Rev. Mod. Phys. 36, 216 (1964).

[2]P. G. De Gennes, Phys. Lett. 5, 22 (1963).

[3]P. G. De Gennes, *Superconductivity of Metals and Alloys* (Benjamin, New York, 1966), Chap. 7.

[4]J. D. Clarke, Proc. Roy. Soc., Ser. A 308, 447 (1969).

[5]J. E. Zimmerman and A. H. Silver, Phys. Rev. 141, 367 (1966).

[6]A. H. Silver and J. E. Zimmerman, Phys. Rev. 157, 317 (1967).

[7]J. S. Langer and V. Ambegaokar, Phys. Rev. 164, 498 (1967).

[8]R. O. Zaitsev. Zh. Eksp. Teor. Fiz. 50, 1055 (1966) [Sov. Phys. JETP 23, 702 (1966)].

[9]Referring to Table I we note that the solution in region A is such that $f_\infty^2 > \frac{2}{3}$ which means that the current density never reaches its critical value $J_c = 2\sqrt{3}/9$ in region A. It is possible to show analytically that the solution in region B is of type 1 for $1-f_0^2 \ll 1$ and of type 2 for $f_0 \ll 1$; it switches from one to the other at a value of $f_0^2 > \frac{2}{3}$ such that $J = \gamma^{1/2} f_0 (1-f_0^2)^{1/2}$. Other solutions were also found, but were rejected because they were not bounded (for $f_\infty^2 < \frac{2}{3}$), or could not be matched to the well-behaved solution in region A.

[10]Yu. G. Mamaladze and O. D. Cheishvili, Zh. Eksp. Teor. Fiz. 50, 169 (1966) [Sov. Phys. JETP 23, 112 (1966)].

[11]That $f_\infty < 1$ is an artifact of our one-dimensional model. Under actual experimental conditions, a weak link between bulk superconductors and the current flowing on the surface of the bulk superconductor, Δ should reach its equilibrium value ($f \rightarrow 1$ and $\varphi = \text{const}$) roughly within a coherence distance away from the junction. The cutoff X_c in expression (4) can be introduced to correct for this artifact. The actual $J(\varphi)$ curves should appear skewed to the right, as a result of a corresponding correction $2X_c(1-f_\infty^2)^{1/2}$ to the phase, but this has a negligible effect for sufficiently small γ, e.g., the slope $(dJ/d\varphi)_{\varphi=\pi}$ can be shown to be $\frac{1}{2}(X_c + d/\gamma)^{-1} \sim \gamma/2d$ for $d \gg \gamma$.

[12]It is not clear whether the portion of the $J(\varphi)$ curve beyond the maximum J_m corresponds to a physically realizable equilibrium solution. Theoretical considerations for a homogeneous superconductor carrying a uniform current show that the decreasing part of the corresponding $J(p_s)$ curve is unstable irrespective of load-line considerations. {See L. G. Aslamazov and A. I. Larkin, Pis'ma Zh. Eksp. Teor. Fiz. 9, 15 (1969) [JETP Lett. 9, 87 (1969)]. In the limit $\gamma = 1$, the corresponding part of our $J(\varphi)$ curve corresponds to the "saddle-point" solution considered by Langer and Ambegaokar, Ref. 7.} The relevant fluctuations may be stabilized in a short link, however [see A. Schmid, J. Low Temp. Phys. 1, 13 (1969)].

[13]Aslamazov and Larkin, Ref. 12.

[14]J. E. Lukens and J. M. Goodkind, Phys. Rev. Lett. 20, 1363 (1969).

[15]D. E. McCumber, Phys. Rev. 181, 716 (1969).

X-RAY DIFFRACTION DURING SHOCK-WAVE COMPRESSION*

Quintin Johnson, A. Mitchell, R. Norris Keeler, and L. Evans
Lawrence Radiation Laboratory, University of California, Livermore, California 94550
(Received 7 August 1970)

X-ray diffraction has been observed for the first time from material under shock compression. This was accomplished by directing a single pulse of x rays at LiF which was under compression from a shock wave, and observing the (200) diffraction line from the shock-compressed state. The experimental window for observing the effect was ~20 nsec; the pressure behind the shock front was ~130 kbar.

