KERNFORSCHUNGSZENTRUM

KARLSRUHE

Juni 1970

KFK 1229
IAEA-CN-26/10

Institut für Angewandte Kernphysik

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The Temperature Dependence of the average Transmission of Gold *)

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*) Paper presented at the Second International Conference on Nuclear Data, Helsinki 1970

Gesellschaft für Kernforschung mbH., Karlsruhe

ABSTRACT

The average neutron transmission of gold was measured with fairly thick samples between 10 and 60 keV at 11° C and at 800° C. The observed temperature effect is caused by thermal expansion of the sample (which enhances the transmission) and by Doppler broadening of resonances (which tends to lower it on the average). The experimental data were used to check the adequacy of various methods for the calculation of resonance cross sections from level statistics. In particular one- and multi-level R matrix representations were tested. The results will be discussed.

ZUSAMMENFASSUNG

Die mittlere Neutronen-Transmission von Gold wurde zwischen 10 und 60 keV bei 11° C und 800° C mit einer dicken Probe gemessen. Der beobachtete Temperatureffekt wird durch thermische Ausdehnung der Probe (bewirkt eine Erhöhung der Transmission) und durch Doppler-Verbreiterung von Resonanzen (erniedrigt sie im Mittel) verursacht. Die experimentellen Daten dienten dazu, die Gültigkeit verschiedener Methoden für die Berechnung von Resonanz-Querschnitten mit Niveau-Statistik zu prüfen. Im Besonderen wurden Ein- bzw. Vielniveau R-Matrix Darstellungen untersucht. Die Ergebnisse werden diskutiert.

THE TEMPERATURE DEPENDENCE OF THE AVERAGE TRANSMISSION OF GOLD

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1. INTRODUCTION

The temperature dependence of the average transmission of materials with unresolved resonance cross sections is important for calculations of the Doppler coefficient of fast reactors. Measurements on fairly thick samples of natural tungsten at room temperature and at 755°K revealed an appreciable temperature effect on the average transmission between 5 and 100 keV [1]. An attempt was made to explain this effect as caused by (a) thermal expansion of the sample and (b) Doppler broadening of unresolved resonances. Monte Carlo methods based on level statistics were used to generate the resonance structure of the cross sections by sampling from the appropriate width (Porter-Thomas) and level-spacing (Wigner) distributions. It was found that in order to reproduce the experimental data rather large strength functions and very small effective nuclear radii were required. A more detailed interpretation [1], however, suffered from the fact that tungsten is a mixture of essentially four isotopes. Furthermore, level-level interference effects could not be taken into account. It seemed desirable to make a similar study on a monotope.

In the present work gold was used. There is only one isotope and its level statistics (strength functions, average level spacings, average level widths) are well known from analyses of resonances in the low energy region up to 2100 eV [2, 3]. Level-level interference effects were studied by calculating the cross sections with a multi-level formula. As the resonance structure of gold is similar to that of tungsten the results should be comparable.

2. MEASUREMENTS

The average transmission of a thick gold sample was measured between 10 and 60 keV with time-of-flight techniques. A pulsed 3 MV Van de Graaff accelator was used to produce 10 ns bursts of neutrons via the $Li^7(p,n)$ reaction. The energy resolution was ~ 3 keV at 30 keV, hence all data represent statistically meaningful averages over compound resonances (mean s-wave level spacing: 16.8 eV). The sample thickness, n_o = 0.0808 nuclei/barn, corresponded to roughly one mean free path at 30 keV. Data were taken with the sample at room temperature (284°K) and at 1073°K. The measured transmission values, each an average of three experimental runs are shown in Fig. 1 together with the corresponding values calculated with the multi-level formula (smooth curves). The temperature effect (relative change of average transmission by heating the sample from 284°K for 1073°K) is shown in Table I, the calculated one is given in Table II both for single-level and multi-level formulae. The measurement shows large fluctuations in contrast to the calculated values. There is evidence for intermediate structure (resulting from statistical fluctuations in level density and width) in the cross section of gold, as was already pointed out by Seth in an earlier publication [4]. A comparison with high resolution capture data [5, 6] reveals that the peaks in the average total cross section at 18, 24, 29 and 42 keV correspond to peaks in the capture cross section (Fig. 2). This structure is important for the interpretation of shell transmission data at 24 keV which provide absolute capture cross section values (see contribution CN/26 to this conference).

