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DESCRIPTION OF FILE 1402 FOR SILICON FOR THE LIBRARY "BROND"

- Revision of MAT 2015 and Integral Data Tests -

D. Hermsdorf
Technical University Dresden
Section of Physics

August 1986

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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Preface

This report is aimed to supplement the report INDC(GDR)-20/L by

i) description of modifications of file 2015 into the present version MAT 1402 for Silicon and

ii) inclusion of remarks on the reliability of microscopical data by comparison with integral experiments.

Both, updating and testing of data have been carried out in an international co-operation with the Centre po Jadernim Dannim (CJD) at Obninsk which is responsible for maintenance of the library BROND. This report compiles some original contributions by following authors:

- A.I. Blokhin, A.V. Ignatyuk
  "Re-evaluation of resolved resonances parameters for Silicon"
- D. Hermsdorf, A.V. Ignatyuk
  "Neutron capture cross sections for Silicon in the energy range from 1 to 10 MeV"
- L. Adamski, M. Herman, A. Marcinkowski
  "Evaluation of the Cross Sections for the $^{28}Si(n,p)^{28}Al$ and the $^{181}Ta(n,2n)^{180}Ta$ Reactions"
  Report IAE 1976/E-IV/Pl/A, 1983
- A.I. Blokhin, I.V. Kravchenko
  "Calculation of group-constants with code RECENT"
- D. Hermsdorf
  "Consistency checks of microscopic data by intercomparison with integral quantities".

As usual, the file 1402 described here is under permanent development in order to include most recent experimental and theoretical results to meet to a better extend refined reactor application requirements. The report documents the status of MAT 1402 at December 1985.

Contents

1. Introduction

In review papers published recently neutron nuclear data for Silicon are reported to be of high importance for practical applications in dosimetry, shielding /1/ and geology /2/. Furthermore, such data are necessary for investigation of radiation damage effects in Silicon as an essential component of contemporary nuclear instrumentations (electronics, radiation detectors).

At present data files for Silicon exist in various libraries of evaluated neutron nuclear data, which differ mainly by the age of evaluation and the reaction types included. Sometimes the files are designed to meet special applicative demands.

Any new evaluation should be carried out as independent from each other as possible. Nevertheless, data from other files approved successfully should be adopted advantageously. On the other hand, weak points discovered in a file by sensitive data tests should be investigated carefully to ensure an improvement in quality of any new file. Unfortunatly, only a few results are published concerning intercomparisons of microscopic data from different libraries /3,4/ and systematical testing of them by calculations of integral quantities determined experimentally with sufficient accuracy too /1/.

In the latter study it has been concluded that neutron emission data for Mg, Ca, Ti, V, Cr, Ni, Cu, Nb, W air and concrete included now in the library ENDF/B-V have to be further evaluated to better meet the demands for shielding applications.

All these arguments strongly initiate a further permanent revision of MAT 1402 maintained by the CJD in the FEI Obninsk.

2. History of the file for Silicon for BROND library

The principal evaluation had been finished in August 1981. After formatting in version V of ENDF/B rules and checking, the file was released in May 1982 under MAT 2015. A documentation of this first version was published in reports INDC(GDR)-20/L and 22/L respectively /3,4/.

Since that times, numerous more are less stringent changes in the data have been done. Therefore following versions were released meanwhile:

version 2, MAT 2015

distributed in May 1984 including corrections for integral cross sections (MF3) only traced out by CHECKER and FIZCON;

version 3, MAT 1401

distributed in December 1984 including new data for (n,p) and pointwise representation of data in the resolved-resonance-region produced by RECENT basing on version 2;

version 4, MAT 1402

distributed in December 1985 including new data for (n,γ) in the range from 1 to 10 MeV and new evaluated MLBW-resonances-parameters for all isotopes ($^{28, 29, 30}Si$).

As usual, any new version will supersede the former one in those quantities under modification.

This report documents all changes in data having done up to December 1985.

3. Changes in evaluated nuclear data

3.1. Resolved-resonances-parameters

For the principal version of the Silicon file (MAT 2015) Single-Level-Breit-Wigner parameters for resolved resonances had been determined by adjusting compiled parameters /5/ to fit the total cross section in the energy range from 100 keV to 1.56 MeV.

But, this quantity is insensitive against resonances from minor constituents of the natural Silicon. Therefore, parameters for $^{29,\,30}Si$ had been ignored totally. Furthermore, higher-order momenta waves (p, d-waves) important for the capture channel can't be really fitted on the basis of the total cross section only. All these neglections and approximations results in too small capture cross sections in the region from 1 to 100 keV roughly. Basing on more recent compilations /6,7,8/ a re-evaluated set of MLBW-parameters for all isotopes have been prepared /9/ and incorporated into the actual version MAT 1402.

Virtual levels ensure the correct simulation of the 1/v-law in the capture cross section.

In table 1 the statistics of resonances in $^{28,\,29,\,30}Si$ is summarized.

Table 1: Statistics of MLBW-parameters in MAT 1402.

Isotope	Abundance (in %)	Energy range (in keV)	Number of resonances l=0	l=1	l=2	Total
^{28}Si	92.23	0 - 1851.7	6	22	16	44
^{29}Si	4.67	0 - 663	1	8	0	9
^{30}Si	3.10	0 - 849.9	1	2	9	12
^{nat}Si	100.0	0 - 1560	8	32	25	65

3.2. Si(n,γ) cross sections

Comparing the principal evaluation (and versions 2 and 3 also) with data obtained from other libraries mainly two striking deviations were noted:

i) too small cross sections from 1 to 100 keV
and
ii) too large cross sections from 2 to 10 MeV.

The first one is strongly connected with missing contributions of resonances from minor components ($^{29,30}Si$) in earlier versions. Therefore, by inclusion of re-evaluated and completed MLBW parameters for all isotopes in the actual version this shortcoming has been corrected for.

Table 2: Capture cross sections obtained by Belanova et al. /10/.

Energy (in keV)	Cross section (in mbarn)
24 $\pm$ 3	42 $\pm$ 8
220 $\pm$ 20	10 $\pm$ 5
830 $\pm$ 40	2 $\pm$ 1 *

* the value 20 $\pm$ 10 given in the original paper /10/ was a misprint. The corrected value 2 $\pm$ 1 is also referred by Stavisskij et al. /11/.

These data are confirmed within the order of magnitude by the high-resolution experiment carried out by Macklin et al. (published in Phys. Rev. 129 (1963) 2695).

