JOURNAL OF MATERIALS SCIENCE 23 (1988) 4231–4236

Neutron transmission measurements of zinc and lead single crystals

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Neutron transmission measurements of zinc and lead single crystals have been carried out in a neutron wavelength band from 0.03 to 0.55 nm at different orientations of the crystal with regard to the beam direction. The measurements were performed using both time-of-flight and fixed-angle scattering spectrometers installed in front of the ET-RR-1 reactor horizontal channels. It was found that the position of the observed dips in the neutron transmission measurements corresponded to the reflections from the (*hkl*) planes of the hexagonal zinc single crystal which was cut along the (0 0 2) plane, while in the case of lead, the single crystal was cut perpendicular to the (3 1 1) plane. The reflectivity from the (0 0 2) plane of zinc was determined using both transmission and reflection methods. The maximum reflectivity was found to be 55% when the zinc crystal was orientated at 45° to the beam direction. The wavelength spread of the observed reflectivity curve was found to be in agreement with the calculated one, taking into consideration the spectrometer's resolution and the crystal mosaic spread.

1. Introduction

Large metallic zinc and lead single crystals are intensively used for neutron diffraction work and especially for monochromatization [1]. Single crystals have found wide application as thermal neutron bandpass filters for fission reactors [2–5]. Brugger *et al.* [6] reported the results of their transmission measurements with a single silicon crystal. For such a purpose they used a large single crystal (28 cm in length). In their work they prove that such a length is sufficient for removing neutrons of energies ~ 1 eV, but it is not sufficient to remove the γ-radiation accompanying neutrons from the reactor. Harvey *et al.* [7] have reported their transmission measurements with a copper single crystal. Recently, Adib *et al.* [8] have studied the transmission of a germanium monocrystal for thermal neutron energies. They reported that the total neutron cross-section of germanium at a neutron energy of 0.05 eV is lower by less than one-third of its value at 1 eV, and that it is useful to use a germanium single crystal cooled to liquid nitrogen temperature as a bandpass filter for neutron energies below 0.1 eV. From the measured behaviour of the total cross-section of a germanium single crystal reported by Adib *et al.* [8], one can see that its use as a bandpass filter is limited due to the relatively high absorption cross-section ($\sigma_\gamma(0.025\,\text{eV}) = 2.3\,\text{b}$) [9]. Consequently, it is useful to study the transmission of both zinc and lead single crystals in the thermal neutron energy range, since they are more effective in removing gamma radiation and moreover their neutron absorption cross-sections are relatively low ($\sigma_\gamma(0.025\,\text{eV}) = 1.1\,\text{b}$ and $\sigma_\gamma(0.025\,\text{eV}) = 0.17\,\text{b}$ for zinc and lead, respectively [9].

The present work deals with neutron transmission measurements carried out both for zinc and lead single crystals in the neutron wavelength band from 0.03 to 0.55 nm at different orientations of the crystals with regard to the beam direction.

The present work also presents measurements of the reflectivity from the (0 0 2) plane of zinc single crystals as determined using both transmission and reflection methods.

2. Experimental details

Large single crystals of zinc and lead were grown by slow cooling of the melt. They were orientated by means of X-rays, cut mechanically and then etched chemically. Their mosaic spread was about 1 to 10 min of arc. The crystals were obtained from the Polish Academy of Sciences, Institute of Nuclear Research.

2.1. Zinc single crystal sample

Zinc crystallizes in the hexagonal system with parameters $c = 0.4947\,\text{nm}$ and $a = 0.2665\,\text{nm}$. The zinc single crystal used during the measurements was a segment of a cylindrical shape 8 cm in diameter. The 0 0 2 plane was parallel to the face of the cylindrical segment with cross-sectional area 6 × 16 cm.

2.2. Lead single crystal sample

Lead crystallizes in a cubic face-centred form with

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$a_0 = 0.495$ nm. The lead single crystal used during the measurements had a parallelepiped shape with dimensions 6 × 17.6 × 1.1 cm. The 6 × 17.6 cm face was perpendicular to the (3 1 1) plane.

2.3. Time-of-flight spectrometers

The measurements were performed using both time-of-flight and fixed-angle scattering spectrometers installed in front of the ET-RR-1 reactor horizontal channels. The TOF spectrometer has a mechanical chopper with a rotor of Pertinax 160 mm in diameter and having a cigar-shaped slit. The slit sizes at the entrance and outlet are 2 × 25 mm while the slit size at the centre of the rotor is 5 × 25 mm. The flight path is 4.2 m. The rotation rate of the rotor can be controlled in the range from 800 to 3600 r.p.m., with an accuracy of 0.14% [10].

