Investigation of Color Centers by a Single-Photon Counting Method

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THE detection of nuclear particles by means of scintillation counters has received much attention in the last few years. The energy of the incident particles is partly converted into a large number of visible photons by using a suitable phosphor. A photo-multiplier tube, coupled to the crystal then produces voltage pulses.

It is evident that when a "photon-emitter" is placed in front of a photo-multiplier, single photons may be counted. Such a photon-emitter may be obtained by irradiating alkali-halide crystals with x-rays. The x-ray energy absorbed by the crystal is partly stored in the form of excited electrons trapped by lattice defects. The excited electrons recombine with the holes with the emission of photons. These photons were observed with the use of an R.C.A. 5819 photo-multiplier coupled to the irradiated crystal. The irradiation with x-rays and the mounting of the crystal on the photo-multiplier window were carried out in the dark to prevent unnecessary bleaching of the colored crystals.

The electronic circuits, consisting of a preamplifier and linear amplifier and linear amplifier of gain 60X, and a scale of 640, were conventional. About 1300 volts from a highly stabilized, low ripple power supply was applied to the tube. The distribution of pulses obtained from the crystal was roughly similar to the distribution of noise pulses from the photo-multiplier with approximately the same maximum pulse height, but were much greater in number, suggesting that single photons were being counted.

Some preliminary results obtained at room temperature are shown in Fig. 1. Curves *I* and *II* correspond respectively to single crystals of NaCl and KBr. Both crystals had been irradiated with 55 kv 3ma x-rays at a distance of 9 cm from the source for 15 minutes. Curves *III* and *IV* both refer to the KBr crystal just mentioned, but irradiated at a distance of 5 cm from the source for 15 minutes. The noise pulses constituted less than 0.07 counts per minute in the scale of 640 which is so small that they cannot be shown conveniently on the graph. That curves *III* and *IV* do not coincide is perhaps due to the fact that the high voltage in the tube was slightly different for the two cases and the pulse size distribution is very critical to a change in this voltage. We should note that curve *I* for NaCl gives only part of the observations and appreciable counting rates were observed even after a day.

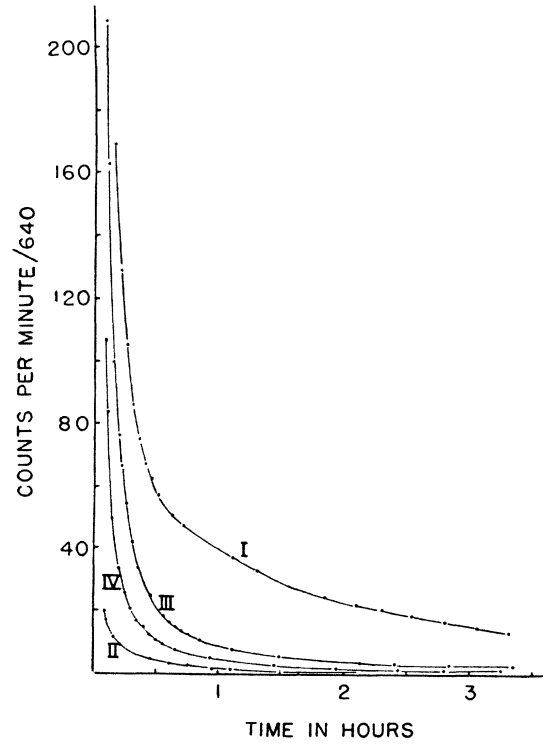

FIG. 1. Counting rate as a function of time after irradiation with x-rays. Curve *I* corresponds to NaCl and curves *II*, *III*, and *IV* to KBr crystals.

Preliminary experiments have also been carried out keeping the crystals at the temperature of dry ice. For the same discriminator setting and the same time after irradiation the counting rate for NaCl and KBr was only about 0.05 percent of that at room temperature. Also, the time interval over which the counting rate falls to half its initial value is less by a factor of 4 at dry ice temperature compared with room temperature.

The strong temperature dependence of the counting rate shows that direct recombination of a trapped electron with a hole in the upper filled band is very unlikely. Apparently recombination can only take place after the electrons are excited into the conduction band.