3. CALCULATIONS

Two effects influence the transmission of a heated sample:

3.1 Thermal expansion

The thermal expansion of the sample was treated with the expression

$$n_t = \frac{n_o}{(1+\alpha t)^2} \quad ,$$

where n_t and n_o are the sample "thicknesses" (nuclei/barn) at centrigrade temperatures t and 0, respectively; the expansion coefficient in the temperature range about 800°C was taken as $\alpha = 18.56 \cdot 10^{-6}/^oC$ [8]. The sample expansion tends to increase the transmission.

3.2 Doppler Broadening of Resonances

The measured transmission data are energy averages over many resonances,

$$\langle T \rangle = \langle e^{-n_t \sigma_t} \rangle$$

where σ_t is the Doppler-broadened total cross section for centigrade temperature t; the brackets denote energy averages or, more precisely, convolutions with the resolution function. For the calculation of $\langle T \rangle$ a modification of the SESH code [9] was used. This code yields energy averages of $\exp(-n_t\sigma_t)$ over many Doppler-broadened resonances from level statistics. The input parameters S_o, D_o and Γ_γ (S-wave strength-function, mean level spacing and radiation width) were obtained from the Saclay data [2, 3] and are summarized in Table III. The usual Fermi gas expression was used for the spin and energy dependence of the level spacings. In order to study level-level interference effects the computations were performed with single-level and with multi-level expressions for the total cross section. In the first case the cross section was calculated as a sum of single-level Breit-Wigner terms. Doppler broadening can then be described analytically by the shape functions ψ and φ (also known as Voigt profiles). For the multilevel treatment it was calculated as convolution of the cross section with the usual Gaussian [10]. An effective temperature as defined by Lamb [11] was used to account for the binding of the nuclei in the crystal lattice.

Doppler broadening lowers the average transmission, whereas the sample expansion increases it. Hence one has two counteracting effects with heated samples.

Results of the multilevel calculations are shown in Figs. 1 (smooth curves) and 2.

4. CONCLUSION

The average transmission of gold was measured in the keV region at room temperature and at $800^{\circ}C$ with a sample thickness of roughly one mean free path. The objective was to study the temperature effect caused by the unresolved resonance structure of the gold cross section. The main conclusions from the present work are:

(1) The total cross section of gold in the keV region (Fig. 1) shows intermediate structure closely corresponding to that observed in the neutron capture cross section [5, 6, 14].

(2) Two counteracting effects determine the temperature dependence of the average transmission $\langle T \rangle$: Doppler broadening of unobserved resonances tends to lower $\langle T \rangle$, thermal expansion of the sample tends to increase it with increasing temperature. Below ~ 50 keV Doppler broadening dominates for gold, at higher energies thermal expansion becomes predominant (Fig. 1).

(3) For a sufficiently high energy, e.e. when the resonance structure is practically completely smeared out by Doppler broadening, sample expansion predominates even below 50 keV. For example around 24 keV Doppler broadening dominates below $400^{\circ}C$, sample expansion

above 700°. Between 400 and 700°C the two effects balance each other (Fig. 3).

(4) Computer calculations using level statistics and Monte Carlo methods appear to describe the temperature dependence of $\langle T \rangle$ adequately. The influence of level-level interference (multi-level effects) on the temperature effect is negligible, as verified by calculations with summed-single-level and multi-level cross section expressions.

(5) The fluctuations of the average cross section is correlated to fluctuations of the temperature effect. The temperature effect is found to be large whenever the average transmission is large and vice versa (Fig. 1). This behavior indicates that the resonance structure is more pronounced (resonances are stronger and/or more widely spaced) in the intermediate-structure minima of the average cross section. More detailed insights require additional information. Recently attempts have been made to simulate such intermediate structures for fissile isotopes in the unresolved-resonance region [12, 13]. Large numbers of resonance "ladders" were generated by sampling from the appropriate width and spacing distributions. Then the ladders which best describes measured average quantities were selected for further predictions. It would be interesting to know whether these ladders would also lead to the observed correlation between temperature effect and average transmission fluctuations.

