Reports

Formation of Diamond by Explosive Shock

Abstract. Samples of graphite have been recovered after exposure to explosive shocks of 300,000-atm estimated intensity. X-ray and electron-diffraction examinations prove the existence of diamond in this material. The mechanism proposed for the formation of diamond under these conditions is simple compression in the *c*-axis direction of the rhombohedral form of graphite.

In the course of a program to study the effects of explosive shocks on various minerals (*1*), samples of spectroscopically pure artificial graphite were exposed to shock pressures estimated at 300,000 atm for 1 μsec (*2*). The recovered fragments, which microscopically resembled the original material, were rather brittle and did not possess the greasy feel of normal graphite when ground in a mortar. When a piece of this material was rubbed between a polished sapphire and a glass slide, fine scratches appeared on both the glass and the sapphire. X-ray diffraction patterns of the shocked graphite and of control specimens were made with filtered iron radiation in a Phillips camera 114-mm in diameter. The pattern of shocked graphite showed three additional lines, weak and slightly broadened, which could be indexed as the (111), (220), and (311) diamond reflections. These are the only possible reflections from diamond with filtered iron radiation. The line positions coincided with a standard pattern of diamond powder made in the same camera, and the lattice spacing agreed with that reported by Swanson and Fuyat (*3*).

Some of this shocked graphite (*4*) was ground in a glass mortar to −325 mesh and centrifuged in bromoform, density 2.87 g/cm^3. Since the respective crystal densities of graphite and diamond are 2.25 and 3.5, only particles containing at least 50 percent diamond by volume could settle. X-ray-diffraction, electron-diffraction, and microscopic examinations were made of the dense fraction. With filtered copper radiation all the permissible diamond lines were observed. However, the lines were so broadened that the K-alpha doublet could not be resolved even for the (331) reflection. Transmission electron-diffraction patterns of individual particles were made with a Hitachi model HU-10 apparatus. One of these particles, about 1 μ^3 in volume, gave a pattern of partial-diffraction rings which corresponded to the first ten diamond reflections. Microscopic examination showed the particles to be small, generally 10 μ or less in diameter. In appearance, they resemble meteoritic carbonados.

Our most conservative estimates of temperature and pressure during the shock are well within the region of diamond stability. However, in the very short time at the pressure available in these experiments, it is unlikely that a mechanism involving wide-scale atomic movement and growth processes can be responsible for the graphite-diamond transition. A comparison of the structures of graphite and diamond reveals an available diffusionless mechanism for the transition.

The basic element of the graphite structure is a sheet of carbon atoms in which each atom is bonded to three other atoms at 120°C, forming a hexagonal network. These sheets are stacked in such a manner that alternate atoms in a sheet lie above the centers of the hexagons in the sheet below. There are two simple stacking arrays that meet this condition. In the more common hexagonal form of graphite the stacking is . . ABAB . .; that is, the atoms in the third sheet lie directly above the atoms in the first. In the rhombohedral form of graphite described by Lipson and Stokes (*5*) the stacking is . . ABCABC . .; that is, the atoms in the third sheet occupy a position symmetrically related to the first two.

It has been pointed out that the arrangement of atoms in diamond differs from rhombohedral graphite only in two respects (*6*). In diamond the sheets of hexagons are puckered and they are much closer together, 2.06 A in diamond versus 3.35 A in graphite. It appears that a simple compression in the stacking (*c*-axis) direction would suffice to convert rhombohedral graphite to a form very close to diamond. To complete the transition the sheets must now become puckered, which requires that each atom move only about 0.25 A.

In the shock-loading experiments a commercial artificial graphite was used. X-ray patterns of this material reveal that it is predominantly hexagonal graphite, but there is considerable disorder in the structure. Comparison of our patterns with Franklin's published patterns (*7*) indicates that this graphite contains about 20 percent disordered structure. It is probable that some of this observed disorder is due to the presence of small domains of rhombohedral graphite.

