Magnetic breakdown orbits in beryllium

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(Received 1 September 1976)

Magnetoacoustic quantum oscillations, attributed to magnetic breakdown orbits in Be, have been simultaneously recorded along with the derivative of the magnetization, dM/dH. The de Haas–van Alphen, dM/dH, data were integrated to obtain $M(B)$. In a recent paper we have shown that the breakdown quantum oscillations were FM distorted by large magnetic interactions [due to $M(H)$] in Be. The demodulation of the FM spectrum has now been accomplished by using $B = H + 4\pi M(B)$ in the Fourier analysis of the data. The present results confirm our earlier assignment of certain FM spectral lines to breakdown orbits. The de Haas–van Alphen data show no evidence of breakdown oscillations, which were large for the case with magnetoacoustic quantum oscillations.

INTRODUCTION

In a recent paper[1] we reported on the observation of magnetoacoustic quantum oscillations (MAQO's) in Be. The data were taken with sonic frequencies up to 1.9 GHz in magnetic fields up to 100 kOe. At that time we reported the first direct observation of quantum oscillations, with $1/B$ periods, directly related to electron orbits resulting from magnetic breakdown (MB) between the cigar and coronet pieces of the Be Fermi surface. However, Be exhibits a large magnetic interaction effect, whereby the internal B field is not simply related to the applied H field. Instead, $B=H+4\pi(1-L)M(B)$, where L is the demagnetizing factor and $M(B)$ is the sample magnetization which in the present case is dominated by de Haas–van Alphen (dHvA) oscillations from electrons on the cigar "hips" and "waist.[1]" The result is, that when MAQO's are recorded as a function of $1/H$ (rather than $1/B$) and Fourier spectrum analyzed, a severe FM distortion of the oscillations results (Fig. 6 of Ref. 1). We in fact find that the amplitude of $M(B)$ in gauss actually exceeds the ΔB spacing of the MAQO peaks.

PRESENT WORK

The MB orbits, which are the subject of the present discussion, lie in the basal plane of the Be Brillouin zone. Hence the direction of $\vec{H}$ coincides with the [0001] crystal direction. Figure 1 shows several of the MB orbits possible for this case. Other orbits, such as those including area $2A$ and $A+\alpha^1$, where the electron makes extra trips about the cigar-waist orbit α^1, are also possible. Unfortunately, the FM modulation frequency, due to the magnetic interactions, is either due to α^1 or some weighted average of α^1 and α^2 (the cigar-hip frequency). (α^2 differs from α^1 by only 3%.)

The result of this combination of circumstances is that the FM spectrum of the MB MAQO's exhibits spectral lines separated by α^1, making it difficult to decide if any two spectral lines are for instance due to A and $A+\alpha^1$ or just due to A but with FM sidebands. In Ref. 1 we concluded, due to amplitude beats in the MB MAQO's, that the spectrum must be the FM sidebands for *both* A and $A+\alpha^1$. Figure 2 shows a recent FM spectrum for these MB data. The data of this spectrum were taken with our more precisely calibrated 75-kOe magnet rather than with the 100-kOe magnet used for the data shown in Fig. 5 of Ref. 1.

In order to determine the true nature of the MB MAQO data, it was decided to simultaneously record de Haas–van Alphen data by measuring dM/dH. This was accomplished by winding 13 turns of No. 40 Cu wire around a 1-cm cubic specimen of Be. The plane of the winding was perpendicular to [0001]. As previously reported[1] the MAQO's could only be observed for $\vec{q}$, the sound wave vector, perpendicular to [0001]. For the present work the sound was propagated with $\vec{q}\parallel[11\bar{2}0]$. The Be cube was from our less pure Franklin Institute material.[1] The very pure Be

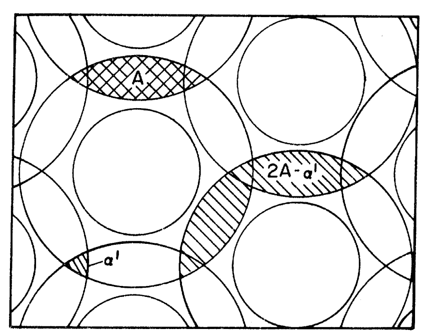

FIG. 1. Possible magnetic breakdown orbits A and $2A-\alpha^1$ in the basal plane. $\vec{H}$ is along the [0001] axis.

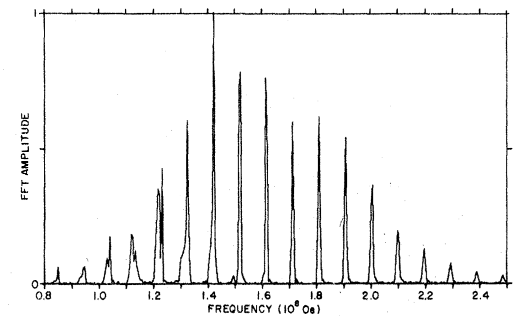

FIG. 2. Frequency spectrum of the high-frequency magnetic-breakdown magnetoacoustic quantum oscillations. (FFT, fast Fourier transform.) The H field range of the data used was 63–73 kOe. Here $\vec{H} \parallel [0001]$, $\vec{q} \parallel [11\bar{2}0]$, and 533-MHz shear waves, polarized along $[10\bar{1}0]$, were used.