The deviations in the MeV-range also results from a crucial lack of experimental data and theoretical uncertainties in prediction of fast neutron capture in medium weight nuclei additionaly. The situation has been studied in terms of three different capture mechanisms using corresponding computer codes:

i) *statistical model* (FISPRO /12/, STAPRE /13/);
ii) direct-semidirect model (DSD) (FISPRO /12/);
iii) pre-equilibrium model for γ's (PEQGM /14,15/).

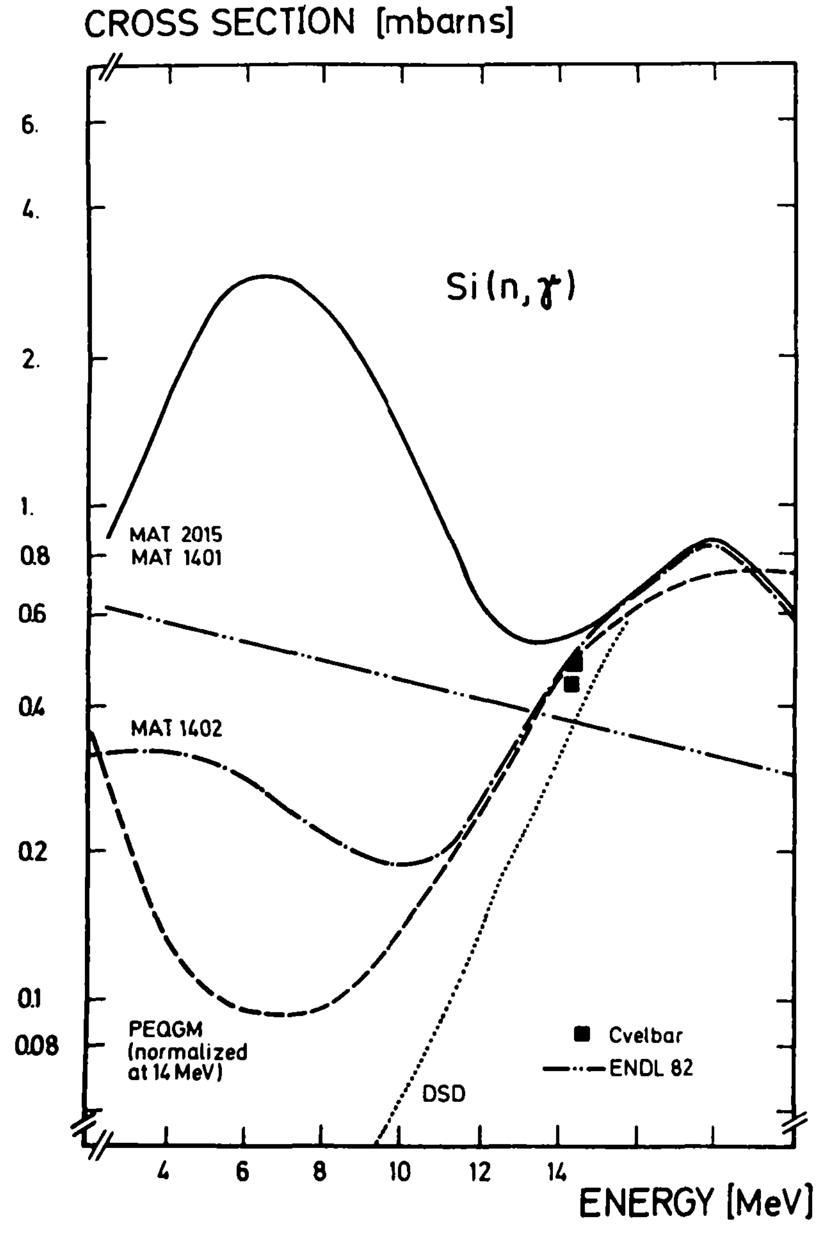

Fig. 1: Si(n,γ) cross sections.
The cross sections adopted for former versions (MAT 2015, MAT 1401) are compared to new calculations by pre-equilibrium and direct models and the re-evaluated data for the present version MAT 1402 and ENDL-82.

The energy dependence of fast neutron capture cross sections is characterized by a more or less deep minimum at 6 MeV roughly. The depth of this minimum is mainly caused by the slope of rapid decrease in the statistical model contribution.

On the other hand, this deep valley will be filled up by both long-range tails from resolved (or unresolved) resonances in the high keV-region and the contribution from DSD at low energies also.

The accuracy of theoretically predicted capture cross sections depends strongly on several parameters which have to be carefully adjusted by use of experimental data. Such free (or at least pre-fixed) quantities are $\overline{\Gamma}_{\gamma}$, level-density parameter a, giant dipol resonance parameters, MLBW-parameters, pre-equilibrium emission parameters etc.

The calculated results are shown in fig. 1. It have to be mentioned, that the cross sections obtained by the code PEQGM are too large by a factor of about 5.5. This is in general agreement with a factor of 4 roughly found for ^{93}Nb by Akkermans and Gruppelaar /15/. Such an overestimation of capture cross sections is caused by improper modelling of pre-equilibrium emission of γ-quanta by Bětak and Dobeš /16/. Therefore, in the absence of experimental data for reliable parameter adjustment the re-evaluation of capture cross sections for Silicon was guided by the energy dependence of cross sections in other nuclei in this mass range (^{23}Na, ^{26}Mg, ^{30}Si) compiled in /17/.

3.3. Si(n,p) cross sections

After finishing the principal evaluation for Si(n,p) two other evaluations had been performed independently /18,19/. These new results are intercompared with MAT 2015 in fig. 2.

Remarkable deviations appear in two energy ranges:

i) the low energy excitation function up to 9 MeV reflecting the resonance structure of the compound nucleus

and

ii) at high energies from 12 to 20 MeV including contributions from multi-particle emissions (n,np) and (n,2p).

