these data show a progressive decrease in hole concentration and conversion to *n* type. Such behavior is expected because of transmutations.

In order to separate the effects due to transmutations from those due to lattice defects, a second *p*-type sample was (1) exposed to $\sim 2.5\times 10^{17}(nvt)_f$, (2) subsequently annealed at 350°C for 16 hours, and (3) then, while shielded from thermal and resonance neutrons with Cd and In foil, exposed to an additional $2.5\times 10^{17}(nvt)_f$. Hall coefficient and resistivity curves taken after each of these operations are shown in Fig. 3. The first exposure converts the sample to *n* type (Curves II) in the expected manner. The heat treatment presumably anneals the lattice defects, thereby causing an increase in both *n* and μ_n (Curves III). On further irradiation, the specimen being shielded from thermal neutrons, both the Hall coefficient and resistivity are increased (Curves IV). The results of the last two operations, in agreement with the findings for *n*-type material, indicate strongly that fast neutron induced lattice defects act as electron traps in InSb.

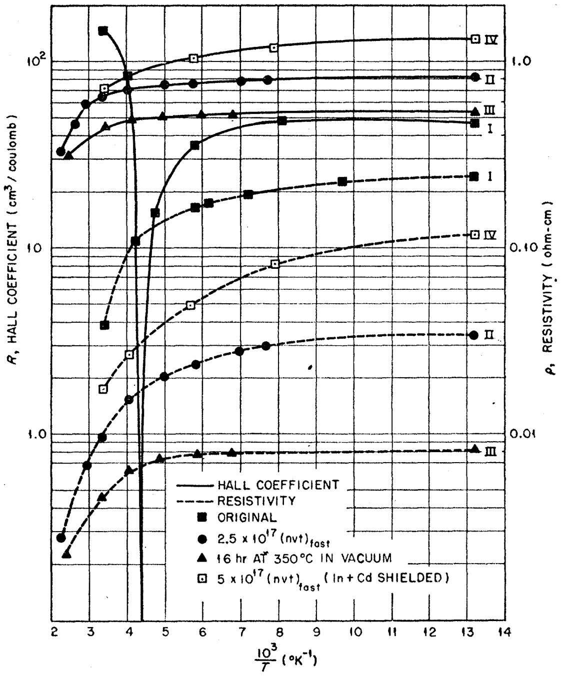

FIG. 3. Hall coefficient and resistivity of irradiated InSb. The Hall coefficient curves are denoted by *R* and the resistivity curves by *ρ*.

These preliminary studies indicate that (1) donor impurities are introduced into InSb by transmutations in the expected manner, and (2) lattice defects introduced by fast neutron bombardment act as electron traps in *n*-type material. Data are insufficient at the present time to show whether these defects behave predominantly as acceptors or hole traps in *p*-type material.

The authors wish to acknowledge the aid of E. S. Schwartz who assisted in the bombardment work.

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[7] Because of the large capture cross section of In, there is an appreciable attenuation of the thermal neutron flux toward the center of the specimen. Hence the concentration of Sn impurity is expected to be significantly higher at the surface than at the interior of the specimen. Such an effect may possibly explain these anomalies, since one might expect the Hall voltage of a *p*-type interior and that of an *n*-type exterior to neutralize each other to some extent.

Incoherent Neutron Scattering by Polycrystals

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IN evaluating the total incoherent cross section σ of a polycrystal, it is customary to decompose σ into partial cross sections σ_l for the production or destruction of l phonons:

$$\sigma = \sum_{l=0}^{\infty} \sigma_l. \tag{1}$$

The convergence of (1) becomes progressively poorer with increasing neutron energy and the structure of the higher terms is exceedingly complicated.[1] Furthermore, it results from the extensive numerical calculations of Squires[2] for magnesium that in this case, at a temperature about twice the Debye temperature θ, the terms with $l>1$ give a sizable contribution to the cross section even at zero-incident neutron energy.

