$$\bar{E}_{\perp} = \hbar F/2(2m_{rx})^{1/2} E_{111}^{1/2}, \quad (5)$$

where m_1, m_2 are density of states masses, m_{rx} is the reduced mass in the field direction, E_{111} is the indirect energy gap, n is the average number of phonons, and M^2V is the square of the phonon matrix element times the volume. Again we have assumed $\zeta_p >> \bar{E}_{\perp}$. The right-hand side of Eq. (4) should be summed over the 4 conduction band minima but we assume that just one minimum is most favorably aligned for tunneling. For this minimum $m_{rx}^{-1} = 0.08^{-1} + 0.04^{-1}$. We have determined M^2V from the magnitude of indirect optical absorption[6] to be

$$M^2V = 1.3\times10^{-47} \text{ erg}^2 \text{ cm}^3.$$

Using the above values together with the value of F determined for the direct case, we calculate a current density of 4×10^{-3} amp/cm^2 at 0.05 volt reverse bias, which is to be compared with the experimental value of 2×10^{-2} amp/cm^2. The factor of 5 discrepancy is within the uncertainty of the theoretical estimate. However, it is clear from Fig. 1(a) that the experimental curve shape does not agree with theory in the region between 0.05 ev and 0.12 ev since the slope increases rapidly with energy instead of becoming constant for $V_i >> \bar{E}_{\perp}$. ($\bar{E}_{\perp} = 0.015$ ev in this case.) The current increase is not rapid enough to be due to thermal excitation to the energy of the (000) minimum. We suggest that the increase is due to the impurity admixture of states in the (111) and (000) minima. In perturbation terminology, the particle tunnels into a virtual state in the (000) minimum and is then impurity-scattered into the (111) minimum. The rapid increase in current with voltage would then be due in part to the decrease of the energy denominator.

Holonyak et al.[1] have observed phonon-assisted tunneling in Sb-doped junctions of germanium but not in P- and As-doped junctions. A possible interpretation is that impurity scattering dominates phonon scattering for the latter two impurities. Since the k-vector change is a large one, a variation with the specific impurity is to be expected. Their results are also consistent with the observation that Sb has the smallest ionization energy of the column V impurities, hence the wave function is least concentrated at the core. A good test of this interpretation would be a comparison of direct and indirect tunneling currents in the reverse characteristic for Sb, As, and P. The latter two should have the smaller ratio.

[1]Holonyak, Lesk, Hall, Tiemann, and Ehrenreich, Phys. Rev. Letters 3, 167 (1959); L. Esaki, J. Phys. Soc. Japan (to be published).

[2]L. V. Keldysh, J. Exptl. Theoret. Phys. U.S.S.R. 34, 962 (1958) [translation: Soviet Phys. JETP 34(7), 665 (1958)].

[3]L. V. Keldysh, J. Exptl. Theoret. Phys. U.S.S.R. 33, 994 (1957) [translation: Soviet Phys. JETP 33(6), 763 (1958)].

[4]E. O. Kane, J. Phys. Chem. Solids (to be published).

[5]Zwerdling, Roth, and Lax, Phys. Rev. 109, 2207 (1958).

[6]Macfarlane, McLean, Quarrington, and Roberts, Phys. Rev. 108, 1377 (1957).

OPTICAL DETECTION OF PARAMAGNETIC RESONANCE SATURATION IN RUBY*

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In order to extend the technique of optical pumping to solids, it is convenient to employ a solid system with sharp optical lines.[1] One such material is ruby which consists of Cr^{+++} ions in a host crystal of Al_2O_3. The optical spectrum of ruby has been studied extensively[2-6] and includes two sharp lines denoted by R_1 and R_2 which appear in both absorption and emission. The Zeeman effect of these lines was also observed and has recently been investigated both theoretically and experimentally in detail.[7,8] The results of the above-mentioned work are shown in the high-field transition diagrams of Fig. 1. The expected zero-field intensities were obtained by assuming[9] that the optical matrix elements are magnetic-field independent and adding the appropriate values for the degenerate levels. It is apparent that many possibilities exist for preferentially depopulating one of the sublevels of the ground state. For example, a mixture of R_1 and R_2 radiation polarized with the electric vector along the optic axis can be expected to depopulate pref-

