Letters to the Editors

Thermal Neutron Inelastic Scattering Effects in a Single Crystal Neutron Spectrometer

The thermal neutron spectrum emerging from the "Apsara" reactor (swimming pool type) was measured with a single crystal spectrometer. The curve of neutron counting rate vs Bragg angle showed fluctuations which were much higher than the statistical errors. Earlier similar fluctuations have been reported by Pattenden and Baston (1). The exact cause of these fluctuations had not been under-

tained with Al (111) is shown[1] in Fig. 1. Similar fluctuations in the curve at different Bragg angles were observed in the case of Be (1233), LiF (111) and NaCl (200) reflections. In order to ensure that these fluctuations are not caused by any peculiarities in the incident spectrum from the reactor, the beam hole was surrounded on all sides by 75 cm of graphite just adjacent to the reactor core. The above curves were repeated with and without a 15 cm long graphite plug at the end of the beam hole. The fluctuations persisted in each case. The curve in Fig. 1 was obtained without the
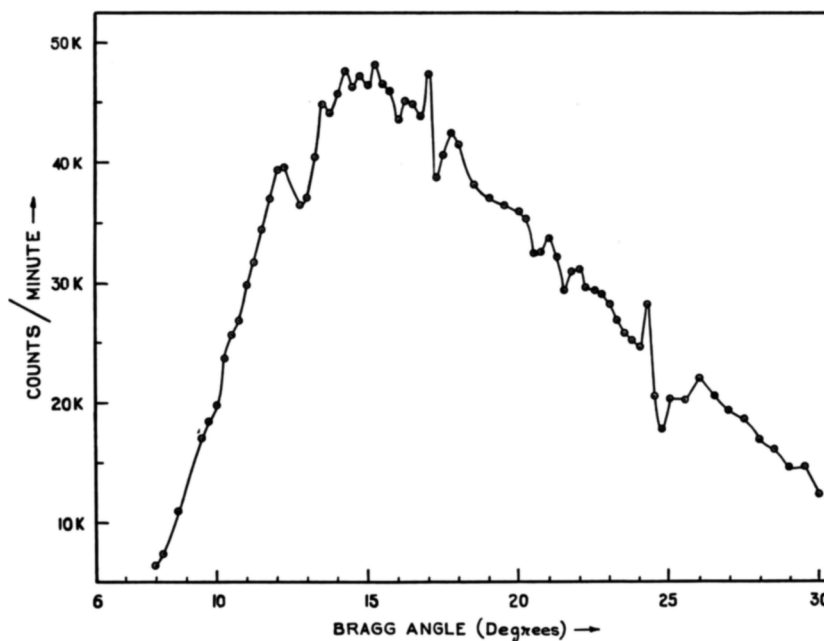

Fig. 1. Counting rate vs Bragg angle curve obtained with Al (111) reflections.

stood so far. The purpose of this note is to show that some of these fluctuations are due to inelastic scattering of thermal neutrons by the crystal.

In the present measurements, neutrons were obtained through a 10 cm diam aluminum tube extending up to the core of the reactor. A steel collimator, having in the center a single slit, 2 mm wide, 5 cm high, and extending up to 120 cm, was kept at the other end of the aluminum tube before the monochromating crystal. The neutron detector consisted of a 4 cm diam enriched BF_3 counter (containing 94 per cent B^{10}) of an active length of 48 cm, filled to a pressure of 60 cm Hg. An additional 9 cm long collimator made of aluminum boxes, filled with boron carbide having a slit 5 mm wide and 7.5 cm high, was placed in front of the counter. A typical counting rate vs Bragg angle curve ob-

graphite plug but a 10 × 60 × 80 cm layer of graphite was introduced between the reactor core and the end of the beam hole.

As a possible cause of the above fluctuations, the distribution of inelastically scattered neutrons by the crystal was evaluated. For this use was made of the equations of conservation of momentum and of energy (2), viz:

$$\mathbf{k} - \mathbf{k}' = 2\pi\tau - v \tag{1a}$$

$$k'^2 = k^2 \pm (2m_0/\hbar)cq \tag{1b}$$

The notations are the same as employed in reference 2.

[1] The aluminum single crystal (6 × 12 × 1 cm) was supplied by the Commissariat à l'Énergie Atomique, France.