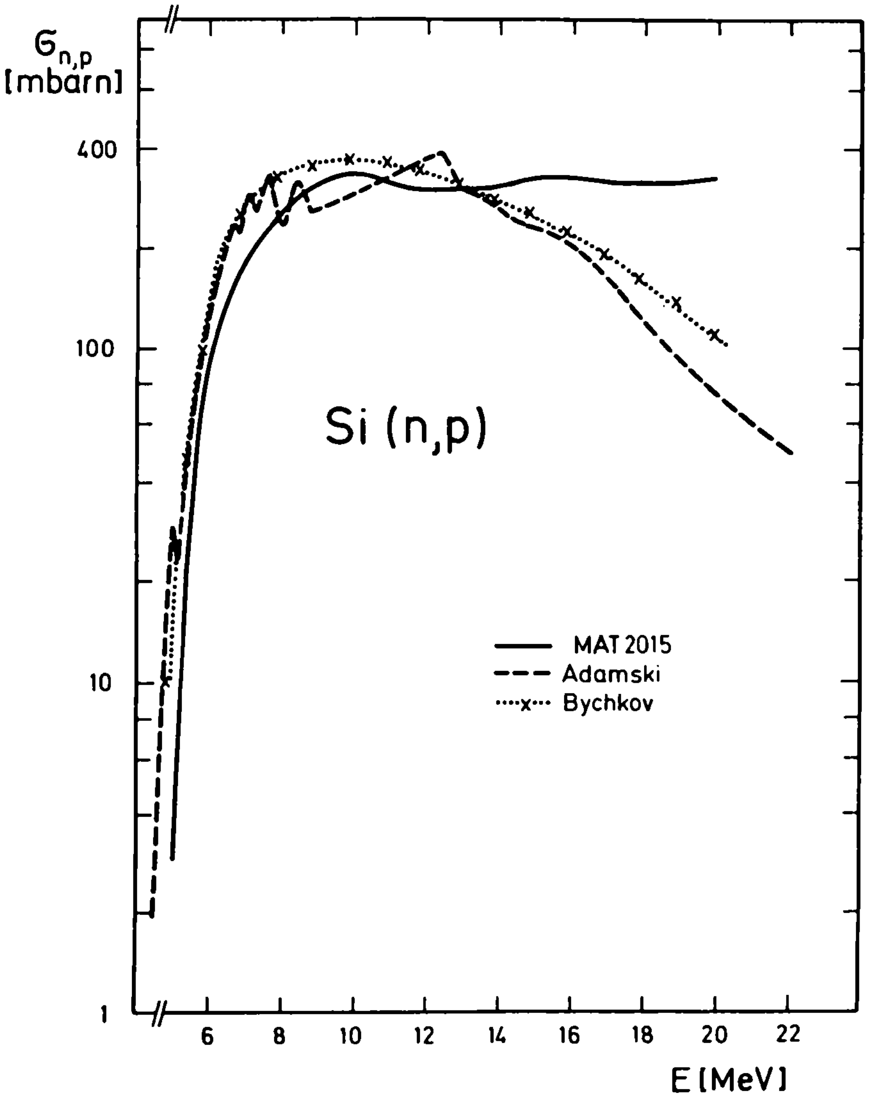

Fig. 2: Si(n,p) cross sections.
Comparison of recent evaluations by Bychkov et al. /18/ and Adamski et al. /19/ and former version of the present file (MAT 2015).

The intermediate energy range from 9 to 12 MeV can't be verified by any new experiment. The actual version MAT 1402 is based on Adamskis' evaluation /19/ by adopting the data from threshold to 9 MeV. Above 9 MeV no changes in the data given in earlier versions seems necessary. Larger cross sections in comparison to other estimations /18,19/ are due to contributions from (n,pn) reaction lumped together in MT103 by ENDF/B-format rules.

3.4. Non-elastic cross sections

A new experiment for σ_{nX} yielding 0.93 ± 0.04 at 14.9 MeV has been reported very recently /20/. Together with the an earlier one (1.02 ± 0.06 barns at 14 MeV) there are now some indications for lowering the recommended values in MAT 1402. Such a revision will be prepared in the nearest future.

4. Comparison of microscopical data with integral experiments and calculations

4.1. Group constants calculations

The application of evaluated microscopical data in reactor physics calculations proceeds on the basis of higher condensed cross sections (or related quantities), the so-called group constants. They are defined as mean values in energy bins by averaging the pointwise data with an influence spectrum according to

$$\langle \sigma \rangle^{i} = \int_{E_i}^{E_{i+1}} dE\, \sigma(E)\, f(E) \qquad (1)$$

for the i^{th} group.

The influence spectral shape f(E) is choosen in accordance with the reactor type or critical arrangement under investigation.

Table 3: 27-group constants for total and elastic scattering cross sections.

Nr.	σ_{nT}/barns			$\sigma_{n,n}$/barns		
	BNAB-78	2015	1402	BNAB-78	2015	1402
-1	1.8224	1.8697	1.8653	0.801	0.49846	0.49846
0	1.8155	1.8369	1.8364	0.671	0.47194	0.4720
1	1.9776	1.9659	1.9644	0.839	0.66954	0.66953
2	2.3116	2.3437	2.3416	1.519	1.5735	1.5734
3	2.3797	2.4872	2.4842	1.915	1.9585	1.9582
4	3.113	3.3434	3.1793	2.9583	3.1954	3.0317
5	3.489	5.5796	4.2365	3.4873	5.5784	4.2356
6	3.144	3.7858	3.8785	3.1431	3.7852	3.8779
7	5.535	5.2456	8.0169	5.5339	5.2451	8.0164
8	2.768	2.6078	3.1581	2.7666	2.6059	3.1573
9	1.700	1.6184	3.8167	1.6977	1.6201	3.8133
10	1.436	1.9295	1.3193	1.4277	1.9351	1.3143
11	1.717	2.0530	1.8416	1.7097	2.0438	1.8354
12	2.107	2.1101	2.0570	2.0988	2.0937	2.0447
13	2.158	2.1368	2.2031	2.1496	2.1170	2.1792
14	2.158	2.1492	2.1488	2.1495	2.1278	2.1460
15	2.159	2.1549	2.1648	2.1503	2.1329	2.1555
16	2.159	2.1576	2.1723	2.1501	2.1352	2.1600
17	2.159	2.1589	2.1758	2.1500	2.1363	2.1620
18	2.159	2.1595	2.1775	2.1497	2.1369	2.1630
19	2.160	2.1598	2.1783	2.1502	2.1371	2.1635
20	2.160	2.1599	2.1786	2.1501	2.1373	2.1637
21	2.162	2.1600	2.1789	2.1500	2.1374	2.1638
22	2.166	2.1601	2.1821	2.1500	2.1374	2.1639
23	2.172	2.1605	2.2024	2.1500	2.1375	2.1640
24	2.181	2.1809	2.2149	2.1500	2.1375	2.1641
25	2.196	2.2003	2.2208	2.1500	2.1375	2.1641
T	2.289	2.2867	2.3170	2.1500	2.1376	2.1643

Table 4: 27-group constants for $\bar{\mu}$ and absorption cross sections.

