Table I. Preparation history of the samples.

| Sample No. | Gas | Deposition temperature (C°) | Remarks |
|---|---|---|---|
| R-22 | methane | 2300 | heat treated at 2500°C for 1 h |
| R-65 | propane | 1900 | |
| R-67 | propane | 1800 | deposited in $N_2$ gas atmosphere |
| R-68 | propane | 2200 | deposited in $N_2$ gas atmosphere |

sample to sample. It seems very likely that more samples would show a decrease of the magnetoresistance if we could extend experiments to still higher fields.

So far, we have observed the sign of the magnetoresistance of some samples to change from positive to negative and then back to positive, and in other samples from negative to positive and then back to negative. Although we have not yet succeeded in obtaining two peaks for either one of the signs, it seems to be very likely that the whole picture of the field-dependence character might be oscillatory.

We can conclude nothing decisively at the present stage, but the uniqueness of the observed field dependence of the magnetoresistance is interesting. Furthermore, since we have some reasons to believe that the effective masses of the charge carriers in some pyrolytic carbons of turbostratic nature are extremely small,[3] it seems very probable that the observed phenomena are caused by the Schubnikow–de Haas effect. If this conjecture is valid, the observation of a Schubnikow–de Haas effect at such high temperature is quite stimulating.

[1]K. Takeya and K. Yazawa, J. Phys. Soc. Japan. 19, 138 (1964).

[2]International Symposium on Carbon, Tokyo, Japan, K. Takeya and K. Yazawa, 1964 (to be published).

[3]K. Takeya, K. Yazawa, N. Okuyama, and H. Akutsu, following Letter [Phys. Rev. Letters 15, 111 (1965)].

## EVIDENCE FOR THE EXISTENCE OF EXTREMELY LIGHT CARRIERS IN PYROLYTIC CARBONS

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In the preceding Letter we reported on an observation of oscillatory magnetoresistance of pyrolytic carbons. A possible explanation of this unusual behavior might be the Schubnikow–de Haas effect. So far, the Schubnikow–de Haas effect has been observed in a few materials, only at liquid-helium temperature, and the period in terms of $(1/H)$ is of the order of $10^{-5}$ at most. But if $m^*$ is of the order of $10^{-3}m_0$, there is the possibility of observing the effect even at the liquid-nitrogen temperature, with a much longer period.

Assuming a simple parabolic band, the necessary condition for the oscillatory part to be sufficiently large is, as is well known,

$$\pi^2 kT/\mu_B{}^*H = 2\pi^2 m^* ckT/eH \lesssim 1, \qquad (1)$$

while the period is expressed as

$$P = \Delta(1/H) = eh/m^* cE_F. \qquad (2)$$

Although the observed behavior is somewhat different from the usually reported de Haas effect, both as to the temperature range and as to the oscillation period, both observed tendencies are consistent in indicating an extremely small mass of carriers.

So far the only element that has been used for doping carbons substitutionally is boron. As has been reported elsewhere, we have succeeded in doping pyrolytic carbons with nitrogen up to a content of several hundred ppm.[1,2] Some of the electronic properties of these new doped materials have been reported already, and a somewhat more detailed report will be

Table I. Hall coefficients of doped samples.

| Sample no. | Impurity content | $R_H$(300°K) | $R_H$(77°K) |
|---|---|---|---|
| R-65 | | 0.36 | 1.53 |
| R-67 | $10^{-6}$ $N_2$ | 0.38 | 2.26 |
| I-11 | $10^{-5}$ $N_2$ | 0.6 | 3.5 |
| I-18 | $10^{-4}$ $N_2$ | −0.03 | −0.07 |

made in the near future. Here we would like to report that unusually large Hall coefficients are observed for some of these materials (see Table I), leading again to the inference of small mass of the conductors.

Values of the Hall coefficient for a semiconductor or semimetal obtainable by varying the impurity concentration are limited to a definite range determined by the band gap, the mobilities, and the effective masses of the carriers. It has now been well established that the mobility ratio $b$ of electrons and holes in pyrolytic carbons does not differ much from 1.08, and also that the phenomenologically postulated conduction and filled bands in pyrolytic carbons are slightly overlapped or at most 20 meV apart.