TABLE I

VALUES OF $q/2\pi$ (A^{-1}) OBTAINED IN INELASTIC SCATTERING OF NEUTRONS OF DIFFERENT ENERGIES AT SOME BRAGG ANGLES

Neutron Energy (ev)	At											
	12°		12°40′		13°		23°		24°15′		24°45′	
	a	b	a	b	a	b	a	b	a	b	a	b
0.0114	No	No	No	No	No	No	No	0.145	No	0.14	No	0.13
0.0182	No	No	No	No	No	No	No	0.09	No	0.10	No	0.10
0.0211	No	No	No	No	No	No	No	0.08	No	No	No	0.10
0.0227	No	No	No	No	No	0.20	No	0.07	No	No	No	0.10
0.0246	No	No	No	0.19	No	0.19	No	0.05	No	No	No	No
0.0268	No	0.20	No	0.19	No	0.17	No	No	0.10	No	0.10	No
0.0293	No	0.18	No	0.17	No	0.16	0.09	0.10	0.10	No	0.09	0.13
0.1247	0.09	0.10	0.11	0.13	0.13	0.15	No	No	No	No	No	No

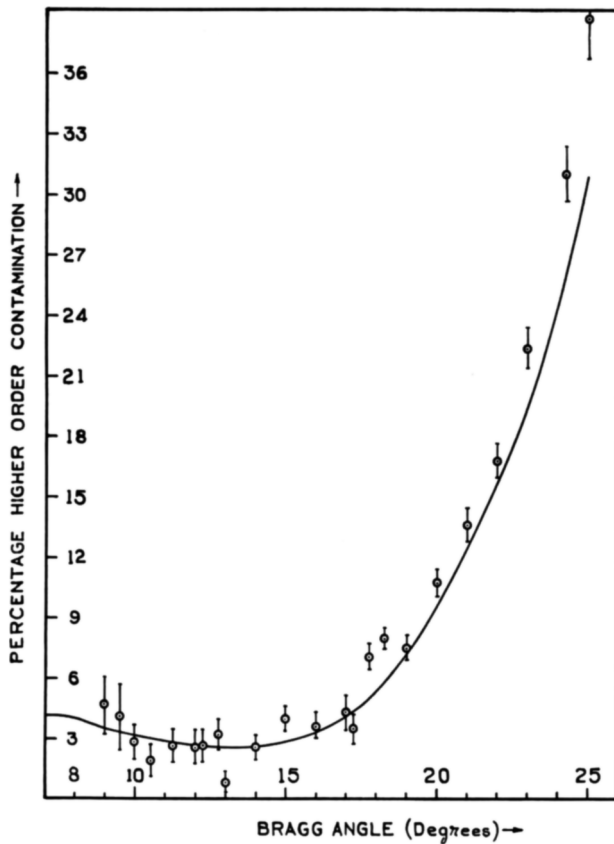Column (a) refers to emission and (b) to absorption of a phonon.

FIG. 2. Percentage of higher order contamination vs Bragg angle for Al (111) reflection. ⊙ = Experimental values obtained with calibrated Pyrex plates (suitably normalized). Solid curve is obtained from theoretical calculations of reflectivity of Al (111) crystal.

The value of c, sound velocity, was evaluated for different values of q from frequency–wave number curves (2) for an Al (111) plane. Using Eqs. (1), the possible initial energies of the neutron, which after an inelastic collision get scattered at a given Bragg angle, were evaluated. The corresponding values of $q/2\pi$ obtained at some Bragg angles, where large fluctuations in the counting rate are observed, are given in Table 1. The calculations of intensity were not made. It is seen from Table 1 that at and about 12°40′ and 24°15′, neutrons having energies near about 0.025 ev (Maxwellian peak) do not contribute after suffering an inelastic collision, thus causing a dip in the counting rate vs Bragg angle curve, Fig. 1.

The diffracted beam from the Al (111) plane was analyzed with a view to checking the presence of neutrons of different energies apart from the expected neutron energies, i.e., E, $4E$, $9E$, etc., corresponding to a particular Bragg angle θ. For this the transmission of two calibrated Pyrex plates[2] was determined at different Bragg angles and the fraction of higher order neutrons was found, using the conventional method (3, 4). The fraction of higher order neutrons was also evaluated theoretically (5) from the reflectivity curves of the Al (111) plane. The mosaic spread of the crystal was estimated to be a 10 min arc from the rocking curve of the crystal taken with and without a 0.4 mm thick Cd foil before the counter. The reactor spectrum incident on the crystal was assumed to be of the form (6)

$$N(E)dE = E^{1/2}\exp(-E/0.025)$$
$$+ 7.5 \times 10^{-5}E^{-3/2}[1 + (0.12/E)^{16}]^{-1} \quad (2)$$

The solid curve in Fig. 2 represents the theoretical values (after correcting for the efficiency and the gap in the counter) of percentage of higher order contamination. It is seen that the experimental values (plotted as circles) show a variation from the theoretical curve at some Bragg angles (e.g., at 13°, 15°, and 18°) where large fluctuations also appear in Fig. 1. These differences persist even when an appreciably different spectrum [than that given by Eq. (2)] was used in the calculations e.g., the constant accompanying $E^{-3/2}$ term was varied from 3.2×10^{-5} to 10×10^{-5}.