The fixed-angle scattering spectrometer consists of a rotor, suspended in a magnetic field, spinning at a maximum speed of 16 000 r.p.m. and producing bursts of polyenergetic neutrons at the sample. The rotor, 32 cm in diameter, has two curved slits for producing two bursts of neutrons per revolution. The slits have radius of curvature 65.65 cm and 7 × 10 mm cross-sectional area. The flight path from the chopper's centre to the centre of the sample is 1.30 m while the flight path from the sample centre to the counter centre is 2.0 m. The spectrometers are described in detail elsewhere [11, 12].

3. Results and discussion

3.1. Zinc single crystal

Fig. 1 shows the neutron transmission obtained through a hexagonal zinc single crystal as a function of neutron wavelength at angles of 0, 18, 32, 51 and 66° between the neutron beam direction and the normal to the 6 × 16 cm sample face, i.e. normal to the (0 0 2) plane.

From Fig. 1 one can see that when the zinc single crystal is perpendicular to the beam direction ($\psi = 0$), it transmits 75% of the neutrons with wavelengths longer than 0.25 nm, while the transmission is reduced to about 60% for neutrons with wavelengths shorter than 0.08 nm. At other orientations the transmitted neutron spectrum is strongly distorted by the reflections from $(h\,k\,l)$ planes of zinc. Thus the zinc single crystal, when fixed perpendicular to the neutron beam direction, can be used to remove neutrons from the reactor beam with wavelengths shorter than 0.08 nm.

The behaviour of the neutron transmission through the zinc single crystal orientated at different angles with regard to the beam direction shows sharp dips. These dips are due to reflections from the $(h\,k\,l)$ planes of zinc. The wavelength values corresponding to these reflections are found to be in good agreement with those calculated according to the equation [1]

$$\lambda_{hkl} = \left\{2\left[\frac{l}{c}\cos\psi - \frac{2}{3^{1/2}a}\left(\frac{h}{2}+k\right)\sin\psi\right]\right\} \Big/ \left[\frac{4}{3a^2}(h^2+k^2+hk)+\frac{l^2}{c^2}\right] \qquad (1)$$

where ψ is the angle between the (0 0 2) plane and the neutron beam direction and a, c are the zinc lattice parameters.

The reflectivity from the (0 0 2) plane was determined from the measured behaviour of the neutron transmission through zinc, using both the transmission and reflection methods. The zinc single crystal was fixed at 45° with regard to the neutron beam directions. The reflected neutrons were measured by the same neutron detector used for neutron transmission but the detector in this case was fixed perpendicular to the beam direction and at 2.0 m from the sample. Thus the flight path was the same as in the transmission measurements.

Fig. 2a shows two observed neutron spectra (after subtraction of the background), before and after transmission through the sample. From these two spectra the reflectivity curve of zinc was determined according to the relation

$$\text{Reflectivity} = \frac{(\text{incident neutrons}) - (\text{transmitted neutrons})}{\text{incident neutrons}} \times 100$$

The result of such calculation is displayed in Fig. 2b.

Fig. 2c shows the recorded neutron spectrum reflected perpendicular to the neutron beam direction (i.e. $2\psi = 90°$) under the same operating conditions. The single-crystal reflectivity in this case (reflection method) was determined as

$$\text{Reflectivity} = \frac{\text{reflected neutrons}}{\text{incident neutrons}} \times 100$$

Fig. 2d presents the behaviour of the reflectivity using the reflection method where the values of the incident neutrons are taken from Fig. 2a after subtraction of the background.

From Figs 2b and d one can see that values of the full width at half-maximum (FWHM) of the reflectivity curves using both methods were equal and had a value of $50 \pm 10\,\mu$sec. This value is in reasonable agreement with the value of the spectrometer's uncertainty $\Delta t = 52.6\,\mu$sec. Thus the mosaic spread of the zinc crystal used is less than the divergence of the beam. In our case the neutron beam divergence is 0.5°.

From Figs 2b and d one can also see that the maximum reflectivity by the transmission method (73%) is higher than by reflection (55%). Such a discrepancy is due to the contribution of reflections from other $(h\,k\,l)$ planes in the case of the transmission method.

3.2. Lead single crystal

Fig. 3 shows the neutron transmission obtained through a cubic lead single crystal as a function of neutron wavelength at angles of 0, 31, 42 and 77° between the neutron beam direction and the normal to the sample face, i.e. normal to the (3 1 1) plane.