Nr.	σ_{abs}/mbarn BNAB-78	2015 *	1402 *	$\bar{\mu}$ BNAB-78	2015	1402
-1	528.4	0.5677	0.581	0.7952	0.821	0.81046
0	601.5	0.76276	0.276	0.6410	0.696	0.76963
1	392.6	2.5602	0.229	0.5214	0.663	0.61317
2	33.6	2.3496	0.3028	0.4047	0.528	0.54540
3	3.7	1.1332	0.3385	0.4349	0.545	0.49083
4	0.7	0.48282	0.307	0.3199	0.448	0.40115
5	0.7	0.91849	0.596	0.3003	0.4481	0.41325
6	0.9	0.609	0.4226	0.1549	0.4017	0.36497
7	1.1	0.5166	0.428	0.0690	0.4017	0.19570
8	1.4	1.887	0.6987	0.0274	0.0710	0.10028
9	2.3	0.254	3.726	0.0567		0.071244
10	8.3	0.193	0.9095	0.0467		0.071541
11	7.3	0.2486	1.54	0.0320		0.071680
12	8.2	0.323	4.103	0.0239		0.071746
13	8.4	0.437	20.853	0.0239		0.071776
14	8.5	0.633	0.738	0.0239		0.071791
15	8.7	0.919	0.985	0.0239		0.071799
16	8.9	1.34	1.444	0.0239		0.071804
17	9.0	1.968	2.119	0.0239		0.071807
18	9.3	2.878	3.105	0.0239		0.071809
19	9.8	4.23	4.56	0.0239		0.071811
20	9.9	6.216	6.69	0.0239		0.071812
21	12.0	9.099	9.816	0.0239		0.071814
22	16.0	13.39	14.42	0.0239		0.071815
23	22.0	19.655	21.17	0.0239		0.071816
24	31.0	28.76	31.04	0.0239		0.071818
25	46.0	42.335	45.611	0.0239		0.071819
T	139.0	128.69	138.85 **	0.0239	0.0718	0.071823

* for MAT 2015 and MAT 1402 in σ_{abs} the capture cross section has been considered only.

** note that the thermal-group-constant is different from the 2200 m/s cross section value by an averaging of a 1/v-dependence in an energy region 0.0215 to 0.215 eV.

Table 5: 27-group constants for reaction cross sections (in barns).

Reaction	Group number -1	0	1	2	3	4	5	File
$\sigma_{n,n'}$	0.493	0.543	0.746	0.759	0.461	0.154	0.001	BNAB
	0.508	0.759	0.846	0.725	0.524	0.186	0.0277	2015
	0.50815	0.75953	0.84032	0.72579	0.52512	0.14706	0.0003	1402
$\sigma_{n,2n}$	0.008	0.003	0.0	0.0	0.0	0.0	0.0	BNAB
	0.00238	0.00106	0.00002	0.0	0.0	0.0	0.0	2015
	0.0024	0.001065	0.000024	0.0	0.0	0.0	0.0	1402
$\sigma_{n,p}$	0.248	0.283	0.249	0.026	0.0	0.0	0.0	BNAB
	0.298	0.312	0.218	0.018	0.0	0.0	0.0	2015
	0.3105	0.3137	0.2687	0.03165	0.0	0.0	0.0	1402
$\sigma_{n,\alpha}$	0.261	0.312	0.143	0.007	0.003	0.0	0.0	BNAB
	0.130	0.206	0.182	0.010	0.0004	0.0	0.0	2015
	0.1316	0.2062	0.182	0.01017	0.00044	0.0	0.0	1402
$\sigma_{n,d}$	0.019	0.006	0.0	0.0	0.0	0.0	0.0	BNAB
	0.137	0.029	0.0	0.0	0.0	0.0	0.0	2015
	0.1376	0.0338	0.000172	0.0	0.0	0.0	0.0	1402

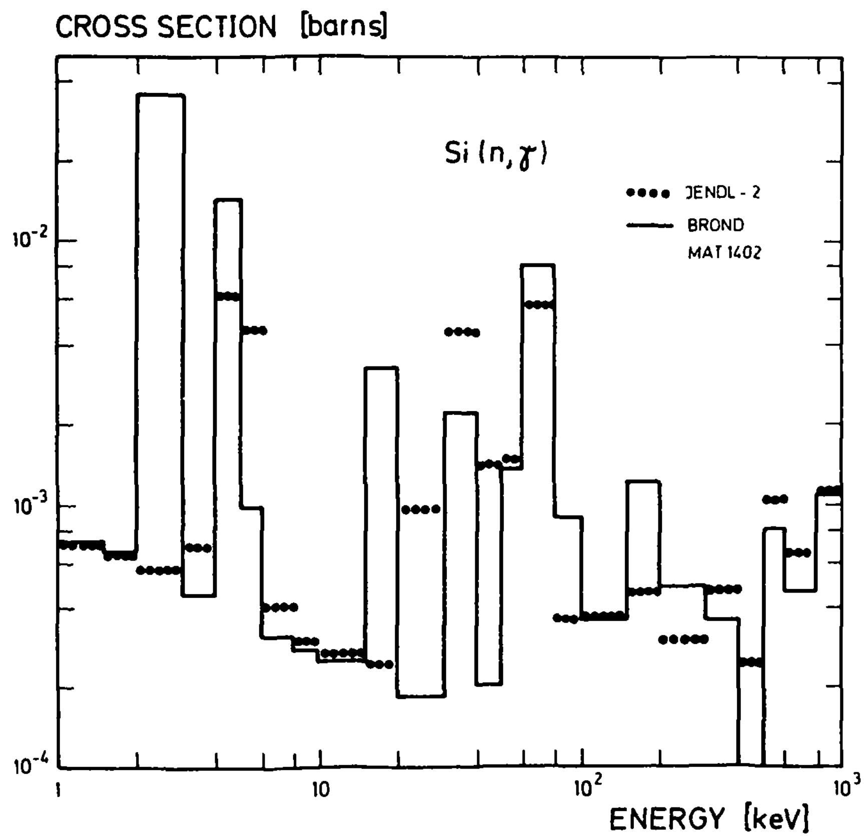

Fig. 3: Si(n,γ) cross sections in the keV region.
Parts of 74-group constants lying in the keV range calculated on the basis of MAT 1402 and the library JENDL-2 are compared.

The total number N of groups varies in a wide range from 2 to 640 are more. Commonly, the 27-group structure is applied /21/. The new version MAT 1402 has also been processed by means of ENDF/B-processing codes LINEAR, RECENT, SIGMA1, GROUPIE to calculate 27-group constants. In tables 3, 4 and 5 all results are compiled and compared to those constants produced by the former version (MAT 2015).

Furthermore, the widely used group constants BNAB-78 which base on ENDL-76 mainly are given for intercomparison.

