be expected from the uncertainties in both the theory and the experiment.

Work has been done on a number of other materials including MnO, Cr_2O_3, and $ZnFe_2O_4$ and is being continued with a view to studying the dependence of the energy distribution on the temperature, the angle of scattering, and the degree of magnetic order. An account of this work will be submitted to the *Canadian Journal of Physics*.

The author is indebted to Dr. D. G. Henshaw for the excellent aluminum crystals used in these experiments.

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Annealing Process in Neutron-Irradiated LiF

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THE previous work[1] on neutron irradiated LiF crystals showed that the lattice expansion was caused by equal numbers of vacancies and interstitial atoms. It was also shown, by analyzing the annealing data for nonuniformly irradiated crystals, that the annealing process was of order higher than one. We will now derive a more exact order, an activation energy, and a jump frequency for the lattice defects causing the expansion by analyzing the annealing data for uniformly irradiated crystals.

As described previously,[1] two crystals were covered with 0.03 in. of cadmium during irradiation to insure a uniform irradiation. The lattice parameter changes as derived from density measurements, $(\Delta a/a)_\rho$, for the crystals after irradiation and after 10-minute anneals at successively higher temperatures, are summarized in Table I. The probable error in $(\Delta a/a)_\rho$ is $\pm 1.3\times 10^{-5}$, and the blank spaces represent anneals not performed.

TABLE I. The lattice parameter changes after irradiation and successive thermal anneals.

Condition	$10^4(\Delta a/a)_\rho$ Crystal Cd-3	Crystal Cd-4
Irradiated	8.02	8.51
315°C anneal	7.65	8.16
345	6.64	7.08
375	4.62	5.18
410	2.06	...
425	...	1.25

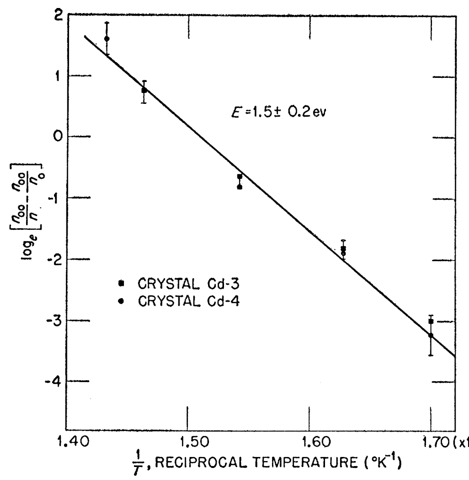

FIG. 1. Annealing data assuming a second-order process.

Assume that the lattice defects change position by a random walk process. Then if we have a single rate process with activation energy E for unit motion, the probability for taking one step at temperature T varies as $e^{-E/kT}$, and the rate of change of the total defect concentration n is

$$dn/dt = -cn^\gamma e^{-E/kT},$$

where c is a constant and γ is the order of the reaction. The solution of this equation for $\gamma > 1$ may be expressed in the form,

$$\log_e\{(n_{00}/n)^{\gamma-1} - (n_{00}/n_0)^{\gamma-1}\} = \log_e\{(\gamma-1)n_{00}^{\gamma-1}ct\} - E/kT, \quad (1)$$

where n_{00} is the defect concentration for the irradiated condition and n_0 is the concentration for the start of each anneal at temperature T.

We assume n is proportional to $(\Delta a/a)_\rho$ so that both n_{00}/n and n_{00}/n_0 may be determined from ratios of the data in Table I. Since the anneals were performed for a fixed time interval, the plot of $\log_e\{(n_{00}/n)^{\gamma-1} - (n_{00}/n_0)^{\gamma-1}\}$ *versus* $1/T$ should be a straight line for the correct order γ, and the slope should determine the activation energy. A straight line is obtained for $\gamma = 2$, as shown in Fig. 1, and the slope indicates an activation energy of 1.5±0.1 ev. The possibility of $\gamma = 1$ was eliminated in reference 1, and the plot for $\gamma = 3$ is curved as shown in Fig. 2. The annealing process is then of the second order as expected from the random recombination of non-neighboring, isolated vacancies and interstitials, or Frenkel defects.

