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THE TOTAL NEUTRON CROSS-SECTION OF Nb AT DIFFERENT  
TEMPERATURES FOR NEUTRONS WITH ENERGIES BELOW 1 eV

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THE TOTAL NEUTRON CROSS-SECTION OF Nb AT DIFFERENT  
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## ABSTRACT

Total neutron cross-section measurements have been performed for natural Nb at liquid nitrogen, room and 425 °K temperatures in the energy range from 2 MeV - 1 eV.

The measurements were performed using two time-of-flight spectrometers installed in front of two of the ET-RR-1 reactor horizontal channels. The neutron diffraction pattern of Nb, at room temperature, was obtained using a double axis crystal spectrometer installed also at the ET-RR-1 reactor.

The obtained total neutron cross-sections were analyzed using the single level Breit-Wigner formula. The coherent scattering amplitude was determined from the Bragg reflections observed in the total neutron cross-section of Nb and the analysis of its neutron diffraction pattern.

The incoherent and thermal inelastic scattering cross-sections of Nb were determined from the analysis of the total cross-section of Nb beyond the cut-off wavelength. The following results have been obtained:

$$\sigma_t = (6.30 \pm 0.20)b$$

$$\sigma_{coh} = (6.0 \pm 0.3)b$$

$$\sigma_{incoh} = (2.0 \pm 1.0)b$$

$$b_{coh} = (6.91 \pm 0.08)fm$$

The following resonance parameters, of the bound level, were obtained:

$$E_0 = (10.0 \pm 0.5)eV$$

$$\Gamma = (140 \pm 11)meV$$

$$g\Gamma_0 = (0.086 \pm 0.006)meV$$

## 1. Introduction

Nb is of considerable interest for reactor calculations as it is a fission product nucleus and extensively used as a cladding material. Moreover, due to its relatively low absorption cross-section ( $\sim 1$  barn at 0.025 eV) and relatively high  $Z$  number, it is useful in the form of a single crystal of Nb, as a thermal neutron band pass filter [1]. Consequently the measurement of its thermal total neutron cross-sections is worth while.

The only available total neutron cross-section values of Nb, below 1 eV, are those of Rainwater et al. [2] and of Serpa [3]. These two sets of data are represented in Fig. 1, where the values of the experimental data are obtained from the Nuclear Data Section of the IAEA. One can notice, from Fig. 1, that the two sets are in good agreement at neutron energies above 0.2 eV, but at neutron energies below 0.2 eV the discrepancy is remarkable.

It is believed that such discrepancy could be due to the difference in the form of the samples. Rainwater et al. [2] used a Nb sample in powder form with a slight Ta impurity, while Serpa [3] used a metallic sample. In a metallic sample the extinction effects, on Nb grains, may explain the strong irregularities in the total neutron cross-section behaviour obtained by Serpa [3].

The present work deals with measurements of the total neutron cross-section carried out, with spec pure Nb in a fine powder form, in the energy range from 2 MeV - 1 eV. They also include measurements carried out at liquid nitrogen temperature, and at 425 °K, in order to estimate the thermal diffusion scattering cross-section.

## 2. EXPERIMENTAL DETAILS

### 2.1. Samples Preparation

The sample used was prepared from spec pure fine Nb powder. The powder was packed in a copper container with a thin copper window, having a thickness 11.37 gr/cm<sup>2</sup>, this sample was used for neutron cross-section measurements. For the neutron diffraction pattern, the Nb powder was packed into a thin-walled aluminium can, 15 mm in diameter.

### 2.2. Nb Neutron Diffraction Measurement

The measurements were carried out using monochromatic neutron with  $\lambda = 1.016$  Å selected out of the reactor spectrum by diffraction from a lead single crystal cut along the (111) plane. The neutron diffraction pattern obtained between  $2\theta$  equal to  $20^\circ - 75^\circ$  at room temperature is represented in Fig. 2. Seven well separated peaks were identified, confirming the Nb structure; no other lines were observed.

The integrated intensities for the observed reflections were calculated using the area method and then corrected for background and the Lorentz factor. The intensities due to different reflection planes are calculated using the general structure factor formula [4]. The coherent scattering amplitude of Nb was deduced using the reliability factor method. The minimum reliability factor R was found to be 5 % for a coherent scattering amplitude value of  $b_{\text{coh}} = (6.92 \pm 0.01)$  fm.

