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AVERAGE GROUP DATA FOR ²⁴¹Pu IN THE

0.1 - 21.5 keV ENERGY REGION

N.T. Koyumdzhieva and N.B. Yaneva Nuclear Research and Power Institute, Sofia, Bulgaria

(Translated from a Russian original published in Yadernye Konstanty 4/1990)

Translation editor: Dr. Alex Lorenz

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ABSTRACT

Group neutron data for ²⁴¹Pu neutron were calculated for the unresolved resonance region (0.1-21.5) keV using multilevel R-matrix formalism.

INTRODUCTION

Neutron data for the heavy isotopes of Pu are essential to improve fuel processing in the U-Pu cycle and also to predict reactor characteristics for a nuclear power plant. Recent efforts have been directed towards obtaining reliable physical models to have a reliable description of available experimental results and also to extrapolate neutron cross-sections in a region for which no (or little) experimental information exists [1].

In recent years several evaluations [2, 3, 4] have been made for ²⁴¹Pu in the unresolved resonance region. All these evaluations were based on the single-level Breit-Wigner formalism [5] with the addition of elastic scattering from the permanent background to the resonance cross-section to allow for the effect of inter-resonance interference and the contribution of widely spaced resonances. In the present paper the ²⁴¹Pu neutron data (average neutron cross-sections, resonance

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self-shielding factors and their Doppler broadening) are calculated. Multilevel R-matrix formalism of the nuclear reactions (Reich-Moore approximation) [6] is used and allowance made for the statistical distributions of average resonance parameters by using the Monte-Carlo statistical method.

Average resonance parameters

Energy averaged resonance parameters are used to parameterize neutron cross-sections in the unresolved resonance region. They are constants for the given energy range (energy group) and their values change when they undergo transition to a different energy group. It is in this sense that we refer to the energy dependence of average resonance parameters.

In this paper we took the average resonance parameter values from the JAERI evaluation [3] and reduced them to the BNAB energy ranges [7] by the linear interpolation method.

The average radiative width $\overline{\Gamma_{\gamma}}$ and the potential scattering radius R_c are taken as energy independent values. For all spin states $\overline{\Gamma_{\gamma}} = 0.4$ eV and $R_c = 9.8$ fm (Table 1).

The average spacing between the resonances of a compound nucleus with spin J^{*} is $D_J = \frac{2(2I+1)}{(2J+1)}$ D_{obs} , where I is the nuclear target spin, J is the compound nucleus spin, D_{obs} is the average observed spacing between resonances in the low energy region. The energy dependence for D_J starts to develop when $E_n > 4$ keV, and this dependence is taken into account in D_{obs} (Table 2). Not making allowance for the energy dependence D_{obs} in the energy group (10-21.5) keV leads to a 2.4% drop in the average radiative capture cross-section $\overline{\sigma_r}$ and to a 1.5% drop in the average

In our evaluation, we make allowance for the contribution of p-resonance states of the compound nucleus as one state averaged over spin J. We are able to do this because the p-resonance

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contribution to the neutron cross-sections in the region examined is relatively small (≈10%). Then we obtain the average spacing between the p-resonances from the following equation:

$$\overline{D}_{(p)} = \frac{1}{\sum_{j} p_{j}} \frac{1}{\sum_{j} (1/D_{j})},$$

where p_j is the resonance density of a compound nucleus with a spin J^s .

The power functions for s-states \overline{S}_{o} and for p-states \overline{S}_{1} are heavily energy dependent. We obtain their average group values from the JAERI evaluation by reduction to the corresponding energy groups in the BNAB system by quadratic interpolation.

The average fission widths are also dependent on the energy value. We used the same procedure as for the power functions to obtain the fission widths for each compound nucleus state J^* . In the calculation process we retain the ratio of the fission width in one spin state to the fission width in every other, as it is done in the JAERI evaluation. Since we consider the p-resonance contribution of the compound nucleus as one state averaged over the spin conditions $J^* = 1^-$, 2^- , 3^- , 4^- , then $\overline{\Gamma_{f(p)}}$ is obtained as an average of the fission widths of these states. All the energy dependent average resonance parameters are given in Table 2.

The degrees of freedom for the neutrons (\mathbf{v}_n) , the fission (\mathbf{v}_r) and radiative (\mathbf{v}_r) widths are given in Table 1. For compound nucleus s-resonance states the values \mathbf{v}_n and \mathbf{v}_r are the same as those obtained by other authors [2]. For the generalized p-state we take $\mathbf{v}_n = 1$ and $\mathbf{v}_r = 1$. The contribution of each of the two fission channels for the $J^{\mathbf{x}} = 2^+$ state is considered equal as the use of the Porter-Thomas distribution to describe Γ_r fluctuations is only justified in cases of very weakly or very strongly diverging relative contributions of the channels, and when they are equal the integral values of \mathbf{v} can be used rather than \mathbf{v}_{eff} [2]. The average number of prompt fission neutrons $\mathbf{v}_n = 2.913 + 0.149 \ E_n$ agrees with the JAERI evaluation.

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Results and discussion

Calculations were carried out using the MNCARL program [8]. Group averages were calculated for the neutron cross-section values. The radiative capture cross-section $\overline{\sigma_{\gamma}}$ and the fission cross-section $\overline{\sigma_{f}}$ were calculated using the procedure proposed by Luk'yanov with the aim of optimizing the calculation process. If we write the K-matrix elements in the form: $K_{nn} = A_1 + A_2$, $K_{ff} = B_1 + iB_2$, $K_{nf} = C_1 + iC_2$ then:

$$\overline{\sigma} = 4 - \frac{2^{+2N+B_2(N-M)+B_1Q}}{|\Delta|^2}$$
(1)

$$\overline{\sigma}_{f} = 4 - \frac{C_1^2 + C_2^2}{|\Delta|^2},$$
(2)

$$N = A_2 B_2 + C_2^2$$

$$M = A_1 B_1 - C_1^2$$

$$Q = A_1 B_2 + B_1 A_2 - 2C_1 C_2$$

$$|\Delta|^2 = (1 + A_2 + B_2 + N - M)^2 + (A_1 + B_1 + Q)^2.$$

where:

The calculation of the cross-section using formulas (1)-(2) gives identical results to calculations using (1 - iK) matrix elements [9].