Table I: Experimental Transmission and relative change

ENERGY [keV]	⟨T⟩ 11°C	⟨T⟩ 800°C	$\frac{\Delta\langle T\rangle}{\langle T\rangle}$ [%]	σ_{tot} [b]
14.24	0.4019	0.3828	4.75	14.26 ± 0.23
15.24	0.4016	0.3871	3.61	14.09 ± 0.19
16.36	0.3957	0.3843	2.88	14.10 ± 0.17
17.60	0.3848	0.3814	0.88	14.27 ± 0.15
18.99	0.3898	0.3785	2.89	13.94 ± 0.14
20.55	0.3962	0.3790	4.34	13.57 ± 0.12
22.31	0.4044	0.3919	3.09	13.16 ± 0.11
24.31	0.3901	0.3878	0.58	13.45 ± 0.10
26.59	0.4007	0.3904	2.57	12.96 ± 0.08
29.20	0.3914	0.3861	1.35	13.11 ± 0.08
32.22	0.4032	0.3986	1.14	12.60 ± 0.08
35.73	0.4074	0.3974	2.45	12.33 ± 0.08
39.85	0.3953	0.3863	2.27	12.58 ± 0.07
44.73	0.3929	0.3928	0.02	12.53 ± 0.07
50.56	0.4105	0.4074	0.75	11.87 ± 0.06
57.61	0.4182	0.4232	-1.19	11.53 ± 0.12

Table II: Calculated Transmission and Temperature effect

	ONE LEVEL			MULTI-LEVEL		
Energy [keV]	$\langle T\rangle$ 11°C	$\langle T\rangle$ 800°C	$\frac{\Delta\langle T\rangle}{\langle T\rangle}$ [%]	$\langle T\rangle$ 11°C	$\langle T\rangle$ 800°C	$\frac{\Delta\langle T\rangle}{\langle T\rangle}$ [%]
10	0.3649	0.3497	4.16	0.3708	0.3557	4.07
15	0.3703	0.3599	2.80	0.3760	0.3649	2.95
20	0.3768	0.3701	1.77	0.3817	0.3736	2.12
24	0.3822	0.3778	1.15	0.3873	0.3815	1.49
30	0.3902	0.3886	0.41	0.3945	0.3920	0.63
40	0.4028	0.4044	-0.39	0.4075	0.4071	0.09
50	0.4144	0.4182	-0.91	0.4180	0.4205	-0.59
60	0.4250	0.4302	-1.22	0.4285	0.4322	-0.86

Table III: Input values for calculations

A	$S_o \cdot 10^4$	$S_1 \cdot 10^4$	D_o [eV]	D_1 [eV]	Γ_γ [eV]	R' [Fm]
197	1.98	0.3	16.8	8.4	0.13	8.69

Table IV Variation of Transmission with Temperature at 24 keV

t [°C]	$n_t \cdot 10^2$ nucl/barn	$\langle T \rangle \pm \Delta\langle T \rangle$ MULTI-LEVEL	$\langle T \rangle \pm \Delta\langle T \rangle$ SINGLE-LEVEL
100	8.06	0.3849 ± 0.0029	0.3806 ± 0.0039
200	8.03	0.3834 ± 0.0029	0.3792 ± 0.0038
300	8.01	0.3816 ± 0.0030	0.3778 ± 0.0037
400	7.98	0.3819 ± 0.0030	0.3773 ± 0.0036
500	7.95	0.3809 ± 0.0031	0.3770 ± 0.0035
600	7.92	0.3813 ± 0.0032	0.3770 ± 0.0034
700	7.88	0.3810 ± 0.0032	0.3775 ± 0.0033
800	7.85	0.3815 ± 0.0033	0.3778 ± 0.0032