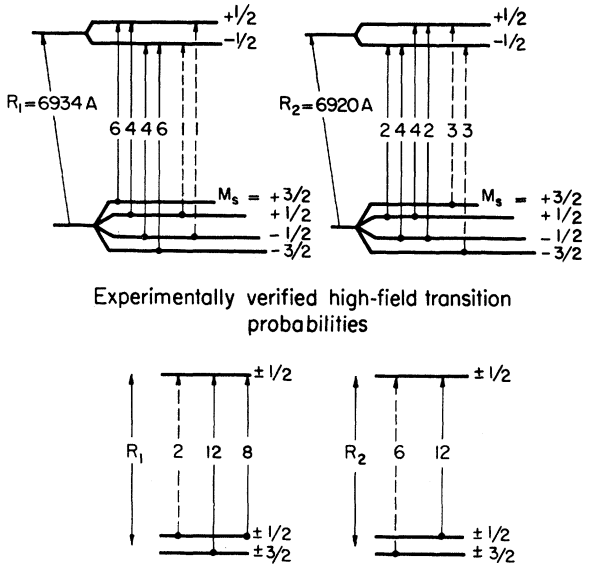

FIG. 1. Transition probabilities for the R lines in ruby. The dashed and solid lines refer to the cases where the exciting light has its electric vector parallel and perpendicular, respectively, to the optic axis. The external magnetic field is parallel to the optic axis.

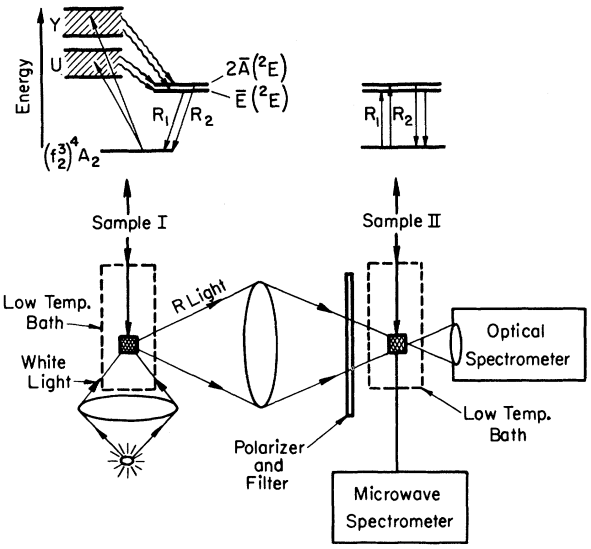

FIG. 2. Schematic diagram of the microwave optical experiments in ruby showing the different optical cycles in the two samples.

erentially the $\pm\frac{3}{2}$ level.

The present experiments were performed at about 2°K (below the lambda point of liquid helium) to lengthen spin lattice relaxation times and to eliminate bubbles in the optical path. At this temperature, the R absorption widths are about 0.6 cm^{-1} for pink ruby.[8] Although broad spectrum sources emit about 0.01 watt of light energy in this bandwidth at 6900 A, there is an associated extraneous background light even with narrow-band optical filters. This background light causes undesirable heating of the sample and excludes optical detection methods.

It is apparent that a source of "resonance radiation" can overcome both of the above difficulties. In the case of ruby, the R lines appear as fluorescent lines upon absorption of light by the Cr^{+++} ions in the two broad bands denoted in Fig. 2 by U and Y. The relaxation from the broad excited states to the sharp levels denoted[7] by ^2E is radiationless, and the decay to the ground state has a lifetime of milliseconds.[10] This photoluminescent effect was utilized in the design of a solid state light source which emits a total of about 0.1 watt in each of the R lines. The details of this source have been described elsewhere.[11]

The experimental arrangement is shown schematically in Fig. 2. Sample I, which is utilized as the source, is irradiated with light from a tungsten source and undergoes the photoluminescent cycle mentioned above. The R fluorescence from sample I is collected, polarized, and focussed on sample II, which is in the cavity of a microwave spectrometer. Due to the temperature dependence of the R frequency,[3,8] it is necessary to keep sample I at liquid nitrogen temperature or cooler so that its R emission frequencies overlap the R absorption frequencies of sample II at liquid helium temperature.[11] In general, optical pumping disturbs the equilibrium populations of the sublevels of the ground state and can be detected by using ordinary paramagnetic resonance techniques. In this case, the R light is chopped, and a corresponding time-varying microwave absorption signal can be synchronously detected. The expected signal-to-noise ratio using this method is marginal with the present apparatus, and although the experiment was tried, the absence of a signal cannot be taken too seriously.