The corresponding resonance self-shielding coefficients f_t , f_f , f_q and f_n and their Doppler broadening $\Delta t^{1,2}$, $\Delta f^{1,2}$, $\Delta \gamma^{1,2}$ and $\Delta n^{1,2}$ were calculated for three temperatures, 300°C, 900°C and 2100°C, and also for the dilution cross-section values $\sigma_o = 1$ b, 10 b, 100 b. Doppler broadening was calculated according to the formulas:

$$\Delta_{i}^{1} = \frac{\sigma_{i}^{(900^{\circ}C)f_{i}^{(900^{\circ}C;\sigma_{o}^{\circ})-\sigma_{i}^{(300^{\circ}C)f_{i}^{\circ}(300^{\circ}C;\sigma_{o}^{\circ})}}{\sigma_{i}^{(300^{\circ}C)}}$$
$$\Delta_{i}^{2} = \frac{\sigma_{i}^{(2100^{\circ}C)f_{i}^{\circ}(2100^{\circ}C;\sigma_{o}^{\circ})-\sigma_{i}^{(900^{\circ}C)f_{i}^{\circ}(900^{\circ}C;\sigma_{o}^{\circ})}}{\sigma_{i}^{(300^{\circ}C)}},$$

where i = t, f, γ , n. All the calculation results are given in Tables 5-8.

As can be seen from Table 2, the energy dependence $\overline{\Gamma_{f(p)}}$ is very weak. Calculations showed that not making allowance for the energy dependence $\overline{\Gamma_{f(p)}}$ in the energy range (0.1-21.5) keV has no effect on the average radiative capture cross-section values which are very sensitive to the average fission width values. In this case $\overline{\Gamma_{f(p)}}$ was calculated as the average of the initial fission width values of all p-resonance channels; $\overline{\Gamma_{f1}} = 960$ MeV, $\overline{\Gamma_{f2}} = 270$ MeV, $\overline{\Gamma_{f3}} = 600$ MeV, $\overline{\Gamma_{f4}} = 230$ MeV (see JAERI [3]).

Kon'shin et al. [10] calculated the particle contributions of each spin state J^{\bullet} in average fission cross-sections and of the radiative capture cross-section. From these calculations it can be seen that, owing to p-wave spin states, the fission cross-section is approximately 1% of the total fission cross-section at $E_n = 1$ keV. The same also applies to the radiative capture cross-section. When $E_n = 10$ keV, however, these contributions increase respectively by 10% for $\overline{\sigma_{\gamma}}$ and 20% for $\overline{\sigma_{f}}$. Then use of one averaged p-resonance state in the 11th energy group results in a 10% reduction in $\overline{\sigma_{\gamma}}$ and an approximately 18% reduction in $\overline{\sigma_{f}}$. Therefore we are limited to using one averaged p-resonance state only up to an energy value of $E_n = 2$ keV. The average fusion widths of the states $J^{\bullet} = 1^{\circ}$, 2° , 3° , 4° in energy groups 13, 12 and 11 are given in Table 3.

In Table 4 the calculated group cross-sections of the present work are compared with the group cross-sections obtained on the basis of a full system of evaluated data [2]. These are the only average group cross-sections for ²⁴¹Pu in the BNAB energy ranges known to us. It can be seen that the calculated radiative capture cross-sections $\overline{\sigma_{1}}$ of the present paper are systematically higher than Kon'shin's group cross-sections. Comparison with the only available experimental data by Weston [11] (Fig. 1) shows good agreement, with the exception of the 17th energy group (100-215) eV. The experimental data are taken from Ref [3].

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In Fig. 2 the fission cross-section is compared with experimental results.

Conclusion

The average group data (e.g., average neutron cross-sections, resonance self-shielding coefficients, and their Doppler broadening) were calculated on the basis of a self-consistent approach to the calculation of the resonance structure of neutron cross-sections. The average group data were calculated in the BNAB system energy groups.

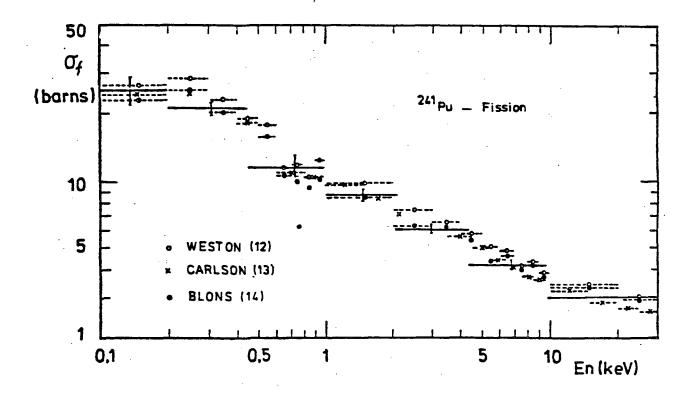


Fig. 1. Comparison of evaluated group radiative capture cross-sections $\overline{\Gamma_\gamma}$ (solid line) with experimental data.