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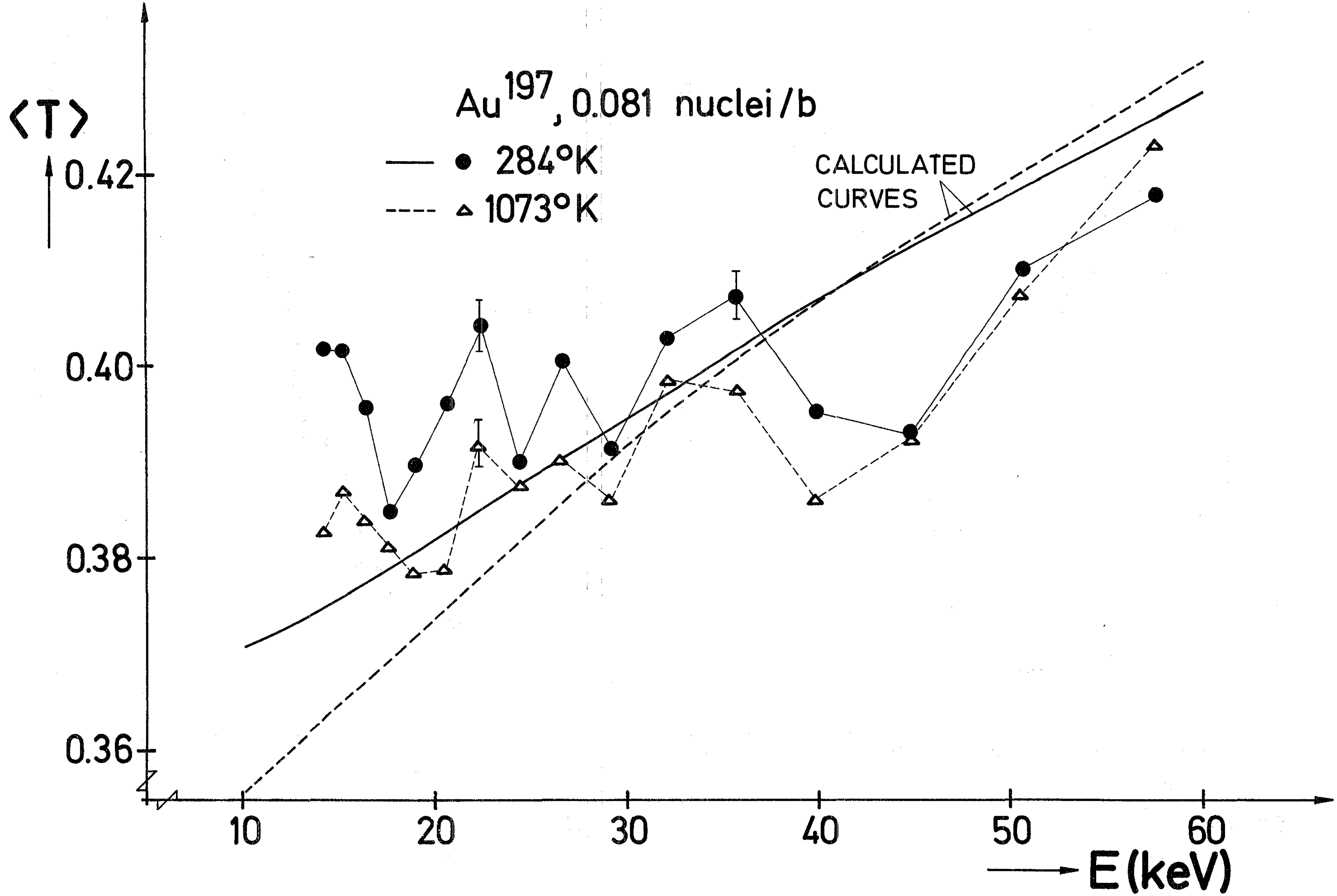
FIGURE CAPTIONS

Fig. 1 Average transmission of gold versus energy at room temperature and at 1073°K