Thus it is felt that neutrons of energy other than E_1, $4E_1$, and $9E_1$ are also present in the diffracted beam and this results from the inelastic scattering of thermal neutrons

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[2] The Pyrex plates were calibrated by Dr. R. Joly with a neutron crystal spectrometer at Saclay, France.

by the crystal. The presence of neutrons of energy $< E_1$ has also been observed by Pattenden (7) during measurements with a Be crystal. The contamination of the diffracted beam by neutrons of energies different from the expected ones may be more pronounced at some angles. More careful measurements of the energy spectrum of the diffracted beam by a single crystal (when the incident beam is taken from a reactor) are desirable since this instrument has been widely used for cross-section measurements.

Thanks are due to Mr. L. S. Kothari for pointing out the inelastic scattering effects as a possible cause of the fluctuations and for help in the calculations. Thanks are also due to Messrs. Raghavendra Rao and K. Sri Ram for their help during measurements. Continued assistance of Messrs. J. N. Soni, Virendra Singh, and M. L. Barde is gratefully acknowledged. The author is thankful to Dr. R. Ramanna for his help throughout the course of this work.

NOTE ADDED IN PROOF

Calculations of the intensity of inelastically scattered neutrons were recently made at a few Bragg angles. The contributions of such neutrons at $17°45'$ and $26°$ came out to be much larger than at neighboring angles, thus causing peaks at these angles. The details will be published shortly.

Similar fluctuations in the case of Be crystal have been explained by H. J. Hay, A.E.R.E. Harwell (Private communication, April 1959) as due to double Bragg-reflections. Spencer and Smith have also reported similar findings [*Bull. Am. Phys. Soc.* May 1, 1959] in Be and NaCl crystals.

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Heat Transfer to Water Flowing Parallel to Tube Bundles

A fuel element assembly consisting of cylindrical fuel rods cooled by water flowing parallel to the axis of the rods is one of the arrangements most frequently encountered by the reactor designer. For this situation, the usual procedure for calculation of nonboiling heat transfer coefficients in the fully turbulent region is to use a modified version of

Colburn's (1) equation

$$\frac{hD_e}{k} = 0.023 \left(\frac{D_e G}{\mu}\right)^{0.8} \left(\frac{C_p \mu}{k}\right)^{1/3} \qquad (1)$$

where h is the heat transfer coefficient, k the thermal conductivity of the fluid, C_p the specific heat of the fluid, μ the liquid viscosity, and D_e an equivalent diameter equal to four times the hydraulic radius. All the fluid properties are generally evaluated at the film temperature except C_p, which is taken at the bulk temperature.

The possibility that the effect of tube spacing is not adequately described by Eq. (1) has been considered by several investigators. Deissler and Taylor (2) studied the problem analytically and concluded that at a given Reynolds number, based on D_e, the more open lattices should provide higher heat transfer coefficients. Their results, however, were not presented in a form readily adaptable to engineering design.

Heat transfer coefficients on the shell side of unbaffled heat exchangers were experimentally investigated some years ago by Short (5). The lattice spacing effect he observed could not be described adequately by use of the equivalent diameter alone. However, his studies were confined to the flow transition region at Reynolds numbers between 10^3 and 10^4. More recently Wantland (6) investigated the heat transfer characteristics of two additional arrays in the transition region. The results of this study were also at variance with Eq. (1).

The primary concern of the reactor designer is with the fully turbulent region at Reynolds numbers above 2.5×10^4. Experimental studies of this region with water flowing outside of tube bundles have been carried out by Miller *et al.* (4) and Dingee *et al.* (3). For a lattice spacing where the ratio of the center to center distance between tubes, S, to the tube diameter, D, was 1.46, Miller *et al.* found the data could be described by an equation of the same form as Eq. (1), but with a different coefficient.

$$\frac{hD_e}{k} = C \left(\frac{D_e G}{\mu}\right)^{0.8} \left(\frac{C_p \mu}{k}\right)^{1/3} \qquad (2)$$

The value of C was determined as 0.032. *Dinge et al.* (3) investigated several more closely spaced lattices and found that, while the data did not depart greatly from the results predicted by Eq. (1), the more open lattice spacings tended to give somewhat higher heat transfer coefficients. Both investigators took precautions to allow a sufficient downstream length of remove entrance effects.
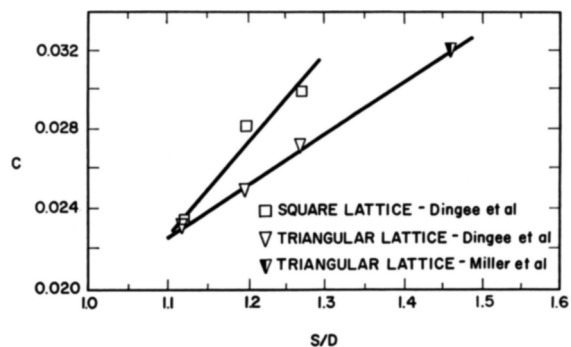

FIG. 1.