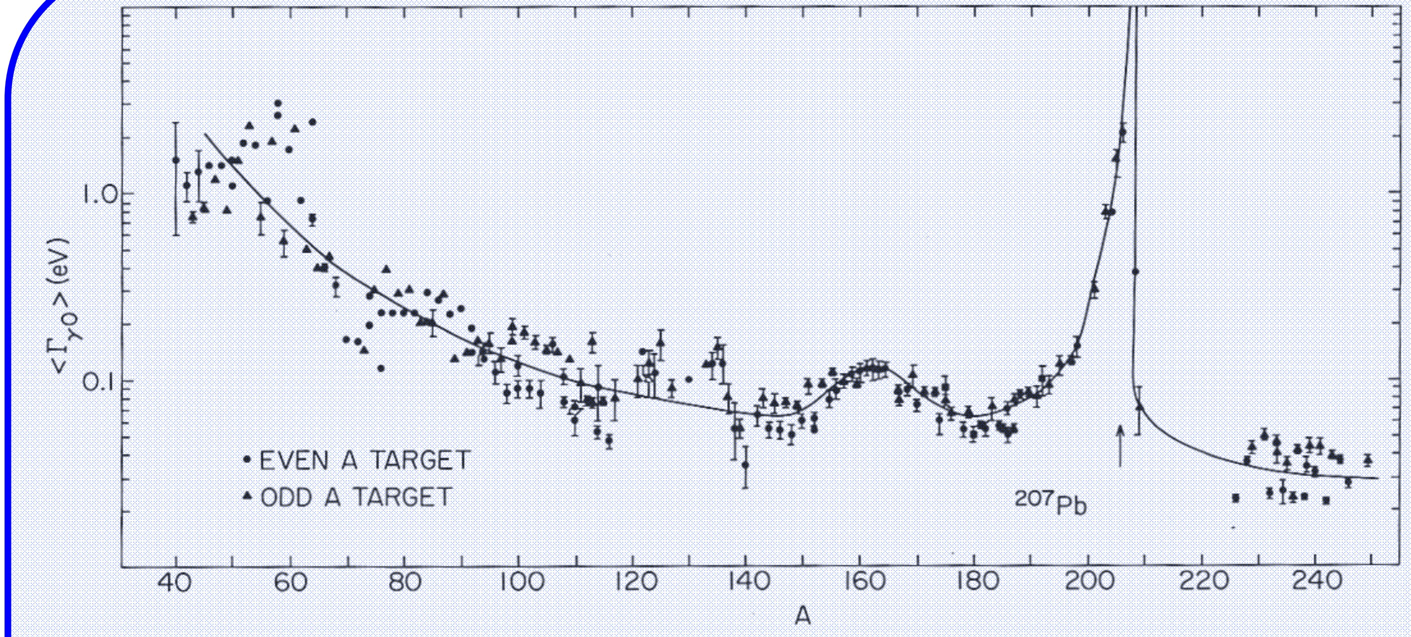
Measured at 190m flight path

$$P(D) = \frac{\pi}{2}\left(\frac{D}{\langle D\rangle^2}\right)e^{-\pi\left(\frac{D}{2\langle D\rangle}\right)^2}$$

The behavior of the eigenvalues of a symmetric matrix with random Gaussian distribution