The investigations are being continued in the hope that quantiative measurements may lead to a better understanding of the decay processes involved.

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Photovoltaic Effect of $P-N$ Junctions in Germanium*

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A PIECE of germanium, one part of which is a p-type semiconductor and the other part is N-type, forms at the junction a barrier of high resistance and photosensitivity. Light which is effective photoelectrically is practically entirely absorbed within a very small thickness ($<10^{-3}$ cm). In samples having a thickness of a fraction of a millimeter and more only a part of the junction area is activated and generates an emf V_p. This emf is in series with r, the resistance of the activated part of the barrier. In parallel with this combination are the resistance R of the unactivated part of the barrier and the capacitance C of the barrier. The barrier is in series with the bulk resistance of the sample, which is comparatively negligible, and the input resistance R_e of the amplifier. To obtain maximum voltage R_e should be large compared with R. Figure 1 shows curves of measured voltage *versus* R_e for two temperatures. The experiments reported below were made with sufficiently large R_e so that its effect can be neglected.

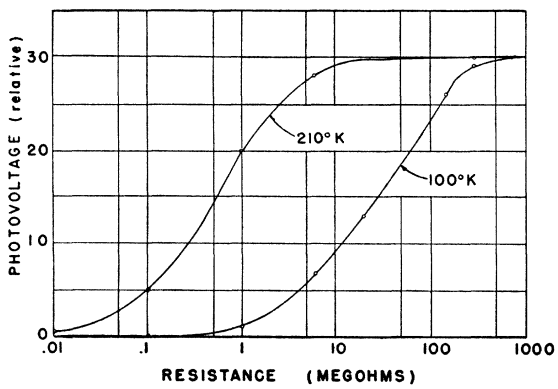

FIG. 1. Effect of external load resistance on photo-voltage.

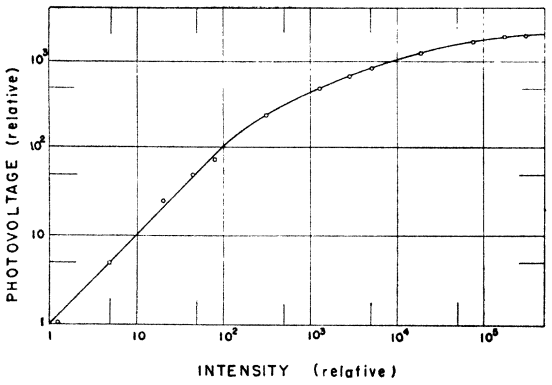

FIG. 2. Photo-voltage as function of light intensity.

It has been shown[1] that the photo-emf developed across a $P-N$ barrier is given by

$$V_p=\frac{kT}{e}\left(\log\frac{n_p}{n_N}-\log\frac{np_o}{nN_o}\right)\simeq\frac{kT}{e}\log\frac{n_p}{np_o}=\frac{kT}{e}\log\left(1+\frac{\Delta n_p}{np_o}\right),$$

where n is the concentration of conduction electrons and subscript o refers to the state of thermal equilibrium without illumination. The value of Δn_p is determined by the balance between the rate of excitation, which is proportional to light intensity, and the rate of relaxation. It follows from this equation that V_p increases approximately linearly with the light intensity only for $\Delta n_p<np_o$; it increases more slowly at higher intensities. Figure 2 shows the measured photo-voltage as a function of the light intensity.[2]

The relaxation of excited electrons is due to: (1) current flow through R, (2) volume recombination and (3) diffusion and recombination at the surfaces.[3] Since R increases, and the recombination rate decreases, with decreasing temperature, the sensitivity should increase. The experimental result is shown in Fig. 3. The light intensities used were kept sufficiently low to insure linearity of response. At 100°K the sensitivity is about 10,000 times higher than at room temperature; with the sample in a metal Dewar background light scattered into the window was sufficient to produce a photovoltage already in the non-linear region. With R_e equal to the room temperature value of R the photo-voltage was still several times higher than at room temperature, indicating that the increase of R alone does not account for all of the increase in sensitivity. The drop of response toward long wave-length is due to the decrease in excitation rate. The absorption of germanium drops very sharply beyond 1.7μ corresponding to the forbidden-energy gap.[4]