We propose that the graphite-to-diamond transition observed in our experiments took place in properly oriented domains of rhombohedral graphite in the manner already described. In support of this mechanism is the fact that we have not yet been able to detect diamond in shock-loaded specimens of pure hexagonal graphite. The failure of Riabinin (*8*) to form diamond in a similar shock-loading experiment may have been due to a lack of the rhombohedral phase in his original material (*9*).

PAUL S. DECARLI
Poulter Laboratories, Stanford Research Institute, Menlo Park, California

JOHN C. JAMIESON
Department of Geology, University of Chicago, Chicago, Illinois

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper.

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to contributors" [*Science* **125**, 16 (1957)].

References and Notes

- P. S. DeCarli and J. C. Jamieson, *J. Chem. Phys.* **31**, 1675 (1959); P. S. DeCarli, R. J. P. Lyon, J. C. Jamieson, manuscript in preparation.
2. We do not have sufficient equation-of-state data for graphite to permit refined calculations of temperature and pressure during the shock.
3. H. E. Swanson and R. K. Fuyat, *Natl. Bur. Standards U.S. Circ. No. 539* (1954), vol. 2.
4. The formation of diamond in shock-loaded graphite has been observed repeatedly and reproducibly in the Poulter Laboratories during the past 1½ years. Work is in progress to test the proposed mechanism and to define more accurately the pressure and temperature in the specimens during the shock.
5. H. Lipson and A. R. Stokes, *Proc. Roy. Soc. London* **A181**, 101 (1942).
6. A. F. Wells, *Structural Inorganic Chemistry* (Oxford, New York, ed. 2, 1951); K. Lonsdale, *Rend. seminar. fac. sci. univ. Cagliari* **29**, suppl. (1960).
- R. E. Franklin, *Acta Cryst.* **4**, 253 (1951).
8. Iu. N. Riabinin, *Zhur. Tekh. Fiz.* **26**, 2661 (1956).
9. This work was performed while one of us (J.C.J.) was a guest at the Poulter Laboratories. We thank Thomas C. Poulter, director of the Poulter Laboratories, for his advice and support. We also thank E. Anders, University of Chicago, for convincing us that the transition was feasible, and B. Alder of Lawrence Radiation Laboratory for some of his unpublished experimental results.

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Role for Ganglionic Norepinephrine in Sympathetic Synaptic Transmission

Abstract. Transmission of nerve impulses in superior cervical sympathetic ganglia of cats and rabbits is markedly enhanced after reserpine-induced depletion of ganglionic norepinephrine. Transmission is also enhanced by administration of adrenergic blocking agents. In contrast, reserpine-induced release of ganglionic norepinephrine in animals pretreated with a monoamine oxidase inhibitor results in a pronounced depression of ganglionic transmission, which lasts until the ganglionic norepinephrine disappears. These results support the concept that norepinephrine in ganglia modulates the action of acetylcholine.

The fact that stimulation of preganglionic sympathetic nerves releases catecholamines from ganglia (*1*), together with the recent discovery that sympathetic ganglia contain considerable amounts of norepinephrine (*2*), prompts speculation on the role of the amine in the regulation of synaptic transmission. In this regard, Marrazzi and others have demonstrated that the injection of epinephrine and norepinephrine causes inhibition of ganglionic transmission (*3*). However, conclusions concerning the physiological role of a naturally occurring amine are questionable when they are based on studies of the injected substance. For example, the injection of histamine and even serotonin, a substance absent from sympathetic ganglia, also modifies ganglionic transmission (*4*).

We decided that a more direct approach to studying the role of norepinephrine in ganglia would be to compare synaptic transmission before and after depletion of the amine. The present report describes experiments which implicate ganglionic norepinephrine as a modulator of transmission in sympathetic ganglia. In these experiments changes in synaptic transmission were measured in cats and rabbits under chloralose anesthesia by applying graded electrical stimuli to the superior cervical sympathetic nerve and recording the electrical activity postganglionically before and after the intravenous injection of reserpine in various doses. The norepinephrine content of the superior cervical sympathetic ganglion was determined by a specific fluorimetric procedure which measures total (bound plus free) catecholamine and detects as little as 0.040 μg of amine (*5*).