From Fig. 3 one can see that when the 1.1 cm thick lead single crystal is fixed perpendicular to the neutron beam then about 85% of the neutrons with wavelengths longer than 0.3 nm can pass through the crystal, while the transmission of neutrons with wavelengths shorter than 0.3 nm is reduced to about 60%. Thus it seems

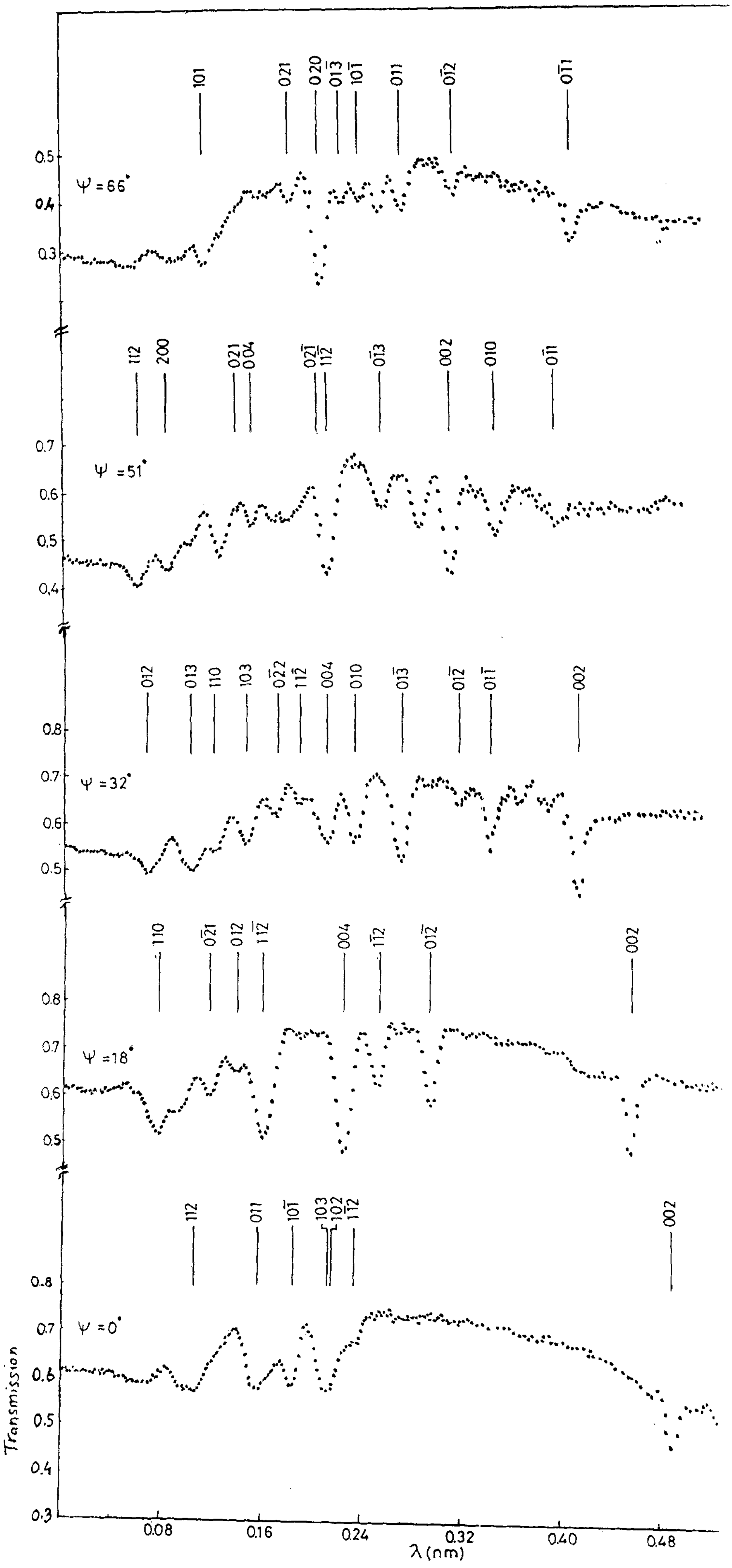

Figure 1 Neutron transmission through zinc single crystal.