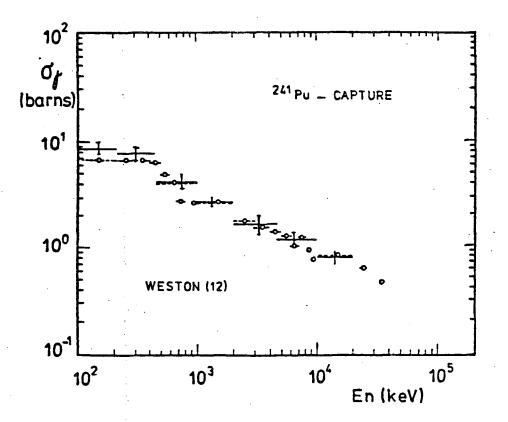


Fig. 2. Comparison of evaluated group fission cross-sections $\overline{\Gamma}_r$ (solid line) with experimental data.

lable 1

ζ	J ^π	a ¹	ν n	ν _f	ν _γ	R fm .c	Γ, ev
0	2*	0.4167	1	2	<u>6</u>	9.8	0.04
0	З+	0.5833	1	. 1	8	9.8	0.04
L	1	0.2500	1	2	ω	9.8	0.04
1	2ີ	0.4167	2	2	, œ	9.8	0.04
1	3	0.5833	2	2	-00	9.8	0.04
L 	4	0.7500	1	2	0 0	9.8	0.04
.:	orbi	ital moment o	of s- and	i p-neuti	cons,		
7ª:	compo	und nucleus	spin and	l parity,			
1.:	stati	stical facto	r				

Average inter-resonance spacing $\overline{D_{J}}$ and degrees of freedom for neutrons \mathbf{v}_{n} , fission \mathbf{v}_{r} and radiative \mathbf{v}_{γ} widths for compound nucleus s- and p-resonances

Table 2

Energy dependence of the strength functions \overline{S}_{o} and \overline{S}_{1} and of the average fission widths for $s - \overline{\Gamma_{f(2+)}}$ and $\overline{\Gamma_{f(9+)}}$) and p-resonances $(\overline{\Gamma_{f(p)}})$ and D_{obs}

] (ł	5 ₁ .10 ⁻⁴	eV	eV	eV	D _{obs} eV
1	17		•		-	0.6838	0.85
1	16	1.3376	1.9712	0.7962	0. 4770	0.3425	0.85
1	15	1.0695	1.5761	0.8207	0.3531	0.4914	0.85
ł	14	1.1474	1.6909	0.8356	0.3595	0.5004	0.85
1.	13	1.1728	1.7283 /	0.9632	0.4144	0.5768	0.8415
ł	12	1.1615	1.7116	1.0141	0.4363	0.6073	0.833
	11	1.1446	1 6868	1.0272	0.4419	0.6158	0.8245

		Table 3	
Average	fission	widths $\overline{\Gamma}f$ for p-resonance state	es
		above E _n = 1 keV	

		$J^{\pi}=1^{-1}$	•		•	1
1-		1.0752		•		1
ł	12	1.1320	0.3184	0.7075	0.2876	İ
I	11	1.1467	0.3225	0.7166	0.2748	ł

Table 4 Average group cross-sections $\overline{\sigma}_t$, $\overline{\sigma}_f$, $\overline{\sigma}_\gamma$ and $\overline{\sigma}_n$

				σ _r ,barn				barn
Group	[2]	present	[2]	Present	[2]	present	[2]	present
17	46.747	48.391	26.006	26.040 ±4.910	6.872		13.869	13.700 ±0.374
16				21.640				
15				11.440 +0.920				
14			-	8.137 70.120				
13	-	21.067 ±0.151		6.003 ±0.010				13.220 ±0.051
12		18.269 ±0.072	-	4.144 ±0.041				12.900 ±0.034
11				2.934 ±0.030				

-			
1			
	Group	o barn	300°C 300°C 2100°C 300°C 300°C 2100°C
		1	0.4495 0.4804 0.5185 0.5285 0.5752 0.6246
		10	0.5075 0.5422 0.5817 0.5919 0.6368 0.6822
·	17	100	0.7051 0.7455 0.7823 0.7899 0.8234 0.8528
1		1000	0.9224 0.9416 0.9550 0.9551 0.9656 0.9733
I		1	0.4731 0.5229 0.5752 0.5551 0.6216 0.6216
I		10	0.5318 0.5827 0.6322 0.6209 0.6809 0.7330
	16	100	0.7320 0.7772 0.8131 0.8196 0.8552 0.8827
	1	1000	0.9336 0.9506 0.9616 0.9657 0.9742 0.9800
1	·	1	0.6248 0.6752 0.7150 0.6524 0.7156 0.7622
I	l	10	0.6892 0.7365 0.7717 0.7204 0.7743 0.8129
I	15	100	0.8632 0.8934 0.9129 0.8912 0.9169 0.9338
1		1000	0.9766 0.9832 0.9870 0.9832 0.9879 0.9307
I	I	1	0.7250 0.7683 0.7995 0.7480 0.8016 0.6383
1		10	0.7842 0.8216 0.8471 0.8061 0.8491 0.8779
-	14	100	0.9200 0.9383 0.9493 0.9341 0.9509 0.9614
1	<u> </u>	1000	0.9880 0.9912 0.9930 0.9908 0.9934 0.9949
1	1	1	0.7943 0.8239 0.8434 0.8158 0.8534 0.8770
1	1	10	0.8470 0.8708 0.8858 0.8645 0.8933 0.9109
ł	13	100	0.9520 0.9614 0.9668 0.9595 0.9692 0.9748
I		1000	0.9934 0.9948 0.9956 0.9948 0.9961 0.9969
Ī	 	1	0.8523 0.8693 0.6791 0.8818 0.9045 0.9174
İ	1	10	0.8968 0.9094 0.9165 0.9180 0.9342 0.9433
1	12	100	0.9726 0.9767 0.9788 0.9787 0.9833 0.9858
I	1	1000	0.9366 .0.9370 0.9974 0.9974 0.9981 0.9984
1	 	1	0.8910 0.8988 0.9028 0.9236 0.9340 0.9396
İ		-	0.9270 0.9323 0.9350 0.9492 0.9562 0.9601
İ	11	-	0.9824 0.9838 0.9846 0.9879 0.9897 0.9907
ļ		-	0.9976 0.9976 0.9976 0.9986 0.9988 0.9989
-			

