Table 1. Cosmogenic radioactivities in the Bondoc meteorite. The nodule, of mass 120 g, contained 84 percent iron and 7.7 percent nickel; the silicate phase, of mass 360 g, contained 33.9 percent iron and 3.19 percent nickel.

Isotope	Activity ($dpm\ kg^{-1}$)	
	Nodule	Silicate
Be^{10}		1.8 ± 0.3
Al^{26}		6.0 ± 0.9
Mn^{53}	106 ± 7	43 ± 4
Ni^{59}	52 ± 6	≤ 40
Cl^{36}	3.0 ± 0.9	

A comparison of Be^{10} and Al^{26} in the stone phase yields a similar conclusion. If the Be^{10} activity has been reduced to 10 percent of its value at saturation, because of great terrestrial age, then an age of 9×10^6 years is indicated, sufficient to eliminate measurable Al^{26}.

This leaves only shielding as the major cause of the low activities. From a radiochemical analysis of stone meteorites (*7*) we would expect, in a shielded sample containing 1.8 dpm Be^{10} per kilogram of Bondoc silicate, about 6 dpm Al^{26}, and 35 dpm Mn^{53}; these values are in good agreement with the activities observed in the stone phase of Bondoc. The expected Ni^{59} activity is quite uncertain but should probably be in the neighborhood of 1 dpm g^{-1} nickel, or 32 dpm kg^{-1} silicate. The observed Cl^{36}, Mn^{53}, and Ni^{59} activities in the nodule are compatible with a depth of 20 to 25 cm in a very large iron (*5*) or approximately 50 cm in a smaller stony-iron.

Assuming that the recovered Bondoc meteorite represents the center of the original body, we can estimate a lower limit for the pre-atmospheric mass. Our measurements were made on a fragment from the outer portion of the 890-kg mass recovered (equivalent to a stony-iron sphere of about 35-cm radius). Approximately 30 cm of stony-iron material would be required to equal the shielding effect of 20 to 25 cm of nickel-iron. The resulting 65-cm-radius stony-iron would have a mass of about 7000 kg.

In an independent calculation, we assumed that the primary cosmic radiation is attenuated in a meteorite with a mean absorption of 200 g cm^{-2} and found that a pre-atmospheric mass of greater than 6000 kg is necessary to account for the factor-of-ten attenuation in Be^{10} and Al^{26} activities, assuming logarithmic dependence of specific activity on depth. Since both the Be^{10} and Al^{26} are produced in significant amounts by secondary flux in stone meteorites (which increases initially with depth before dropping off), this last assumption is not completely valid; that is, the result is probably low. If the Bondoc specimen did not come from the center of the original body, then, by either calculation, the pre-atmospheric mass was greater than 6000 to 7000 kg.

Table 2. Stable rare-gas isotopes in the silicate phase.

Isotope	Concn. ($10^{-8}\ cm^3\ g^{-1}$)*	
	Cobb (*2*)	Hintenberger (*3*)
He^3	9.12	8.28
He^4	169	206
Ne^{20}	2.8	1.75
Ne^{21}	2.9	1.75
Ne^{22}	3.0	1.68
Ar^{36}	1.12	
Ar^{38}	0.68	
Ar^{40}	330	

* Standard temperature and pressure.

PHILLIP J. CRESSY, JR.*
JULIAN P. SHEDLOVSKY†

Department of Chemistry, Carnegie Institute of Technology, Pittsburgh, Pennsylvania

References and Notes

1. H. H. Nininger, *Science* **139**, 345 (1963).
2. J. C. Cobb, unpublished data (1964).
3. Von H. Hintenberger, H. Konig, L. Schultz, H. Wanke, *Z. Naturforsch.* **19a**, 327 (1964).
4. E. Anders, *Space Sci. Rev.* **3**, 583 (1964).
5. J. H. Kaye, dissertation, Carnegie Institute of Technology; *U.S. At. Energy Comm. Rept. NYO-8923* (1964).
6. M. Honda, S. Umenoto, J. R. Arnold, *J. Geophys. Res.* **66**, 3541 (1961).
7. P. J. Cressy, Jr., dissertation, Carnegie Institute of Technology; *U.S. At. Energy Comm. Rept. NYO-8924* (1964).
8. We thank J. H. Kaye for measuring the Ni^{59} activity in the stone phase, and J. C. Cobb for use of unpublished data. Research supported by AEC contract At (30-1)-844.
* Present address: Goddard Space Flight Center, Greenbelt, Md.
† Present address: National Center for Atmospheric Research, Boulder, Colo.