原子力学会誌Vol23(1981)624

S-波平均放射幅

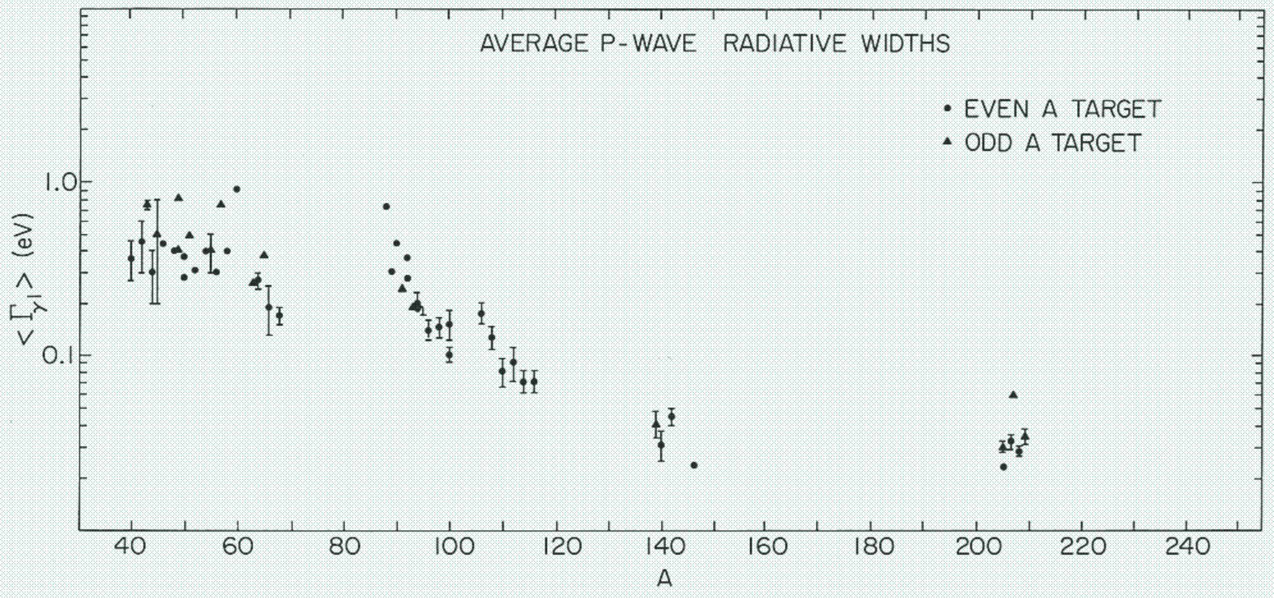


S-波中性子平均放射幅の質量依存性。実線は実験データをなぞる。

放射幅の分布

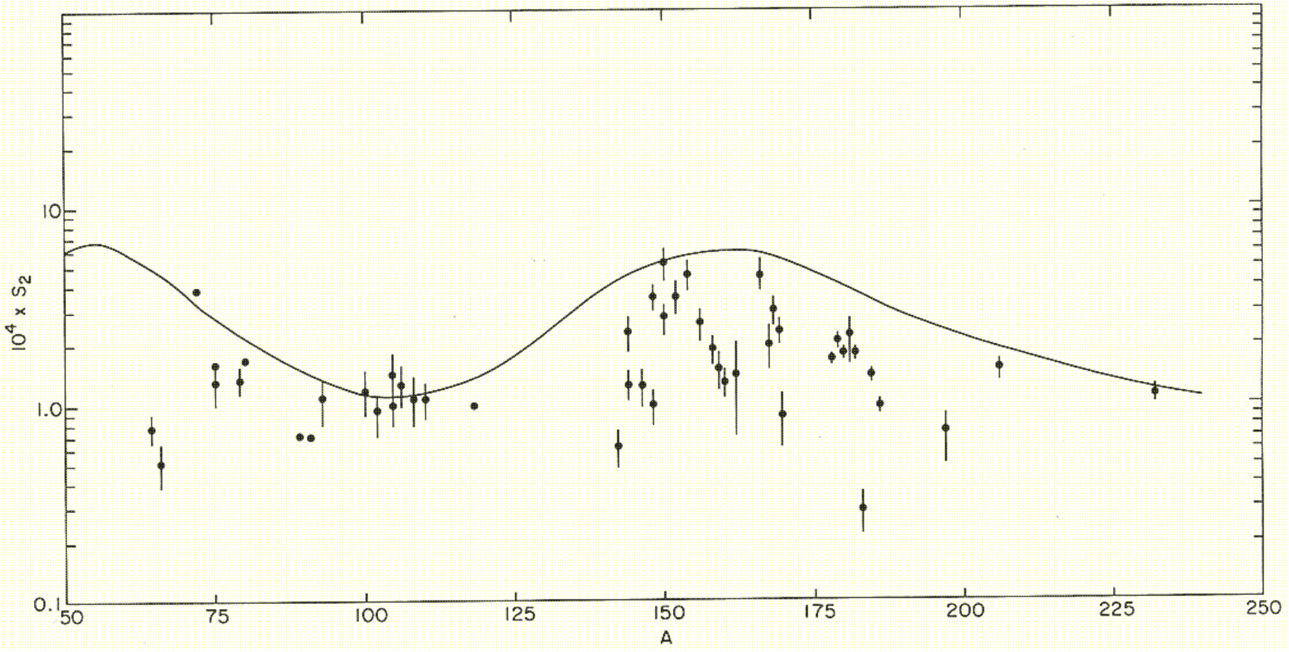
$$P(x,\nu)=\frac{\frac{\pi}{2}}{\Gamma\left(\frac{\nu}{2}\right)}\left(\frac{\nu}{2}x\right)^{\left(\frac{\nu}{2}-1\right)}e^{-\left(\frac{\nu}{2}\right)x}$$