Table 5 Self-shielding resonance factors f_t and f_f

Table 6 Self-shielding resonance factors f_{γ} and f_n

$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	*************			موجد هم جب چن وب جو خاه د				
1 0.4082 0.4822 0.5546 0.8833 0.5344 0.9044 10 0.4676 0.5441 0.6142 0.9047 0.9108 0.9165 17 100 0.6881 0.7554 0.8078 0.9423 0.9552 0.9607 1000 0.9250 0.9487 0.9632 0.9874 0.9508 0.9251 100 0.5037 0.5261 0.5922 0.8392 0.8533 0.8641 10 0.5037 0.5870 0.6532 0.8592 0.8392 0.8333 0.93842 16 1000 0.7247 0.7876 0.8300 0.9333 0.9383 0.9383 100 0.5961 0.6944 0.7428 0.9032 0.9144 0.9223 11 0.5664 0.7468 0.7934 0.9233 0.9330 0.9395 15 1000 0.8641 0.9044 0.9237 0.9552 0.9964 0.9270 14 0.7105 0.7764 0.8192 0.9167 0.9270 0.9235 14 1000 0.9274 0.9264			 	f _y		 1	f	
10 0.4676 0.5441 0.6142 0.9047 0.9108 0.9165 17 100 0.6881 0.7554 0.8078 0.9483 0.9552 0.9607 1000 0.9250 0.9487 0.9632 0.9874 0.9308 0.9252 1000 0.9250 0.9487 0.5322 0.8392 0.8533 0.8664 100 0.5037 0.5670 0.6532 0.7580 0.8723 0.8942 16 100 0.7247 0.7876 0.8300 0.9121 0.9337 0.9272 1000 0.5363 0.9560 0.9072 0.9780 0.9337 0.9273 100 0.5664 0.7468 0.7954 0.9032 0.9144 0.9223 100 0.66841 0.7668 0.9271 0.9032 0.9144 0.9223 110 0.7715 0.6659 0.9237 0.9252 0.9946 0.9270 1200 0.9276 0.9267 0.9567 0.9267 0.9253 <t< th=""><th>Group</th><th>o barn</th><th>300°C</th><th>900°C</th><th>2100°C</th><th>300[°]с </th><th>900°C</th><th>2100°C</th></t<>	Group	o barn	300°C	900°C	2100°C	300 [°] с	900°C	2100°C
17 100 0.6881 0.7554 0.8078 0.9483 0.9552 0.9607 1000 0.9250 0.9487 0.9632 0.9874 0.9306 0.9225 1 0.4408 0.5261 0.5932 0.8392 0.8533 0.8664 10 0.5037 0.5670 0.6532 0.8392 0.8723 0.8342 16 1000 0.7247 0.7876 0.8000 0.9181 0.9304 0.9338 1000 0.9363 0.9560 0.9572 0.9720 0.9837 0.9328 100 0.5664 0.7463 0.7924 0.9233 0.9320 0.9395 110 0.66841 0.9044 0.9233 0.9320 0.9395 0.9395 15 100 0.8641 0.9044 0.9233 0.9395 0.9397 0.9753 0.9970 100 0.9785 0.9637 0.9522 0.9944 0.9233 0.9230 0.9335 14 100 0.9214 0.9642 0.9365 0.9453 0.9503 14 100 0.9214	1	1	0.4082	0.4822	0.5546	0.8883	0.8344	0.9004
1000 0.9250 0.9487 0.9632 0.9874 0.9206 0.925 1 0.4408 0.5261 0.5982 0.8392 0.8533 0.8684 10 0.5037 0.5870 0.8532 0.8592 0.8723 0.8942 16 100 0.7247 0.7876 0.8300 0.9181 0.9304 0.9388 1000 0.9363 0.9560 0.9672 0.9760 0.8337 0.9387 11 0.5961 0.6684 0.7428 0.9032 0.9144 0.9223 110 0.6684 0.7468 0.7954 0.9233 0.9395 0.9395 15 100 0.8641 0.9044 0.9237 0.9352 0.9395 100 0.9786 0.9625 0.9837 0.9252 0.9964 0.9270 110 0.7745 0.8305 0.6628 0.9365 0.9453 0.9250 0.9365 14 1000 0.9214 0.9444 0.9264 0.9271 0.9365 </th <th>1</th> <th>10</th> <th>0.4676</th> <th>0.5441</th> <th>0.6142</th> <th>0.9047</th> <th>0.9108</th> <th>0.9165</th>	1	10	0.4676	0.5441	0.6142	0.9047	0.9108	0.9165
1 0.4408 0.5261 0.5992 0.8392 0.8533 0.8644 10 0.5037 0.5870 0.6532 0.8590 0.8723 0.8942 16 100 0.7247 0.7876 0.8300 0.9181 0.9304 0.9398 1000 0.9363 0.9560 0.9672 0.9780 0.9337 0.9272 1 0.5961 0.6684 0.7428 0.9032 0.9144 0.9233 10 0.6684 0.7463 0.7954 0.9323 0.9330 0.9396 15 100 0.8641 0.9044 0.9233 0.9330 0.9396 15 100 0.8641 0.9044 0.9271 0.9652 0.9700 100 0.9745 0.8055 0.9657 0.9652 0.9970 0.9335 14 100 0.9745 0.8305 0.8626 0.9453 0.9503 14 100 0.9214 0.9444 0.9264 0.9376 0.9660	17	100	0.6881	0.7554	0.8078	0.9483	0.9552	0.9607