16 April 1965

Crystal Multiplication without Nucleation

Abstract. *Disk-shaped ice crystals grow out from the surface of polycrystalline ice in undercooled water. The rupture of the neck of the attached disk is a means of multiplying the number of viable crystals in the surrounding undercooled water. This is a source of frazil ice in streams and a source of new crystals in metal castings which are grain-refined by stirring.*

It has frequently been observed in metals (*1*) and water (*2*) that the number of crystals that are formed during freezing can be greatly increased by causing the liquid to move, in relation to the solid, while freezing is taking place. A process of multiplication of the crystals has been identified and studied in water which is undercooled (that is, water below its equilibrium temperature, 0°C). This process of crystal multiplication accounts for the phenomenon of frazil ice, and for the multiplication of growing crystals (that is, grain refinement) caused by the agitation of metal castings during freezing.

Disk-shaped ice crystals were observed to grow on the surface of bulk ice when the bulk ice was placed in slightly undercooled water. These disks only touch the surface of the bulk ice at one place on their periphery (Fig. 1). The disks remain circular during their growth and have been grown to a diameter of 1 cm (with a thickness of 0.7 mm) (*3*). A disk will sometimes be broken off by the force of buoyancy, and the point of attachment becomes the site for a new disk to grow. In this manner a single site can create two or three crystals per second, and these crystals trail away from the site much as bubbles trail away from a site in a beaker of boiling water where a crevice in the glass permits a vapor bubble to remain while new bubbles are generated (*4*). The "attached" disks have been described (*5*), but the important features for crystal multiplication are that (i) the disks grow with a fine bridge which is easily ruptured to set the disk free and (ii) a new disk grows at the site of detachment.

Frazil ice has been described (*6*) as being thin, free-floating, rounded ice disks which occur in streams and riv-

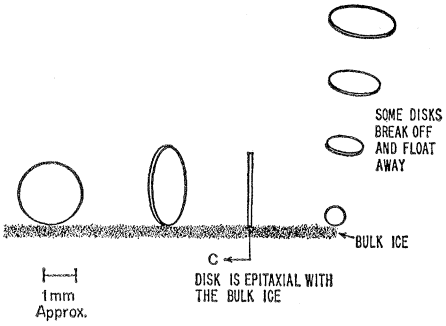

Fig. 1. The growth of attached crystals on polycrystalline bulk ice is observed when the latter is placed in contact with slightly undercooled water (0.01° to 0.03°C). At higher undercooling the growth becomes dendritic. This drawing represents a typical observation (Δ T = 0.2°C after 1 to 2 minutes).

ers when the water undercools. Turbulent streams and rivers in northern latitudes often are undercooled as much as 0.01°C because of the cooling effect of the free surface which is not covered with ice. There is always ice along the shore and at other places in such streams, and we suggest that the frazil-ice disks form on that ice and are pulled off into the stream.

Schaefer (*6*) reports a concentration of frazil ice approaching 10^6 disks per cubic meter on the Mohawk River where the air temperature was about −20°C and the wind velocity about 3 m/sec. These ice disks form large spongelike masses which gather on rocks and other underwater objects. When a chain, a series of vertical bars, or a wire screen is submerged in water containing frazil-ice particles in suspension, Schaefer reports a build-up on the upstream side which becomes quite thick and prevents water from getting past. This often happens at the trash racks at the intake of a hydroelectric generator system where the accumulation of frazil ice may be so rapid and the effects so damming that the complete power-generating system may be forced out of operation unless effective and continuing measures are employed to remove or prevent such build-up. Schaefer notes (*6*), "nothing is more dramatic than to witness a 30,000 kw hydro[electric] plant removed from the operating electrical network in less than an hour by the accumulation of these tiny frazil ice particles on the intake racks." There has been further research on frazil ice by Arakawa (*7*), but the mechanism of its formation in streams has not been established.

