FERMI SURFACE STUDY OF CeSb*

CONF-841184--6
DE85 002532

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September 1984

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Manuscript submitted to the 30th Annual Magnetism and Magnetic Materials Conference, November 27-30, 1984, San Diego, California.

*Work supported by the U.S. Department of Energy.

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Abstract

A Fermi surface study of the ferromagnetic phase of CeSb is presented. The γ frequency branches arising from the electron surfaces at the X points, three separate frequency branches from the hole surfaces at the Γ point and the low frequency branch α have been observed. The effective mass ratios are low and range from ~ 0.2 for the α branch to ~ 1.0 for the high frequency branch of γ. The low effective mass ratios suggest that the admixture of the conduction states with the f state is small. We have observed a drastic change in the appearance of the dHvA signal at the phase transition between the ferromagnetic and lower field antiferromagnetic phases: The low frequency α oscillation suddenly disappears as the crystal enters the antiferromagnetic phase. By utilizing the change in the signal appearance, the transition field strength has been measured as a function of the field direction. The present experimental results, particularly the origin of the α oscillation, are discussed in the light of the p-f mixing theory and recent band structure calculations based on localized f orbitals.

PACS numbers: 71.25Hc, 75.30Kz.

Introduction

The intermetallic compound CeSb is well known to exhibit unusual magnetic properties and complex phase diagrams. Below about 8K three phases, S_2, S' and F, occur as the field is increased.[1] The stacking sequence of the ferromagnetically ordered (100) planes with up (↑) or down (↓) magnetization is different in each phase i.e., (↑↑↓↓↑↑↓) for S_2, (↑↑↓) for S' and (↑) for F. We observed de Haas-van Alphen (dHvA) oscillations in all three phases. In this paper we report in detail on the Fermi surface properties in the ferromagnetic phase F.

The dHvA frequencies in the ferromagnetic phase of CeSb have been previously studied by Kitazawa et al.[2] They observed the frequency branches γ from the ellipsoidal electron surfaces at the X points, the β branch from the hole surfaces at Γ and the α branch which has been interpreted in terms of the p-f mixing theory.[3] The present experimental results, as well as the differences from their results, will be discussed in the light of the p-f mixing theory and recent band structure calculations[4] of CeSb.

Experiment

The crystals of CeSb were prepared by prereacting Ce and Sb in silica tubes at low temperatures and then recrystallizing the compound at 1800-1900°C in sealed molybdenum crucibles. In order to make the demagnetization field homogeneous, spherical samples of ~ 1 mm diameter were prepared by spark-erosion. The dHvA signals were detected at fields up to 15T and temperatures down to 0.35K using the field modulation technique. The dHvA frequencies presented in this paper are not corrected for the effect of the ferromagnetic magnetization, which depends on both field strength and direction. We estimate this correction to be at most a few percent.

Results and Discussion

The dHvA frequencies observed in the (010) and ($1\bar{1}0$) planes are shown in Fig. 1. For clarity, many of the harmonics and combination frequencies which we observed are not shown. The frequency and the shape of the lowest frequency branch α agree well with those reported by Kitazawa et al. The origin of the α branch will be discussed later.

The β_1 branch has been observed only for a finite range of field directions. However, we conjecture that β_1 arises from a closed sheet of the Fermi surface and is not observed near [111] because its signal is weak. The shape of the β_1, β_2, and β_3 branches indicate that they arise from approximately spherical surfaces around a high symmetry point. We interpret the β_1, β_2, and β_3 branches as arising from three separate hole surfaces around Γ. Kitazawa et al. observed a nearly flat branch β (in their notation) between the α and 2α branches. The shape of the β branch does not agree with that of either β_1 or β_2, but could be made up of parts of β_1 and β_2 connected differently than in Fig. 1.

The overall features of the γ branches can be well explained with three equivalent elliposidal Fermi surfaces at the X points. However, in the (010) plane and for the directions between [111] and [001] in the ($1\bar{1}0$) plane, we have not observed any obvious low frequency branch of γ. For these field directions, the low frequency branch of γ is expected to arise from the elliposidal surface at the X point where the X-Γ direction is parallel to the direction of the magnetic moment. The branch labelled 2α in Fig. 1 occurs approximately where the missing lower branch of γ is expected to be. However, the frequency of the 2α branch is very close to twice that of α, and the harmonics and the field dependence of the amplitude of the 2α branch are consistent with it being predominantly the second harmonic of α. Therefore we conclude that the low frequency branch of γ is missing or that its amplitude is very weak. In this respect we differ with Kitazawa et al. who report seeing the low frequency branch of γ between [111] and [001] in the $(1\bar{1}0)$ plane and in the (010) plane. Our interpretation of the missing low frequency branch of γ and the origin of α will be discussed later. We have found large and unsystematic splittings in the γ branches as shown in Fig. 1, whose origin we do not yet understand.