10 0.5037 0.5870 0.6532 0.8530 0.8723 0.8942 16 100 0.7247 0.7876 0.8300 0.9181 0.9304 0.9398 1000 0.9363 0.9560 0.9672 0.9760 0.9303 0.9237 0.9237 0.9237 100 0.5961 0.6584 0.7463 0.9233 0.9330 0.9396 15 100 0.6584 0.7463 0.9237 0.9330 0.9396 15 100 0.8641 0.9044 0.9271 0.9397 0.9753 0.9790 1000 0.9786 0.9659 0.9937 0.9652 0.9964 0.9970 1000 0.97745 0.6305 0.6626 0.9368 0.9255 0.9964 0.9970 14 1000 0.9214 0.9444 0.9564 0.9766 0.9255 0.9365 14 1000 0.9254 0.9257 0.9375 0.9376 0.9376 0.9366 13 1000 0.9254 0.9257 0.9373 0.9477 0.9335 0.9471 0.9383		1000	0.9250	0.9487	0.9632	0.9874	0.9906	0.9925
16 100 0.7247 0.7876 0.8300 0.9181 0.9304 0.9388 1000 0.9363 0.9560 0.9572 0.9760 0.9337 0.9272 1 0.5961 0.6844 0.7428 0.9032 0.9144 0.9223 10 0.6684 0.7468 0.7954 0.9233 0.9330 0.9396 15 100 0.6641 0.9044 0.9271 0.9597 0.9755 0.9790 1000 0.9786 0.9659 0.9697 0.9652 0.9964 0.9970 1000 0.9786 0.7764 0.6192 0.9167 0.9255 0.9365 10 0.7745 0.8305 0.8626 0.9366 0.9453 0.9355 14 100 0.9214 0.9444 0.9364 0.9255 0.9970 0.9355 0.9660 14 100 0.9889 0.9253 0.9274 0.9350 0.9366 10 0.9549 0.9668 0.9733 0.9477 0.9353 0.9570 13 1000 0.9942 0.9958	1	1	0.4408	0.5261	0.5992	0.8392	0.8533	0.8664
1000 0.9363 0.9560 0.9572 0.9780 0.9837 0.9672 1 0.5961 0.9584 0.7428 0.9032 0.9144 0.9223 10 0.6684 0.7468 0.7954 0.9233 0.9330 0.9395 15 100 0.8641 0.9044 0.9271 0.9697 0.9755 0.9790 1000 0.9786 0.9659 0.9637 0.9652 0.9644 0.9970 1000 0.9786 0.9659 0.9637 0.9652 0.9964 0.9970 100 0.7105 0.7764 0.8192 0.9167 0.9270 0.9235 10 0.7745 0.8305 0.8628 0.9366 0.9235 0.9235 14 100 0.9214 0.9444 0.9564 0.9765 0.9256 0.9274 0.9350 0.9396 14 100 0.9284 0.9925 0.9924 0.9375 0.9477 0.9355 0.9366 10 0.9549 0.9269 </th <th>1</th> <th>10</th> <th>0. 5037</th> <th>0.5870</th> <th>0.6532</th> <th>0.8590</th> <th>0.8723</th> <th>0.8842</th>	1	10	0 . 5037	0.5870	0.6532	0.8590	0.8723	0.8842
1 0.5961 0.6844 0.7428 0.9032 0.9144 0.9223 10 0.6684 0.7468 0.7954 0.9233 0.9330 0.9395 15 100 0.8641 0.9044 0.9271 0.9697 0.9755 0.9790 1000 0.9786 0.9659 0.9637 0.9552 0.9964 0.9235 100 0.7105 0.7764 0.6192 0.9167 0.9270 0.9335 10 0.7105 0.7764 0.6192 0.9167 0.9270 0.9335 14 100 0.9214 0.9444 0.9564 0.9365 0.9625 0.9361 0.9255 0.9364 0.9255 0.9364 0.9350 0.9365 14 100 0.9244 0.9564 0.9274 0.9355 0.9660 10 0.8502 0.8653 0.9274 0.9355 0.9365 0.9365 10 0.9549 0.9669 0.9733 0.9471 0.9633 0.9635 100	16	100	0.7247	0.7876	0.8300	0.9181	0.9304	0.9398
10 0.6664 0.7468 0.7954 0.9233 0.9330 0.9395 15 100 0.8641 0.9044 0.9271 0.9397 0.9753 0.9790 1000 0.9766 0.9559 0.9837 0.9522 0.9964 0.9970 1 0.7105 0.7764 0.8192 0.9652 0.9964 0.9335 10 0.7745 0.6305 0.8628 0.9366 0.9235 0.9335 14 100 0.9214 0.9444 0.9564 0.9766 0.9865 0.9865 100 0.9639 0.9255 0.9942 0.9376 0.9660 0.9366 14 100 0.9639 0.9255 0.9423 0.9376 0.9660 100 0.9639 0.9255 0.9274 0.9355 0.9366 13 100 0.9549 0.9659 0.9271 0.9355 0.9361 13 100 0.9549 0.9657 0.9373 0.9644 0.9984 0.9483 100 0.9111 0.9282 0.9377 0.9385 0.9384	1	1000	0.9363	0.9560	0.9672	0.9760	0.9837	0.9872
15 100 0.8641 0.9044 0.9271 0.9697 0.9755 0.9790 1000 0.9786 0.9659 0.9697 0.9652 0.9964 0.9970 1 0.7105 0.7764 0.8192 0.9167 0.9270 0.9335 10 0.7745 0.6305 0.8628 0.9366 0.9453 0.9503 14 100 0.9214 0.9444 0.9564 0.9766 0.9255 0.9666 1000 0.9289 0.925 0.9242 0.970 0.9255 0.9266 14 1000 0.9289 0.925 0.9242 0.970 0.9255 0.9366 100 0.9869 0.925 0.9274 0.9355 0.9366 0.9367 13 100 0.9549 0.9669 0.9733 0.9671 0.9683 13 1000 0.9942 0.9258 0.9957 0.9361 0.9432 0.9458 100 0.9111 0.9282 0.9377 0.9385 0.9432 0.9458 12 100 0.9767 0.9320		1	0. 5961	0.6844	0.7428	0. 9032	0.9144	0.9223