Figure 1 shows the maximum and minimum obtainable Hall-coefficient values as a function of band overlap, with the effective mass of the carriers as a parameter. The curves were calculated on a computer using the following equations:

$$n=\frac{8\pi m_e^*}{h^2C_0}kT\ln\left[1+\exp\left(\frac{E_0-E_F}{kT}\right)\right],$$

$$p=\frac{8\pi m_h^*}{h^2C_0}kT\ln\left[1+\exp\left(\frac{E_F}{kT}\right)\right],$$

$$R_h=\frac{1}{e}\frac{p-b^2n}{(p+bn)^2}.$$

It can be seen that in order to account for the observed large values of the Hall coefficient, it is necessary to postulate the effective mass of the electron to be smaller than $0.007m_0$, taking the band overlap equal to zero.

Here we should recall that the $\gamma_1$ value de-

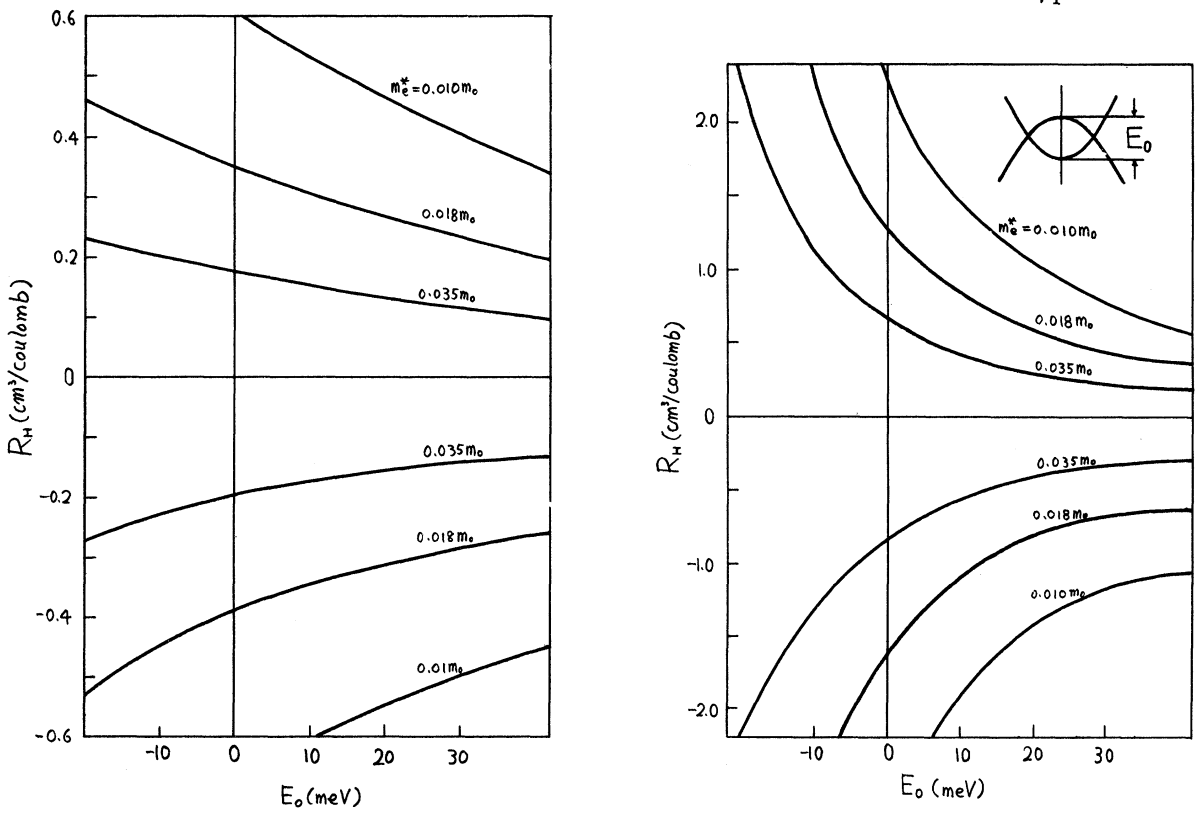


FIG. 1. Maximum and minimum values of Hall coefficient at (a) 300°K and (b) 77°K as a function of the distance $E_0$ between band edges with the electron effective mass $m_e^*$ as a parameter. Mobility ratio is assumed to be 1.08, and $E_0$ is taken positive when the bands overlap. For all curves, $m_e^*/m_h^*$ is taken equal to 0.035/0.055.

