weak. The microwave magnetic field is always perpendicular to the static field.

Such anomalous absorptions cannot be explained by a single ion in the ^2D state in any allowable crystalline field. The first possibility for the origin of this anomaly may be that ions are not in the ^2D state in this case of very strong crystalline fields. The second possibility is that the absorption is not effected by a single Cu^{++} ion, but by a molecule containing Cu^{++} and other atoms. The third one is that a number of Cu^{++} ions are located at small distances from each other so that their electron spins mutually interact strongly. We note that the absorption of $Mn(CH_3COO)_2 \cdot 4H_2O$ shows a single peak with $g=2.0$.

The authors' thanks are due to Assistant Professors K. Kambe and E. Ishiguro for their discussions. A more detailed report will appear in J. Phys. Soc. Japan.

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Electron-Hole Recombination in Germanium

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POWER rectifiers have been described that consist of thin wafers of high purity germanium whose opposite faces are heavily doped with donor and acceptor impurities.[1] Since the current flow depends largely upon the generation and recombination of holes and electrons within the high purity region, this geometry is well adapted to the study of the recombination process. A two-body collision mechanism leads to a rate that is proportional to the square of the carrier concentration at high levels of injection where holes and electrons are present in nearly equal numbers. Measurements show, however, that the rate varies linearly with concentration over a wide range of concentration and temperature.[2] These observations can be accounted for by assuming that recombination takes place largely through the agency of recombination centers distributed throughout the germanium.

A steady-state recombination rate given by[3]

$$R=(np-n_i^2)/[t_p(n+n_0)+t_n(p+p_0)], \qquad (1)$$

results from a simple model in which the centers give rise to an energy level lying in the forbidden band. The electron and hole concentrations are given by n and p, their product under equilibrium conditions being n_i^2. The lifetime for electrons when the centers are completely empty is given by t_n; t_p is the hole lifetime with all centers occupied by electrons. The recombination centers lie at an energy level defined by n_0 and p_0 which are the equilibrium electron and hole concentrations in a sample whose Fermi level coincides with the position of the recombination centers.

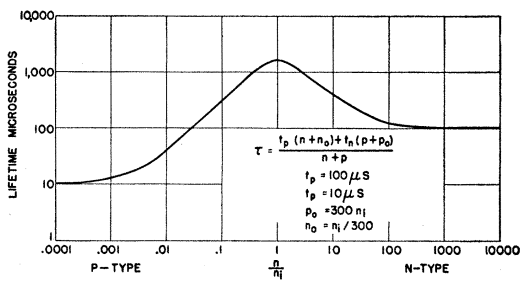

FIG. 1. Variation of lifetime with impurity content.

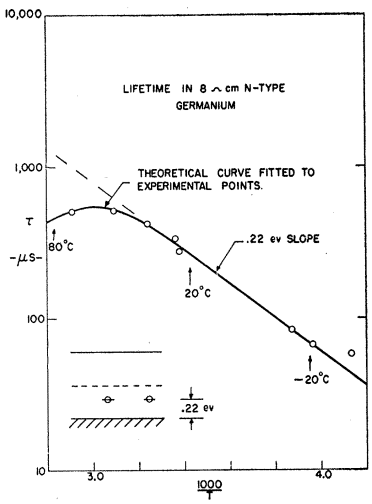

FIG. 2. Variation of lifetime with temperature.

In the derivation of Eq. (1), it is assumed that the rate of capture of electrons is proportional to the number of empty centers and to the number of free electrons. The rate at which electrons are emitted by these centers is proportional to the number of occupied centers. Analogous statements apply to the capture and emission of holes.

It is readily seen that Eq. (1) can account for the linear relation between carrier concentration and recombination rate mentioned in the first paragraph. With high level injection, n and p become equal and much greater than n_i, n_0, or p_0 so that $R \simeq n/(t_n+t_p)$. Rectifier characteristics calculated on the basis of Eq. (1) can be fitted to the data in a very satisfactory manner.[4] The lifetime for holes and electrons at high level injection (t_n+t_p) is usually found to be approximately 100 μsec.