We propose a mechanism for the formation of frazil ice based on the observation of attached disks described above. The moving water in the stream is undercooled by its contact with the cold air, and there is a negative temperature gradient in the stagnant boundary layer on the bulk ice which is always present in the streams. The frazil-ice disks grow out of the ice much like those in Fig. 1, but they break off as they grow into the moving water and never reach the size shown there. The site at which the first disk breaks away is the site of formation of a new disk. This mechanism is capable of generating millions of disks in a very short time.

The same kind of mechanism could operate in metal castings, where grain refinement can be accomplished by stirring (*1*). If a gradient of the driving force for crystallization can be developed in the boundary layer on the solid-liquid interface, then conditions are favorable for growth of attached crystals (*5*). Growth must be retarded on the interface and increase as the attached crystals grow out into the moving liquid. The narrow neck which is characteristic of attached growth is easily ruptured by a small force on the crystal or melted by a current of warm liquid.

BRUCE CHALMERS
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts
R. B. WILLIAMSON
Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge

References and Notes

1. B. Chalmers, *The Principles of Solidification* (Wiley, New York, 1964), p. 278.
2. This is particularly evident in the "ice machine" constructed at Harvard University in 1957 for the 1958 Brussels World's Fair. The prototype of the Brussels machine has been used at Harvard for research on the growth of ice.
3. E. Miksch, Ph.D. thesis, Harvard University, 1963.
4. L. McG. Trefethen, film "Surface Tension in Fluid Mechanics" (Educational Services Inc., Watertown, Mass. 1963).
5. R. B. Williamson, Ph.D. thesis, Harvard University, 1964.
6. V. J. Schaefer, *Trans. Am. Geophys. Union* **31**, 885 (1950).
7. K. Arakawa, *J. Fac. Sci. Hokkaido Univ. Ser. II* **4**, No. 5, 311 (1954); **4**, No. 6, 355 (1955); *J. Glaciol.* **2**, 463 (1955).
8. Supported by AEC; presented in partial fulfillment of requirements for the Ph.D. degree at Harvard University by R.B.W.

25 March 1965

Xenon-Photosensitized Formation of Metastable Nitrogen

Abstract. *Metastable nitrogen molecules are produced by collision with xenon atoms excited with 1470-Å radiation. The photolytically excited species were detected by measuring the rate at which electrons were ejected from a gold surface. Hydrogen was shown to be more efficient than helium in quenching the photo-excited xenon atoms.*

The ejection of electrons from a gold surface by metastable atoms and molecules has been observed and used to study the collisional deactivation of xenon atoms excited by 1470-Å radiation. Nitrogen, hydrogen, and helium were used as collision partners in these deactivation studies.

The apparatus consisted of two parallel planar gold and nickel electrodes (0.5 cm apart) mounted at one end of a cylindrical glass vessel (12 cm in diameter). A lithium fluoride window (13 mm in diameter) was attached with Apiezon wax at the opposite end of the vessel, avoiding line-of-sight irradiation of the electrodes. Pressures of Xe, N_2, H_2, and He were measured with a thermocouple gauge calibrated for each individual gas. A pressure of 2×10^{-7} torr was attained prior to each set of measurements. The Ni electrode was maintained at 4 volts positive with respect to the Au, and currents were measured with an electrometer having a maximum full-scale sensitivity of 1×10^{-13} amperes.

The Xe resonance lamp was similar to the one described by Okabe (*1*). Absorption of the resonance radiation by atmospheric oxygen was avoided by causing dry nitrogen to flow between the windows of the lamp and the reaction vessel. A small amount of radiation scattering in the vessel resulted in a small photoelectric current of about 5×10^{-13} amperes. All current measurements made with absorbing gas present were corrected for this photoelectric effect.

Figure 1*a* is a graph of electron current flow from the Au to Ni electrodes as a function of Xe pressure. The exciting radiation is 1470 Å, since the interposition of a methane filter between the lamp and reaction vessel