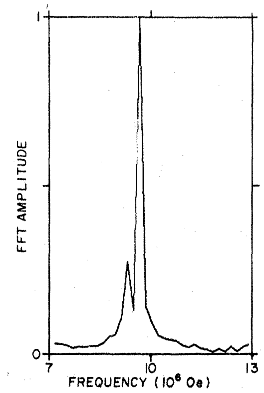

FIG. 4. Frequency spectrum of dM/dH oscillations for H between 63 and 73 kOe.

specimens[1] used for some of our earlier data could not be used for the present work because they are in the form of small disks which prevent the use of coils simultaneously with transducers for $\vec{q} \perp [0001] \parallel \vec{H}$. The coil output emf is proportional to dM/dH in the specimen (note: M is really a function of B). The dM/dH data were both electronically analog integrated and computer integrated from the digitally recorded dM/dH data to get $M(B)$ as a function of H. Considerable care was required to remove thermal emf's and to buck the background emf due to the sweeping field. By recording dM/dH simultaneously with the MAQO data, the effect of the demagnetizing factor L is the same for both measurements and it is lumped in with the resulting $M(B)$ determined by integration. Hence the internal B field is given by

$$B = H + 4\pi M(B) , \qquad (1)$$

with $M(B)$ experimentally determined including the effects of L.

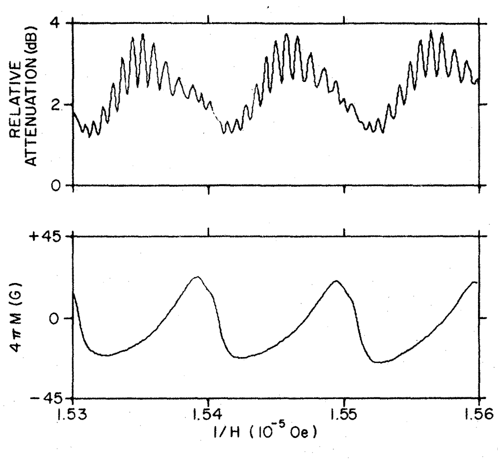

FIG. 3. Magnetoacoustic quantum oscillations and magnetization oscillations both plotted (from digitally recorded data) vs $1/H$. The data were recorded at 1 K. The magnetoacoustic data are from a very small portion of data used to generate Fig. 2. The high-frequency quantum oscillations are attributed to magnetic breakdown. The low-frequency quantum oscillations and oscillations in $4\pi M$ have periods identified with "cigar" orbits.

Figure 3 shows plots of both $4\pi M$ (dHvA) oscillations and relative attenuation (MAQO) oscillations as functions of $1/H$. The dHvA oscillations show no evidence of the high-frequency MB oscillations which are clearly evident in the attenuation. If one looks at a range of about 15 dHvA periods, the locations of the nodes of the beats in the amplitude of the MB MAQO's are observed to shift in phase with respect to the dHvA oscillations. A fast Fourier transform (FFT) of the dHvA data as a function of $1/H$ is shown in Fig. 4. The data show a split peak the larger of which is located at 9.72×10^6 G—"cigar-hip" frequency. The figure shows that the dHvA effect is dominated by the hip orbits. Figure 5 shows the low-frequency part of the FFT

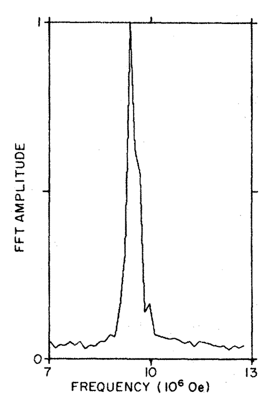

FIG. 5. Frequency spectrum of low-frequency ("cigar") magnetoacoustic quantum oscillations for H between 63 and 73 kOe.

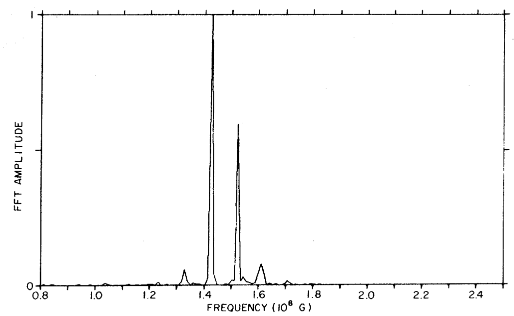

FIG. 6. Frequency spectrum of the magnetic breakdown magnetoacoustic quantum oscillations for B between 63 and 73 kG. The data were the same as used for Fig. 2, but corrected by $4\pi M(B)$ to be in terms of $1/B$ rather than $1/H$.

for the MAQO data over the same H field range as that of Fig. 4. This peak is dominated by the "cigar-waist" frequency—9.42×10^6 G. These two figures (4 and 5) are consistent with the fact that the beats of the MAQO's of Fig. 3 shift in phase with respect to the dHvA oscillations. These FFT's also explain why the nodes and antinodes of the MB MAQO's remain phase locked with respect to the low-frequency MAQO on which they are riding. This is because it is expected that the beating is due to the orbits A and $A+\alpha^1$ of Fig. 1 and α^1, the difference frequency, is just the cigar-waist frequency—9.42×10^6 G, which is the major contribution to the spectrum in Fig. 5.