Table 1 lists the effective mass ratios measured along high symmetry directions. Accurate mass measurements were difficult because other dHvA frequencies, harmonics, or combination frequencies always existed close to the frequency of interest. The errors are estimated to be about 20% for the low frequencies α, β_1 and β_2 and about 10% for the other frequencies. The effective mass ratios are low and range from ~ 0.2 for α to ~ 1.0 for the high frequency branch of γ. The low effective mass ratios suggest that the admixture of the conduction states with f states is small at the Fermi energy.

Figure 2 illustrates the drastic change in the dHvA signal at the phase transition between the ferromagnetic and the antiferromagnetic phases. The α oscillation suddenly disappears as the crystal enters into the antiferromagnetic phase. The details of the dHvA frequency changes between the phases will be reported in a later publication.

Figure 3 shows the transition field strength H as a function of the field direction, derived from traces like that shown in Fig. 2. The anisotropy of H closely follows the function $H_0/\cos\theta$, where H_0 is the field strength along the easy axis [001] and the θ is the angle between the field direction and the easy axis. This result is consistent with the fact that magnetic moment is pinned along one of the easy axes <100>.

Let us discuss the origin of the α oscillation and the missing or weakening of the low frequency branch of γ. The p-f mixing theory[3] claims that a characteristic hole surface with a neck along the direction of the magnetic moment is produced through the p-f mixing interaction. Kitazawa et al.[2] attributed the origin of the α oscillation to an orbit around the neck. According to this model, the missing of the low frequency branch would be interpreted as follows: The low frequency branch of γ sits close to the second harmonic branch of α and its amplitude is not strong enough to be observed separately from the second harmonic of α.

An alternative explanation for our experimental results has been given by the recent spin-polarized band structure calculation of Norman and Koelling[4] which assumes a dehybridized or localized f electron in an ordered $j = 5/2$, $\mu = 5/2$ state. Due to the moment staying on one of the easy axes the non-spherical f electron density breaks the cubic symmetry of the potential seen by the conduction electrons. Therefore the three electron surfaces at the X points are no longer equivalent. Band calculations for this system without cubic symmetry show that the α branch originates from the electron surface at X which would have been responsible for the low frequency branch of γ if the cubic symmetry were not broken. The calculated areas and the effective mass ratios of the observed branches are in a reasonable agreement with the present experimental results.

Both the p-f mixing theory and the band structure calculation predict other frequency branches than those presently observed: According to the p-f mixing theory branches from the electron surfaces of the down spin electrons at the X points and additional branches from the characteristic hole surface are expected. According to the band structure calculation there is another set of three hole surfaces at Γ and electron surfaces at X corresponding to the other spin band which is shifted in energy by the ferromagnetic order. The band calculation shows that some of these spin splittings are small, perhaps leading to opposite spin Fermi surface areas which are hard to distinguish experimentally. Although higher harmonics and combination frequencies of the fundamental frequencies have been observed up to the frequencies of ~ 3000T, we have not found other obvious branches. Further careful studies on the dHvA frequencies will be required to clarify this point.

Acknowledgments

We thank Drs. Michael Normal and Dale Koelling for many stimulating discussions. W. J. acknowledges the support of the Swiss National Science Foundation. This work was supported by the U.S. Department of Energy.

References

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Figure Captions

Fig. 1. dHvA frequency branches in (010) and ($1\bar{1}0$) planes.

Fig. 2. Recorder trace of the dHvA signal at the phase transition between the ferromagnetic and antiferromagnetic phases for increasing field along <100> at a temperature of 1.0K. The upper and lower traces correspond to the in-phase and out-of-phase components of the signal, respectively.

