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## NOVEL TECHNIQUE OF ACOUSTIC DE HAAS-VAN ALPHEN EFFECT AND APPLICATION TO $\text{LaB}_6$

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**Abstract.** – We present the clear evidence that the new Fermi surface structure exists in the interconnecting necks of  $\text{LaB}_6$ , which have been found by the acoustic de Haas-van Alphen effect.

### 1. Introduction

The lanthanum hexaboride,  $\text{LaB}_6$ , has attracted remarkable attention as the non-f electron reference material for another rare earth hexaborides which show various interesting properties of f-electrons. The study of Fermi surface (FS) of  $\text{LaB}_6$  is considerably important to understand electronic structures of rare earth hexaborides.

Lots of de Haas-van Alphen (dHvA) experiments on  $\text{LaB}_6$  have been performed [1-3]. It was concluded that FS of  $\text{LaB}_6$  consists of interconnecting ellipsoids at X points and thin necks [3] along  $\Sigma$  lines in the simple cubic Brillouin zone. Whereas, no band calculation has succeeded [4] in realization such very slender necks.

Recently Harima *et al.* [5] have performed a new band calculation, motivated by the present data, which proposes that the FS of  $\text{LaB}_6$  consists of ellipsoids at X points connected by the short and thick necks and the quite small ellipsoid-electron-pockets which are elongated along  $\Sigma$  lines and overlap on the necks.

In the present report, we would like to show the clear evidence that the small ellipsoidal FS [5] really exists on the necks and the low frequency quantum oscillations denoted  $\rho$ -branches [3] are identified as the small ellipsoids, which have been firstly found by the acoustic dHvA effect.

### 2. Experimental

We have developed the ultrasonic apparatus based on the phase comparison method [6] with the high resolution ( $\Delta v/v < 5 \times 10^{-8}$ ) and low input power ( $\simeq 500$  nW). The high performance is realized by using  $\text{LiNbO}_3$  transducer prepared in the optical instrument work shop of our institute. The low input power apparatus is applicable to low temperature experiments [7] in a dilution refrigerator. The high resolution enables to observe the quantum oscillations of longitudinal  $C_{11}$ , transverse  $C_{44}$  and  $(C_{11} - C_{12})/2$  modes' elastic constants of  $\text{LaB}_6$  [8] corresponding to all of

the extremal orbits which have been reported [1-3]. In this paper, the acoustic dHvA data of  $C_{44}$  mode's elastic constant corresponding to  $\rho$ -branch is shown. The configuration,  $(k_x, u_y)$ , of the present ultrasonic experiments is that the sound propagation ( $\mathbf{k}$ ) and displacement ( $\mathbf{u}$ ) direction are parallel to the  $\langle 100 \rangle$  and  $\langle 010 \rangle$  crystal axes of  $\text{LaB}_6$ , respectively. The sound frequency of 70 MHz have been used. Considering possibility of rotation and anisotropy effect in the itinerant electron system, we have measured the angular dependence of acoustic dHvA effect for rotating magnetic field directions in the various crystallographical planes as the  $(011)$ ,  $(101)$ ,  $(0\bar{1}1)$ ,  $(0\bar{1}0)$  and  $(110)$  at 1.3 K. The magnetic field is generated by a superconducting magnet up to 8 T. The  $\text{LaB}_6$  single crystal of present experiments exhibits the residual resistance ratio  $\simeq 65$ .

### 3. Results and discussion

The effective cyclotron mass of  $0.042 m_0$  in the  $\langle 100 \rangle$  direction of  $\rho$ -branch have been observed by the temperature dependence of amplitude of the  $C_{44}$  mode's acoustic quantum oscillation, which is consistent with others [1-3]. The Dingle temperature is about 2.0 K for  $\rho$ -branch.