### 2.3. Total Neutron Cross-Section Measurements

The measurements were performed using two time-of-flight spectrometers installed in front of two of the ET-RR-1 reactor horizontal channels. A Be block, 20 cm thick, was used during the measurements both with and without the sample in order to increase the effect to background ratio as well as to remove neutrons of energies higher than 5 MeV. The measurements were carried out for neutrons below 5 MeV using a cryostat with liquid nitrogen and an automatically controlled heater, where the temperature could be fixed within  $\pm 5^\circ$  C, in the interval between  $25^\circ - 400^\circ$  C.

The spectrometer resolution at different intervals of the whole energy range under consideration could be varied from 3  $\mu\text{sec/m}$  to 20  $\mu\text{sec/m}$ . The spectrometers are described in detail elsewhere [5-7].

### 3. RESULTS AND DISCUSSION

Fig. 3 shows the dependence of the total Nb neutron cross-section on wavelength and neutron energy at room temperature (closed circles), as measured in the energy range from 2 MeV - 1 eV along with the cross-section measured at liquid nitrogen temperature (open circles), and at 425 °K (open triangles) for neutrons below 5 MeV.

It is noticeable that the behaviour of the present total neutron cross-sections, at neutron energies higher than 0.3 eV, is in agreement with those reported by Rainwater et al. [2] and by Serpa [3]. (See Fig. 1).

The total neutron cross-section of Nb, in the energy range from 1 eV - 0.08 eV, was fitted using the least squares method and was found to be

$$\sigma_t = (5.76 \pm 0.04) + (0.09 \pm 0.01) E^{-1/2}$$

where E is in eV. This value is in reasonable agreement, within the statistical accuracy, with the expression

$$\sigma_t = (6.4 \pm 0.2) + (0.1 \pm 0.04) E^{-1/2} \text{ reported by Rainwater et al. [2].}$$

A value of  $(6.30 \pm 0.20)b$  is obtained in the present work for the total neutron cross-section of Nb at 0.0253 eV. It is in agreement with the values of  $(6.9 \pm 0.2)b$  reported by Rainwater et al. [2] and of  $(5.11)$  obtained by Serpa [3].

The contributions of the known close and faraway resonances  $\sigma_r$  to the cross-section have been calculated using the single level Breit-Wigner formula, where the required resonance parameters were taken from the BNL-325 [8]. A bound negative energy level with the parameters

$$E = - (10.0 \pm 0.5) \text{ eV}, \quad \Gamma_f = (140 \pm 11) \text{ meV and}$$

$$g\Gamma_m = (0.086 \pm 0.006) \text{ meV}$$

was introduced in order to account for the obtained neutron energy dependence of  $(\sigma_t - \sigma_r)$ .

The observed behaviour of the Nb total neutron cross-section shows sharp cut-offs at neutron wavelengths corresponding to the double interplanar distance d of the Nb crystal structure. Since the sample used is in fine powder form (the grain size is less than  $10^{-4}$  cm), the extinction effects could be neglected. Table 1 gives the cut-off values of  $\Delta\sigma_{hkl}$  corresponding to the reflection of neutrons with wavelengths from the planes with Miller indices hkl, the multiplicity factor  $M_{hkl}$ , and the interplanar distance hkl. The coherent scattering amplitude of Nb is calculated for each hkl plane (last column of Table 1) considering both the resolution and Debye-Waller factor. The average value of  $b_{coh}$  has been determined and found to be  $b_{coh} = (6.9 \pm 0.2) \text{ fm}$  which is in good agreement with the value of  $b_{coh} = (6.92 \pm 0.01) \text{ fm}$  obtained from neutron diffraction, and is also in agreement within the statistical accuracy with the value of  $(7.11 \pm 0.04) \text{ fm}$  given in the BNL-325 [8].

Table 1: The Nb Bragg cut-offs

hkl	M <sub>hkl</sub>	$\lambda$ , Å	d, Å	$\Delta\sigma_{hkl}^b$	b <sub>coh</sub> , fm
110	12	4.66	2.33	7.5 $\pm$ 0.5	6.9 $\pm$ 0.1
200	6	3.30	1.65	1.3 $\pm$ 0.2	6.9 $\pm$ 0.3
211	24	2.68	1.34	2.5 $\pm$ 0.2	6.8 $\pm$ 0.1
220	12	2.32	1.16	0.8 $\pm$ 0.2	7.0 $\pm$ 0.4
310	24	2.08	1.04	1.1 $\pm$ 0.2	7.0 $\pm$ 0.3
222	8	1.90	0.95	0.25 $\pm$ 0.2	6.8 $\pm$ 1.3
321	48	1.76	0.88	1.2 $\pm$ 0.2	7.0 $\pm$ 0.3

At liquid nitrogen temperature, the total neutron cross-section of Nb beyond the cut-off wavelength was found to follow the expression

$$\sigma_t = (2.0 \pm 1.0) + (0.14 \pm 0.07) E^{-1/2}$$

which yields a value of  $(2.0 \pm 1.0)$  for the incoherent elastic scattering cross-section.