Keating[2] has suggested that the irradiation-induced distortion cannot be due to isolated vacancies and interstitials, but to large aggregates of imperfections. His data show a lattice expansion only one-tenth as

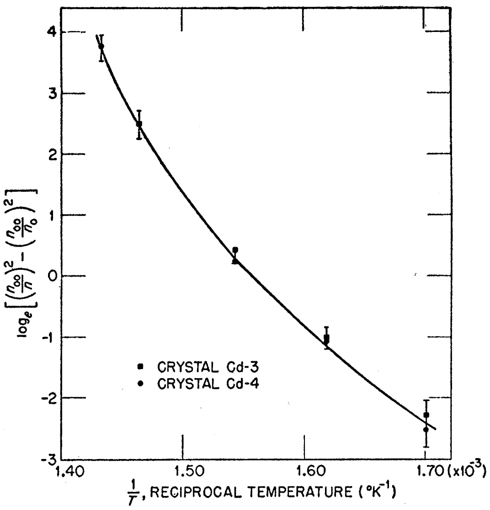

FIG. 2. Annealing data assuming a third-order process.

large as the data of reference 1 for equivalent irradiations. It is possible that the temperature of irradiation was much higher in Keating's experiment, annealing the lattice expansion.

The jump frequency, or frequency with which the defect takes an atomic step, may be estimated from our data. The fractional rate of decrease of the defect concentration is $-(1/n)(dn/dt)$, and the number of random atomic steps taken before a vacancy meets an interstitial is $1/n$. Therefore, the jump frequency is

$$\nu=-(1/n^2)(dn/dt)=ce^{-E/kT}.$$

For the temperature T_0 at which the left-hand side of Eq. (1) is zero, we have

$$c=(1/n_{00}t)e^{E/kT_0}.$$

The temperature T_0 may be obtained from Fig. 1, but n_{00} can only be estimated. We take n_{00} as equal to $(\Delta a/a)_p$ (for the irradiated condition) within an order of magnitude. Then $n_{00}\approx 8\times 10^{-4}$, $t=600$ sec, $1/T_0=1.52\times 10^{-3}$, and the jump frequency is

$$\nu\approx 6\times 10^{11}e^{-E/kT}\ \text{sec}^{-1}.$$

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Anisotropy of Bremsstrahlung and Pair Production in Single Crystals

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IT has been pointed out by Landau[1] that the Bethe-Heitler formulas for bremsstrahlung and pair production will need modification for electrons and photons of energy greater than 10^{12} ev passing through condensed matter. The Bethe-Heitler theory requires that charged particle and photon interact coherently over a path length of the order of

$$L=\lambda[1-(v/c)\cos\theta]^{-1}, \tag{1}$$

where λ is the photon wavelength, v the charged particle velocity, and θ the angle between the directions of charged particle and photon. When the charged particle energy E is relativistic, the angles of emission will in general be such that

$$L\sim\lambda E^2/m^2. \tag{2}$$

Landau observes that multiple Coulomb scattering will reduce the longitudinal distance traveled by the electron by

$$\Delta=KL^2/E^2, \tag{3}$$

over a path length L, where K is the Coulomb scattering constant of the material. The Bethe-Heitler theory will break down when $\Delta>\lambda$, i.e., when

$$K\lambda E^2>m^4. \tag{4}$$

In lead, this condition is satisfied for all photons when the electron energy reaches 5×10^{12} ev.

We here consider a quite different effect of the coherent path-length idea, which should be easily observable at energies of the order of 500 Mev, for example with the Cornell synchrotron beam. Suppose an electron is incident on a single crystal of lead, at an angle α to a line of nearest-neighbor atoms, i.e., at an angle $(90°-\alpha)$ to a (110) plane. The spacing of the atoms in the line is $d=3.5$ A. The number of atoms included within the path length (2) will be

$$N=(\lambda_0/d)(E/m)=7\times 10^{-3}(E/m) \tag{5}$$

for photon energy equal to E, and will be greater than this for photons of lower energy. Here $\lambda_0=24\times 10^{-11}$ cm is the Compton wavelength. Thus for $E=500$ Mev, $N\geq 7$ for all photons. Now a large matrix element for bremsstrahlung arises when the electron passes through an atom within the Thomas-Fermi screening radius

$$R=a_0Z^{-\frac{1}{3}}=1.2\times 10^{-9}\ \text{cm}. \tag{6}$$

When the angle α is less than

$$\alpha_0=(R/Nd)=137Z^{-\frac{1}{3}}(m/2\pi E)=0.3°, \tag{7}$$

the effective matrix element will be multiplied by N each time such a passage occurs, while the effective number of targets will be reduced by a factor N.

We expect therefore that the total bremsstrahlung intensity will be enhanced by a factor $N\sim 7$ when the electron beam is within 0.3° of a line of nearest neighbor atoms. Exact quantum-mechanical calculations are being undertaken to confirm the existence of the effect and to estimate its magnitude. Even if the crude classical argument in this letter is optimistic by a factor of