Radiation-Induced Expansion of Semiconductors*

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GONSER and Okkerse[1,2] recently suggested that deuteron bombardment of GaSb and InSb crystals below −130°C introduced spikes having the higher density liquid configuration, which returned to the normal configuration upon warming to 20°C. Their x-ray measurements[1] seemed to support this hypothesis and indicated a lattice parameter increase accompanied by a dimensional contraction.

We have irradiated 3×3 mm areas of polished GaSb, InSb, and Ge crystals ∼1 mm thick with 9-Mev deuterons at temperatures below −130°C. At 20°C, after removing surface contamination,[3] surface contours were determined interferometrically.[4] After a flux (ϕ) of 3×10^{16} cm^{-2}, the bombarded GaSb surface (110) was visible elevated (even to the naked eye). A step surrounding a rounded plateau marked the bombarded region. A similar InSb specimen (110) surface exhibited no step but a hill-like elevation, while a Ge specimen ($\phi=3\times10^{16}$ cm^{-2}) showed no comparable elevation.

A GaSb specimen ($\phi=7.5\times10^{16}$ cm^{-2}) was examined at 20°C interferometrically and with x-rays. A step ∼0.3 micron high follows the bombardment boundary and the maximum elevation of the bombarded region is ∼2.0 microns. The unirradiated surface is tilted upward measurably at distances several mm from the boundary; here an abrupt $\frac{1}{8}°$ (maximum) increase in tilt occurs. The total volume increase is of the order of $\frac{1}{2}$% of the total irradiated volume. Both lattice-parameter increases and local tilting of the (110) planes were observed using a stationary and a moving film to record the reflected Cu$K\alpha$ beam as the crystal was turned through the fourth-order position. The beam was well collimated in the plane of incidence and divergent at right angles thereto. The inclinations agreed in every respect with the surface contours detected interferometrically, indicating that the elevation must be produced largely by elastic processes rather than by slip. Electron micrographic examination[5] of a similar specimen gave no indication of slip lines or bands but showed characteristically finer etch patterns in the bombarded region. Absence of important plastic deformation was indicated by the sharpness of the diffraction lines. Comparable intensities of diffraction were obtained from bombarded and unbombarded regions. Comparing line widths with α-doublet separations, the estimated range of misorientation was not in excess of 3 min of arc and of lattice parameter was less than 1 part in 4000 over distances of ∼25 microns, except possibly at the boundary line. Reflection of divergent polychromatic x-rays by the crystal was enhanced in a very narrow region at the boundary, suggesting a more mosaic structure here. Relative to the value just outside the bombarded region a lattice parameter increase (0.12%) was observed at the point of maximum elevation. Most of this increase occurred at or immediately inside the position of maximum tilt. This increase will account for only a fraction of the maximum surface extension, which was ∼1% of the deuteron range. Elastic stresses and an undetected lattice parameter change distributed over the unbombarded area might account for part of the difference.

The observed expansion seems near the maximum limit one might estimate from point-defect considerations.[6]

An InSb specimen ($\phi=3\times10^{16}$ cm^{-2}) showed similar effects, including a step-like lattice parameter increase, although here the surface contour indicated only general rounding. After two hours anneal at 150°C, the lattice parameter returned to its normal value and residual inhomogeneous microstrains were introduced along the boundary while some surface elevation remained.

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[1] U. Gonser and B. Okkerse, Phys. Rev. **105**, 757 (1957).
[2] U. Gonser and B. Okkerse, Bull. Am. Phys. Soc. Ser. II, **2**, 157 (1957).
[3] A surface contamination layer independent of the specimens, of optical density exceeding 1, and probably largely carbon was introduced by bombardment. Interferometric observation suggested by Professor H. Y. Fan, before warming bombarded specimens, indicated an apparent surface depression, but an unknown part of the effect was due to the contamination layer.
[4] A versatile interferometer designed by K. W. Meissner [Physik. Z. **30**, 965 (1929)], based on the principal of the Michelson interferometer, was employed.
[5] Carried out by Dr. J. F. Radavich. The results appear somewhat similar to those of R. Chang [J. Appl. Phys. **28**, 385 (1957)] who has observed preferential appearance of third-order (0.1–0.5 micron) etch patterns after neutron (but not gamma) irradiations of Ge and Si.
[6] See, for example, J. D. Eshelby, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 3, p. 79, on the continuum theory of lattice defects, and F. Seitz and J. S. Koehler, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 2, p. 404, for discussion and reference.

