

to the observation of the rubidium resonance. It is believed that the rubidium atoms are oriented by spin exchange with the sodium and that the disorientation imparted to the rubidium by the rf field is transferred to the sodium by the same process. Thus resonance disorientation of the rubidium results in a reduction of the optical transmission of the absorption cell.

The sodium and rubidium densities have been estimated from optical absorption and scattering measurements to be 2×10^{10} and 1×10^{10} atoms/cm³ respectively. Using these values and taking the rubidium argon relaxation rate to be about 10^{-2} sec, we find that the spin-exchange cross section Q , is given by

$$Q \approx 2 \times 10^{-14} \text{ cm}^2.$$

This result might be in error by as much as a factor of three.

A simple theoretical estimate has been made of this cross section by use of the method of Purcell and Field.⁴ For this purpose a Morse potential was fitted to the known parameters of the NaRb molecule.⁵ The theoretical value is $Q = 5 \times 10^{-14} \text{ cm}^2$.

Further work is in progress to obtain a more precise value of the cross section and to extend the method to other systems.

We wish to express our appreciation for helpful discussions to Dr. P. Franken, Dr. J. D. Jackson, Dr. M. Karplus, and Dr. C. P. Slichter.

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¹H. G. Dehmelt, Phys. Rev. 109, 381 (1958).

²P. Franken has kindly informed us, by private communication, of his results on a similar experiment with potassium; see Franken, Sands, and Hohart, preceding Letter [Phys. Rev. Lett. 1, 54 (1958)]. Prior to hearing of Dr. Franken's results we had made a search for spin-exchange orientation of rubidium which was unsuccessful because of alloying of the sodium and rubidium. It was realized at that time that this difficulty could probably be overcome by the use of an absorption bulb of the type described in this letter. Subsequent to learning of Dr. Franken's result such a bulb was constructed and positive results were obtained.

³In the preparation of this manuscript it was learned that H. G. Dehmelt has observed similar effects in the Cs-Rb system [P. Franken (private communication)].

PROPOSAL FOR DETECTION OF NEGATIVE-MASS CARRIERS BY CYCLOTRON RESONANCE

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The purpose of this note is to point out that cyclotron resonance¹ is a very sensitive way of detecting and exploring negative effective mass carriers.² The discussion and calculations here refer specifically to the transverse negative mass of heavy holes in Ge and Si, but the technique in principle can be utilized in other crystals.

Figure 1 shows the energy contours for the heavy holes in Ge and Si. The effective mass for any direction perpendicular to the (100) is negative for all the carriers that are inside the cones. The half-angle θ of the negative-mass

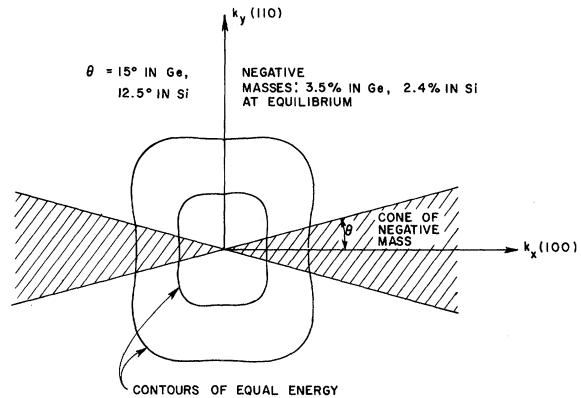


FIG. 1. Energy contours for heavy holes in Germanium and silicon.

cone is 15° in Ge and 12.5° in Si. These values are obtained from the band structure using the values for the constants A , B , and C derived from cyclotron resonance absorption on the positive-mass carriers.^{3,4} In Fig. 1 the k_y and k_z directions are along (110) directions. The values of θ are not very different from the above for k_y and k_z in any directions perpendicular to the (100) axis. For instance, in Ge, θ is 5% smaller than the value above if k_y and k_z are chosen along the other two (100) crystallographic directions.