The separate consideration of one-phonon processes has some merit in the study of the energy distribution of the scattered neutrons and of coherent effects.[3] Because of the existence of strong compensation effects, however, (1) is not a reasonable expansion for the total incoherent cross section. This may be illustrated by the example of the static approximation, which neglects the energy changes in the scattering process. Here σ is independent of neutron energy and temperature, while the partial cross sections σ_l depend on these quantities by

$$\sigma_l/\sigma = \frac{1}{l!}\frac{1}{x}\int_0^x t^l e^{-t}dt = x^{-1} - e^{-x}\sum_{m=0} \frac{x^{m-1}}{m!}, \tag{2}$$

with $x = 4k^2\alpha(T)$. (k is the wave number of the incident neutron, $\alpha(T)$ the mean-square nuclear displacement, and T the temperature.)

In a previous paper[4] a simple asymptotic expression for the cross section has been derived without recourse to (1) and has been explicitly evaluated in the Debye approximation. For heavy nuclei this expression holds as soon as the neutron energy is slightly larger than the Debye temperature, and for lighter nuclei at somewhat higher energies. There remains, however, the problem of finding a simple and accurate representation of the cross section valid for all energies. This may be achieved by using a procedure, which has previously been discussed for the particular case of an oscillator at zero temperature.[4] It consists in expressing the neutron variables (wavelength, velocity) in terms of the neutron energy E and thereupon expanding the cross section in powers of the ratio M^{-1} of neutron to nuclear mass:

$$\sigma = s + \sum_{n=1} \sigma^{(n)} M^{-n}, \tag{3}$$

where s is the bound incoherent nuclear cross section. In contrast to (1), the expansion (3) converges rapidly for all energies provided that M is moderately large compared to both one and T/θ. Under these conditions, which are well satisfied in most practical cases for temperatures right up to the melting point, σ is well represented at all energies by

$$\sigma = s + \sigma^{(1)}/M + \sigma^{(2)}/M^2, \tag{4}$$

and often the contribution of $\sigma^{(2)}$ amounts to a small correction only. Furthermore, the structure of $\sigma^{(1)}$ and $\sigma^{(2)}$ is considerably simpler than even that of σ_1 and σ_2, and thus the evaluation of the cross section in the Debye approximation becomes a relatively easy matter.

TABLE I. The coefficients in the expression (5) for the cross section.

n	a_n	b_n	c_n	d_n	e_n	f_n	g_n
0	1.2	0.4286	0.0556	1.3221	2.1141	0.7410	−0.1044
2	5	1.5	0.1786	−8.0590	3.8562	1.6600	0.1877
3	−12	0	−0.3333	0	0	0	0
4	5.25	0.825	0.0825	−41.042	−5.439	−1.262	0.2666
5	0	0	0	96	0	5.333	0

The following results for the particular case of low energy and high temperature ($E \ll \theta$, $T \gg \theta/2\pi$), which is of frequent experimental interest,[2,5] may serve to illustrate the advantages of the method, which of course come even more fully into play at higher energies.

$$\sigma^{(1)} = s \sum_{n=0,2,3,4} \lambda^{1-n}(a_n T - b_n + c_n T^{-1}) + O(\lambda^{-5}),$$
$$\sigma^{(2)} = s \sum_{n=0,2,4,5} \lambda^{1-n}(d_n T^2 - e_n T + f_n + g_n T^{-1}) + O(\lambda^{-5}). \tag{5}$$

Here T is measured in units of θ, and $\lambda = (\theta/E)^{\frac{1}{2}}$ is the neutron wavelength in dimensionless units. The coefficients are given in Table I.

For Mg, taking $\lambda = 5.94$, $T = 2.05$, Squires[2] calculates σ by using six terms in (1). The terms with $l > 1$ amount to 46 percent of σ_1. His result is in agreement with that obtained from (4) and (5), with the $\sigma^{(2)}$ term amounting to only half a percent of the $\sigma^{(1)}$ term.

The results for general energy and temperature, which will be given in a forthcoming paper, provide a detailed answer to questions previously raised[6] about the energy dependence of the cross section.

The author is indebted to L. Van Hove and G. C. Wick for valuable discussions.

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[1] In the Debye approximation, expressions for σ_l for $l = 0$ and 1 have been given by J. M. Cassels [Progr. Nuclear Phys. 1, 185 (1950)] and for general l by Squires (reference 2).

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Color Centers in Alkali Silicate Glasses

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THE study of color centers in quartz and fused quartz was reported elsewhere.[1] We have extended our study to the color centers in silicate glasses which contain alkali ions.