duced by Marchand on the basis of susceptibility measurement[3] for pyrolytic carbons is about $\frac{1}{10}$ of that for single-crystal graphite. The density of states in graphite is expressed as

$$N(E)=\frac{8}{3\pi^2\gamma_0^2a^2c_0}\{\pi|E|+2\gamma_1\}.$$

If one neglects the first term in this expression, Marchand's result leads to an effective mass of $\frac{1}{10}$ of the single-crystal value.

We also have some evidence of large tunneling probabilities in a silicon pyrolytic carbon junction,[2,4] which again supports the assumption of the extremely small mass of the carriers.

All these experimental findings seem to coincide in leading to the result that the effective mass of the carriers in some pyrolytic carbons is much smaller than it is in single crystals. The only hindrance to this conclusion is the problem of density of states, since it is known that the carrier concentrations in pyrolytic carbons and in single crystals of graphite do not differ much. This difficulty, however, seems to be overcome when one accepts McClure's treatment[5] for poorly ordered carbons. According to his views, the electronic state in turbostratic carbons should be represented by an assembly of many bands with small densities of states. Since these bands are supposed to converge into four bands as the graphitization proceeds, one should postulate a density of states $1/n$ times that of a single crystal if there are $4n$ such bands.

[1]T. Nozaki and K. Yazawa, Bull. Chem. Soc. Japan 37, 1891 (1964).
[2]To be published.
[3]A. Marchand, Carbon 1, 75 (1963).
[4]K. Takeya, K. Yazawa, and N. Okuyama, Annual Convention of the Institute of Electrical Engineers of Japan, 1965 (to be published).
[5]International Symposium on Carbon, Tokyo, Japan, 1964 (to be published).

## ASYMMETRY OF $(d,p)$ CROSS SECTION FOR A POLARIZED $He^3$ TARGET*

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This Letter discusses the expected left-right asymmetry for the $He^3(d,p)He^4$ (g.s.) reaction when a polarized $He^3$ target is used. In particular, various types of proton–target-nucleus and proton–final-nucleus interactions have been investigated under the direct-reaction assumption. The relationship between the proton-spin polarization for an unpolarized target, $P(\theta)$, and the left-right asymmetry[1] for a polarized target, $A_{LR}(\theta)$, has then been calculated. The asymmetry $A_{LR}(\theta)$ is defined by

$$A_{LR}(\theta)=q^{-1}[\sigma_L(\theta)-\sigma_R(\theta)]/[\sigma_L(\theta)+\sigma_R(\theta)], \quad (1)$$

where $q$ is the polarization of the target nucleus and $\sigma_L(\theta)$ and $\sigma_R(\theta)$ are the left-side and right-side differential cross sections. Equation (1) is calculated with transition amplitudes[2]

$$A_{LR}(\theta)=\frac{-2\sum_{M_f,\nu_d,\nu_f}\mathrm{Im}\{\langle M_f,\nu_f|T|\nu_d,M_i=\frac{1}{2}\rangle^*\langle M_f,\nu_f|T|\nu_d,M_i=-\frac{1}{2}\rangle\}}{\sum_{M_f,\nu_d,\nu_f,M_i}|\langle M_f,\nu_f|T|\nu_d,M_i\rangle|^2}, \quad (2)$$

where $M_i$, $M_f$, $\nu_d$, and $\nu_f$ are the $z$ components of the spins of the target nucleus, the final nucleus, the incident deuteron, and the emitted proton, respectively. The $z$ axis is chosen along the beam direction. The polarization $P(\theta)$ is given by[2]

$$P(\theta)=\frac{2\sum_{M_f,M_i,\nu_d}\mathrm{Im}\{\langle M_f,\nu_f=\frac{1}{2}|T|M_i,\nu_d\rangle^*\langle M_f,\nu_f=-\frac{1}{2}|T|M_i,\nu_d\rangle\}}{\sum_{M_f,M_i,\nu_d,\nu_f}|\langle M_f,\nu_f|T|M_i,\nu_d\rangle|^2}. \quad (3)$$