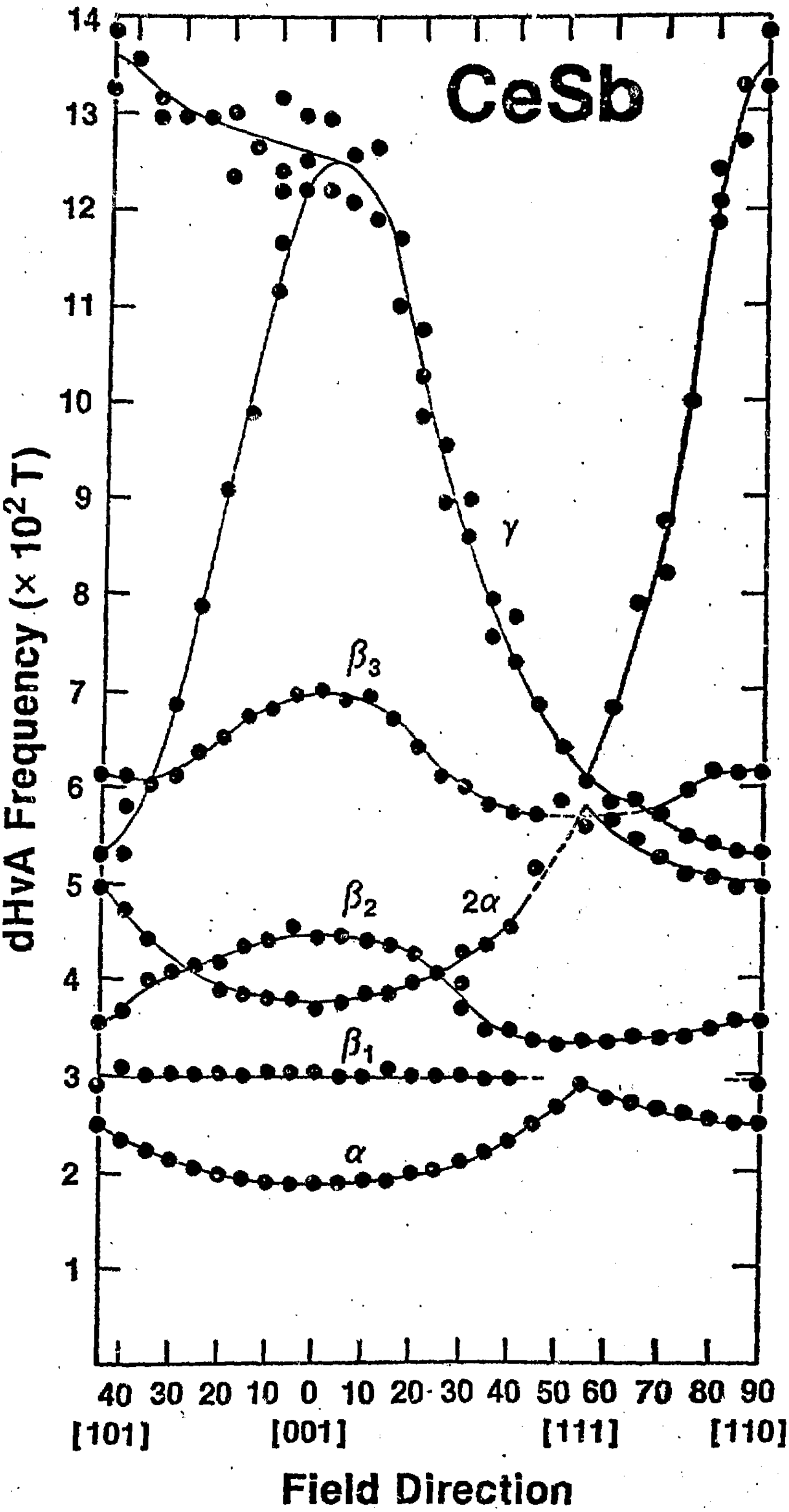
Fig. 3. Transition field strength as a function of the field direction at 1K. The solid line indicates the function of $H_0/\cos\theta$. The symbols and denote the transition points measured when increasing and decreasing the field, respectively.