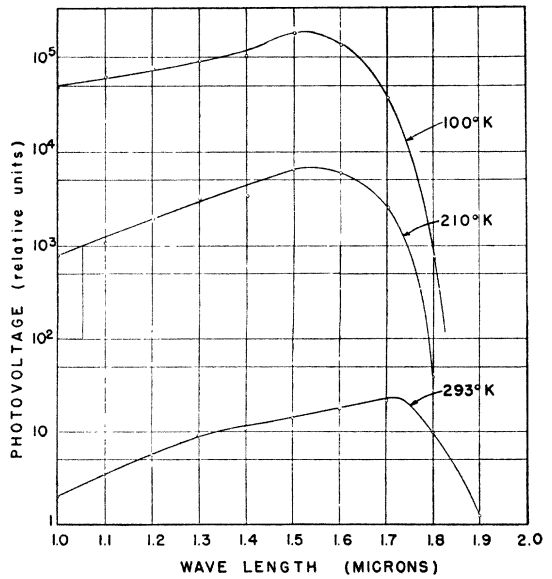

FIG. 3. Temperature dependence of spectral response.

Observations were made of the building up and the decay of the photovoltage under pulsed irradiation. These processes are approximately exponential. The values of the time constant measured for a certain sample are 1500 μsec. at 100°K, 130 μsec. at 210°K, and less than 12 μsec. at room temperature. For sufficiently large R_e (see Fig. 2) these values are independent of R_e. It must be pointed out that the speeds of these processes depend not only on the rate of change of V_p but are affected also by the values of C and R. If V_p changes very fast then the building up and decay will have simply a time constant CR. However, observations made with different values of R_e and external capacitance across the sample indicate that this is not the case. The experiments are being continued.

* Work assisted by a Signal Corps Contract.

[1] H. Y. Fan, Phys. Rev. **75**, 1631 (1949).

[2] Results obtained using white light were reported earlier, M. Becker and H. Y. Fan, Phys. Rev. **75**, 1631 (1949).

[3] H. Suhl and W. Shockley, Phys. Rev. **75**, 1617 (1949).

[4] M. Becker and H. Y. Fan, Phys. Rev. **76**, 1530 (1949).

Neutron Groups from $Be^9(\alpha,n)C^{12}$

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THE radium-beryllium mixture is commonly used as a source of neutrons. It gives a continuous distribution of neutron energies up to 13 Mev. The neutrons are produced by a wide distribution of α-particle energies and are emitted at all angles to the α-particles. Several earlier efforts[1] have been made to infer excited states of the residual C^{12} nucleus from the neutron spectrum.

We have bombarded a thick beryllium target with 1.4 Mev α-particles produced in the Illinois Institute of Technology electrostatic generator. Ilford C2 plates 100 microns thick were exposed at 90° to the beam. Two thousand tracks of recoil protons within 12° of the neutron direction were measured. The number of tracks within 0.1 Mev energy intervals was plotted, using a range-energy curve for the plates.[2] The number of neutrons was obtained from the number of measured tracks of recoil protons by applying a suitable geometrical correction[3] and a correction for cross section for neutron-proton scattering. The energies were increased by 2.7 percent, the average amount by which the neutron energies exceed the energies of the recoil protons. The final energy spectrum of the neutrons is shown in Fig. 1. The thickness of the target did not contribute greatly to the breadth of the groups. A thick target yield curve showed that half of the neutrons were produced by α-particles of energies between 1.27 and 1.40 Mev.

The Q-values corresponding to the two groups were computed in two different ways. Using a mean energy for each group and a mean effective bombrading energy, Q was found to be 5.65 and 1.19 Mev for the high and low energy groups, respectively. This gives the energy of the excited state of C^{12} as 4.46 Mev. The second computation used the procedure outlined by Livingston and Bethe[4] and assumed that the range straggling in the plates would not be much greater than in air. It led to Q-values of 5.78 and 1.34 Mev and an energy of the excited state of C^{12} of 4.44 Mev. The difference between the two sets of results is caused by some unexplained breadth of the groups. The Q-value calculated from masses is 5.72±0.08 Mev. The agreement in either case is satisfactory, since the range-energy relation for the plates may be in error by 2 percent.