For conservation of the fine structure in the resolved-resonances-region a 74-group constants set is preferable applied. Fig. 3 show a part of this set for the neutron capture cross section in the keV range which has been critically revised for MAT 1402 (see chapter 3.2.).

4.2. Spectrum-averaged cross sections

4.2.1. Fission-spectrum averaged threshold reaction cross sections

By definition spectrum averaged cross sections are determined according to

$$\langle \sigma \rangle = \int_{0}^{\infty} dE\, \sigma(E)\, \chi(E) \qquad (2)$$

by weighting the point-wise data with a normalized neutron soure (or flux density) distribution $\chi(E)$.

Here $\chi(E)$ represents the fission spectrum resulting from spontaneous (^{252}Cf) or induced fission (^{235}U).

Estimates of $\langle \sigma \rangle$ are made either by integral measurements directly or by differential data integrated according to the relation given above.

Table 6: Compilation of calculated and recommended (experimental or systematical) fission spectrum averaged cross sections (in /ubarns).

Reaction	⟨σ⟩ Recommended by Experiments **	⟨σ⟩ Recommended by Systematics *	⟨σ⟩ Calculated by MAT 2015 ***	⟨σ⟩ Calculated by MAT 1402 ***
(n,2n)	-	^{28}Si: $0.1^{+70\%}_{-40\%}$	-	-
		^{29}Si: $590^{+70\%}_{-40\%}$	-	-
		^{30}Si: $7^{+70\%}_{-40\%}$	-	-
	-	^{nat}Si: $30^{+70\%}_{-40\%}$	2.58	2.58
(n,p)	^{28}Si: 9660±550, 7120±230	^{28}Si: 6400±800	-	-
	^{29}Si: 1790±790	^{29}Si: 3300±200	-	-
	^{30}Si: -	^{30}Si: -	-	-
	^{nat}Si: ~7000..10000	^{nat}Si: ~6300	7500	10210
(n,α)	-	^{28}Si: $560^{+80\%}_{-40\%}$	-	-
	-	^{29}Si: $7900^{+80\%}_{-40\%}$	-	-
	-	^{30}Si: 155±20 %	-	-
	-	^{nat}Si: 907	131	131
(n,d)	-	^{nat}Si: 118	64.2	64.2

Continuation of table 6:

(n,t)	-	^{nat}Si: 0.95	0.0047	0.0047
(n,^{3}He)	-	^{nat}Si: 0.045	0.0033	0.0033

Footnotes to table 6:

* averaged with ^{235}U-thermal fission spectrum /22/;

** experiments performed with ^{252}Cf spontaneous fission spectrum /23,24/;

*** calculations performed with ^{252}Cf spontaneous fission spectrum corrected for the high-energy enhancement in the spectral shape.

This quantities are very sensitive against energy shifts and peak - cross sections of threshold reactions. Therefore, evaluated cross sections of threshold reactions are processed and compared with integral experiments oftenly.

In table 6 calculated averaged cross sections for (n,2n), (n,p), (n,α), (n,d), (n,t) and (n,^{3}He) are compiled and compared with experiments or systematics taken from refs. /22,23,24/.

Generally, our knowledge on threshold reaction cross sections averaged over fission spectrum is far from proved accuracy.

4.2.2. Reactor-neutron fission spectrum averaged cross sections for γ-ray production

4.2.2.1. Production cross sections for discrete γ-lines

Recently a very comprehensive collection of experimental data for (n,n'γ) reactions induced by a reactor fast neutron spectrum has been published by Demidov et al. /25/.

All measurements have been obtained at 90° between the reactor neutron beam axis and the detector axis (direction of γ-quanta) only.

At this angle no γ-ray energy shift due to Doppler effect is observed but corrections for the angular distribution of γ-quanta in $(n,n'\gamma)$ reactions has to be taken into account necessarely. The fast neutron spectrum of the reactor (WWR type)can be approximated by

$$N(E_n) \sim \exp(-0.7\ E_n) \qquad (3)$$

for $E_n > 1$ MeV.

The experimental observables are the intensities of discrete γ-transitions which are proportional to the total population P of the corresponding level. The direct population P_s of the level via the (n,n') reaction only has to be corrected for cascade population contributions P_c by the relation $P_s = P-P_c$. This correction is reported to be small /25/.

Therefore, P_s is determined by

$$P_s = \int_{E_{thr.}}^{E_{max}} \sigma_{n,n'\gamma}(E_n, 90^o)\ N(E_n)\ dE_n \quad . \qquad (4)$$

According to equ. 4 averaged cross sections had been calculated using integrated γ-production cross sections $\sigma_{n,n'\gamma}(E_n)$ for discrete γ-lines from MF13 of the file 1402 to yield

$$\langle\sigma\rangle = \int_{E_{thr.}}^{20\ \mathrm{MeV}} \sigma_{n,n'\gamma}(E_n)\ \exp(-0.7 \cdot E_n)\ dE_n \quad . \qquad (5)$$

A direct intercomparison is practically impossible because of

- an unknown normalization constant C (see equ. 3);
- considerable corrections of the anisotropy of angular distributions up to 30 % /25/.

At first the calculated cross sections $\langle\sigma\rangle$ has to be corrected for by a factor F defined as

$$F(E_n,E_\gamma) = \frac{\sigma_{n,n'\gamma}(E_n)}{4\pi\sigma_{n,n'\gamma}(E_n,90^\circ)} \qquad (6)$$

and

$$\langle\sigma\rangle_{corr} = \left\langle \frac{\sigma}{F} \right\rangle \quad . \qquad (7)$$

However, the factor F depends on E_n and E_γ not only but also the radiation type, multipole order and their mixing ratio δ, influence strongly this factor /26/.

Unfortunatly, these dependences have been investigated experimentally and theoretically for some special cases only.

For Silicon, the anisotropy of angular distributions for the emission of discrete γ-lines were measured from E_n = 3 to E_n = 14 MeV for E_γ = 1.77 MeV /27,28,29,30;31/, E_γ = 2.83 MeV /27,28/, E_γ = 3.19 MeV /27,28/ and E_γ = 4.49 MeV /27/ only.

All experimentally verified data for F are summarized in fig. 4. The values of F have been plotted against an energy difference $D = E_n - E_\gamma^{thr}$. The experimental uncertainties are in the order of 20 % and more.