Reserpine in doses up to 0.2 mg/kg had no effect on ganglionic transmission; a definite increase was produced with 0.6 mg/kg, and maximal enhancement with 1.25 mg/kg. In control animals not given reserpine, the evoked potential remained relatively constant over a period of 20 hours. As shown in Table 1, facilitation of synaptic transmission was associated with a reduction in the level of amine of more than 90 percent.

Table 1. Norepinephrine concentration in cat superior cervical ganglia 4 hours after administration of various doses of reserpine. The drug, dissolved in water as the lyophilized phosphate salt, was given intraperitoneally, and the animals were killed 4 hours later. Norepinephrine concentrations are mean values, and numbers in parentheses indicate the number of animals.

Dose of reserpine (mg/kg)	Norepinephrine content ($\mu g/g$)
	7.1 (16)
0.005	6.9 (4)
0.025	5.0 (8)
0.050	3.0 (6)
0.200	1.0 (8)
0.600	< 1.0 (6)

Figure 1 (typical of 12 experiments) shows the postganglionic response evoked by submaximal and supramaximal stimuli at various times after administration of reserpine (2.5 mg/kg). After a latent period of about 4 hours the evoked potential was definitely higher than the control value; it continued to increase and was maximal in about 7 hours. The enhancement of the potential persisted throughout the 12 hours of the experiment. In

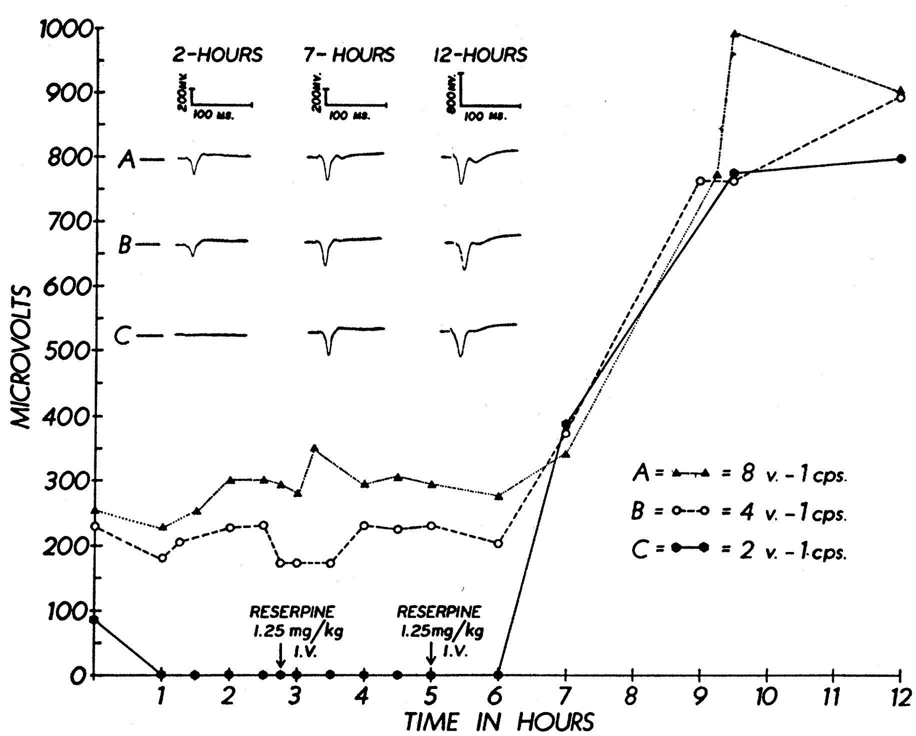

Fig. 1. Effect of reserpine on amplitude of postganglionic potential in response to graded electrical stimuli applied preganglionically to superior sympathetic ganglion. Stainless steel electrode pairs were used. Subthreshold (2 volts, 1 cy/sec, 0.01 msec) and supramaximal (8 volts, 1 cy/sec, 0.01 msec) stimuli were applied in control period. Reserpine (2.5 mg/kg) was administered in divided doses at the indicated times. Records of 10 potentials, 1 second apart, measured at 2, 7, and 12 hours (upper left of the figure), indicate the reproducibility of the response. Note the reduction in amplification required to record the 12-hour response.