Non-centro-symmetric superconductors
Li$_2$Pd$_3$B and Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B: amplitude and phase fluctuation analysis of the experimental magnetization data

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Abstract

We report on magnetization data obtained as a function of temperature and magnetic field in Li$_2$(Pd$_{1-x}$Pt$_x$)$_3$B and Li$_2$Pd$_3$B non-centro-symmetric superconductors. Reversible magnetization curves were plotted as $M^1/2$ versus $T$. This allows study of the asymptotic behavior of the averaged order parameter amplitude (gap) near the superconducting transition. Results of the analysis show, as expected, a mean field superconducting transition for Li$_2$Pd$_3$B. By contrast, a large deviation from the mean field behavior is revealed for Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B. This is interpreted as due to the strength of the non-s-wave spin-triplet pairing in this Pt-containing compound which produces nodes in the order parameter and, consequently, phase fluctuations. The diamagnetic signal above $T_c(H)$ in Li$_2$Pd$_3$B is well explained by superconducting Gaussian fluctuations and agrees with the observed mean field transition. For Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B the diamagnetic signal above $T_c(H)$ is much higher than the expected Gaussian values and appears to be well explained by three-dimensional critical fluctuations of the lowest-Landau-level type, which somehow agrees with the scenario of a phase mediated transition.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Superconductivity has been found in the Li$_2$(Pd$_{1-x}$Pt$_x$)$_3$B, $x = 0$–1 system [1–3]. This system shares properties with low-$T_c$ superconductors due to its low-$T_c$ and high-$T_c$ due to its perovskite-like structure. It has a non-centro-symmetric lattice structure producing an asymmetric spin–orbit-coupling which violates Pauli’s parity principle allowing an admixture of triplet to singlet states in the superconductor order parameter [4–8]. Such an admixture of states with different symmetries induces anisotropy in the order parameter, which, depending on the strength of the asymmetric spin–orbit-coupling, can lead to the existence of line nodes [6]. As is well known, the existence of line nodes in the order parameter allows quasiparticle excitations at low temperatures, affecting the density of states [6]. Line nodes also play an important role in the order parameter fluctuations near $T_c$, since phase and amplitude fluctuations have different contributions in the node and in the anti-node producing a change in the density of states near $T_c$ [9]. Such a change in the density of states modifies the shape...
on data near $T_c(H)$. The work is motivated by reported deviations from the BCS-like expected behavior observed at low temperatures for the penetration depth [4] and for the Knight shift [5] in Li$_2$Pt$_3$B which strongly suggested the existence of line nodes in this compound. Also, it is interesting to investigate whether the strength of the asymmetric spin–orbit-coupling (or the strength of the spin-triplet admixture) observed in Li$_2$Pt$_3$B holds for Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B. To the best of our knowledge, there is no report in the literature devoted to diamagnetic fluctuation studies in the Li$_2$(Pd$_{1-x}$Pt$_x$)$_3$B system.

2. Experimental details

The experiment was conducted by careful and precise measurement of magnetization data by a 5 T MPMS Quantum-Design magnetometer on Li$_2$Pd$_3$B ($T_c = 8.1$ K) and Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B ($T_c = 5.8$ K) samples. Samples were obtained by arc melting as described in [1–3] and are of high-quality, each of them exhibiting a single phase and sharp transition. All magnetization data were obtained with a sample cooled from temperatures well above $T_c$ in zero applied magnetic field. Magnetic field was applied in the no-overshoot mode and data were obtained by heating the sample with fixed increments of temperature (0.1 K in the region near $T_c(H)$).

We also obtained field-cooled magnetization curves, $M$ versus $T$, in order to obtain the reversible magnetization. Data were obtained from 1.8 K up to temperatures well above $T_c(H)$. This allows extraction of the normal state magnetization, $M_{\text{back}}$, which was subtracted for each corresponding curve.