Reactions $Al^{27}(\alpha,p)Si^{30}$ and $P^{31}(\alpha,p)S^{34}$ at 30.5 Mev*

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ON the basis of general arguments concerning the nuclear states involved, Butler[1] has recently developed a theory of direct nuclear reactions. The purposes of this letter are to support Butler's general predictions in a reaction that has not previously been studied intensively at moderately high energies and to point out a limitation of his detailed predictions, as summarized in his Eq. (57). Illustrated in Figs. 1 and 2

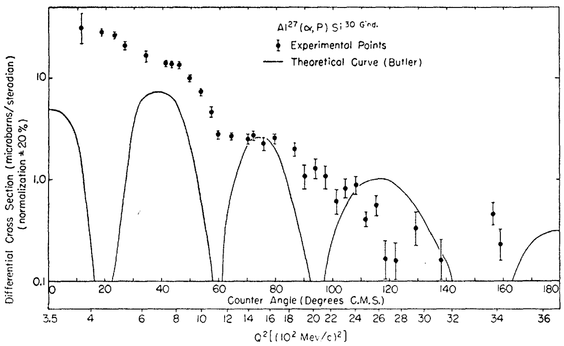

FIG. 1. Differential cross section of protons from the ground-state $Al^{27}(\alpha,p)Si^{30}$ reaction induced by approximately 30.5-Mev alpha particles. The theoretical curve is based on Eq. (57) of reference 1, with $l=2$, $r_n=4.98\times10^{-13}$ cm, $Q=|(26/30)\mathbf{k}_p-(26/27)\mathbf{k}_\alpha|$. The peak at approximately 74 degrees was used in evaluating the parameter r_n and in normalization of the theoretical curve to the experimental data.

are differential cross sections corresponding to the ground-state (α,p) reactions on Al^{27} and P^{31} induced by approximately 30.5-Mev alpha particles. In both cases, we observe the forward peaking characteristic of processes not involving compound-nucleus formation, as well as secondary maxima. Our results show the following deviations from the predictions of Butler's approximate form: (1) a much more pronounced forward peaking and (2) not so pronounced secondary maxima.

The more significant discrepancy between Butler's prediction and our results concerns the forward peaking. In his prediction, the form factor arises from assumptions regarding primarily the form of the nuclear wave function in the region in which the reaction takes place. In the case of 20- to 40-Mev alpha particles, their short mean free path in nuclear matter[2] requires that the region of interaction lie near the nuclear surface. As illustrated in Fig. 1, Butler's form factor does not change sufficiently rapidly with angle to fit the data

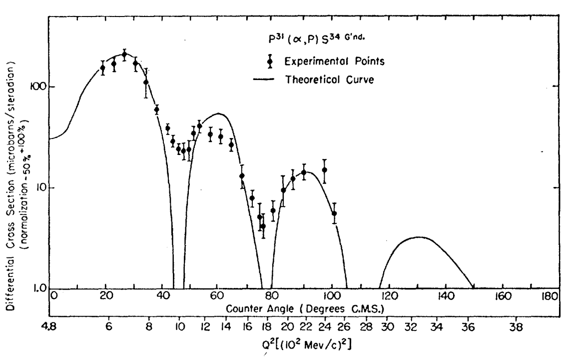

FIG. 2. Differential cross section of protons from the ground-state $P^{31}(\alpha,p)S^{34}$ reaction induced by approximately 30.5-Mev alpha particles. The theoretical curve is $K\exp(-Q^2/Q_0^2)|j_l(QR)|^2$ where $l=0$, $R=5.90\times10^{-13}$ cm, $Q=|(30/31)\mathbf{k}_\alpha-(30/34)\mathbf{k}_p|$, $Q_0=320$ Mev/c. The peak at 27 degrees was used in evaluating the parameter R and in normalization. An experimental upper limit for the differential cross section for the counter angle range 102 to 167 degrees (c.m.) is 6 microbarns/steradian.