The one phonon annihilation process was calculated following the procedure reported by Cassels [9]. The calculated values of inelastic thermal scattering at both room and 425 °K temperatures, beyond the cut-off wavelength, were incoherently added to the total cross-sections of Nb measured at liquid nitrogen temperature.

Fig. 3 shows the result of calculations both at room temperature (dashed line) and at 425 °K (solid line).

One can notice (see Fig. 3) that the behaviour of the total neutron cross-section at room temperature is in agreement with the calculated one; at 425 °K the calculated values are slightly less than the measured ones. Such discrepancy could be due to the multiphonon annihilation process.

It is also noticeable that the dependence of the Nb inelastic thermal scattering cross-section on temperature is weak as the Debye temperature of Nb is relatively small (250 °K).

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#### Figure Captions

- Fig. (1) : The total neutron cross-section of Nb below 1 eV
- Fig. (2) : The neutron diffraction pattern of Nb obtained at room temperature
- Fig. (3) : The total neutron cross-section of Nb as dunction of both wavelength and energy.

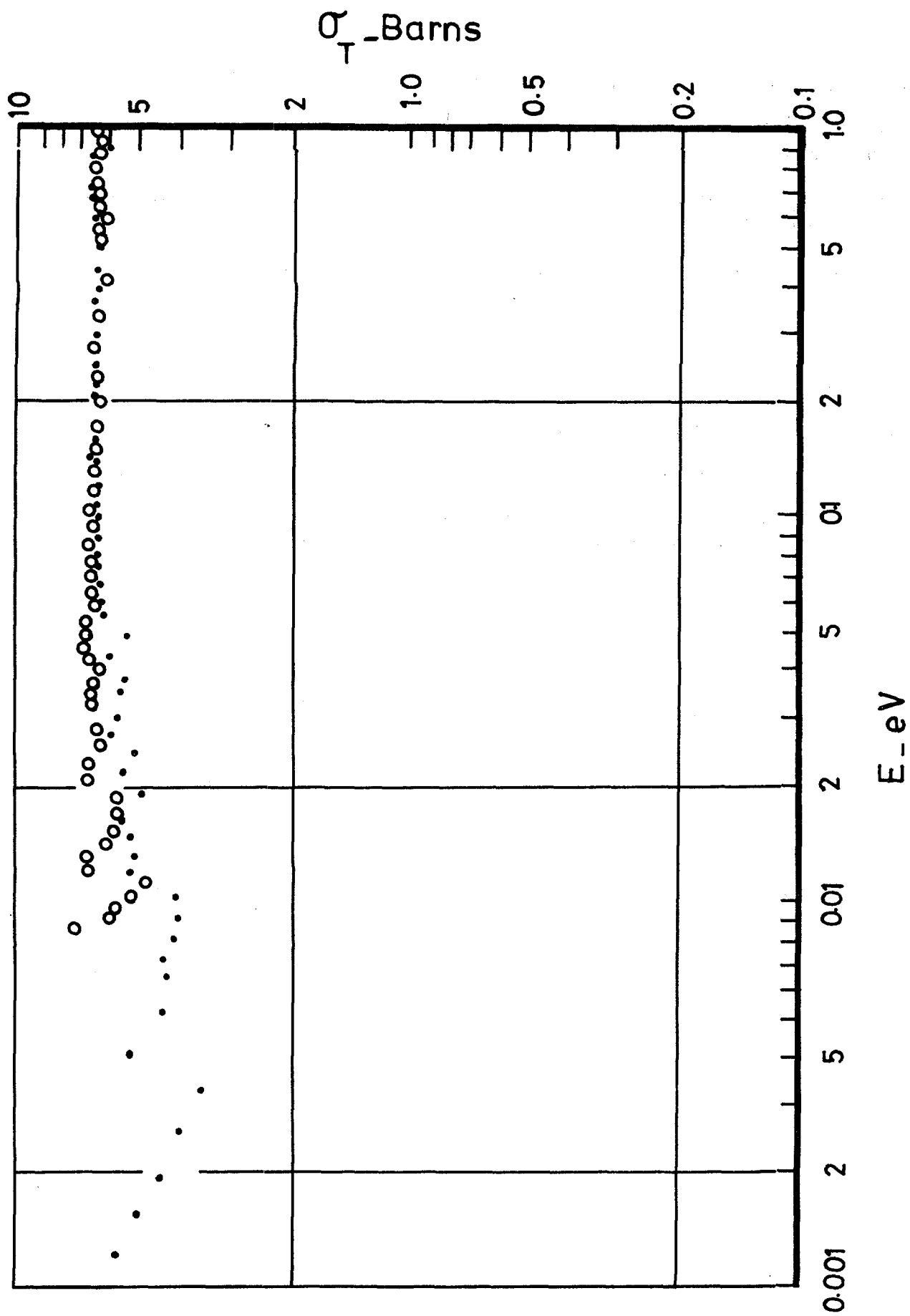


Fig.(1)

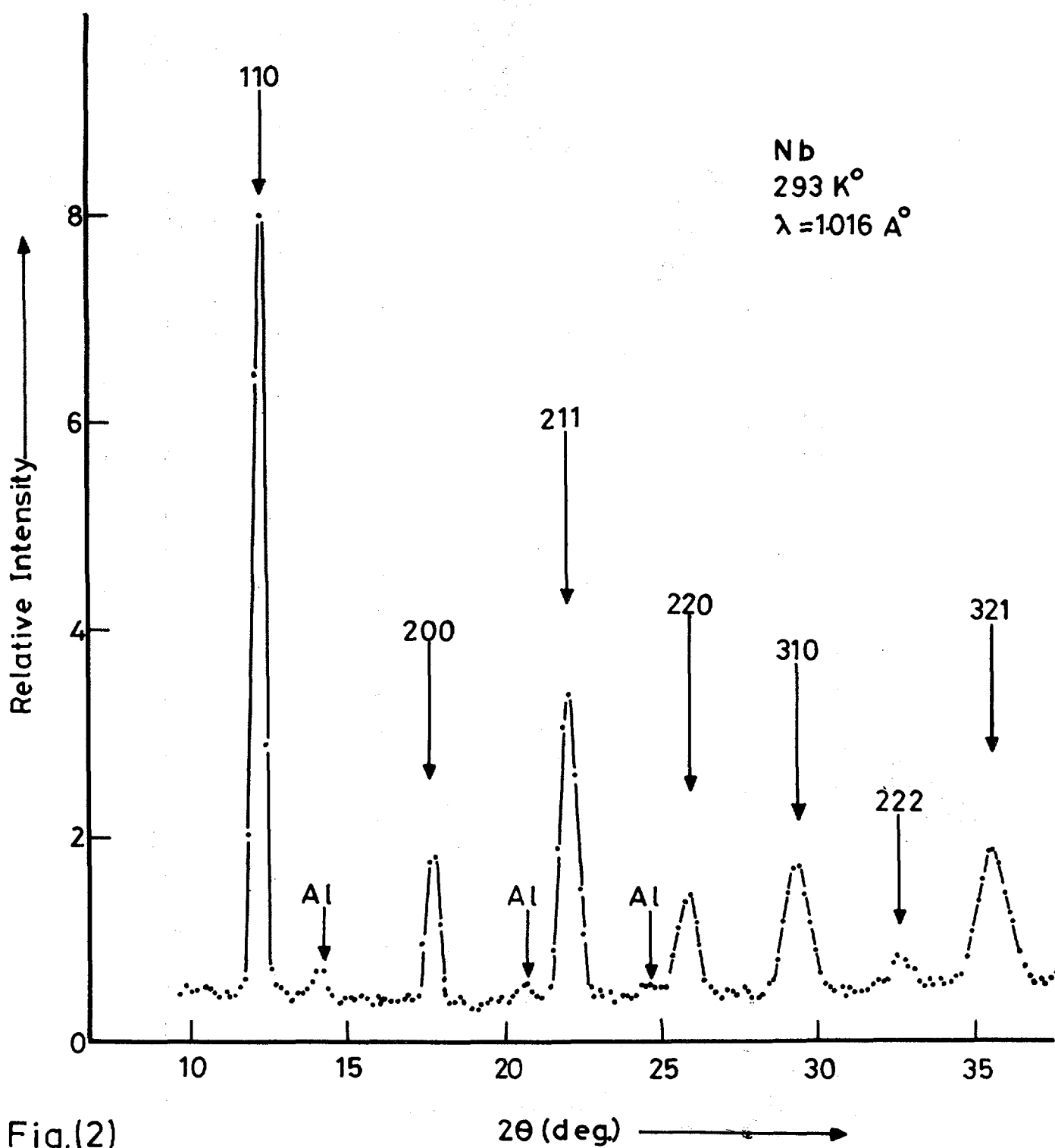


Fig.(2)