Table 1

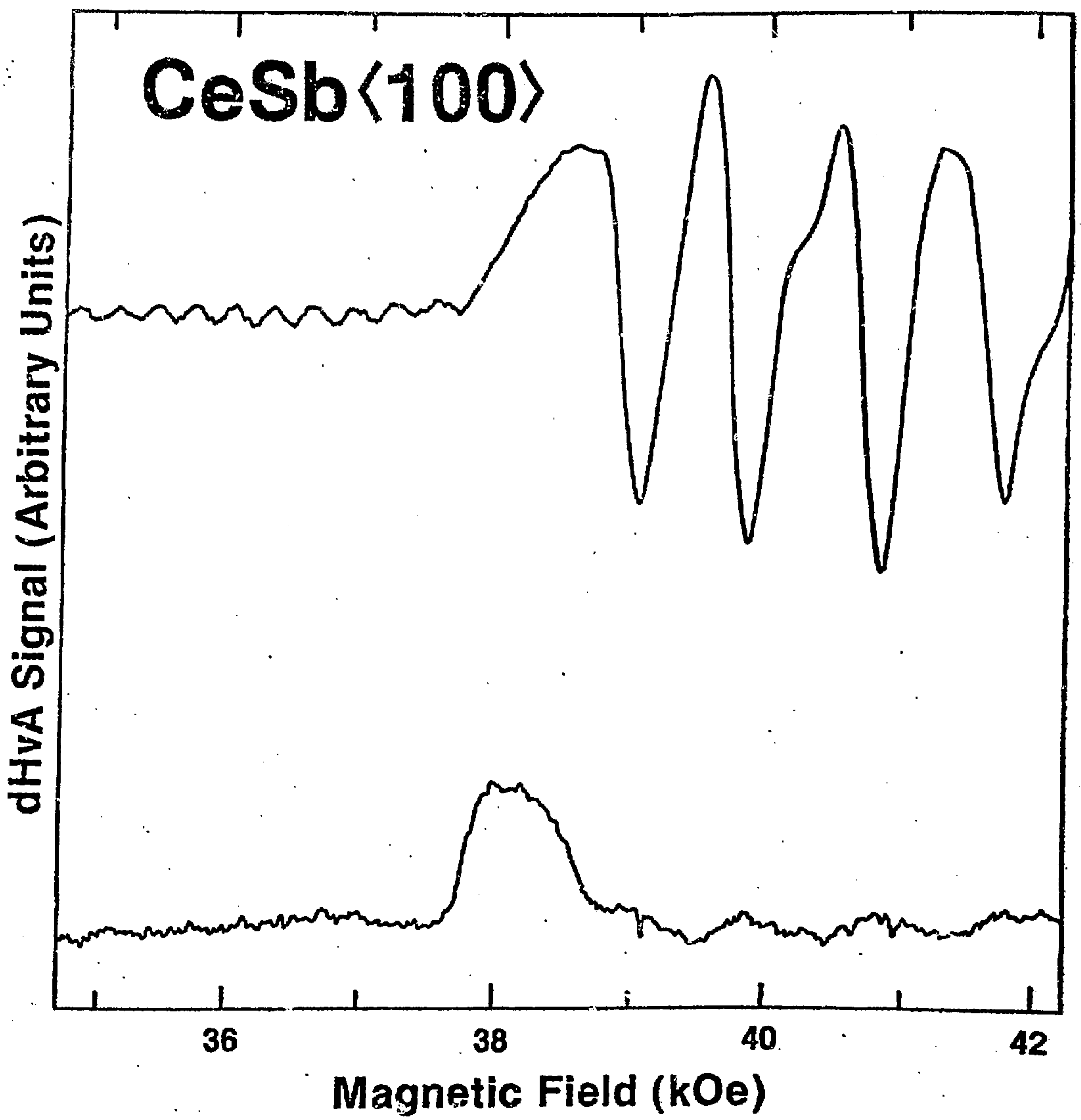
Effective mass ratios

γ_ℓ denotes the low frequency branch of γ. γ_h and γ_h' refer to the high frequency branch of γ, which is observed to split into two or more peaks at certain angles. - indicates that the frequency is not present for that direction or that the effective mass ratio was not measured.