P-波の平均放射幅



P-波中性子平均放射幅の質量依存性。

D-波平均放射幅



D-波中性子平均放射幅の質量依存性。実線は計算値

2006.2.1

SIOB ^{148}Sm

CPAF-JAEA

Different sample thickness

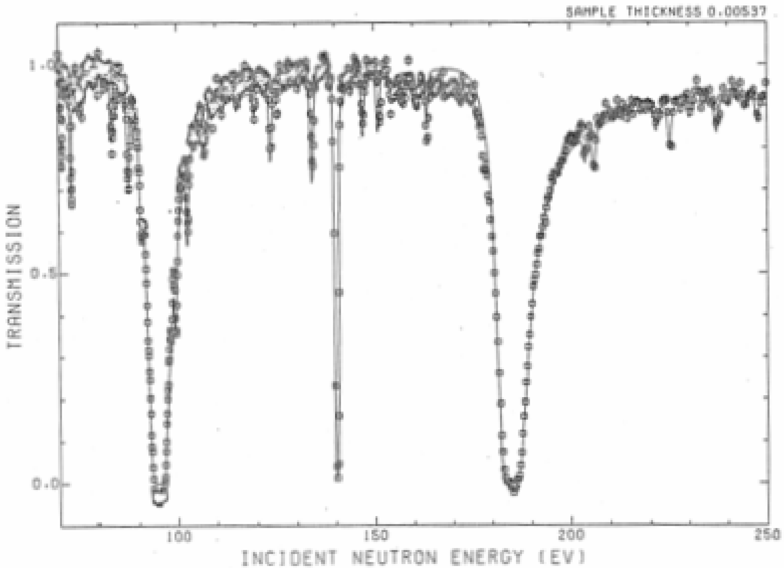


Fig. 1b Example of resonance analysis of the transmission data for ^{148}Sm. The solid line is a multi-level Breit-Wigner fit.

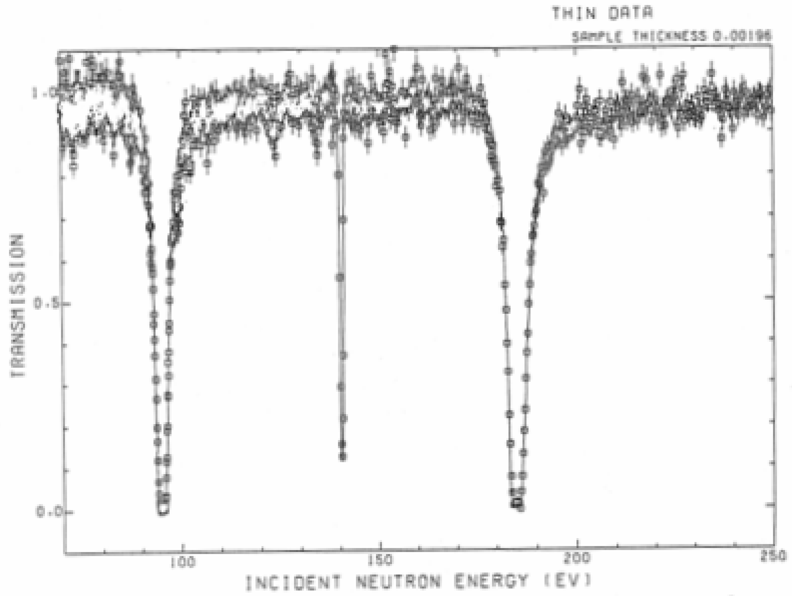


Fig. 2a Example of resonance analysis of the transmission data for ^{148}Sm. The solid line is a multi-level Breit-Wigner fit.