3. Results and discussion

Figures 1(a) and (b) show magnetization curves for both samples obtained after the proper background correction. The insets of figures 1(a) and (b) show data prior to background correction. We observe that the normal state magnetization for both samples follows a Curie–Weiss type of the form, $\chi = \frac{C}{T} - \frac{\theta}{T}$, and are of high-quality, each of them exhibiting a single phase and sharp transition. All magnetization data were obtained with a sample cooled from temperatures well above $T_c$ in zero applied magnetic field. Magnetic field was applied in the no-overshoot mode and data were obtained by heating the sample with fixed increments of temperature (0.1 K in the region near $T_c(H)$).

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with diamagnetism increasing with field, as commonly found in high-$T_c$ superconductors [16].

In the next section we shall analyze the reversible magnetization. Since we are interested in studying the possible effects of the phase fluctuation near $T_c(H)$, it is more convenient to plot the obtained magnetization curves as $M^{1/2}$ versus $T$. This is because near $T_c(H)$ the quantity $M$ is directly proportional to the superconducting order parameter $\Psi$ [17]:

$$M = -|\Psi|^2 (e_h)/mc.$$ (1)

The well known equation (1) was obtained upon application of the Abrikosov approximation [18] to the Ginzburg–Landau equation. Curves of $M^{1/2}$ versus $T$ near $T_c(H)$ provide information on the asymptotic behavior of the order parameter which can be expressed as $M^{1/2} \approx [T_c(H) - T]^{m}$, where $T_c(H)$ is the mean field transition temperature and $m$ is the mean field exponent. The theoretical mean field exponent value is $m = 1/2$, for both s-wave BCS superconductors [17], and d-wave superconductors within Ginzburg–Landau theory [19]. Since the studied systems here have a low $T_c$, one would expect that neither the amplitude nor the phase fluctuations should play an important role, and the resulting transition should be of the mean field type [20] with $m = 1/2$. However, the existence of line nodes in the order parameter can make phase fluctuations important.

It has been shown in [9] that the presence of nodes and anti-nodes in the order parameter has definite consequences for the phase and amplitude fluctuations, which can have an effect on the superfluid density of states, reducing the gap in the vicinity of $T_c$. Such a change in the gap may alter the expected mean field value of the exponent $m$, generating a larger value [10, 11]. In figures 2 and 3 are shown the resulting $M^{1/2}$ versus $T$ curves using the data from figures 1(a) and (b) respectively. For each curve we separate the region below $T_c(H)$ where phase fluctuations may play an important role from the region above $T_c(H)$ where amplitude fluctuations generate an anomalous enhancement of the magnetization. The analysis is focused only in the reversible regime, and, for this reason, only $M$ versus $T$ curves obtained at fields above 5 kOe are analyzed. Values of $T_c(H)$ are estimated for each curve from the extrapolation of the linear magnetization to zero (Abrikosov method [17]).

We first discuss the general scaling analysis used to fit the region below $T_c(H)$. This region for each curve is delimited from below by a temperature below which the Abrikosov approximation cannot be applied and from above by a change in the curvature of the curve, or inflection point, occurring near $T_c(H)$. Within this region, each curve from figures 2 and 3 was fitted to the general form $M^{1/2} \approx [T_c(H) - T]^{m}$, where $T_c(H)$ is an apparent transition temperature, and $m$ is a fitting exponent. Deviation of the exponent $m$ from the mean field value 1/2 may indicate a phase mediated transition. Results of the fittings are shown for each curve. The extracted values of $T_c(H)$ for both samples are virtually the same as obtained from the Abrikosov method mentioned above. So, this method applied to the studied samples produces consistent values of the transition temperature. The consistency of the $T_c(H)$ values is shown in the inset of figure 2 and in the lower inset of figure 3. For both insets, values of $T_c(H)$ are plotted together with values of $T_c(H)$. Resulting values of the exponent $m$ for Li$_2$Pd$_3$B suggest a typical mean field behavior (despite two values of $m$ being slightly larger than 1/2, these values are well within the expected mean field value found for instance for the classic superconductor Nb [10]). But, resulting values of $m$ for Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B are much larger than 1/2 ($m = 0.8$ for all curves), and, as discussed above, they point to a phase mediated transition, which is consistent with the existence of nodes in the order parameter. These results also suggest that the strength of the admixture of singlet and triplet spin states in the

![Figure 2](image1.png)

**Figure 2.** Isofield curves of $M^{1/2}$ versus $T$ for Li$_2$Pd$_3$B. The inset shows $T_c(H)$, $T_c(H)$ and $T_n(H)$ plotted against $H$.