under consideration. In the theoretical curve of Fig. 2, we have replaced this form factor by one of the form $\exp(-Q^2/Q_0^2)$, where Q is essentially the linear momentum difference between the incoming and outgoing particles, and Q_0 is an empirical parameter. The $P^{31}(\alpha,p)S^{34}$ case was fitted with a Q_0 of 320 Mev/c, and the $Al^{27}(\alpha,p)Si^{30}$ case can be fitted with a Q_0 of approximately 260 Mev/c.

A possible interpretation of the parameter Q_0 may be obtained if this quantity reflects the momentum distributions of the protons in the initial nucleus and the alpha particle in the final nucleus. This interpretation visualizes the interaction as proceeding via a "knock-out" process in which the incoming alpha particle collides with a proton in the initial nucleus and ejects it. On the other hand, if we visualize a "triton stripping" process, in which the incident alpha particle splits into an absorbed triton and the observed proton, a similar interpretation can be made. However, both of these detailed mechanisms may be too naive because the assumption of preformed heavy particles contradicts the concept of very short mean free paths for heavy particles in nuclear matter.

A natural consequence of this momentum picture for the reaction provides an explanation for the rather low ground-state differential cross sections observed. We note that our incident alpha particles have a momentum of approximately 430 Mev/c; from the known Q-values of the reactions and conservation of momentum and energy there must be a momentum transfer of *at least* 200 Mev/c (cf. Fig. 1). Since the probability for finding a nucleon of high momentum in the nucleus is small, we have a natural explanation for the low differential cross sections for these reactions.

Regarding the second of the above-mentioned deviations, we note that the cases in Figs. 1 and 2 both involve uniquely defined angular momentum change parameters "l"[1]; for such cases, Butler's prediction is for well-defined secondary maxima. The above experimental results confirm the prediction partially, in that the angular positions of the experimental peaks are fitted by Butler's approximate form. The significance of this aspect of the fit may be appreciated by considering that reasonable values of the sole parameter that changes peak angles—the radius parameter—succeed in fitting all the principal maxima in each case. As for the resolution of these secondary maxima, however, Butler's prediction must be contrasted with both the rather rudimentary nature of the peaks in the $Al^{27}(\alpha,p)Si^{30}$ case and the intermediate resolution of the peaks in the $P^{31}(\alpha,p)S^{34}$ case. That this deviation may not be too difficult to understand follows from the assumptions of a sharp cutoff on the interaction volume and the plane wave description of the incident-and emergent-particle wave functions in the approximate calculation. Thus, a more realistic calculation may be necessary to fill in the minima resulting from the above simplifications.[3]

In addition to the data presented in Figs. 1 and 2, we have measured the corresponding differential cross sections for $B^{10}(\alpha,p)C^{13}$ ground state,[4] $Na^{23}(\alpha,p)Mg^{26}$ first excited state, and $Al^{27}(\alpha,p)Si^{30}$ first excited state.[5] Qualitatively different from the other results are the $C^{12}(\alpha,p)N^{15}$ ground-state results.[4,6]

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[3] C. A. Levinson and M. K. Banerjee, Bull. Am. Phys. Soc. Ser. II, **2**, 229 (1957).
[4] C. E. Hunting and N. S. Wall, Bull. Am. Phys. Soc. Ser. II, **2**, 181 (1957).
[5] Reported orally at 1957 Washington meeting of the American Physical Society in conjunction with reference 4.
[6] R. Sherr and M. Rickey, Bull. Am. Phys. Soc. Ser. II, **2**, 29 (1957).