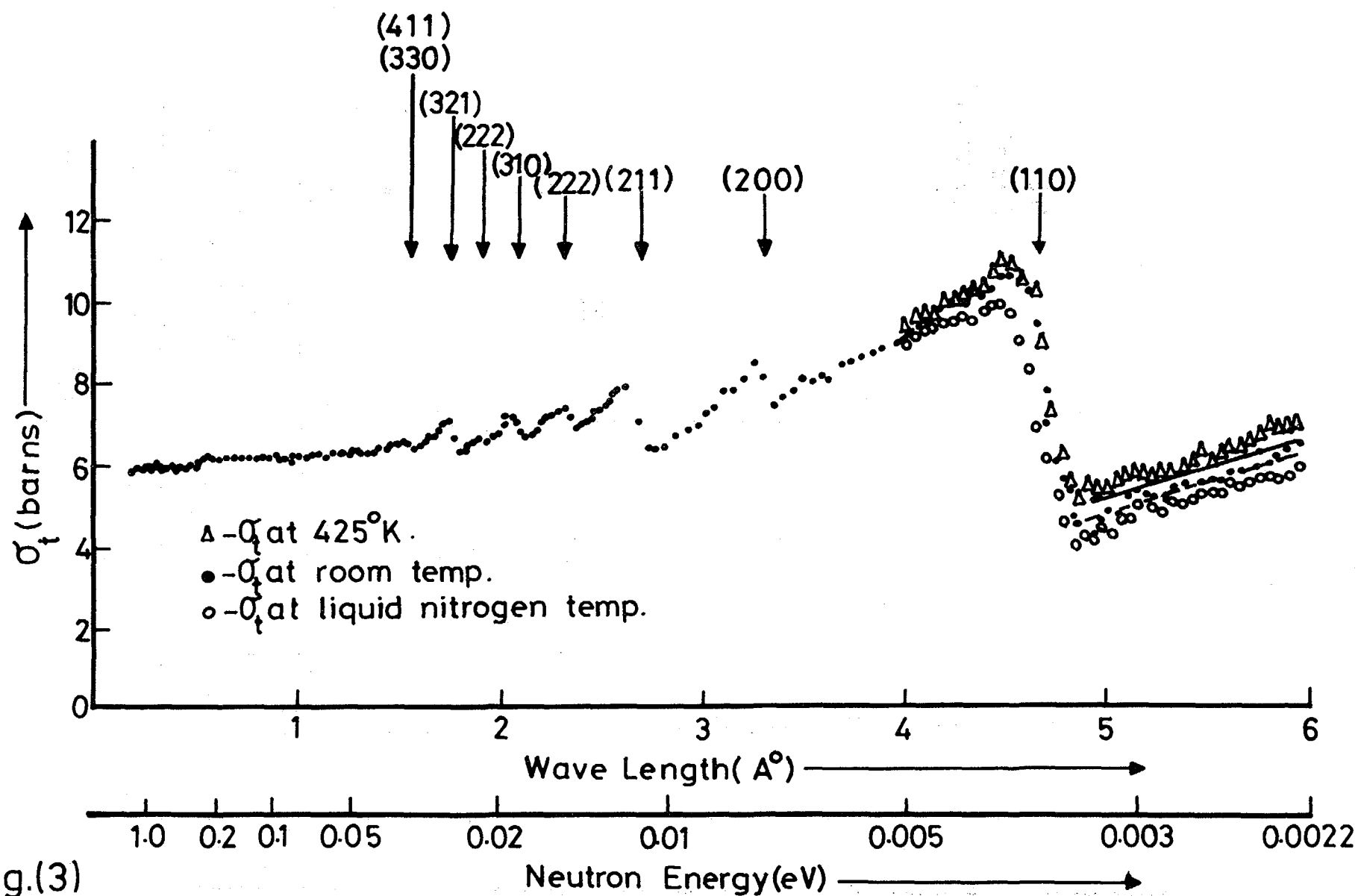


Fig.(3)