If the value of $4\pi M(B)$ as a function of applied H is taken from the data, similar to that shown in Fig. 3, it can be used to find the actual internal value of B by using Eq. (1). The data of Fig. 2 arise from a FFT of attenuation vs $1/H$ digital data. By using the derived values of B for each value of H, the data can be corrected, point by point, into attenuation vs $1/B$ digital data. Figure 6 shows the FFT which results from correcting the data used to generate Fig. 2. When Fig. 6 is contrasted with Fig. 2 the result is striking. The complex FM spectrum of Fig. 2 has now been altered to produce a simple two-frequency spectrum. The two resulting frequencies are 1.43×10^8 and 1.52×10^8 G which are, respectively, identified with orbits A and $A+\alpha^1$ of Fig. 1. The frequencies calculated from the pseudopotential data given by Tripp, Everett, Gordon, and Stark[2] are 1.42×10^8 and 1.51×18^8 G for these same orbits. This agreement is very good, and is in fact much better than we had previously reported for the same orbits. Our earlier data for these particular orbits were taken with a less precisely calibrated 100-kOe Nb_3Sn magnet.

Because of the difficulties inherent in calibrating the electronics used to measure dM/dH, the integral result $4\pi M(B)$ was not precisely known in amplitude. The exact amplitude shown in Fig. 3 for $4\pi M$ was arrived at by altering the approximate result from the system calibration in 1-G steps until the simplest spectrum of Fig. 6 was reached. This resulting amplitude was unique in that other values differing from 1 to 100 G from the final value resulted in much more complex spectra. The shape of the $4\pi M(B)$ oscillations was always carefully preserved as the amplitude was adjusted. This shape is generally consistent with that predicted by Condon[3] for rod-shaped specimens with large magnetic interactions. Namely, the wave form is of a sawtooth shape with the sharp rise on the low H (high $1/H$) side of the oscillation. It is observed that in Fig. 3 the MB MAQO periods have attenuations peaks ~30 Oe apart, whereas the peak to peak excursion of $4\pi M$ is ~45 G. This large percentage modulation causes the complex spectrum of Fig. 2.

Finally, the present measurements may be used to suggest an explanation of a previously puzzling result.[1] The MB MAQO's have only been observed for the case where $\vec{q}\perp\vec{H}\parallel[0001]$. They have not been found at all for the case where $\vec{q}\parallel\vec{H}\parallel[0001]$ for any polarization of $\vec{q}$. In the present measurements there was no evidence of MB oscillations in dM/dH for $\vec{H}\parallel[0001]$. This is quite surprising in that for MAQO's the MB oscillations have amplitudes nearly as large as those for the α oscillations from the cigar. Because of the cubic specimen geometry one would not expect the demagnetizing factor L to be constant over the entire specimen. The observed value of $4\pi M(B)$ in G actually exceeds the period to period spacing in B of the MB oscillations. Hence if L varies widely over the specimen (from 0 to 1), it is possible for contributions to the MB oscillations, from various regions of the specimen, to be out of phase and lead to a serious reduction in amplitude. If L is reasonably constant in a central plane of the specimen with the plane perpendicular to $\vec{H}$, then the sound probe (about 2 mm in diameter) would look at only a small fraction of the total number of orbits contributing to $4\pi M(B)$. However, this small fraction of orbits would be largely adding in phase with each other. If L were to vary along the direction of $\vec{H}$ then when $\vec{q}\parallel\vec{H}$ the phasing would be poor leading to cancellation of the effect.

CONCLUSIONS

The present results support our earlier assignment of the high-frequency MAQO's to MB orbits.[1] The present more accurate results, ±0.5%, are in good agreement with values estimated from the pseudopotential of Tripp, Everett, Gordon, and Stark.[2] The values of $4\pi M(B)$ are consistent with those expected from the work of Condon.[3] No dHvA MB oscillations were observed. This may be related to the fact that MB MAQO's can only be observed for $\vec{q} \perp \vec{H} \parallel [0001]$.

[1]R. W. Reed and E. F. Vozenilek, Phys. Rev. B 13, 3320 (1976).
[2]J. H. Tripp, P. M. Everett, W. L. Gordon, and R. W. Stark, Phys. Rev. 180, 669 (1969).
[3]J. H. Condon, Phys. Rev. 145, 526 (1966).