1000 0.9786 0.9659 0.9697 0.9652 0.9964 0.9970 1 0.7105 0.7764 0.8192 0.9167 0.9270 0.9335 10 0.7745 0.6305 0.6626 0.9366 0.9453 0.9503 14 100 0.9214 0.9444 0.9564 0.9766 0.9925 0.9846 1000 0.9869 0.9255 0.9422 0.9970 0.9976 0.9366 1000 0.9869 0.9255 0.9422 0.9970 0.9976 0.9366 100 0.9869 0.9251 0.9274 0.9355 0.9366 10 0.8502 0.8653 0.9274 0.9355 0.9366 10 0.8502 0.8653 0.9274 0.9355 0.9367 13 1000 0.9549 0.9669 0.9733 0.9471 0.9683 10 0.9942 0.9958 0.9927 0.9921 0.9934 0.9945 10 0.9111 0.9282 0.9337 0.9579 0.9432 0.9458 12 100		10	0.6684	0.7463	0.7964	0.9233	0.9330	0.9396
1 0.7105 0.7764 0.8192 0.9167 0.9270 0.9335 10 0.7745 0.8305 0.8628 0.9368 0.9453 0.9503 14 100 0.9214 0.9444 0.9564 0.9765 0.9255 0.9646 1000 0.92689 0.9925 0.9942 0.9700 0.9255 0.9660 1 0.7974 0.8426 0.8659 0.9274 0.9350 0.9396 10 0.8502 0.8853 0.9051 0.9477 0.9350 0.9396 13 100 0.9549 0.9669 0.9733 0.9671 0.9683 0.9671 13 100 0.9942 0.9258 0.9267 0.9325 0.9432 0.9432 10 0.9111 0.9292 0.9337 0.9379 0.9613 0.9631 12 100 0.9767 0.9326 0.9282 0.9282 0.9284 0.9909 12 100 0.9767 0.9326 0.9282 0.9283 0.9283 0.9283 12 100 0.9272 0	15	100	0.8641	0.9044	0.9271	0.9697	0.9755	0.9790
10 0.7745 0.6305 0.6628 0.9368 0.9453 0.9503 14 100 0.9214 0.9444 0.9564 0.9766 0.9825 0.9646 1000 0.9869 0.9925 0.9942 0.9766 0.9925 0.9976 0.9660 1 0.7974 0.8426 0.9649 0.9274 0.9350 0.9366 10 0.8502 0.8653 0.9051 0.9274 0.9350 0.9366 13 100 0.9549 0.9669 0.9733 0.9671 0.9683 0.9661 13 100 0.9549 0.9258 0.9967 0.9385 0.9671 0.9683 14 0.8725 0.8975 0.9108 0.9385 0.9432 0.9458 10 0.9111 0.9282 0.9387 0.9579 0.9613 0.9631 12 100 0.9767 0.9382 0.9687 0.9984 0.9909 0.9692 0.9989 0.9928 0.9329 12 100 0.9972 0.9972 0.9938 0.9697 0.9989 0.9928	i i	1000	•	•	-	•	•	•
14 100 0.9214 0.9444 0.9564 0.9786 0.9825 0.9846 1000 0.9869 0.9925 0.9942 0.9970 0.9676 0.9660 1 0.7974 0.8426 0.9659 0.9274 0.9350 0.9396 10 0.8502 0.8653 0.9051 0.9477 0.9535 0.9570 13 100 0.9549 0.9669 0.9733 0.9674 0.9684 0.9683 100 0.9549 0.9659 0.9733 0.9671 0.9683 0.9671 0.9683 13 1000 0.9942 0.9258 0.9677 0.9385 0.9934 0.9683 100 0.9942 0.9258 0.9267 0.9385 0.9432 0.9438 12 100 0.9767 0.9320 0.9387 0.9579 0.9613 0.9639 12 100 0.9767 0.9322 0.9382 0.9697 0.9959 0.9959 0.9959 12 100 0.9219 0.9322 0.9385 0.9493 0.9517 0.9528 0.99529		1	0.7105	0.7764	0.8192	0.9167	0. 9270	0.9335
1000 0.9889 0.9925 0.9942 0.9970 0.9976 0.9680 1 0.7974 0.8426 0.8659 0.9274 0.9350 0.9396 10 0.8502 0.8853 0.9051 0.9477 0.9535 0.9570 13 100 0.9549 0.9669 0.9733 0.9649 0.9871 0.9883 1000 0.9942 0.9958 0.9967 0.9931 0.9984 0.9986 1000 0.9111 0.9292 0.9373 0.9385 0.9432 0.9458 12 100 0.9767 0.9327 0.9579 0.9613 0.9631 12 100 0.9767 0.9327 0.9894 0.9909 0.9693 12 100 0.9776 0.9322 0.9327 0.9284 0.9909 1000 0.9972 0.9328 0.9493 0.9517 0.9528 10 0.9219 0.9322 0.9328 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9696 0.9622 0.9626 0.9626 0.9626	I 1	10	0.7745	0.6305	0.8628	0.9368	0.9453	0.9503
1 0.7974 0.8426 0.9254 0.9350 0.9396 10 0.8502 0.8853 0.9051 0.9477 0.9535 0.9570 13 100 0.9549 0.9669 0.9733 0.9649 0.9871 0.9683 100 0.9942 0.9659 0.9733 0.9649 0.9871 0.9683 1000 0.9942 0.9659 0.9967 0.9381 0.9984 0.9966 1 0.8725 0.6975 0.9108 0.9385 0.9432 0.9458 10 0.9111 0.9292 0.9377 0.9579 0.9613 0.9631 12 100 0.9767 0.9320 0.9646 0.9294 0.9909 1000 0.9972 0.9976 0.9622 0.9627 0.9989 0.9329 1000 0.9972 0.9976 0.9385 0.9493 0.9517 0.9528 1 0.9219 0.9322 0.9385 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9385 0.9666 0.9682 0.9690	14	100	0.9214	0.9444	0.9364	0.5786	0.9825	0.9846