In recent work, Johnson, Keeler, and Lyle demonstrated that a Debye-Scherrer pattern can be produced in less than 100 nsec.[1] The x-ray device which is capable of this incorporates a pulsed x-ray generator built according to the principles of Blumlein[2] and Fitch and Howell.[3] The authors in Ref. 1 suggested that this device be applied to the study of materials undergoing shock compression; a report of first experiments towards that goal is published elsewhere.[4] Results of those experiments, while encouraging, were not conclusive because of the difficulty of reliably turning on the x-ray drive at the appropriate time. Using a Blumlein device which was modified to overcome this difficulty, however, we have clearly observed diffraction effects arising from the interaction of x rays and the shock-compressed state of LiF.

For this experiment, we made use of scintillation detectors described elsewhere.[5] These detectors, with a response time ~5 nsec, consisted of four channels, with the center point of each channel separated by 0.19 cm from its neighbor. The resolution of this detector system seriously limited accuracy but was sufficient to demonstrate without question that diffraction effects were observed from the shock-compressed state.

The experimental geometry is shown in Fig. 1. A high-explosive, plane-wave lens was boosted by a TNT pellet 1.27 cm thick. The resultant

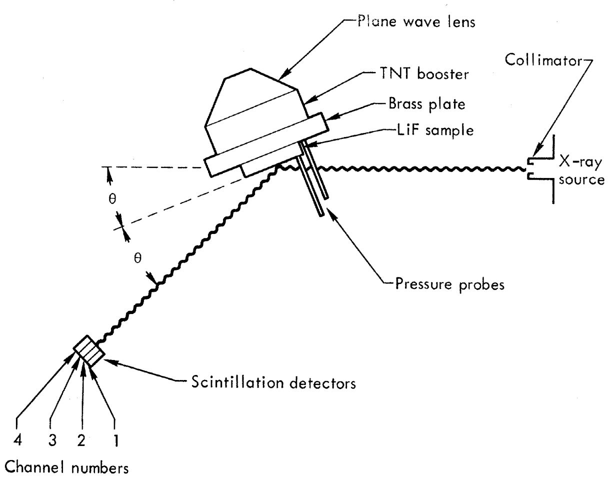

FIG. 1. Sample geometry for x-ray diffraction study of LiF under shock compression.

shock wave traversed a 0.6-cm brass plate before striking a 0.4-cm LiF sample. Two barium titanate pressure-sensitive probes were positioned at the front surface of the brass plate and were used to turn on the x-ray source and oscilloscopes. Another probe was positioned at the front surface of the LiF sample to monitor shock breakout. Shock velocity for this sample was determined from the measured interval time.

The sample was positioned at $22\frac{1}{2}$ deg with respect to the x-ray axis. The detector assembly, mounted on a 2θ arm, was positioned at an angle of about 45 deg. This angle was chosen so that most of the x rays diffracted from the (200) planes entered detector channel 4. The normal signal-to-background ratio for this sample, reflection, and detector is approximately 3.0.[5] A monitor detector, consisting of a single channel, was positioned to intercept a portion of the undiffracted beam. This monitor was used to calibrate the two x-ray pulses required for the experiment and also functioned as a timing check. Timing was further monitored by displaying on oscilloscopes the signals from the pressure probes and a Blumlein current probe.

The most crucial part of the experiment is to synchronize the x-ray pulse with the shock front. Because of x-ray absorption by the sample (95% of the diffracted Cu $K\alpha$ x rays come from the top 0.1 mm of the LiF sample), it is necessary to turn on the x rays just before the shock breakout from the sample; we attempt to do this 30 nsec before.

Two independent processes operate to frustrate the successful culmination of these attempts. First, it is difficult to turn on the x rays exactly when planned because of timing jitter associated with electrical components of the x-ray trigger system. This jitter is generally less than 10 nsec, however, so does not by itself prevent an experiment from being successful. Second, the shock transit time for a particular sample must be estimated beforehand. This cannot be precisely done because of sample variability, especially with regard to density. We found it impossible to obtain LiF samples with high and uniform density and, at the same time, small crystallite size: In general, the higher the density the spottier the diffraction pattern. Densities for our three samples varied from 2.54 to 2.58 g/cm^3. This compares with a theoretical density of 2.64 g/cm^3.

Three trial runs were carried out, with results as shown in Table I. The signal ratio in this table is the ratio of the signal observed during the shock event to that observed during a dry run without shock. The results clearly show that x rays were turned on too early for the second run. Data from this run are included, however, to demonstrate that signal ratios behave as expected when x rays are turned on early.