Large Auroral Effect on Cosmic-Ray Detectors Observed at 8 g/cm² Atmospheric Depth*

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We have observed a large increase in the rate of a single Geiger counter and ionization chamber at high altitude during an intense auroral display on July 1, 1957, at Minneapolis. The equipment was operating at 8 g/cm² atmospheric depth on a constant level plastic balloon when the aurora began at about 0330UT. A large initial burst occurred (see Fig. 1), lasting about ten minutes, followed by a second, less intense, of about fifteen minutes duration and a third, still less intense, peaked at 0420UT. Fluctuations were seen until 0630UT in both instruments. The large initial effect was associated with auroral arcs near the zenith, and the increases in rates were roughly correlated with visual observations of increased brilliance near the zenith. (See arrows in Fig. 1.) It was also observed that strong auroral curtains and other phenomena continued in the north after the instruments had returned to normal cosmic-ray rates. The relative increase is much larger in the ionization chamber, which is of the integrating type containing argon at 8 atmospheres pressure, although the pattern of bursts is similar in both instruments. A clue to the type of radiation causing the increase may be obtained by plotting the ratio of the two instruments which give the relative mean ionization per count (upper graph of Fig. 1). This ratio has the value 0.2 as the balloon rises through the atmosphere from about 0100 (launch) to 0230, and increases to 0.26 above the single counter maximum. The value 0.2 is characteristic of fast singly-charged particles in the lower atmosphere, while the increase at higher altitude may be attributed to the increased flux of heavy primary nuclei. The ratio for the burst excess, however, is 1.3 to 1.4, and remains reasonably constant despite the large intensity fluctuations of both instruments. A ratio of 1.4 corresponds to a proton with relative ionization seven times minimum, of energy 45 Mev and residual range 2 g/cm². Such protons above the atmosphere have a range of 10 g/cm², an energy of 120 Mev, and $\beta=0.45$ assuming vertical incidence. The peak measured flux is 1.0 particle/cm² sec.

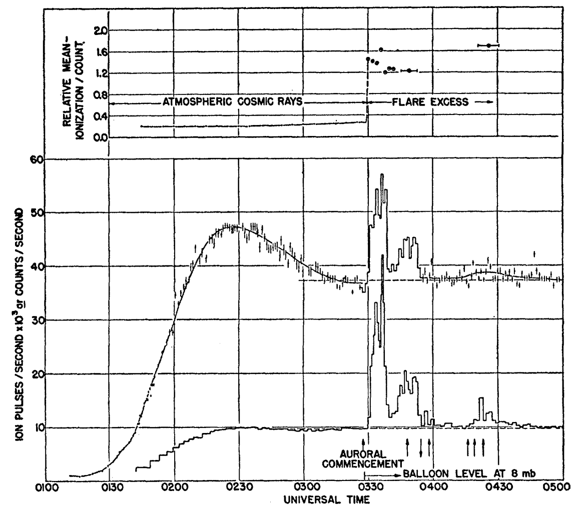

Fig. 1. In the lower section is plotted the counting rate of a single Geiger counter (upper curve), and pulsing rate of an integrating ionization chamber (lower curve), during the auroral display of July 1, 1957. Between 0130 and 0330 the two instruments show the normal transition curves as the balloon rises to altitude. In the upper section is plotted the ratio of the counting rate of the ionization chamber to that of the single counter. The flare effect has a relative mean ionization per count which is 7 times that of fast cosmic-ray particles.

The ratio of ionization per count has also been measured in the laboratory for x-rays of various energies and for γ rays. In the range 500–1000 kev, the ratio 0.2 characteristic of minimum ionizing particles is obtained. The ratio rises rapidly below 100 kev due to the somewhat greater absorption of the Geiger counter brass wall than the 0.025-in. steel of the ion chamber. However, the sensitivity of both the ion chamber and counter drops very rapidly below 40 kev. The response is thus peaked in the region of 50–70 kev, and both the ratio 1.4 and the observation under 8 g/cm² of atmosphere are consistent with x-rays in this energy range. These x-rays must be attributed to electrons of $\beta\approx0.5$ emitting bremsstrahlung in the higher atmosphere. The peak x-ray flux at the equipment is 5 mr/hr.

The auroral display was probably associated with the passage across solar meridian of an active region (039 *C* on the Boulder report)[1] on June 30th and the transit time from sun to earth is about 20 hr. The β for the beam is thus about 0.01. This β is quite consistent with the velocity of incident auroral protons of energies