Expansion of LiF under Neutron Irradiation

D. BINDER AND W. J. STURM
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received March 27, 1957)

The strain gauge method is applied to the relative linear expansion of LiF under neutron irradiation. The result is $(9.9\pm0.3)\times10^{-5}$ per 10^{15} thermal neutrons. An estimate of the number of displacements is in adequate agreement with theory.

A RECENT review article[1] pointed to a disagreement in the literature about the existence of the neutron-induced lattice expansion in LiF,[2,3] which occurs as via the $Li^6(n,\alpha)H^3$ reaction. The work of Binder and Sturm[2] involved density and x-ray measurements of LiF single crystals irradiated with 6×10^{16} thermal neutrons/cm^2. Linear expansions on the order of 0.1% were observed, and the two measurements were shown to be equivalent to within 6%. It was then concluded that equal numbers of interstitials and vacancies were produced by the irradiation.

Keating[3] irradiated LiF crystals for 2×10^{17} and 8×10^{17} *nvt*. By x-ray examination, he observed no lattice expansion outside an experimental error of 0.01%. Mayer *et al.*[4] reported a monotonic expansion up to 0.17% at 3×10^{17} *nvt*, followed by a decrease in the expansion to 0.06% at 10^{18} *nvt*, and to no expansion within an error of 0.02% at 7×10^{18} *nvt*.

A possible resolution of the disagreement between the first two papers, as Mayer pointed out, would be that the expansion observed by Binder and Sturm corresponded to the first stage ($<3\times10^{17}$ *nvt*), and the lack of expansion observed by Keating to the final stage of 10^{18} to 10^{19} *nvt*. This would involve, however, a confusion in the definition of neutron flux between Mayer and Keating involving an error of a factor of 10. The lack of expansion in Keating's work may also be explained by a high irradiation temperature, leading to annealing of the initial effect.

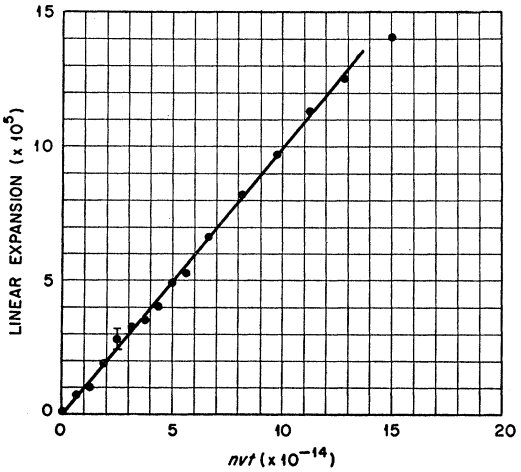

FIG. 1. Linear expansion of LiF *versus* integrated thermal neutron flux.

Since the interpretation of the first stage up to about 10^{17} *nvt* as resulting from equal numbers of vacancies and interstitials depends upon the existence of the expansion, we shall describe an independent method of observing this expansion. This method involves the use of strain gauges, which transform an extension into a resistance change. This allows a measurement of the initial expansion during neutron irradiation.

One Baldwin A5-1 strain gauge was glued with Duco cement to a LiF crystal (obtained from the Harshaw Chemical Company) and another to a fused quartz plate. Both specimens were $\frac{1}{2}$ in. by 1 in., and the LiF crystal was 0.02 in. thick, making the neutron attenuation through the thickness less than 5%. The Baldwin strain indicator used in the measurements gives the ratio of the linear expansions of the LiF crystal to that of the fused quartz control. Since the dimensional changes of the fused quartz plate produced by both neutron irradiation[5] and temperature variations are negligible for this exposure range, the strain indicator gives the linear expansion of the LiF.

The two samples were placed in the ORNL Graphite Reactor, along with a thermocouple for temperature corrections and a cobalt thermal flux monitor. The strain gauges are reliable for as small an irradiation as 10^{15} *nvt*, and, in addition, any uniform small shift in their operating characteristics caused by the irradiation is canceled by the fact that the ratio of two resistance changes is always measured.

The results of the measurements during exposure are shown in Fig. 1, and the linear expansion is $(9.9\pm0.3)\times10^{-5}$ per 10^{15} thermal neutrons/cm^2 at 60°C. If it is assumed, as a rough estimate, that 1% Frenkel defects cause a 1% linear expansion, then there were 1.4×10^3 displacements per (n,α) reaction. This is in adequate

[1] J. W. Glen, *Advances in Physics* (Taylor and Francis Ltd., London, 1955), Vol. 4, p. 381.
[2] D. Binder and W. J. Sturm, Phys. Rev. **96**, 1519 (1954).
[3] D. T. Keating, Phys. Rev. **97**, 832 (1955).
[4] Mayer, Perio, Gigon, and Tournarie, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 7, p. 647.
[5] Primak, Fuchs, and Day, J. Am. Ceram. Soc. **38**, 135 (1955).

agreement with Seitz and Koehler's theoretical estimate[6] of 1.9×10^3.