Fig. 4 shows clearly that pure E2 transitions may have a very strong anisotropy near the treshold with a decreasing tendency for increasing neutron incidence energy. Therefore, to correct $\langle\sigma\rangle$ this energy dependence was taken into account assuming the relation

$$F = 1.3 - 0.02 \cdot (E_n - E_\gamma^{thr}) \quad . \qquad (8)$$

Other γ-transitions may have more complicated (and therefore more uncertain) dependences especially on the multipole mixing ratio δ. There are only rare informations for other γ-transitions:

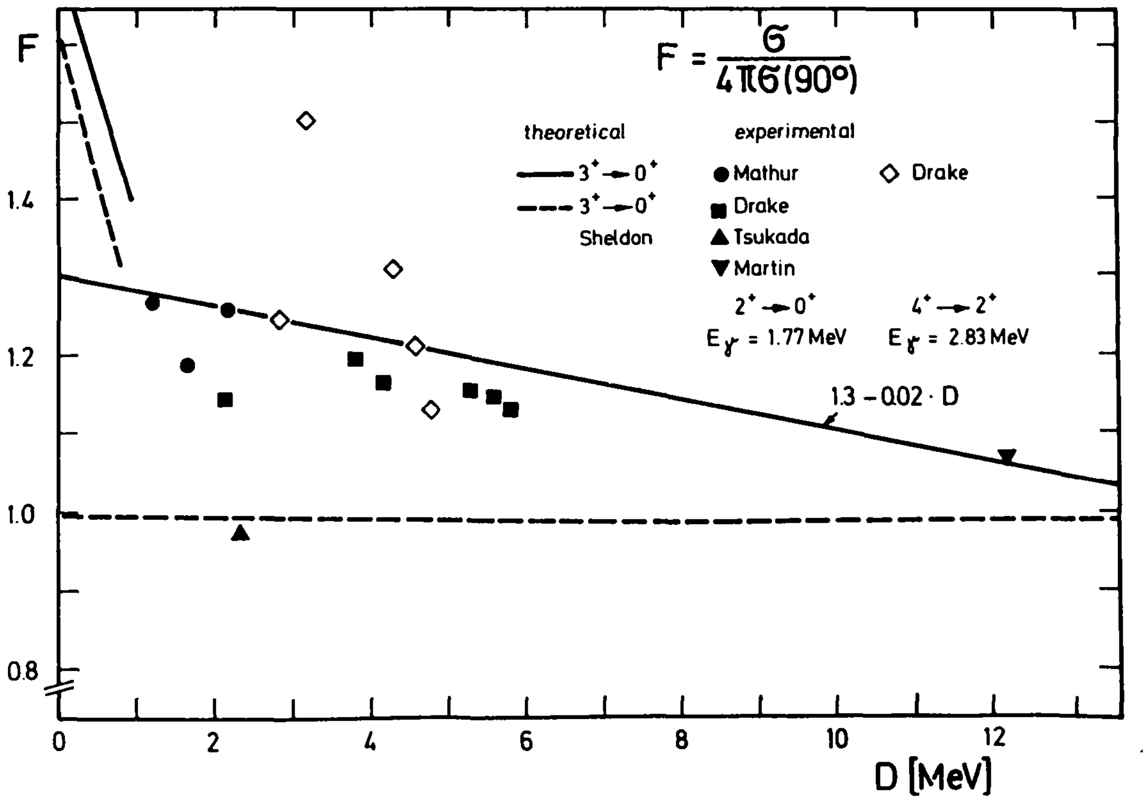

Fig. 4: Factor F for correction of the anisotropy of discrete γ-ray emission induced by fast neutrons.

- $3^+ \rightarrow 2^+$:

according to experiments for the E_γ = 4.49 MeV transition carried out by Drake /27/ for $E_n \approx$ 7 MeV a value for F ≈ 1.02 was found. On the other hand for an analogous transition in Cd /25/ F = 0.85 has been obtained and seems plausible from theoretical aspects /26/.

- $3/2^{+} \rightarrow 1/2^{+}$:

  a theoretical investigation by Sheldon /26/ for the 1.27 MeV-γ-transition in ^{29}Si demonstrates clearly the great sensitivity of F against the multipole mixing ratio δ. For $\delta > 0$ a value of 0.91 has been calculated whereas for $\delta < 0$ F yields 1.14.

But, there is no γ-transitions with mixed electro-magnetic-radiation in Silicon with known mixing ratio δ. Therefore any use of a correction factor is more or less speculative and has not been applied.

All results have been summarized in table 7.

After the correction of the anisotropy effects on $\langle\sigma\rangle$ the normalization constant C can be obtained from $P_s/\langle\sigma\rangle^{corr}$. The variation of C is quite big ranging from 500 to about 1200. A weighted mean value $\bar{C}$ has been calculated to be

$$\bar{C} = 650$$

taking weights proportional to P_s.

Unfortunatly, the experimental values P_s determined by Demidov /25/ are given without any error quotes. Therefore, a critical evaluation of the quotient P_s^{exp}/P_s^{calc} (see last column in table 7) is difficult. A factor of 2 may be understandable under this circumstances.

Therefore, the agreement between measured and evaluated quantities P_s is surprisingly good with only one exception in the case of the 1.263 MeV-γ-line emitted from ^{29}Si.

This strong deviation may have at least two reasons arising from

- unknown correction factor F (no experimental data for either angular distributions or mixing ratio δ) which is very important for such low-energetic γ-rays (see fig. 4);
- the evaluated production cross section $\sigma_{n,n'\gamma}$ for this line has been calculated by statistical model only because there are no experimental data available.

Nucleus	E_γ/MeV	$(I^\pi)_i \rightarrow (I^\pi)_f$ multipolarities	p_s^{exp} /25/	$\langle\sigma\rangle$	$\langle\sigma\rangle$ corr	$\frac{p_s^{exp}}{\langle\sigma\rangle}$ corr	$\frac{1}{C}\langle\sigma\rangle$corr $= p_s^{calc}$	p_s^{exp}/p_s^{calc}
^{28}Si	1.77	$2^+ \xrightarrow[E2]{} 0^+$ ($\delta = 0$)	95	1.84-1	1.48-1	641	96	0.99
^{28}Si	2.84	$4^+ \xrightarrow[E2/M3]{} 2^+$ ($\delta \neq 0$)	2.7	2.68-3	2.40-3	1125	1.56	1.73
^{28}Si	3.199	$0^+ \rightarrow 2^+$	1.0	7.87-4	7.87-4	1270	0.51	1.96
^{28}Si	4.496	$3^+ \xrightarrow[M1/E2]{} 2^+$ ($\delta \neq 0$)	0.9	5.65-4	6.65-4	1360	0.43	2.09
^{29}Si	1.272	$3/2^+ \xrightarrow[M1/E2]{} 1/2^+$ ($\delta \neq 0$)	4.0	9.03-3	1.03-2 ** ($\delta > 0$)	443 (505)**	5.86	0.68
^{29}Si	2.029	$5/2^+ \xrightarrow[E2/M3]{} 1/2^+$ ($\delta \neq 0$)	2.1	3.26-3	3.26-3	644	2.12	0.99
^{29}Si	2.425	$3/2^+ \xrightarrow[M1/E2]{} 1/2^+$ ($\delta \neq 0$)	1.0	1.40-3	1.27-3 *** ($\delta < 0$)	714 (649)**	0.91	1.10
^{30}Si	1.263	$2^+ \xrightarrow[M1/E2]{} 2^+$ ($\delta \neq 0$)	1.1	3.73-4	3.73-4	2950 *	0.24	4.58
^{30}Si	2.235	$2^+ \xrightarrow[E2]{} 0^+$	1.8	4.20-3	3.36-3	535	2.18	0.83

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Table 7: Reactor-neutron spectrum averaged cross section for production of discrete γ-rays.