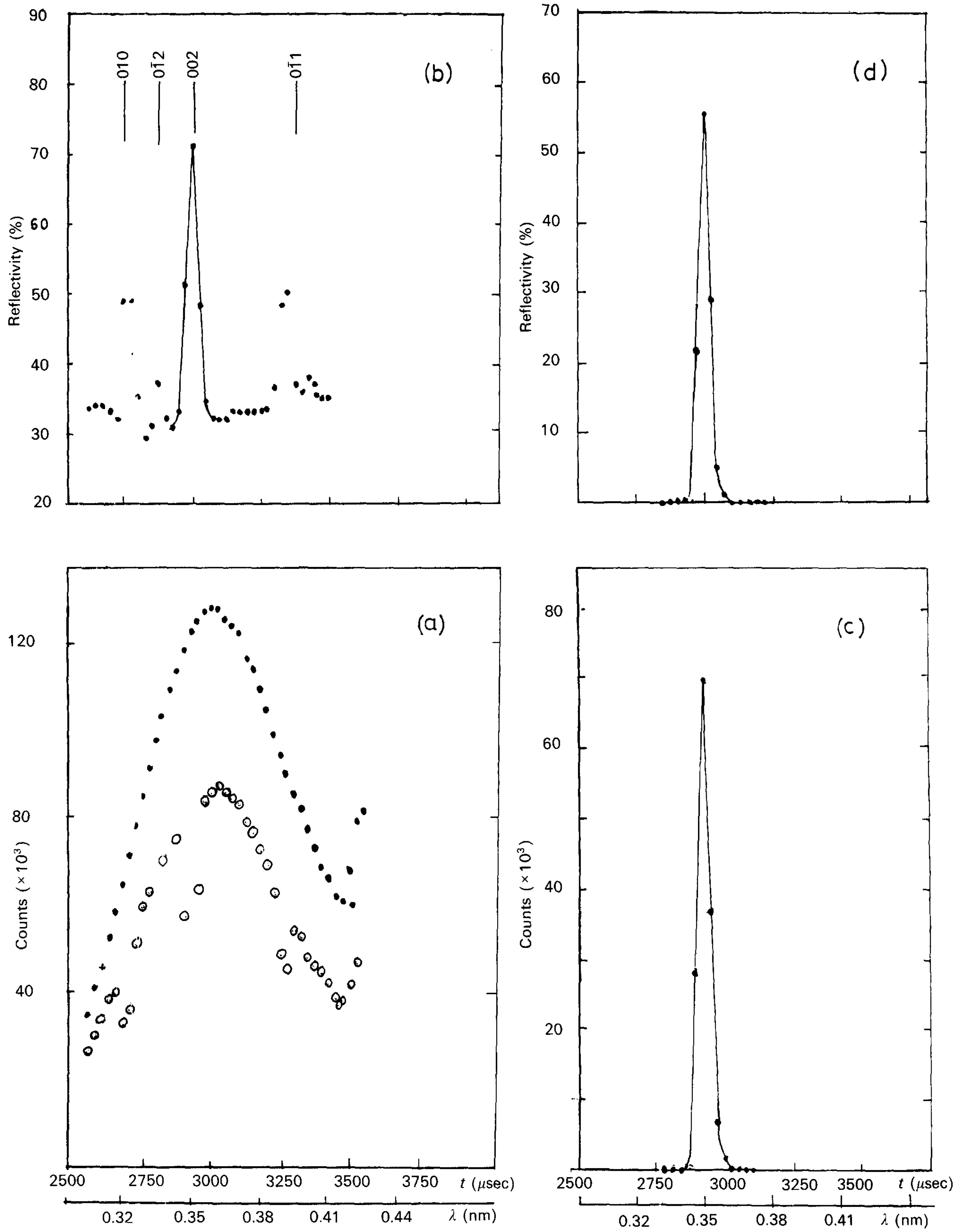

Figure 2 Reflectivity of zinc single crystal. (a) Observed neutron spectra (●) before and (○) after transmission through the crystal; (b) reflectivity calculated from (a); (c) neutron spectrum reflected at $2\psi = 90°$; (d) reflectivity calculated from (c) and (a).

that the filtering characteristics of lead are more favourable than those of zinc. From Fig. 3 one can also see that sharp dips due to Bragg reflections from the cubic lead planes are observed in the behaviour of the transmission at different values of ψ. The wavelength values corresponding to the reflections from each (hkl) plane of a cubic single crystal with lattice parameter a were calculated using the equation [1]

$$\lambda_{hkl} = 2a\left\{\left[\frac{3k+3l}{(22)^{1/2}} - \left(\frac{2}{11}\right)^{1/2}\right]\sin(90-\psi) + \left(\frac{3h+k+l}{(11)^{1/2}}\right)\cos(90-\psi)\right\}\Big/ (h^2+k^2+l^2)$$

