polarized by exchange collisions with the optically pumped Na atoms. The rf depolarization of the K atoms is "passed on" to the Na atoms

* This work has been supported by the U. S. Atomic Energy Commission.

[1] While preparing this manuscript for publication we learned that R. Novick, University of Illinois, has been developing an atom-atom exchange polarization experiment in a sodium-rubidium system; see R. Novick and H. E. Peters, following Letter [Phys. Rev. Lett. 1, 56 (1958)]. We wish to express our gratitude to Professor Novick for several interesting telephone conversations in which ideas common to both of these experiments were discussed.

[2] H. G. Dehmelt, Phys. Rev. 109, 381 (1958).

[3] The Na metal used (Cenco) contains a trace of potassium impurity so that a pre-mixing of the two metals was not necessary.

[4] This filter consists of Corning CS3-69 and CS4-97 plates. It is used to absorb the small amount of potassium resonance radiation emitted by the Osram sodium lamp.

[5] E. M. Purcell and G. B. Field, Astrophys. J. 124, 542 (1956).

[6] G. Herzberg, Spectra of Diatomic Molecules (D. Van Nostrand Company, New York, 1955).

ORIENTATION OF RUBIDIUM ATOMS BY SPIN EXCHANGE WITH OPTICALLY PUMPED SODIUM ATOMS *

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Recently Dehmelt demonstrated that free electrons could be polarized by exchange collisions with optically oriented sodium atoms.[1] In this letter we report on an extension of this method to the orientation of atoms, in particular rubidium, by spin exchange with polarized sodium.[2,3] Rubidium was chosen for testing this method because the low-field Zeeman frequency of its most abundant isotope is well separated from that of sodium. Except for the adsorption bulb, the experimental apparatus is essentially the same as that used by Dehmelt.[1] In our case the bulb consists of a 50 cm^3 spherical flask containing argon at a pressure of about 5 cm Hg and having metallic sodium deposited on its inner surface. The rubidium is contained in a small glass side arm that can be separately heated. The main bulb is maintained at a temperature of about 140°C while the side arm is kept cooler except when it is desired to transfer rubidium into the absorption cell. The experiment is performed in a uniform magnetic field of about 0.46 gauss so that the sodium Zeeman resonance frequency is 320 kc/sec and the rubidium frequency is 213 kc/sec. The bulb is irradiated with circularly polarized sodium resonance light and its optical transmission monitored by a photocell and oscilloscope. The optical transmission of the absorption cell for the circularly polarized sodium light provides a measure of the net polarization of the sodium atoms.[1] Low-frequency Zeeman modulation is used to facilitate observation of the Zeeman resonances. A very intense sodium Zeeman resonance signal is observed when a radio-frequency magnetic field of 320 kc/sec is applied to the absorption bulb. In addition, a resonance is observed at the rubidium Zeeman frequency (Fig. 1). The intensity

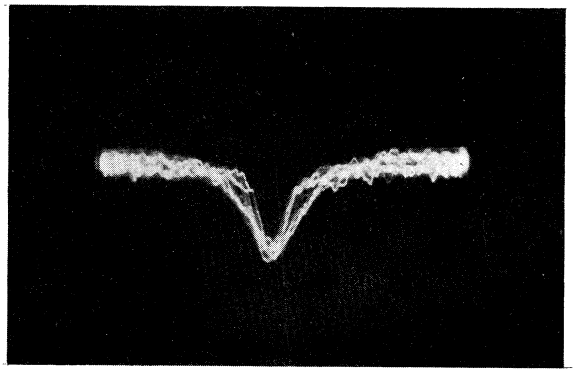

FIG. 1. Rubidium Zeeman resonance as observed by its effect on the optical transmission of a sodium resonance absorption cell.

of the rubidium resonance is about 5% of that of the sodium resonance. The shape of the rubidium resonance is quite distinct from that of the sodium and it only appears when a suitable quantity of rubidium has been distilled into the bulb. Tests with suitable optical filters have shown that the rubidium signal is not due to direct optical pumping of the rubidium by a rubidium impurity in the sodium arc. The rubidium resonances have been observed in two bulbs having slightly different construction. The effect has been observed using both a GE type *NA*-1 sodium arc and an Osram sodium spectral lamp. The sodium and rubidium resonances have been observed simultaneously by applying both 320- and 213-kc/sec signals to the radio-frequency coil surrounding the absorption cell. In this way it was found that the rubidium rosonance disappears when the sodium resonance is saturated, indicating that the oriented sodium is essential

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/cm^3 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

$$Q \simeq 2\times10^{-14}\,\mathrm{cm}^2 .$$

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 $Q = 5\times10^{-14}\mathrm{cm}^2$.

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

[2] P. Franken has kindly informed us, by private communication, of his results on a similar experiment with potassium; see Franken, Sands, and Hobart, 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.

[3] In 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 resonance[1] 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

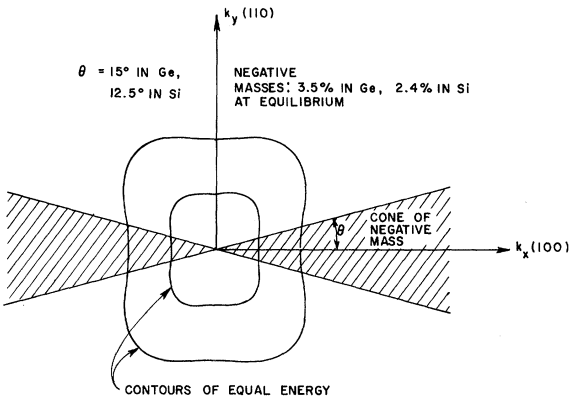

FIG. 1. Energy contours for heavy holes in Germanium and silicon.

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-

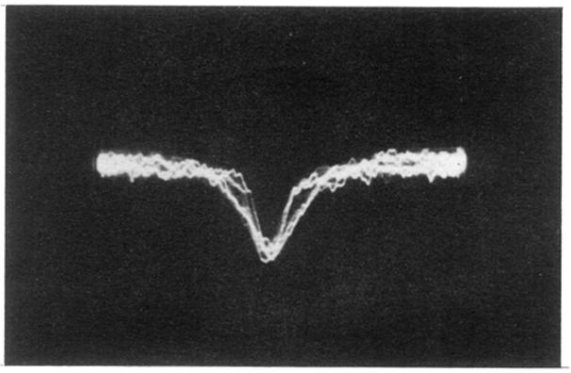

FIG. 1. Rubidium Zeeman resonance as observed by its effect on the optical transmission of a sodium resonance absorption cell.