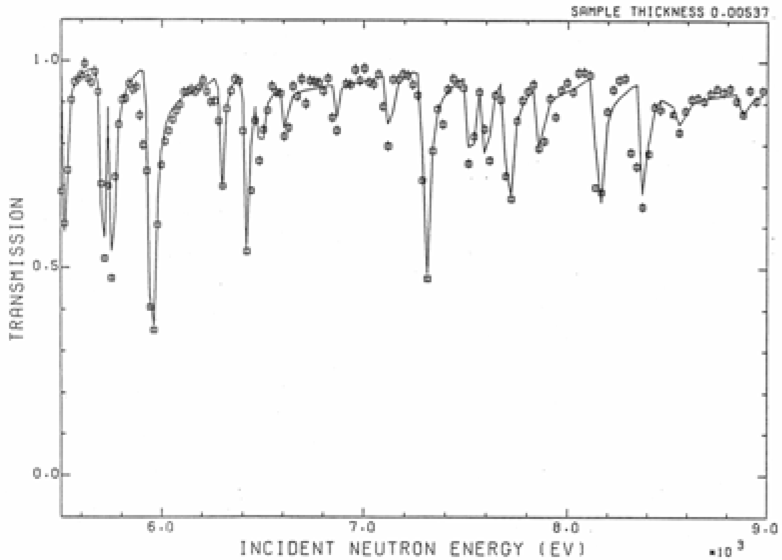


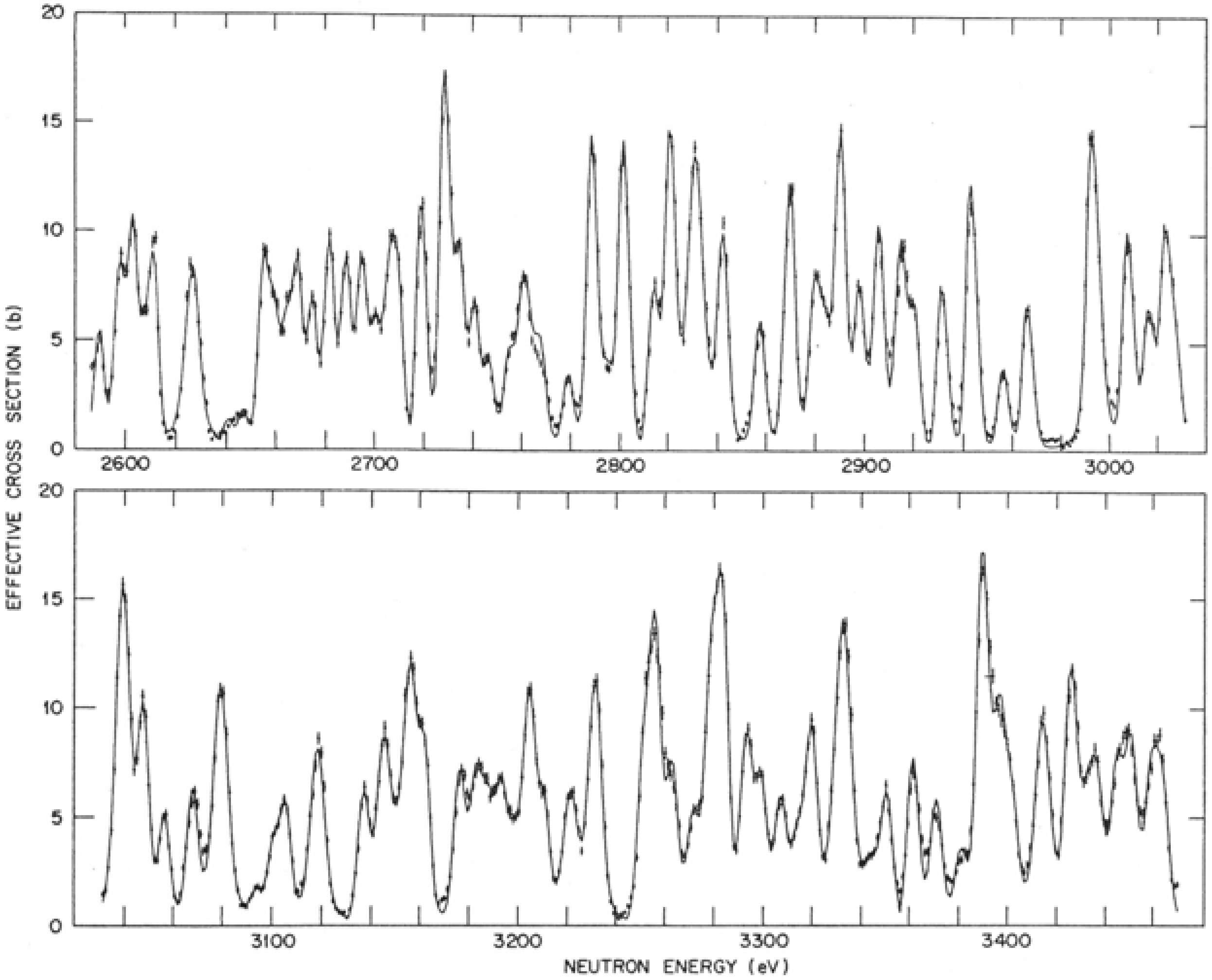
Fig. 1h Example of resonance analysis of the transmission data for ^{148}Sm. The solid line is a multi-level Breit-Wigner fit.