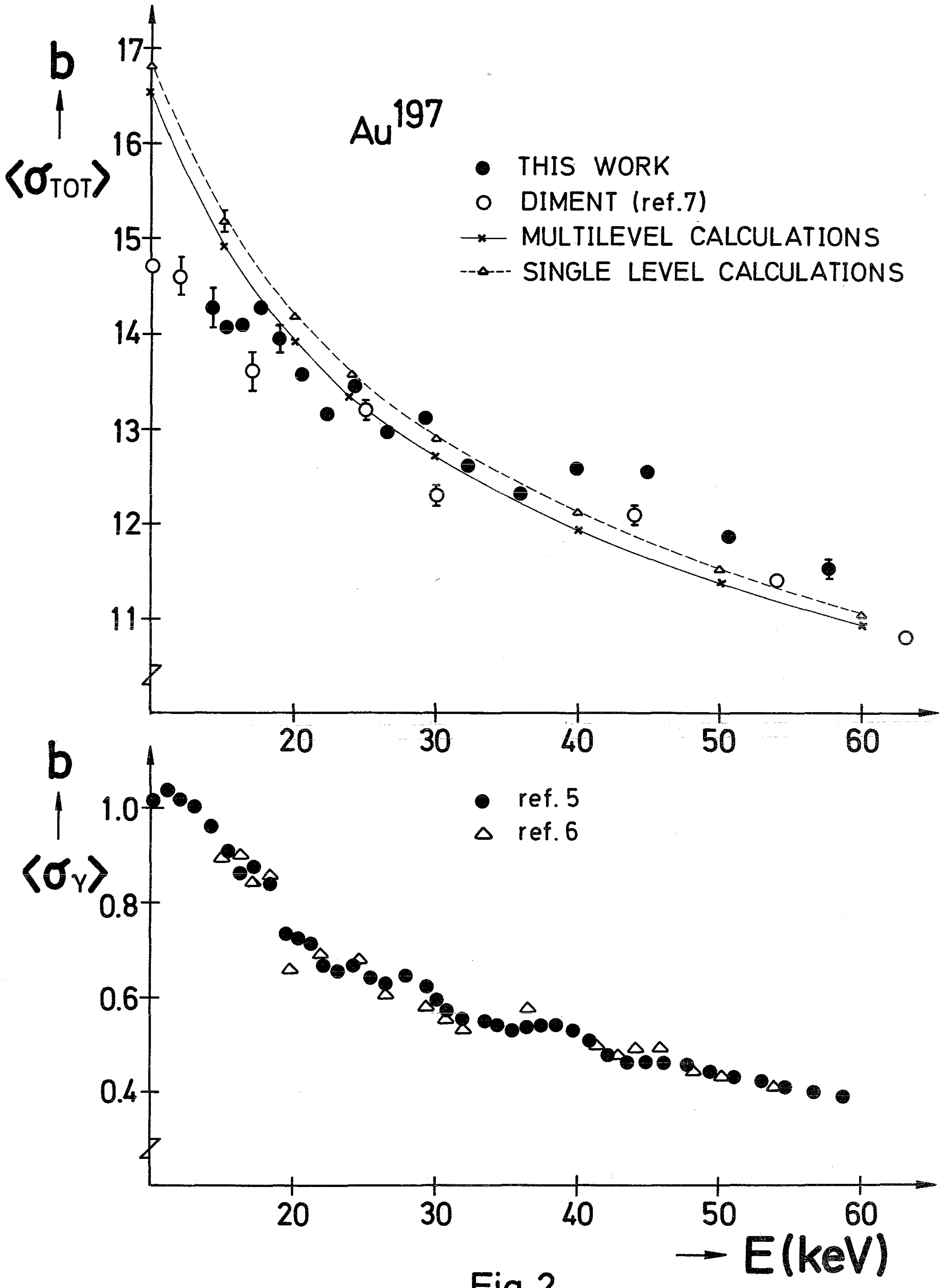
Fig. 2 Average total cross section and average capture cross section of gold versus energy