10 0.8502 0.8853 0.9051 0.9477 0.9535 0.9570 13 100 0.9549 0.9669 0.9733 0.9649 0.9871 0.9683 1000 0.9942 0.9258 0.9967 0.9381 0.9984 0.9466 1 0.8725 0.8975 0.9108 0.9385 0.9432 0.9458 10 0.9111 0.9292 0.9337 0.9579 0.9613 0.9631 12 100 0.9767 0.9320 0.9646 0.9294 0.9909 100 0.9767 0.9320 0.9632 0.9294 0.9909 0.9909 12 100 0.9767 0.9322 0.9325 0.9294 0.9909 0.9329 12 100 0.9972 0.9972 0.9932 0.9284 0.9909 0.9909 100 0.9219 0.9322 0.9385 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9695 0.9666 0.9682 0.9690 11 100 0.9876 0.9695 0.9905	1 <u> 1</u>	1000	0.9869	0.9925	0.9942	0.970	0.9976	0.9580
13 100 0.9549 0.9669 0.9733 0.9849 0.9871 0.9883 1000 0.9942 0.9958 0.9967 0.9381 0.9984 0.9986 1 0.8725 0.8975 0.9108 0.9385 0.9432 0.9458 10 0.9111 0.9292 0.9387 0.9579 0.9613 0.9631 12 100 0.9767 0.9320 0.9646 0.9294 0.9909 1000 0.9972 0.9976 0.9932 0.9637 0.9939 0.9939 1000 0.9972 0.9976 0.9932 0.9637 0.9939 0.9939 1000 0.9219 0.9322 0.9385 0.9637 0.9939 0.9939 1 0.9219 0.9322 0.9385 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9695 0.9656 0.9622 0.9626 0.9626 11 100 0.9876 0.9895 0.9905 0.9922 0.9926 0.9926	1	1	0.7974	0.8426	0. පටප්ප	0.9274	0.9350	0.9396
1000 0.9942 0.9958 0.9967 0.9381 0.9984 0.9986 1 0.8725 0.8975 0.9108 0.9385 0.9432 0.9458 10 0.9111 0.9292 0.9387 0.9579 0.9613 0.9531 12 100 0.9767 0.9620 0.9648 0.9294 0.9909 1000 0.9972 0.9978 0.9982 0.9687 0.9989 0.9909 1000 0.9219 0.9322 0.9385 0.9493 0.9517 0.9528 1 0.9219 0.9322 0.9385 0.9493 0.9517 0.9528 10 0.9473 0.9556 0.9595 0.9666 0.9682 0.9690 11 100 0.9876 0.9895 0.9905 0.9922 0.9926 0.9926	I	10	0.8502	0.8853	0.9051	0.9477	0.9535	0.9570
1 0.8725 0.8975 0.9108 0.9385 0.9432 0.9458 10 0.9111 0.9292 0.9387 0.9579 0.9613 0.9631 12 100 0.9767 0.9620 0.9646 0.9894 0.9904 0.9909 100 0.9972 0.9978 0.9982 0.9887 0.9893 0.9989 0.9929 100 0.9219 0.9332 0.9385 0.8493 0.9517 0.9528 1 0.9219 0.9332 0.9385 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9595 0.9666 0.9682 0.9690 11 100 0.9876 0.9895 0.9905 0.9922 0.9926 0.9926	13	100	0.9549	0.9869	0.9733	0.9849	0.9871	0.9883
10 0.9111 0.9292 0.9337 0.9579 0.9613 0.9631 12 100 0.9767 0.9620 0.9640 0.9894 0.9904 0.9909 1000 0.9972 0.9978 0.9982 0.9887 0.9989 0.9989 0.9989 1 0.9219 0.9332 0.9388 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9595 0.9666 0.9682 0.9690 11 100 0.9876 0.9695 0.9905 0.9922 0.9926 0.9926	1	1000	0,9942	0.9958	0.9967	0.9981	0.9984	0.9986
12 100 0.9767 0.9820 0.9640 0.9894 0.9904 0.9909 1000 0.9972 0.9978 0.9982 0.9987 0.9989 0.9989 0.9989 1 0.9219 0.9332 0.9389 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9596 0.9666 0.9682 0.9690 11 100 0.9876 0.9895 0.9905 0.9922 0.9926 0.9926		1	0.8725	0.8975	0.9108	0.9385	0.9432	0.9458
1000 0.9972 0.9978 0.9982 0.9987 0.9989 0.9989 0.9989 1 0.9219 0.9332 0.9389 0.9493 0.9517 0.9528 10 0.9479 0.9556 0.9596 0.9666 0.9682 0.9690 11 100 0.9876 0.9895 0.9905 0.9922 0.9926 0.9926	[10	0.9111	0.9292	0.9337	0.9579	0.9613	0.9631
1 0.9219 0.9332 0.9389 0.8493 0.9517 0.9528 10 0.9479 0.9556 0.9596 0.9666 0.9682 0.9690 11 100 0.9876 0.9695 0.9905 0.9922 0.9926 0.9928	12	100	0.9767	0.9820	0.9840	0.9294	0.9904	0.9909
10 0.9479 0.9556 0.9595 0.9666 0.9682 0.9690 11 100 0.9876 0.9695 0.9905 0.9922 0.9926 0.9926	1	1000	0.9972	0.9978	0.9982	0.9987	0.9989	0.9989
11 100 0.9876 0.9895 0.9905 0.9922 0.9926 0.9928		1	0.9219	0.9332	0.9389	0.8493	0.9517	0.9528
	- 	10	0.9479	0.9556	0.9598	0.3666	0.9682	0.9690
	1 11	100	0.9876	0.9895	0.9905	0.9922	0.9926	0.9928
1000 0.9985 0.9988 0.9989 0.9991 0.9991 0.9992		1000	0.9985	0.9968	0.9989	0.9991	0. 9991	0.9992