55m flight path

Maximum energy 8.4keV

JAERI memo 61-048 (1986)

Tb Capture Cross Section

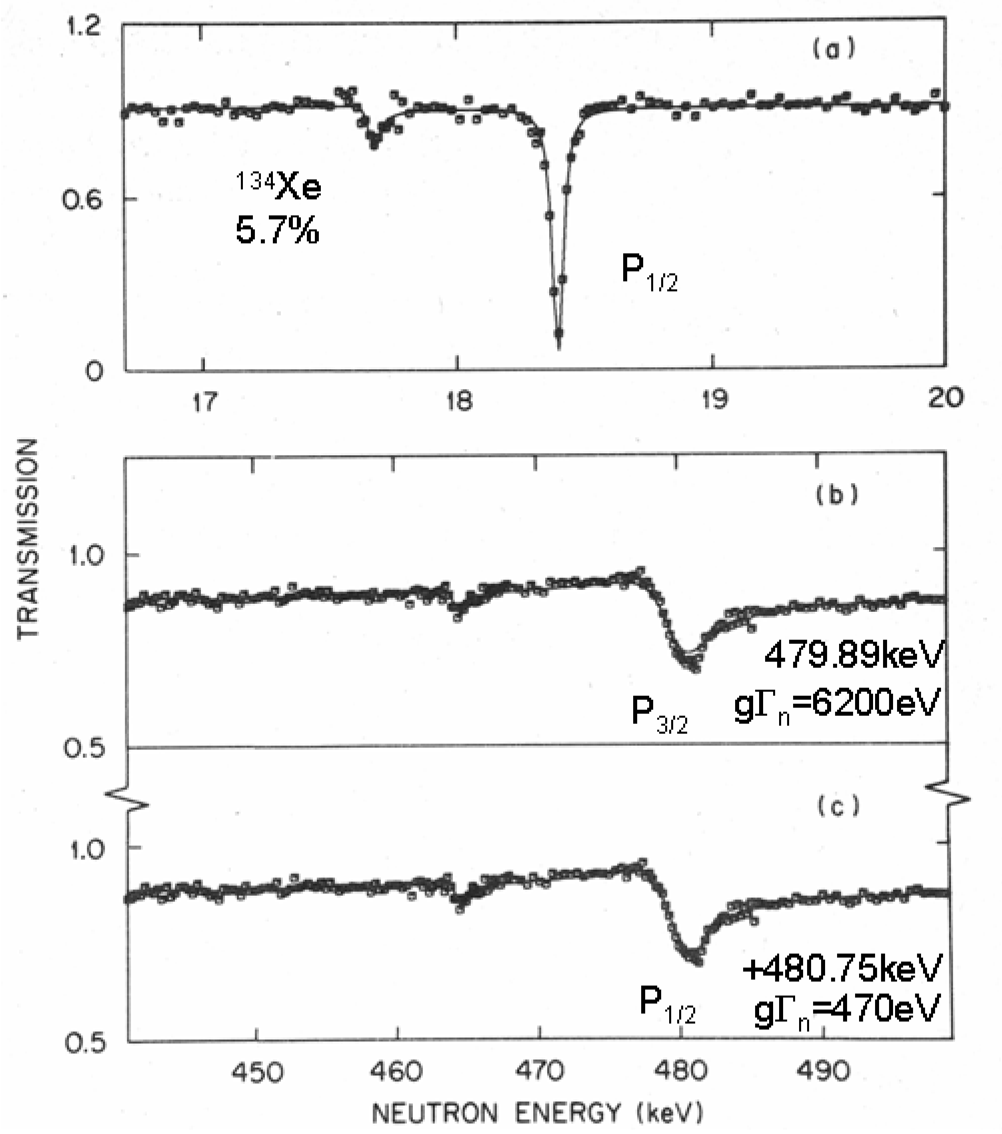


With LSFIT

FIG. 1. The effective capture cross section for a 0.859 g/cm^2 thick metal sample of ^{159}Tb (solid curve) is generated from the least squares fitting program (see Table I) with Doppler broadening, resonance self-protection, multiple scattering, and Gaussian resolution.