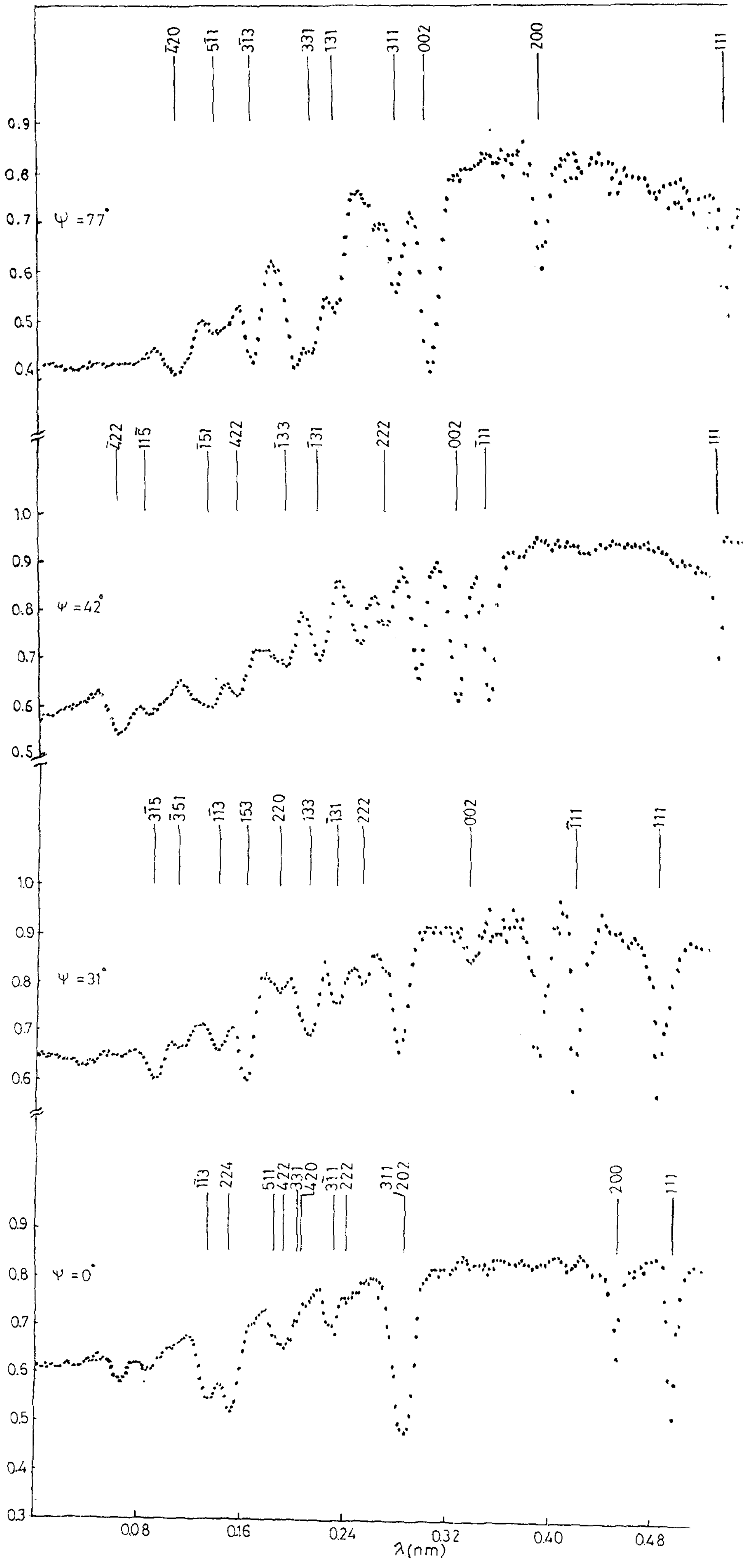

Figure 3 Neutron transmission through lead single crystal.

The results of calculation are presented in Fig. 3. One can notice a reasonable agreement between the position of the observed dips and the calculated ones.

From the transmission curve at $\psi = 77°$ one can see that the reflectivity from the (3 1 1) plane was only 45%. Thus one can conclude that the reflectivity of zinc when used as a neutron monochromator is higher than that obtained with lead. However, a lead single crystal cut perpendicular to the (3 1 1) plane can also be successfully used as a monochromator. Firstly it more effectively reduces the gamma background accompanying the neutron beam and secondly the contamination of the neutron beam from high orders is negligible.

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Received 25 September 1987
and accepted 26 January 1988