Figures 1 and 2 show angular variations of the extremal cross-sectional areas of the FS corresponding to the acoustic dHvA frequencies with the order of  $10^4$  G. All branches shown in figures 1 and 2 are  $\rho_5$  and  $\rho_6$  except  $\rho_3$  and  $\rho_4$  which are antisymmetrical to the  $\langle 110 \rangle$  axis in the  $(001)$  plane. The  $\rho_1$  and  $\rho_2$  branches exist in the  $x$ -plane of the Brillouin zone, and also  $\rho_3$ ,  $\rho_4$  in the  $y$ -plane and  $\rho_5$ ,  $\rho_6$  in the  $z$ -plane, respectively. The ultrasonic configuration  $(k_x, u_y)$  excites the  $\varepsilon_{xy}$  strain in the  $z$ -plane. Therefore it is expected that the Landau orbits around  $\rho_5$  and  $\rho_6$  Fermi surfaces are the most responsible for the  $\varepsilon_{xy}$  strain. The result has been confirmed by Harima *et al.* [9] with the  $\varepsilon_{xy}$  strain dependence of bands corresponding to  $\rho$  branch. The observation of the  $\rho_3$  and  $\rho_4$  branches may be interpreted by the response of the Landau orbit through

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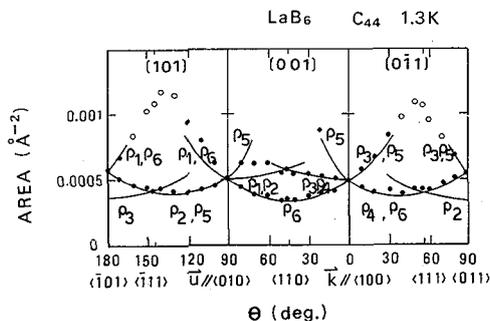


Fig. 1. - Angular variations of extremal cross-sectional area denoted as  $\rho$  branch in the (101), (001), (011) planes. Solid lines show the data observed by torque method [3]. Open circles indicate the data firstly observed by the present experiments.

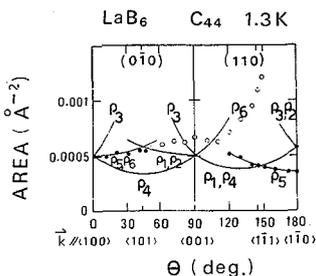


Fig. 2. - Angular variations of extremal cross-section in the (010) and (110) planes.

the rotation effect since the  $(k_x, u_y)$  also excites the rotation of  $y$ -plane around  $z$ -axis.

The angular variation indicated by open circles in figures 1 and 2 have been firstly observed by the acoustic dHvA effect. The results by torque method [3] are transcribed as solid lines. The present results in the (101) and (011) plane are considered as if the interconnecting necks were cut off from main ellipsoidal FS at  $X$  point, if one regards  $\rho$  branches as the interconnecting necks. The curious fact can not be explained by magnetic break down (MBD) effect. MBD breaks out when the electrons accelerated by magnetic field break through a small potential gap. Therefore separated FS becomes interconnecting one by MBD effect and the above mentioned cut off effect never happen. Moreover, the results of magnetoresistance indicate that the necks exist in high field [2, 10]. The cut off effect may happen by non-linear effect of strain. We have investigated the strain dependence of acoustic dHvA oscillations on  $\rho$  branch. No strain dependence is detected [8]. Recently, a new FS model was proposed by Harima *et al.* as mentioned above. The angular variations of cross sectional area in the (101), (011),

(011), (010) and (110) planes are in good agreement with the angular dependence of the proposed small ellipsoidal FS in the thick interconnecting necks. Our developed high resolution ultrasonic system enables to observe acoustic dHvA effect without field modulation technique. Therefore one can easily get the amplitudes of acoustic quantum oscillations. The angular dependences of the amplitudes [8] are also in good agreement with the theory [9].

In summary, we have developed the high performance ultrasonic apparatus and identify  $\rho$  branches as the small ellipsoidal FS proposed by recent band calculation and not as interconnecting necks.

In order to find the dHvA effect of real necks which have not been observed yet, high field and low temperature experiments on a more purified sample are now going on using a dilution refrigerator.

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