Fig. 3 Calculated average transmission at 24 keV versus temperature



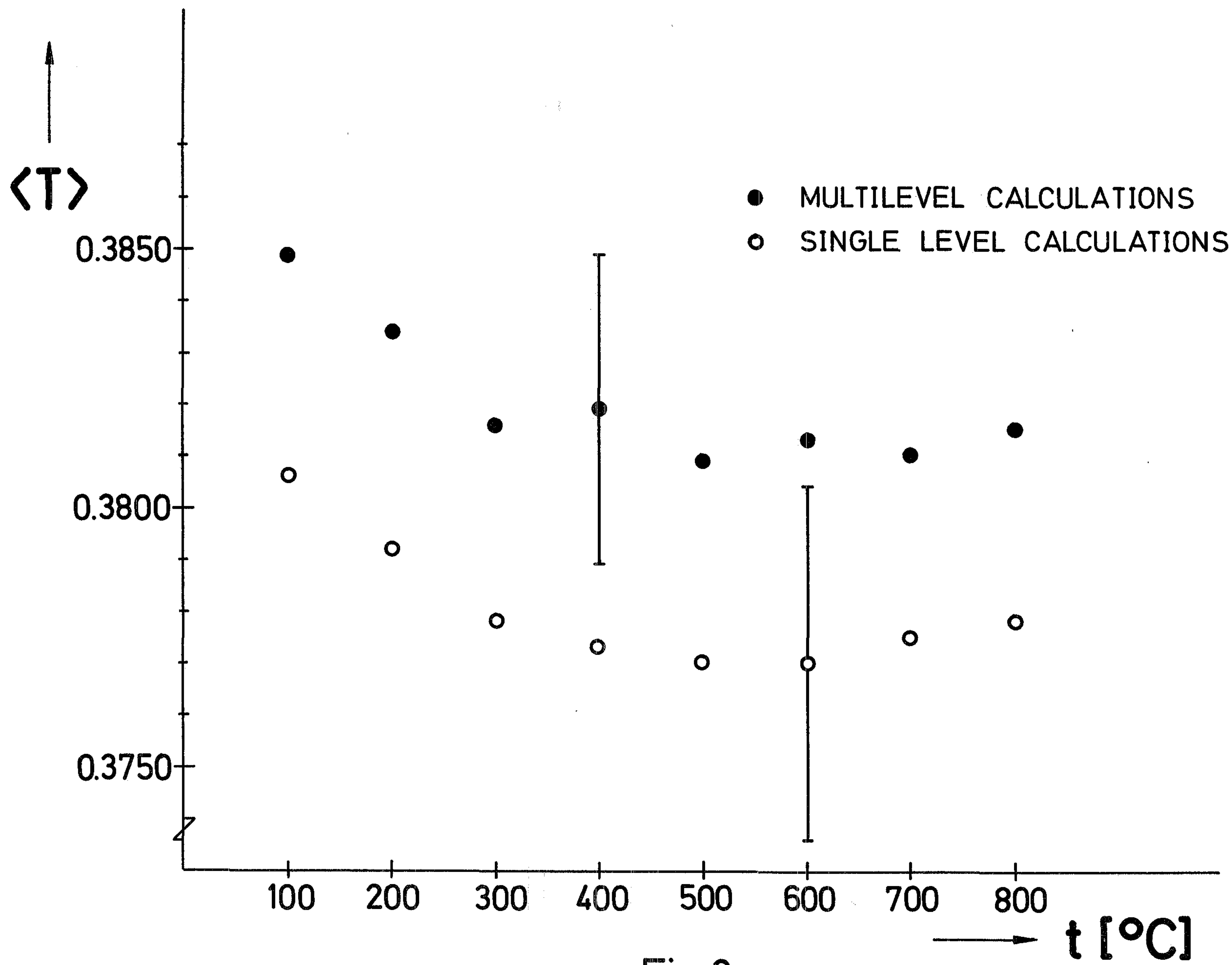
⟨T⟩
Au^{197}, 0.081 nuclei/b
284°K
1073°K
CALCULATED
CURVES
0.42
0.40
0.38
0.36
10
20
30
40
50
60
E (keV)

Fig. 1



b
⟨σTOT⟩
Au197
THIS WORK
DIMENT (ref.7)
MULTILEVEL CALCULATIONS
SINGLE LEVEL CALCULATIONS
17
16
15
14
13
12
11
20
30
40
50
60
b
⟨σγ⟩
ref. 5
ref. 6
1.0
0.8
0.6
0.4
20
30
40
50
60
E(keV)

Fig. 2



⟨T⟩
0.3850
0.3800
0.3750
MULTILEVEL CALCULATIONS
SINGLE LEVEL CALCULATIONS
100
200
300
400
500
600
700
800
t [°C]

Fig.3