^{136}Xe
93.6% enrich

Transmission of ^{136}Xe+n



SAMMY Analysis

(a) The resonance near 18.4 keV is not larger than the resolution of 0.1%. The curve shows a $p_{1/2}$ assignment and gives a better fit than $p_{3/2.}$ The ^{134}Xe resonance near 17.7 keV has a width exceeding the resolution. The peak cross section is proportional to the statistical weight factor which gives a unique p3/2 assignment.

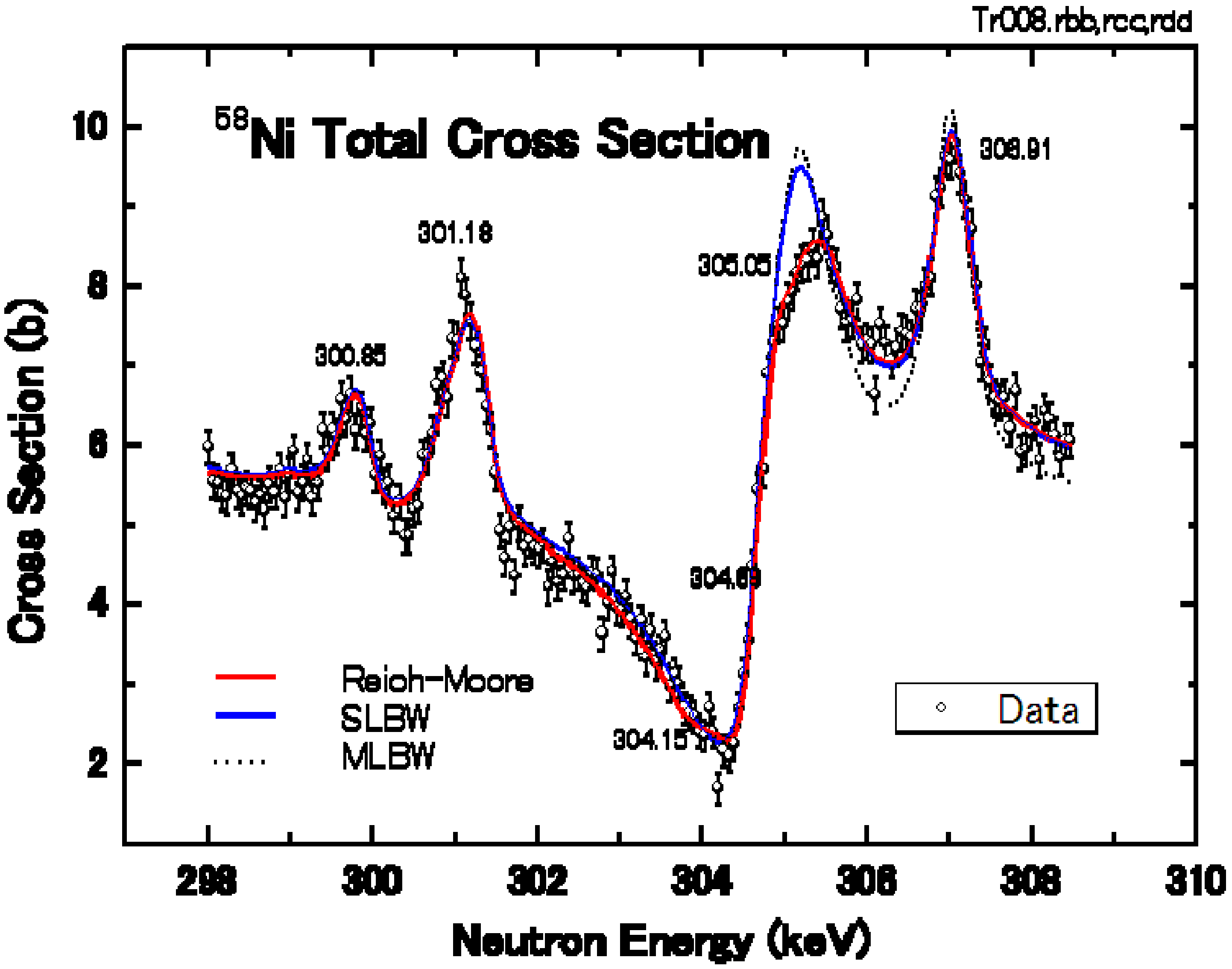
(b) The strong resonance near 480 keV could not be fitted with a single $p_{3/2}$ resonance.