We melted the glass from the purest chemicals (Merck for analysis except in the case of rubidium carbonate which is cp grade) in a platinum crucible in an electric furnace whose heater is platinum ribbon. The glass was annealed and polished. The increase of absorption resulting from irradiation with x-rays (45 kv, 10 ma, tungsten target) at room temperature was measured with a Beckman DU spectrophotometer at room temperature.

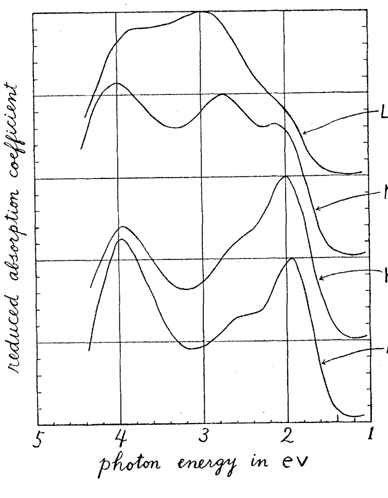

FIG. 1. Induced absorption bands in alkali disilicate glasses. The ordinate is the reduced absorption coefficient.

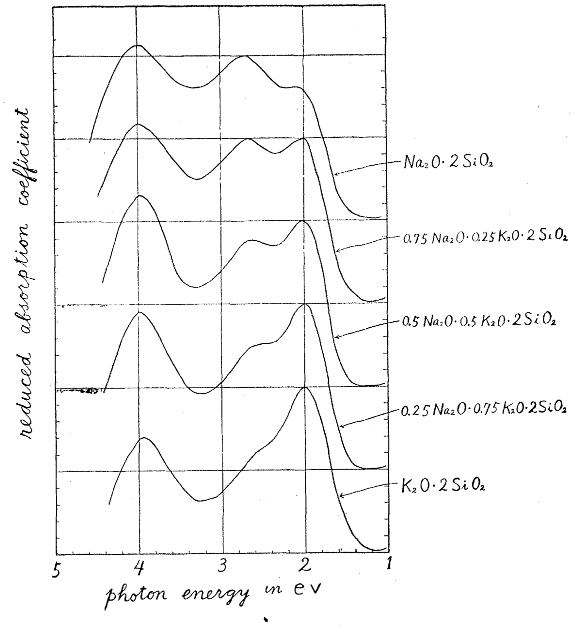

FIG. 2. Induced absorption bands in mixed alkali disilicate glasses. The ordinate is the reduced absorption coefficient.

The induced absorption bands in alkali disilicate glasses whose molecular compositions are $Li_2O \cdot 2SiO_2$, $Na_2O \cdot 2SiO_2$, $K_2O \cdot 2SiO_2$, and $Rb_2O \cdot 2SiO_2$, respectively, are given in Fig. 1.

From Fig. 1 it may be concluded that the visible bands are due to electrons trapped by oxygen vacancies which neighbor alkali ions.

To verify the above, we prepared the mixed alkali disilicate glasses whose molecular composition is represented as $x Na_2O$

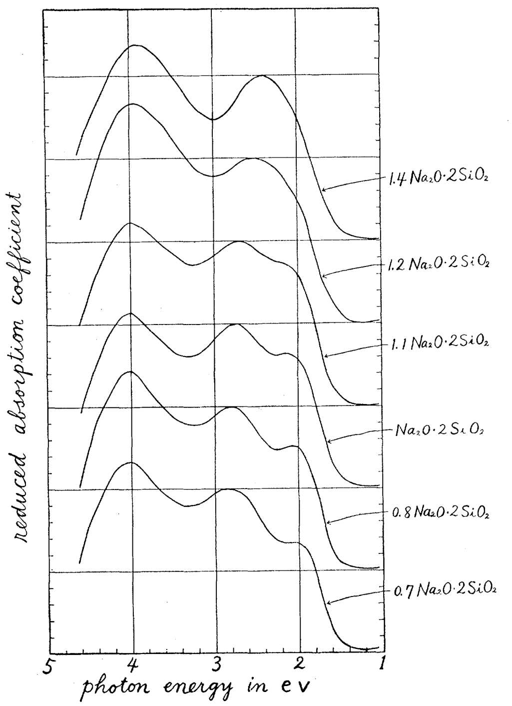

FIG. 3. Induced absorption bands of Na_2O-SiO_2 glasses. The ordinate is the reduced absorption coefficient.