Footnotes to table 7:

* this value has been omitted in averaging of C

** values in paranthesis have been calculated using the optimal factor F.

Summarizing this integral test it can be concluded that

i) evaluated production cross sections for discrete γ-lines mainly based on statistical model calculations (code STAPRE) are in generally reasonable agreement with experimental facts;

ii) the effect of anisotropic angular distributions for γ-transitions of pure E2-radiation can be relatively strong and should be considered for in MF14 in a next version of the Silicon-file.

4.2.2.2. γ-ray emission spectra

Several integral experiments are available on secondary γ-ray emission in thermal and fast reactor spectra /32,33/. Such data are of general importance for shielding applications /34/.

SB2-test /34/

Experiments on secondary γ-ray production cross sections arising from thermal-neutron capture has been carried out by Maerker /32/ with an estimated accuracy of about $\pm$15 % /34/.

Fig. 5 demonstrates the comparison of these experimental results with evaluated γ-ray spectrum for thermal neutrons included in MAT 1402. Further, a calculation based on ENDF/B-V is included too /34/. From this comparison it can concluded that SB2 indicates adequate data for both libraries ENDF/B-V and BROND MAT 1402 too.

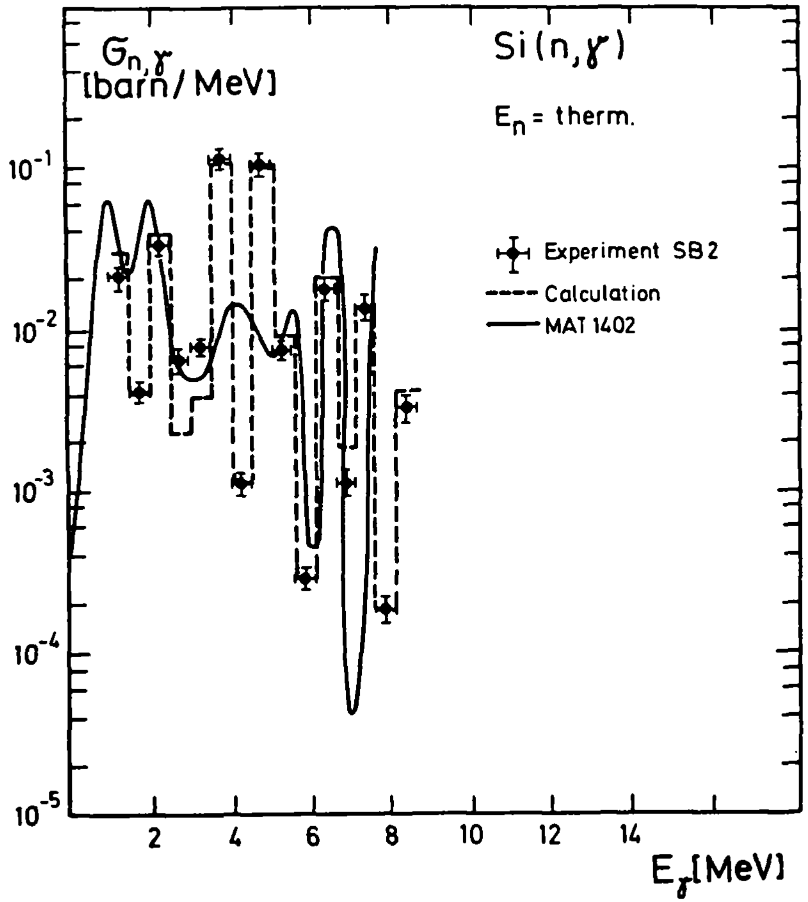

Fig. 5: Thermal-neutron capture γ-ray spectrum.
Comparison of experimental data /32/ with evaluations for MAT 1402 and calculations basing on ENDF/B-V /34/.

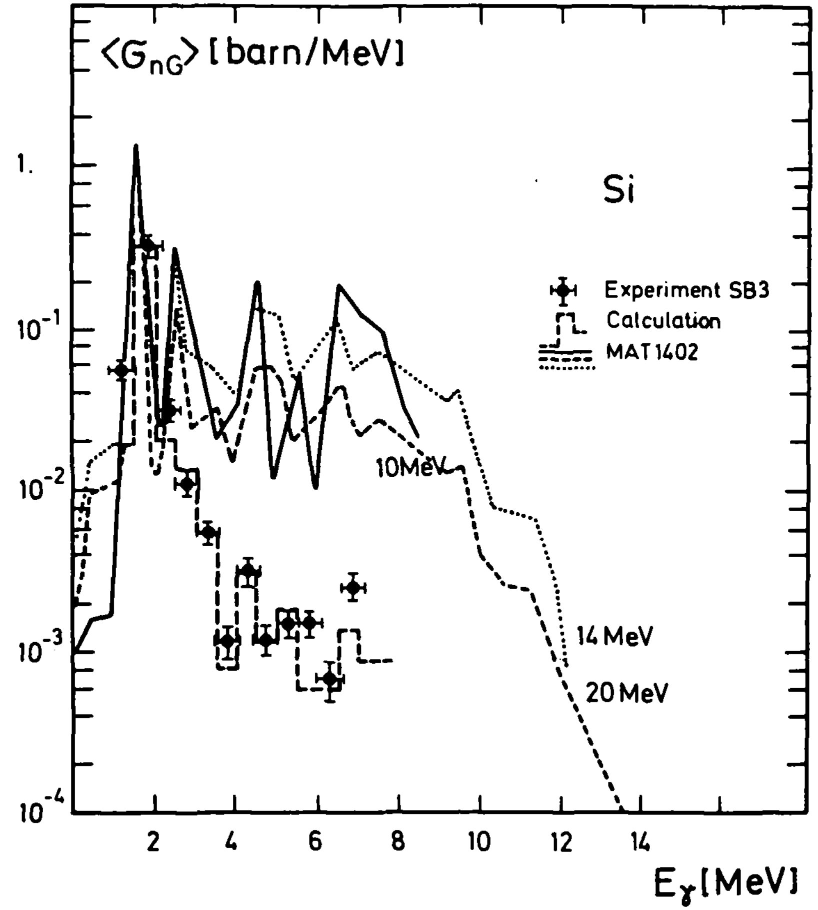

Fig. 6: γ-ray production spectrum induced by a fast neutron spectrum.
Comparison of experimental data /33/ with calculations basing on ENDF/B-V /34/ and MAT 1402.