We have computed that at equilibrium the negative-mass populations are 3.5% and 2.4% of the total heavy hole population in Ge and Si, respectively. In cyclotron resonance work with Ge, for example, total carrier (heavy hole) den-

sities of 10^8 to 10^9 (per cm^3) are usual. Thus negative-mass carriers with densities of 3.5×10^6 to 3.5×10^7 are expected and should be detectable, since the cyclotron resonance technique has sufficient sensitivity³ to detect as few as 10^3 to 10^6 carriers per cm^3 .

The experiments suggested here for the detection of negative-mass carriers are of the usual cyclotron resonance type.^{3,4} If the absolute values of m^* for negative- and positive-mass carriers are quite different, then the negative-mass carriers, at their resonant frequency (using $|m^*|$), will give a larger effect, by comparison to the nonresonant effect of the positive-mass carriers at the same frequency, than that suggested by their equilibrium populations given above. One can also use circularly polarized infrared or microwave radiation and samples with a preponderance of holes, in which case for one direction of H only the positive-mass holes are detected. Reversal of the magnetic field direction should reveal only the negative-mass signal. The preferable axis for application of H is the (100) direction. The effect, of course, is strongly dependent on orientation.

There will be cases for plane polarized waves where negative-mass effects will appear as distortions of the absorption lines due to the positive carriers. It is not clear whether any line distortions or "extra line" signals in previous work^{3,5,6} are due to these effects, since they have not been considered so far. The classical Boltzmann theory for the shape of the absorption lines⁷ neglects negative masses entirely, and a more accurate calculation⁸ for a specific case does not explicitly introduce effects of this type.

Work of this type should directly confirm the re-entrant type of contours in Ge and Si that has been indicated by cyclotron resonance work on positive-mass carriers, and may prove a very sensitive tool for further band structure studies. With the proper distribution, the cyclotron resonance of negative masses could well lead to rf power generation and amplification.

This technique should provide a sensitive method for measuring the feasibility or efficiency of methods proposed by Kroemer,² of populating and utilizing for amplification purposes negative-mass regions of k space.

The author is obliged to Professor Charles Kittel of the University of California, and F. Herman and E. O. Johnson of this Laboratory,

for discussions and helpful suggestions on this subject.

¹The present scheme was earlier suggested in RCA Laboratories Report, Contract No. DA36-039-sc-73054, October 31, 1957 (unpublished).

²H. Kroemer, Phys. Rev. **109**, 1856 (1958).

³Dresselhaus, Kip, and Kittel, Phys. Rev. **98**, 368 (1955).

⁴See the review article by B. Lax in Revs. Modern Phys. **30**, 122 (1958) for a comprehensive list of references on experimental techniques and results.

⁵Fletcher, Yager, and Merritt, Phys. Rev. **100**, 747 (1955).

⁶Behrndt, Rauch, and Zeiger, Quarterly Progress Report, Solid State Research, Lincoln Laboratory, Massachusetts Institute of Technology, February 1, 1958 (unpublished).

⁷Zeiger, Lax, and Dexter, Phys. Rev. **105**, 495 (1957).

⁸J. M. Luttinger and R. R. Goodman, Phys. Rev. **100**, 673 (1955).

HYDROXIDE ABSORPTION BAND IN ALKALI HALIDE CRYSTALS

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Pure alkali halide crystals should be completely transparent from the fundamental absorption edge in the ultraviolet to the ionic absorption edge in the infrared. Many types of impurity produce absorption bands in the ultraviolet region, however, and absorption measurements in this region provide a sensitive indication of their presence. Such measurements have been made on a series of alkali halide crystals grown from the melt in this laboratory, and on several batches of crystals purchased from the Harshaw Chemical Company. In all of these crystals absorption bands were found at the following wavelengths at room temperature:

KBr: 215.0 $m\mu$; KCl: 203.5 $m\mu$;

NaCl: 190 $m\mu$.

From classical dispersion theory,¹ assuming an oscillator strength of unity for the absorbing centers, the impurity density was calculated to be about 10^{16} cm^{-3} for all the crystals studied.

Absorption bands at these wavelengths could be caused by any anionic impurity containing oxygen, except oxide² (O^{2-}), but the most probable impurity was thought to be hydroxide, re-