The equilibrium lifetime which results from Eq. (1) is

$$\tau \equiv \mathrm{Lim}_{\delta n \to 0}(\delta n/\delta R)=[t_p(n+n_0)+t_n(p+p_0)]/(n+p). \qquad (2)$$

The variation of τ with impurity content is illustrated in Fig. 1 for a choice of parameters which gives reasonable agreement with lifetimes observed in samples of germanium at room temperature.

Since n_0 and p_0 vary exponentially with $1/T$ while t_n and t_p should be relatively insensitive to temperature, the lifetime should assume its limiting values t_n and t_p for p- and n-type samples at low temperatures. At higher temperatures, the lifetime increases with temperature as long as the sample remains extrinsic and then decreases again in the intrinsic range. Measurements of lifetime illustrating the variation with temperature in the upper two temperature ranges are shown in Fig. 2. The slope indicated on the graph gives a tentative value of 0.22 electron volt for the position of the recombination centers above the valence band or below the conduction band.

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[3] This expression was presented in the text of reference 2, using somewhat different notation. Shockley has derived it as a special case of a more general treatment which has been submitted for publication.
[4] A detailed treatment of the germanium power rectifier will be published shortly.

An Experimental Test of the Shell Model

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IN a recent letter, Bethe and Butler[1] proposed an experiment to give direct information on the accuracy of the shell model of nuclear structure in ascribing definite orbital angular momen-

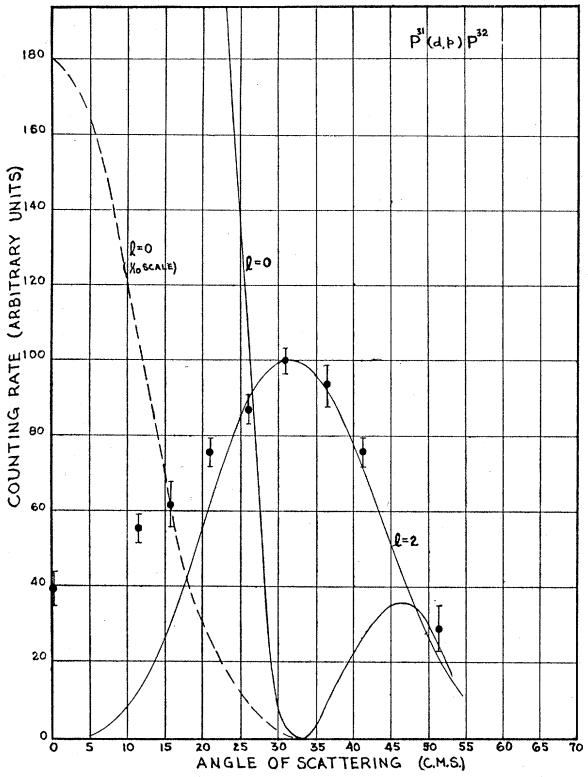

FIG. 1. The angular distribution of the protons associated with the ground state in the reaction $P^{31}(d, p)P^{32}$. The solid curves are calculated from the Butler theory.

tum states to nucleons in a nucleus. According to the Butler[2] interpretation of (d, p) and (d, n) reactions, the angular distribution of the outgoing particle is characterized by the angular momentum l with which the captured particle can be accepted into the appropriate final state. If, for a particular nucleus, the selection rules allow more than one value of l, the target nucleus might be indifferent to which of these it accepts. According to the shell model, however, the target nucleus will accept a particle in one definite orbital angular momentum state only. In the case of phosphorus, the selection rules allow l values of 0 and 2, while the shell model requires an l of 2 only.