(c) It was necessary to introduce a $p_{1/2}$ resonance with the same energy to obtain the reproduction of the transmission dip.

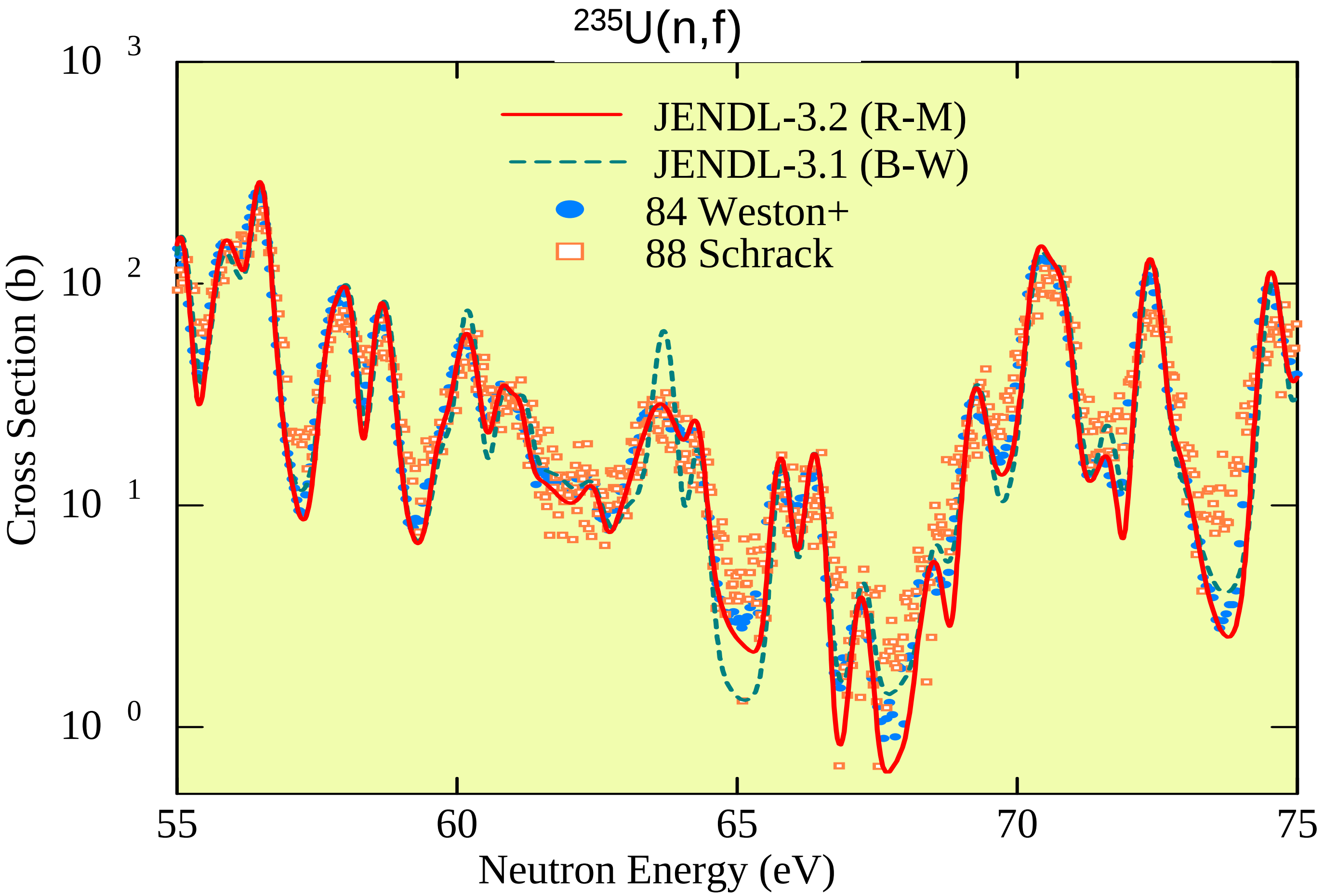
Phys. Rev. C31 (1985) 2041

The ^{137}Xe neutron resonances can be excited through beta decay from ^{137}I .