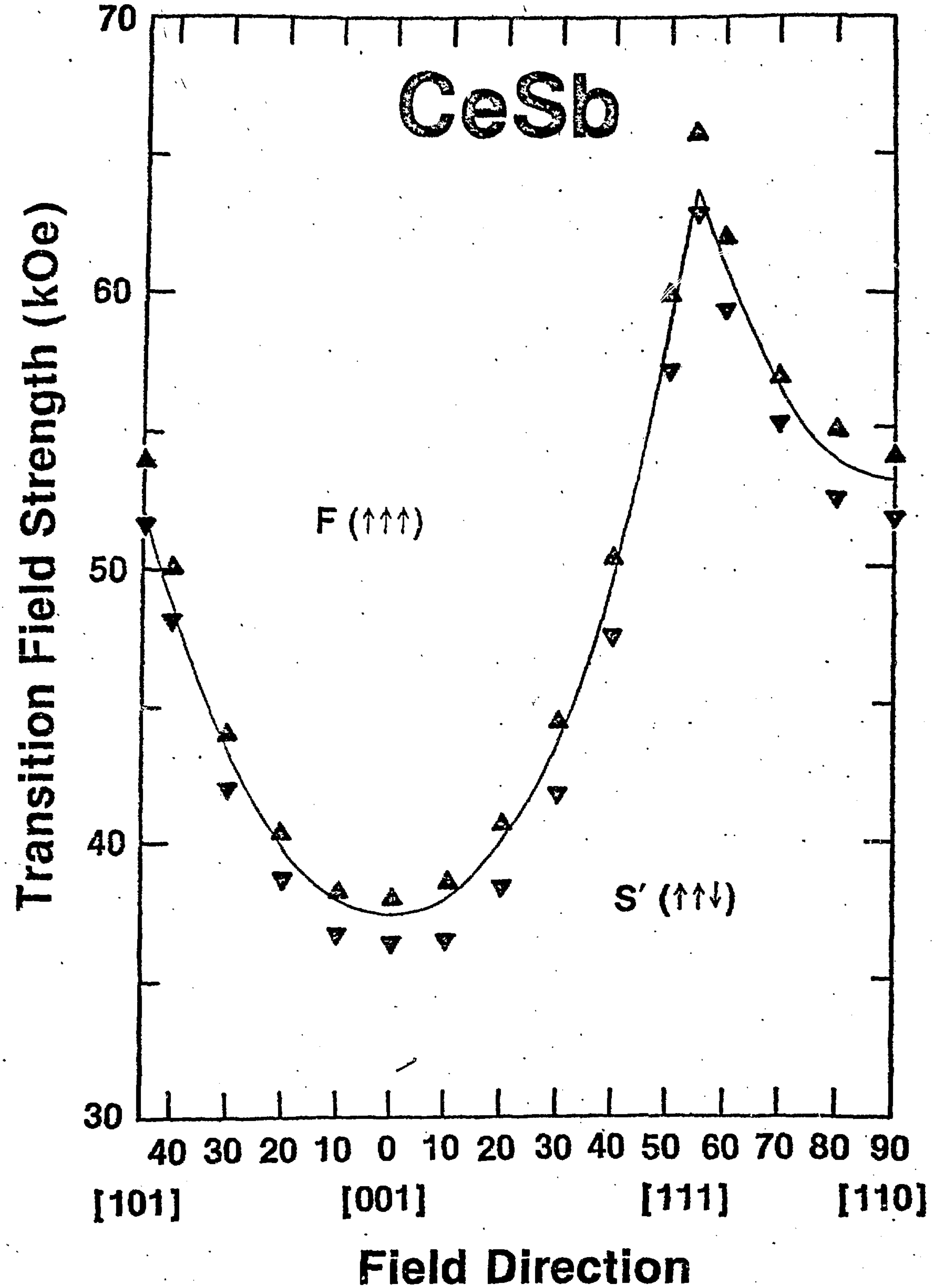
	<110>	<100>	<111>
α	0.31	0.23	-
β_1	-	0.50	-
γ_ℓ	0.49	-	0.53
β_2	0.56	0.97	-
β_3	0.65	0.89	-
γ_h	1.00	0.94	-
γ_h'	0.90	0.82	-



CeSb
dHvA Frequency (× 10² T)
14
13
12
11
10
9
8
7
6
5
4
3
2
1
γ
β3
β2
2α
β1
α
40 30 20 10 0 10 20 30 40 50 60 70 80 90
[101]
[001]
[111]
[110]
Field Direction



CeSb⟨100⟩
dHvA Signal (Arbitrary Units)
36
38
40
42
Magnetic Field (kOe)



CeSb
70
60
50
40
30
Transition Field Strength (kOe)
F (↑↑↑)
S′ (↑↑↓)
40 30 20 10 0 10 20 30 40 50 60 70 80 90
[101]
[001]
[111]
[110]
Field Direction