heavy elements and heat is removed in the formation of Be^7, the equilibrium will favor the production of Be^7. Even if the system achieves equilibrium, the equilibrium will be displaced toward Be^7 by increased pressure, or temperature.

The reaction may always be rate controlled, however, and may never reach equilibrium during the collapse process.

Neutrons generated will be absorbed by the heavy elements present in the star. Nitrogen in particular has a (n,p) resonance of 0.1×10^{-24} cm^2 cross section at 550 kev. Since the most probable energy at 3×10^9 °C is 260 kev, and nitrogen may be expected to be present to an extent of 0.1 to 1 percent, nitrogen will be an important absorber.

After collapse the star becomes unstable and explodes, driving off a considerable fraction of its mass as an expanding gas cloud, probably leaving a core in a highly degenerate state. The exact mechanism of this explosion is not understood. Several possible mechanisms are: (a) the formation of a highly degenerate core, driving the outer layers away by radiation pressure;[4] (b) accelerated decay of Be^7 at increased electron density and the regeneration of helium from Li^7 and hydrogen; (c) rotational instability of the star.

The expanding gas envelope carries with it the Be^7 and C^{14} produced by the reaction. As the density drops, the thermal energy is radiated away as the initial maximum of the light curve. Thereafter the energy source is Be^7 ($T=52.9$ days), decaying according to the decay scheme of Fig. 1. The energy source will follow an exponential curve unless, (a) the diffusion of light to the surface of the gas envelope takes a long time compared to the radioactive life or, (b) the gas envelope becomes so tenuous as to permit appreciable loss of the 480-kev gamma-rays. In the case of two well-known supernovae, observed in 1054 A.D. and in 1937 in extragalactic nebula IC 4182, these restrictions were not found to be limiting from 40 days to 600 days past maximum. The quantity of Be^7 required for these stars was 3×10^{32} g.

After the decay of Be^7, the energy source may progress through intermediate periods, representing fortuitous neutron induced activities, but will rapidly approach the period of C^{14} ($T_{\frac{1}{2}}=4700$ years). In the case of the supernova of 1054 A.D. the gaseous envelope, the Crab nebula, is readily observed.[3] Its energy source corresponds to 10^{32} g C^{14}. Assuming an initial mass of 4×10^{34} g, the nebula should contain about 0.2 percent C^{14} and about 0.7 percent Li^7. Spectroscopic data show an unusually low abundance of hydrogen (<5 percent) but show helium, nitrogen and oxygen.[5] The abundances of these elements have not been derived from the spectrum.

Experiments will be initiated to measure the Be^7 yield from the (α,α) reaction. A more extensive discussion will be presented for publication in this Journal.

* This work was done at Brookhaven National Laboratory under the auspices of the AEC.

[1] W. Baade, Astrophys. J. **88**, 285 (1938); Astrophys. J. **102**, 309 (1945); F. L. Whipple, Proc. Am. Phil. Soc. **81**, 253 (1939).
[2] Duyvendak, Mayall, and Oort, Pub. Ast. Soc. Pac. **54**, 91 (1942).
[3] W. Baade, Astrophys. J. **96**, 188 (1942).
[4] J. R. Oppenheimer and H. Snyder, Phys. Rev. **56**, 455 (1939).
[5] R. Minkowski, Astrophys. J. **96**, 199 (1942).

The Chromium Isotope of Mass 55

DANIEL R. MILLER
Department of Chemistry and Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
April 21, 1950

THE isotope of chromium of mass number 55 has been reported by several investigators to be radioactive, with half-lives of 1.3, 1.6, and 2.3 hr.[1] These observations resulted from the bombardment of chromium with deuterons and slow neutrons, and the activity of about two-hour half-life was attributed to Cr^{55} resulting from a (d,p) or (n,γ) reaction. Most of these reports stated that the activity in question was weak. The absence of a chromium activity of about two-hour half-life among the spallation products of copper[2] and arsenic[3] with high energy deuterons has emphasized the need for further investigation of this assignment.

In order to clarify the situation, 6.0 g of manganese dioxide was irradiated for 2.7 hr. with neutrons of maximum energy 16 Mev, produced by bombarding lithium with 56 microampere-hours of 1.4 Mev deuterons. The irradiated MnO_2 was dissolved in a nitric acid-hydrogen peroxide mixture, inactive Cr^{+3} added as carrier, and the chromium fraction chemically separated and purified. The chemical procedure included $Cr(OH)_3$ precipitation, removal of manganese as MnO_2 from concentrated nitric acid, and several extractions of peroxychromic acid from dilute nitric acid into diethyl ether. One-tenth of the purified chromium fraction was mounted and counted with an end-window (*ca.* 3 mg mica/cm^2). Geiger-Müller tube at about 10 percent geometric efficiency. The activity observed 2.5 hr. after the end of the bombardment was not appreciably different from the background rate; a maximum of five counts per minute might have been due to radioactivity in the chromium sample. It should be pointed out that the counting system used would not have detected electrons of energy less than about 0.07 Mev. One would certainly expect, however, that a β^--emitter of several hour half-life would emit electrons having an energy appreciably greater than 0.07 Mev. Seren, Friedlander, and Turkel[1] report a mass absorption coefficient of 8.3 cm^2 per g of aluminum for the electrons of their 1.3-hr. activity, corresponding to an electron energy of one to two Mev.