Sammy R-M、MLBW



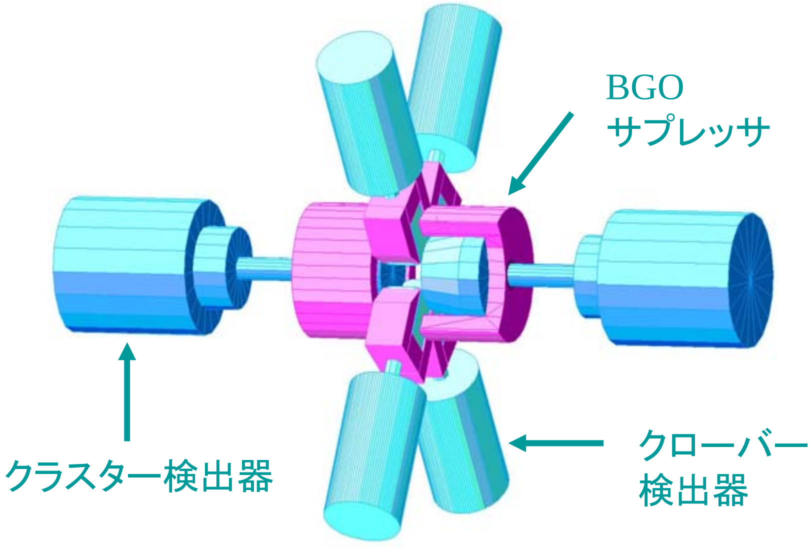
共鳴領域の核分裂断面積



まとめ
共鳴測定の今後の課題

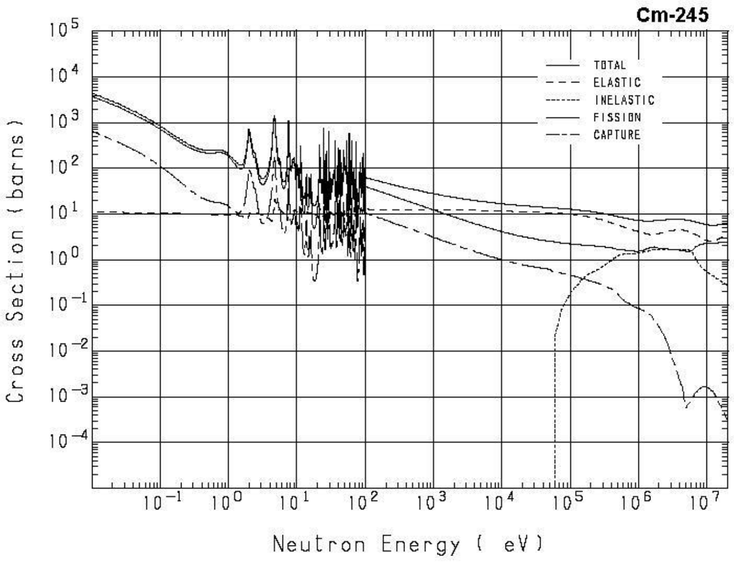
CPAF-JAEA

高精度化
放射性核種の測定
（微少サンプル、高中性子束、
バックグランドの低減）



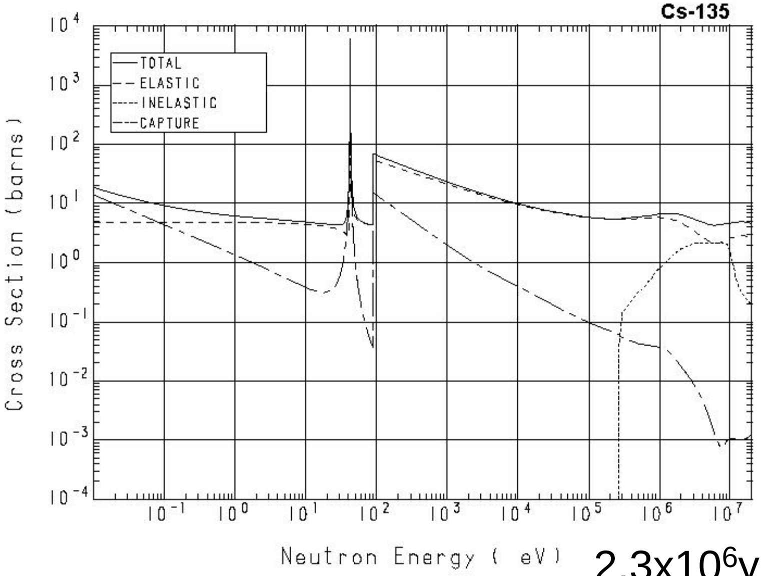
全立体角型多重ガンマ線検出装置

Minor Actinide



8530y

LLFP Long Lived Fission Product



2,3x10^6y