SB3-test /34/

Experiments on secondary γ-ray production cross sections averaged over a fast-neutron spectrum have been performed by Maerker /33/ too. The accuracy is assumed to be in the order of $\pm$30 % only /34/.

Unfortunatly, the spectral shape of incidence source neutrons has not been documented in reference /34/.

Therefore, a direct comparison of properly processed data from MAT 1402 with experimental results and corresponding calculations on the basis of ENDF/B-V is still outstanding. Fig. 6 only demonstrates the unweighted γ-ray spectra at 10, 14 and 20 MeV neutron incidence energy in comparison with integral quantities /33,34/.

According to /34/ the SB3-test also reflects the adequacy of fast neutron-induced γ-ray production cross sections adopted for ENDF/B-V. Unfortunatly these data are unavailable at present.

5. Summary remarks

At present some files of evaluated nuclear data for Silicon exist and are available upon request from NDS or any of the responsible data centres in U.S.A., U.S.S.R. or France.

However, any application of recommended data for a special purpose implies necessarily a very careful choice among these various files according to criteria like actuality, completeness and the storage format for further processing procedures /35/.

In tables 8, 9 and 10 some of important aspects are summarized for decision making in use of any of the available files.

The present version of BROND MAT 1402 is advantageous from above mentioned points of view by the facts

i) of most recently updated data file available (see table 8);
ii) of inclusion of nearly all interesting neutron data types for a great variety of applications in shielding and radiation damage (see table 9);

Table 8: Compilation of characteristica of evaluated nuclear data files for Silicon.

Library	Access number	Date of evaluation (last revision)	Format
UKNDL-80	DFN 25E	1967	UKNDL
ENDF/B-IV	MAT 1194	1974	ENDF/B
ENDL-82 ENDL-84	ZA 14000 ZA 14000	1981 1984	ENDL ENDF/B
JENDL-2	MAT 2140	1976 rev. 1983	ENDF/B
INDL/V	MAT 1430	1979	ENDF/B
SOKRATOR BROND	MAT 2015 MAT 1402	1981 rev. 1985	ENDF/B ENDF/B

iii) of inclusion of γ-ray data types for combined neutron and γ-ray transport calculations necessary for shielding calculations in radiation protection and dosimetry (see table 10).

Table 9: Compilation of data types for neutron differential and integral cross sections in different files for Silicon actual at present.

MT	MF=2	MF=3						MF=4 *					MF=5 **			
	1	1	2	3	4	5	6	1	2	3	5	6	1	2	5	6
1	-	x	x	x	-	x	x	-	-	-	-	-	-	-	-	-
2	-	x	x	x	-	x	x	x	x	x	x	x	-	-	-	-
3	-	x	x	-	-	x	-	-	-	-	-	-	-	-	-	-
4	-	x	x	x	-	-	x	-	-	-	-	-	-	-	-	-
16	-	x	x	x	-	-	x	-	-	-	-	-	x	x	-	x
22	-	x	x	-	-	-	-	-	-	-	-	-	x	x	-	-
28	-	x	x	-	-	-	x	-	-	-	-	-	x	x	-	x
51..90	-	x	x	x	-	-	x	x	x	-	-	x	-	-	-	-
91	-	x	x	x	-	x	x	-	-	-	-	-	x	x	x	x
102	-	x	x	x	-	x	x	-	-	-	-	-	-	-	-	-
103	-	x	x	x	x	x	x	-	-	-	-	-	-	-	-	x
104	-	x	x	-	-	-	x	-	-	-	-	-	-	-	-	x
105	-	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-
106	-	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-
107	-	x	x	x	-	x	x	-	-	-	-	-	-	-	-	x
151	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
251	-	x	x	x	-	-	-	-	-	-	-	-	-	-	-	-
252	-	x	x	-	-	-	-	-	-	-	-	-	-	-	-	-
253	-	x	x	-	-	-	-	-	-	-	-	-	-	-	-	-
700..718	-	x	x	-	-	-	-	x	x	-	-	-	x	x	-	-
720..726	-	x	x	-	-	-	-	x	x	-	-	-	-	-	-	-
780..788	-	x	x	-	-	-	-	x	x	-	-	-	x	x	-	-
719	-	x	x	-	-	-	-	-	-	-	-	-	x	x	-	-
799	-	x	x	-	-	-	-	-	-	-	-	-	x	x	-	-

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Footnotes to table 9:

1) MAT 1402   2) MAT 1194   3) MAT 2140
4) MAT 1430   5) DFN 25E   6) ZA 14000

* isotropic angular distributions assumed for MT omitted from table

** evaporation spectra are included also.

Table 10: Compilation of γ-ray production cross sections for Silicon.

MT	MF=12			MF=13 *			MF=14 **			MF=15		
	1	2	3	1	2	3	1	2	3	1	2	3
4	-	-	-	x	x	x	-	-	-	x	x	x
16	-	-	-	x	-	x	-	-	-	-	-	x
22	-	-	-	x	x	-	-	-	-	x	x	-
28	-	-	-	x	x	x	-	-	-	x	x	x
51..90	-	-	-	x	x	x	-	-	x	-	-	-
91	-	-	-	-	-	-	-	-	-	-	-	-
102	-	x	x	-	-	-	-	-	-	x	-	x
103	-	-	-	x	x	x	-	-	-	x	x	x
104	-	-	-	-	-	-	-	-	-	-	-	-
105	-	-	-	-	-	x	-	-	-	-	-	x
106	-	-	-	-	-	-	-	-	-	-	-	-
107	-	-	-	x	x	x	-	-	-	x	x	x
719	-	-	-	x	-	-	-	-	-	x	-	-
799	-	-	-	x	-	-	-	-	-	x	-	-

1) MAT 1402   2) MAT 2140   3) ZA 14000

* MT4 also contains excitation function for discrete γ-lines

** only isotropic angular distributions for γ-quanta are given.

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