The only unstable chromium isotope which could have resulted from this irradiation is Cr^{55}, produced by a (n,p) reaction on Mn^{55} (the only stable manganese isotope). The results of this investigation (assuming 100 percent counting efficiency) indicate that, if Cr^{55} has a half-life in the previously reported range (1.3 to 2.3 hr.), the cross section for its formation by $Mn^{55}(n,p)$ is less than 5×10^{-5} barn. Alternatively, if a cross section of greater than 10^{-2} barn is assumed, Cr^{55} would have to possess a half-life of less than 15 min. or greater than 100 days in order to have escaped detection.

Nelson and Pool[4] have recently reported results in agreement with these findings. They found no indication of a two-hour chromium isotope by a (d,p) reaction on Cr^{54}—enriched Cr_2O_3, nor by a (n,α) reaction on Fe^{58}-enriched Fe_2O_3. Present evidence therefore seems to offer no substantiation to the assignment of a one- or two-hour activity to Cr^{55}.

The author wishes to thank Mr. W. B. Dayton for his cooperation in performing the cyclotron bombardment.

[1] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947); Amaki, Iimori, and Sugimoto, Phys. Rev. **57**, 751 (1940); Dickson, McDaniel, and Konopinski, Phys. Rev. **57**, 351 (1940).
[2] Miller, Thompson, and Cunningham, Phys. Rev. **74**, 347 (1948).
[3] H. H. Hopkins, Jr., Phys. Rev. **77**, 717 (1950).
[4] M. E. Nelson and M. L. Pool, Phys. Rev. **77**, 682 (1950).

Temperature Dependence of the Energy Gap in Monatomic Semiconductors*

H. Y. FAN
Purdue University, Lafayette, Indiana
April 20, 1950

EXPERIMENTAL evidence indicates that the energy gap in a semiconductor depends upon the temperature. The long wave-length edge of the optical absorption band for both silicon[1] and germanium[2] shifts toward shorter wave-length as the temperature is decreased. The threshold of photoelectric effects in these materials shows corresponding shifts.[3] Furthermore, the variation of intrinsic concentrations of free electrons and holes in silicon, calculated from resistivity and Hall effect data, was found to lead to a temperature dependence of the energy gap.[4]

The volume of the crystal and the excitation of the lattice vibrations change with temperature. Both these effects can produce shifts in the energy levels, thereby changing the energy

TABLE I. Temperature dependence of the energy gap.

	C_c (ev)	C_f (ev)	β (degree^{-1})	$\partial E_G/\partial T$ (ev/degree) Eq. (6)	$\partial E_G/\partial T$ (ev/degree) Eq. (4)+Eq. (6)	$\partial E_G/\partial T$ (ev/degree) experimental
Silicon	9.75	16.9	10×10^{-6}	-1.78×10^{-4}	-5.3×10^{-4}	-4.7×10^{-4}[a] -3.0×10^{-4}[b]
Germanium	2.55	3.6	23×10^{-6}	-0.95×10^{-4}	-1.2×10^{-4}	-4.6×10^{-4}[c]

[a] See reference 1.
[b] See reference 4.
[c] See reference 2.

gap. The effect of volume dilation has been recently considered by Shockley and Bardeen.[5] We shall consider the effect of lattice vibrations, following the method used by Fröhlich and his co-workers[6] for polar crystals. The second-order perturbation gives

$$E(K)=E_0(K)+\sum_q\left[\frac{|H'_{K-q,K}|^2}{E_0(K)-E_0(K-q,n_q+1)}+\frac{|H'_{K+q,K}|^2}{E_0(K)-E_0(K+q,n_q-1)}\right], \quad (1)$$

where K is the electron wave number, n_q is the quantum number of the lattice vibration mode with wave number q, the subscript 0 refers to the unperturbed solution. The matrix elements have the usual expression.

$$H'_{K\pm q,K}=\mp i\frac{1}{N^{\frac{1}{2}}}\frac{2}{3}Cq\left(\frac{\hbar}{2M\omega_q}\right)^{\frac{1}{2}}\begin{Bmatrix}(n_q)^{\frac{1}{2}}\\(n_q+1)^{\frac{1}{2}}\end{Bmatrix}, \quad (2)$$

where N is the total number of unit cells, M is the atomic mass, and C is approximately constant for longitudinal modes and zero for transverse modes. For $kT>\hbar\omega_q$, the longitudinal acoustic waves give

$$E(0)-E_0(0)=-0.175C^2\Omega^{\frac{1}{3}}(mkT/\hbar^2Mc_l^2), \quad (3)$$

where Ω is the volume of the unit cell and c_l is the wave velocity. The value of C can be estimated from the mean free path due to lattice scattering as was done by Lark-Horovitz and Johnson.[7] For the conduction band C_c is to be estimated from electron mobility and m_c is the effective mass of the electrons. For the filled band C_f should be estimated from hole mobility and m_f is the effective mass of the holes with negative sign.