	Table 7							
		140	10 1					
Doppler	broadening	of	self-shielding	factors				

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Group σ_0 , barn Δ_t^4 Δ_t^2 1 0.0309 0.0381 1 0.0347 0.0395 10 0.0404 0.0368 100 0.0192 0.0134 1 0.0503 0.0529	0.0467 0.0449 0.0335 0.0105 0.0671	$ \begin{array}{c c} $
10 0.0347 0.0395 17 100 0.0404 0.0368 100 0.0192 0.0134	0.0449 0.0335 0.0105 0.0671	0.0454 0.0294 0.0077
10 0.0347 0.0395 17 100 0.0404 0.0368 100 0.0192 0.0134	0.0449 0.0335 0.0105 0.0671	0.0454 0.0294 0.0077
17 100 0.0404 0.0368 1000 0.0192 0.0134	0.0335 0.0105 0.0671	0.0294 0.0077
	0.0105	0.0077
1 0.0503 0.0529		
		0.0607
10 0.0514 0.0501	0.0606	0.0528
	0.0364	0.0263
1000 0.0179 0.0119	0.0094	0.0057
1 0.0500 0.0403	0.0826	0.0472
10 0.0468 0.0357	0.0532	0.0393
15 100 0.0296 0.0201	0.0249	0.0177
1000 0.0059 0.0045	0.0038	0.0037
1 0.0430 0.0309	0.0534	0.0366
10 0.0371 0.0251	0.0428	0.0287
14 100 0.0179 0.0106	0.0166	0.0107
1 1000 0.0025 0.0014	0.0024	0.0018
1 0.0296 0.0195	0.0376	0.0236
10 0.0238 0.0150	0.0288	0.0176
13 100 0.0094 0.0054	0.0097	0.0056
1000 0.0014 0.0008	0.0013	0.0008
1 0.0170 0.0098	0.0227	0.0129
10 0.0126 0.0073	0.0162	0.0091
12 100 0.0040 0.0021	0.0046	0.0025
1000 0.0005 0.0003	0.0006	0.0003
1 0.0078 0.0040	0.0104	0.0056
10 0.0053 0.0032	0.0070	0.0039
11 100 0.0014 0.0008	0.0018	0.0010
1000 0.0000 0.0000	0.0002	0.0001

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Group	00.barn	Δr	Δ^2_{γ}	Δ_n^1	Δ ² n.
	1_	0.0740	0.0724	0.0061	0.0060
	1Ŏ	0.0765	0.0701	0.0061	0.0057
17	100	0.0665	0.0514	0.0069	0.0055
	1000	0.0237	0.0145	0.0032	0.0019
	1	0.0864	0.0728	0.0253	0.0721
	10	0.0845	0.0670	0.0833	0.0662.
16	100	0.0646	0.0433	0.0629	0.0424
	1000	0.0217	0.0122	0.0197	0.0112
	1	0.0870	0.0600	0.0112	0.0079
	10	0.0770	0.0514	0.0097	0.0066
15	100	0.0388	0.0248	0.0058	0.0035
	1000	0.0054	0.0061	0.0012	0.0006
	1				
-	10	0.0548	0.0316	0.0025	0.0050
14	100	0.0217	0.0113	0.0039	0.0021
	1000	0.0022	0.0010	0.0006	0.0004
] 1]	0.0452	0.0263	0.0076	0.0046
	10	0.0351	0.0198	0.0058	0.0035
13	100	0.0120	0.0064	0.0022	0.0012
	1000	0.0016	0.0009	0.0003	0.0002
	1 1	0.0250	0.0133	0.0047	0.0026
	10	0.0191	0.0095	0.0034	0.0018
12	100	0.0053	0.0026	0.0010	0.0005
•	1000	0.0007	0.0003	0.0002	0.0000
		0.0113	0.0057	0.0024	0.0011
	10 -	0.0077	0.0040	0.0016	0.0008
11	100	0.0019	0.0010	0.0004	0.0002 !
	1000	0.0003	0.0001	0.0001	0.0000

Table 8 Doppler broadening of self-shielding factors

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