However, in order to verify that preferential optical depopulation of sublevels can occur in ruby at low magnetic fields, another experiment utilizing the same apparatus was attempted. In this case, the low-temperature alignment of the ground state is altered by microwave saturation. This increases the number of centers in the

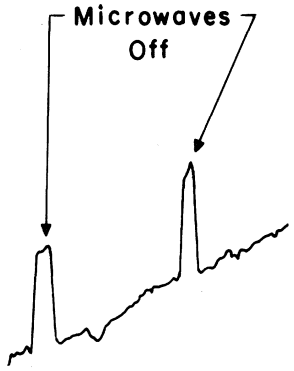

FIG. 3. Recorder tracing of a microwave-induced change of transmitted R_2 light polarized with its electric vector perpendicular to the optic axis.

$m = \pm \frac{1}{2}$ levels of the ground state and should change the R absorption, provided that the rate of optical transitions from the $m = \pm \frac{1}{2}$ levels differs from that of the $m = \pm \frac{3}{2}$ levels. This was actually found to be the case, as can be seen in Fig. 3. The intensity of transmitted R_2 light was displayed on a recorder, and the microwaves were manually turned on and off. The signal corresponds to about a one percent change in transmitted light for complete microwave saturation. The sloping background is due to a drift in the detection apparatus. Signals from R_2 light polarized with its electric vector parallel or perpendicular to the optic axis showed increasing or decreasing light transmission, respectively. This is in qualitative agreement with the transition probabilities shown in Fig. 1. A preliminary study of the amplitudes and signs of the signals indicates that the intensity distribution of light in the source is also contributing to the signal. This may be partially due to a slight frequency shift between the source emission line and the sample absorption line.[11] With the difference in rates of optical absorption now established, it may be possible to enhance this effect and to detect optical pumping directly. These points are being pursued further and will be reported on later.

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[1]A. Kastler, Proc. Phys. Soc. (London) A67, 853 (1954).

[2]O. Deutchbein, Ann. Physik 14, 712, 729 (1932); 20, 828 (1934).

[3]K. S. Gibson, Phys. Rev. 8, 38 (1916).

[4]H. Lehman, Ann. Physik 19, 99 (1934).

[5]J. Becquerel, Compt. rend. 151, 981 (1910).

[6]B. V. Thosar, Phys. Rev. 60, 616 (1941); J. Chem. Phys. 10, 246 (1942).

[7]S. Sugano and Y. Tanabe, J. Phys. Soc. Japan 13, 880 (1958).

[8]S. Sugano and I. Tsujikawa, J. Phys. Soc. Japan 13, 899 (1958).

[9]This assumption is valid only for the case where the external magnetic field is parallel to the optic axis.

[10]G. H. Dieke and L. A. Hall, J. Chem. Phys. 27, 465 (1957).

[11]I. Wieder, Rev. Sci. Instr. (to be published).

FORMATION OF NEGATIVE IONS IN CO BY ELECTRON CAPTURE FROM FAST HYDROGEN ATOMS

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A recent precise measurement of the total cross section for electron loss by a hydrogen atom in collision with a hydrogen molecule has revealed structure in that cross section.[1] A proposal has been made, very tentatively, that enhancement of the cross section occurs at certain energies because at such energies the atomic electron may be captured by the target molecule as well as go into an unbound state. On the basis of the very sketchy evidence available a mechanism for this process was also developed. It was proposed that in collisions leading to the formation of $H^- + H$ the electron first makes a transition into the continuum as the hydrogen atom approaches the molecule, and attains about 0.25 ev of kinetic energy in the proton-electron center-of-mass system. The angular distribution is to be peaked strongly forward. To the molecule then this electron is seen as a free electron which can be captured into a state of