The more general variation method[6] gives an expression similar to (1) except that in the denominators $E_0(K)$ is replaced by $E(K)$. The result reduces (3) by approximately 20 percent. On the other hand, materials with a diamond structure, such as silicon and germanium, have optical branches of vibration. The frequencies of these vibrations are difficult to estimate, but it can be shown that their effect is less than one-third of (3). We shall take (3) as the first approximation. The reduction of the energy gap is then

$$\partial E_G/\partial T=-0.175(\Omega^{\frac{1}{3}}k/\hbar^2Mc_l^2)[m_cC_c^2+|m_f|C_f^2]. \quad (4)$$

The change in energy gap with lattice dilation as given by Shockley and Bardeen[5] is

$$E_{1G}\equiv\partial E_G/\partial(\Delta V/V)=E_{1c}-E_{1f}, \quad (5)$$

where

$$E_{1c}=\tfrac{2}{3}C_c, \quad E_{1f}=\tfrac{2}{3}C_f.$$

This effect alone should give

$$\partial E_G/\partial T=\tfrac{2}{3}(C_c-C_f)\beta, \quad (6)$$

where β is the volume coefficient of expansion. The net result should be the sum of (4) and (6).

The results of the calculations are presented in Table I. To facilitate comparison, the same values for C_c, C_f, β_{si}, and c_l are adopted as used by Shockley and Bardeen. The value of β_{ge} is taken from the tables of Landolt and Börnstein. It is seen that for silicon the lattice vibrations have larger effect in producing the temperature variation of the energy gap than the lattice dilation. For germanium it is smaller but not negligible. The calculated value for silicon agrees well with the experimental result of optical measurements. For germanium the calculated value seems to be too low. The optical measurements are now being repeated with greater precision. It must be pointed out that the values of C_c and C_f were calculated by taking the free electron mass for both m_c and m_f. More accurate knowledge of C's and m's is necessary for better estimation of $\partial E_G/\partial T$.

* Work assisted by a Signal Corps contract.
[1] M. Becker and H. Y. Fan, Phys. Rev. **76**, 1531 (1949).
[2] Measurement by M. Becker.
[3] M. Becker and H. Y. Fan, Phys. Rev. **78**, 301 (1950). Similar results have been reported by F. S. Goucher of Bell Telephone Laboratories.
[4] G. L. Pearson and J. Bardeen, Phys. Rev. **75**, 865 (1949).
[5] W. Shockley and J. Bardeen, Phys. Rev. **77**, 407 (1950).
[6] Fröhlich, Pelzer, and Zienau, Phil. Mag. **41**, 221 (1950). The author is indebted to Professor Fröhlich for discussions.
[7] K. Lark-Horovitz and V. Johnson (private communication).

On the Origin of the Cosmic Radiation from the Sun

K. O. KIEPENHEUER
Yerkes Observatory, University of Chicago, Williams Bay, Wisconsin
March 27, 1950

IT has been shown by Forbush,[1] Ehmert[2] and others that from certain solar flares in suitable heliographic positions there originates cosmic radiation which can be observed on the earth's surface. The intensity is of the order of 1 particle/(cm^2-sec.), the energy of the particles may be as large as 5×10^9 ev. The maximum of cosmic-ray intensity is often reached $\frac{1}{2}$ to 2 hr. after the intensity maximum of the flare itself (H_α).[3] Several explanations have been proposed: Swann[4] thinks that potential differences of the order of 10^9 to 10^{10} volts can be induced by the growth of magnetic fields in sunspots, and Bagge and Biermann[5] think that they can be induced by the observed relative movement of the spots with their fields. But we must not forget that the solar atmosphere in which these fields have to be set up shows an electric conductivity of the order of 10^{15} e.s.u. so that the acceleration path is practically short-circuited. It is generally assumed that the conductivity depends strongly on the presence of a magnetic field. The effect of this field is practically canceled by an electric field which is set up by the movement of charges perpendicular to the magnetic field, as has been pointed out by Schlüter.[6] We shall therefore always use the conductivity in the absence of a magnetic field.

Menzel and Salisbury[7] suggest that a solar flare could be the source of electromagnetic radiation of extremely long wave-length ($\lambda\gtrsim3\times10^{10}$ cm) the field of which is decreasing as $1/r$ at the earth's distance. This field would then be able to accelerate elementary particles to an energy of 10^9 ev or more. But here too it can be said that this radiation would be unable to escape the solar corona, or even to propagate in the interplanetary space with its conductivity of $\sigma\approx10^{12}$ e.s.u. This same objection holds for a proposal of Alfvén[8] which supposes the existence of an electric field inside a solar corpuscular beam producing geomagnetic storms and aurora. His mechanism also cannot explain why the cosmic-ray outburst comes more or less simultaneously with the solar flare.

It seems essential that the acceleration mechanism should affect only a limited number of charged particles. It seems to us that this limitation is merely the result of the high conductivity