The strain gauge data confirm the existence of a neutron induced expansion in LiF. It also indicates that there is a strong saturation of the effect at 6×10^{16} *nvt*, where the expansion[2] averages 2×10^{-5} per 10^{15} thermal neutrons/cm^2. The results of Mayer *et al.*,[4] previously cited, show a continuation of this saturation at 3×10^{17} *nvt*, where the expansion averages 5×10^{-6} per 10^{15} thermal neutrons/cm^2.

[6] F. Seitz and J. S. Koehler, *Solid State Physics* (Academic Press, Inc., New York, 1956), Vol. 2, p. 445.

PHYSICAL REVIEW VOLUME 107, NUMBER 1 JULY 1, 1957

Stark Effect on Cesium-133 Hyperfine Structure*

R. D. HAUN, JR.,† AND J. R. ZACHARIAS
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received March 28, 1957)

The change of the hyperfine-structure separation energy caused by an electric field has been measured in Cs^{133} by the atomic-beam magnetic-resonance method. The shift of the $(F=4, m_F=0)\leftrightarrow(F=3, m_F=0)$ transition frequency in the electric field $\mathcal{E}$ is given by

$$\Delta(\mathcal{E})=-2.29\times10^{-6}(1\pm0.03)\,\mathcal{E}^2 \text{ cps},$$

where $\mathcal{E}$ is in volts/cm. This number is 2.8 times the value predicted from the atomic polarizability measurements of Scheffers and Stark if a simplified theory which neglects hyperfine-structure perturbations of the ground-state wave functions is used.

As a continuation of the high-precision atomic hyperfine-structure measurements made in this laboratory in recent years, the effect of an electric field on the hyperfine-structure energy levels of Cs^{133} has been examined.

The increase $\Delta(\mathcal{E})$ of the

$$(F=4, m_F=0)\leftrightarrow(F=3, m_F=0)$$

transition frequency (for the ground state of Cs^{133}) has been measured in electric fields between zero and 6.7×10^4 volts/cm by the atomic-beam magnetic-resonance technique. The transition frequency for zero electric and magnetic fields is[1] 9 192 631 830$\pm$10 cps. The maximum observed shift of this transition frequency caused by the electric field was approximately 4×10^3 cps. The line widths for the resonance curves obtained in these measurements were approximately 120 cps.

The $(4, 0)\leftrightarrow(3, 0)$ transition was induced by using the Ramsey two-transition-region method,[2] with two microwave cavities separated by a distance $L_{rf}=78.4$ cm along the beam. The electric field was obtained with a parallel-plate condenser of length $L_s=66.0$ cm, located between the two cavities. A crystal-stabilized klystron was used as the microwave source.

Figure 1 is a typical record of the data. With the frequency increasing linearly (toward the right in the figure) a resonance curve was first traced out with the electric field $\mathcal{E}=3.48\times10^4$ volts/cm; then, without changing either the rate or direction of the frequency variation, the electric field was turned off and a resonance curve for $\mathcal{E}=0$ was traced out. The upper horizontal straight line on the record indicates that the electric field is on; the lower line, that the field is off. The markers on the lower margin of the data record were obtained from a "frequency indexer" which put out a pulse each time the frequency changed by 60 cps.

The observed shift $\bar{\Delta}(\mathcal{E})$ of the resonance frequency can be obtained directly from the recorded data by counting the number of 60-cps markers between the two resonance peaks. For the data shown, $\bar{\Delta}(\mathcal{E})=2260$ cps.

Two corrections must be applied to $\bar{\Delta}(\mathcal{E})$ before obtaining the change $\Delta(\mathcal{E})$ of the atomic energy level separation caused by the electric field:

(1) The observed shift $\bar{\Delta}(\mathcal{E})$ of the resonance frequency must be increased by a small factor because the resonance pattern will be asymmetrical when the average energy level separation of an atom in the region between the two transition cavities is not equal to the energy level separation in the cavities. Detailed lineshape calculations (which have been compared with the experimentally observed resonance shapes) indicate that this asymmetry decreases the apparent resonance frequency by $\bar{\Delta}(\mathcal{E})(l_{rf}/L_{rf})+K(B_{rf})$, where l_{rf} is the length of each cavity (1.27 cm), and $K(B_{rf})$ is a correction factor which depends on the magnitude of the

* This paper is based on a thesis submitted by R. D. Haun, Jr., to the Department of Physics, Massachusetts Institute of Technology, 1957, in partial fulfillment of the requirements for the degree of Doctor of Philosophy; the work was supported in part by the U. S. Army (Signal Corps), the U. S. Air Force (Office of Scientific Research, Air Research and Development Command), and the U. S. Navy (Office of Naval Research).

† Now at the Westinghouse Research Laboratories, Churchill Boro, Pittsburgh 35, Pennsylvania.

[1] L. Essen and J. V. L. Parry, Nature **176**, 280 (1955).

[2] N. F. Ramsey, Phys. Rev. **78**, 695 (1950).