The two other trial runs were successful, with timing of the first better than the third. Shock transit time for the x-ray samples is difficult to measure because of the geometrical constraints imposed by the x-ray beam—no shadowing of the beam by pressure probes, etc.—and because of the elastic precursor wave in brass. We found the time interval between the signal from the pressure probe located at the front surface of the brass plate and the signal from the monitor x-ray detector to be within 5 nsec of the planned time, thereby assuring that the x rays would be timed properly if jitter arising from a poor estimate of the shock transit time did not interfere.

Considering the best possible case, for which timing is perfect, detector placement is ideal, etc., we would expect channel 2, positioned approximately to intercept the (200) line of the shock-compressed state, to increase by a factor of about 3.0 and channel 4 to show a decrease to one-third of its dry-run value. Measured ratios for these two channels for the first run were 2.6 and 0.7, respectively, remarkably close to the predicted values for an ideal case. The third run did not approach these values because of the timing error; nevertheless, it is in essential agreement with the first run when allowance is made for the fact that x rays were turned on too

Table I. Results of x-ray diffraction experiment.

Trial run	X-ray turn-on time (nsec before shock breakout)	Channel	Signal ratios (shock/dry run)
1	20	1	...[a]
		2	2.64
		3	1.28
		4	0.70
2	55	1	1.07
		2	0.99
		3	0.99
		4	1.04
3	40	1	1.25
		2	1.40
		3	1.21
		4	...[a]

[a]Signals lost; see text.

early. In runs 1 and 3, signals from one channel were lost because of base-line drift in the oscilloscope monitoring that channel.

The width of these detectors, when considered in relation to the diffraction geometry of the experiment, is such that a line shift from channel 4 to channel 2 corresponds to $\Delta 2\theta = 2.6$ deg. Calculation of the shock pressure using the measured shock velocity and Christian's[6] particle velocity for LiF indicates that the pressure near the front surface of the samples was 130 ± 15 kbar. While this detector system is obviously not capable of great resolution, we note that $\Delta 2\theta = 2.2$ deg can be calculated for this pressure if one assumes that hydrostatic conditions are achieved.

It is of interest to consider factors affecting the diffraction intensity from the shock-compressed state. Using the Dugdale-MacDonald relationship we calculate a shock temperature rise of $113 \pm 16°$ corresponding to a Debye temperature change of 31 %.[7] The intensity decrease brought about by the combined effect of a higher Debye-Waller factor and greater 2θ value amounts only to about 2 %. It is anticipated that the diffraction lines from the shock-compressed state are broadened by pressure gradients across the sample volume illuminated by the x-ray beam; however, it would not be possible to notice this effect with our detector system because of the relatively large aperture of each channel. Normally computed scattering factors no longer apply to atoms under compression. This problem will have to be resolved ultimately when quantitative data become available, but is of no concern at the present.

These results demonstrate that x-ray diffraction can be applied to the study of shock-wave compressed solids, since diffraction effects can be observed. There are at least two important deductions which derive from the observed effects. First, the fact that diffraction took place implies that crystalline order can exist behind the shock front and that the required ordering takes place on a time scale which is short compared with 20 nsec. Second, the location of the (200) reflection of shock-compressed LiF implies that on the unit cell basis this compression is isotropic; i.e., the shock compression is essentially hydrostatic.

We have shown that x-ray diffraction can tell us something about materials undergoing shock-wave compression; now it is necessary to devise a detector scheme capable of better resolution in 2θ in order to obtain quantitative data.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]Q. Johnson, R. N. Keeler, and J. W. Lyle, Nature 213, 1114 (1967).

[2]A. D. Blumlein, British Patent No. 589 127, 12 June 1947.

[3]R. A. Fitch and V. T. S. Howell, Proc. Inst. Elec. Eng. 3, 849 (1964).

[4]Q. Johnson, A. Mitchell, R. N. Keeler, and L. Evans, Trans. Amer. Crystallogr. Ass. 4, 133 (1969).

[5]Q. Johnson, A. Mitchell, and L. Evans, to be published.

[6]R. H. Christian, thesis, University of California, Lawrence Radiation Laboratory Report No. UCRL-4900, 1957 (unpublished).

[7]F. J. Rogers, Lawrence Radiation Laboratory Report No. UCRL-50500, 1968 (unpublished).