We have measured the angular distribution of the protons from the reaction $P^{31}(d, p)P^{32}$ and, although more accurate data are desired, the results are of sufficient interest to warrant a brief note at this time. In Fig. 1, the experimental points for the angular distribution of the protons associated with the ground state are indicated along with the curves for the angular distributions predicted by the Butler theory for l values of 0 and 2. In computing these curves from the expression given by Butler, the following values were used: $r_0=5.7\times10^{-13}$ cm, $a=0.23\times10^{13}$ cm^{-1}, $b=1.4\times10^{13}$ cm^{-1}. The incident deuteron energy was 7.20 Mev (c.m. sytem). The Q of the reaction was measured to be 5.5 Mev which is in reasonable agreement with that of 5.8 ± 0.3 given by Pollard.[3]

The target consisted of a thin coating of pure phosphorus on a backing of 0.0001-inch silver foil. The background due to the silver was negligible at all angles except 0° where the correction was approximately 10 percent. The vertical lines through the measured points represent the standard deviation determined from the total number of counts and are not a measure of the over-all uncertainty in the data. In particular, we believe that the values indicated at small angles (0° to 15°) represent an upper bound to the true situation. No correction has been applied for the finite solid angle of the detector system. In addition, the "tail" of the first excited state of P^{32} overlapped the ground state peak and at small angles produced much the larger counting rate. The correction for this tail was somewhat uncertain, and we were conservative in applying it.

These results indicate that the neutron is captured mainly into a D state, as is predicted by the shell model, rather than an S state, with an amount of admixture not exceeding 5 percent and probably less than 2 percent.[4] It is worth noting that this is also in agreement with the observations on the beta-decay of P^{32}, which presumably decays by means of an "l-forbidden" transition for which $\Delta l=2$ with no change in parity.

The measurements on P^{32} and similar nuclei are being continued. A more detailed report, including a discussion of the techniques of measurement, will be given in the near future.

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[4] Since the ground-state doublet was not resolved, both members are presumably D-states. This does not alter the implications with respect to the shell model.

Electron Capture in Tl^{204}†

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DURING the course of an investigation of the radiations from Tl^{204} carried out in this laboratory,[1] the spectrum of photoelectrons ejected from Pb and U radiators by photons from Tl^{204} was measured. While the radiation was quite weak, two photopeaks each were found with Pb and U radiators. The peaks came at photoelectron energies of 51 and 66 kev for U and 55 and 69 kev for Pb. If it is assumed that these peaks are due to photoelectrons ejected from the L and M shells of Pb and U, respectively, the energy of the radiation responsible for these photoelectrons is 72.0 ± 0.9 kev. Since this is approximately the energy of the K_α line of Hg, it appeared likely that Tl^{204} decays to Hg^{204} by orbital electron capture as well as to Pb^{204} by beta-ray emission.

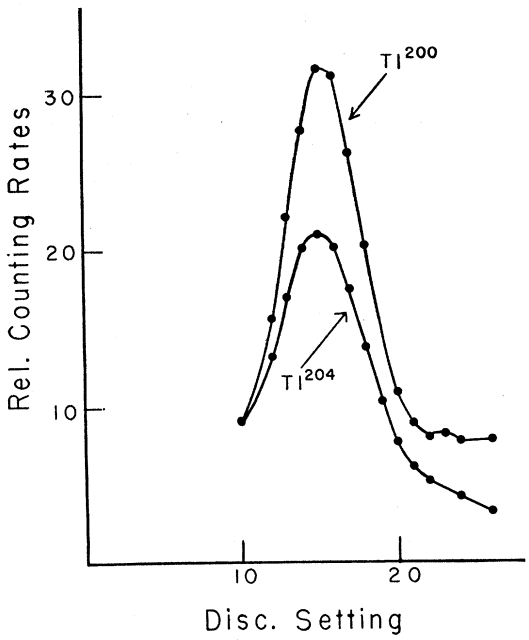

FIG. 1. Pulse-height analysis of the x-rays from Tl^{204} and Tl^{200} using scintillation counters.