![Figure 3](image2.png)

**Figure 3.** Isofield curves of $M^{1/2}$ versus $T$ for Li$_2$(Pd$_{0.8}$Pt$_{0.2}$)$_3$B. The upper inset shows the lowest-Landau-level (LLL) analysis results. The lower inset shows $T_c(H)$ and $T_c(H)$ plotted against $H$. 

order parameter is not negligible for \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \), but it is for \( \text{Li}_2\text{Pd}_3\text{B} \). Probably, the admixture of triplet to singlet states in \( \text{Li}_2\text{Pd}_3\text{B} \) produces some anisotropy in the order parameter, but our analysis supports the idea that there are no nodes.

We now discuss the anomalous enhancement of magnetization that occurs in the vicinity and above \( T_c(H) \), as observed in figures 2 and 3. Our first attempt was to fit the diamagnetic signal above \( T_c(H) \) with the three-dimensional Gaussian-fluctuation expression derived by Schmidt [12]:

\[
M_{\text{fluct}} \approx T/(T - T^*)^2. \tag{2}
\]

\( T^* \) is a fitting parameter and it is expected to coincide with \( T_c(H) \). The Gaussian type of diamagnetic fluctuations above \( T_c(H) \) is commonly observed in many superconducting systems of low-\( T_c \) [12, 21] and also of some high-\( T_c \) (after taking off the short-wavelength fluctuations) [22]. Results of the fittings with Gaussian formula (2) for the magnetization fluctuation on \( \text{Li}_2\text{Pd}_3\text{B} \) curves are shown in figure 2. The fittings are of excellent quality and produced values of \( T^* \) virtually equal to the values of \( T_c(H) \). \( T^* \), \( T_c(H) \) and \( T_c(H) \) are presented in the inset of figure 2. On the other hand, Gaussian expression (2) failed to fit the fluctuation magnetization above \( T_c(H) \) on the curves of \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \); the fittings conducted on the curves from figure 3 produced low-quality fittings with values of \( T^* \) much smaller than the corresponding values of \( T_c(H) \). For example, we present a fit conducted on the 30 kOe data above 2 K where we fixed the value of \( T^* = 2 \) K. It is possible to see from this fitting that the fluctuation magnetization observed above \( T_c(H) \) for \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \) is much larger than the contribution due solely to the Gaussian type of diamagnetic fluctuation. Larger diamagnetic fluctuations below and above \( T_c(H) \) for high magnetic fields have been observed in many superconducting layered systems with large values of the Ginzburg–Landau parameter \( \kappa \) [23, 16]. This situation is commonly explained in terms of lowest-Landau-level (LLL) fluctuation theories. LLL theories consider fluctuation–fluctuation interactions within the Ginzburg–Landau formalism and predict specific scaling-laws that should be obeyed by the magnetization and temperature [16]. To perform the scaling [13, 14] one should replace the temperature \( x \)-axis and magnetization \( y \)-axis of each curve with the respective scaling forms \( (T - T_c(H))/(TH)^{1/2} \) and \( M/(TH)^{1/2} \) and plot together all the scaled curves. This scaling is appropriate to three-dimensional systems, as in the present case. The only free parameter in the scaling procedure is the mean field temperature \( T_c(H) \) which is adjusted for each curve so that all results fall onto a single universal curve. We applied this scaling approach on the reversible data for \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \) (figure 1b) for fields of 5, 10, 20 and 30 kOe. The result is presented in the upper inset of figure 3. One may observe that the collapse of the different \( M \) versus \( T \) curves is almost perfect. Values of \( T_c(H) \) obtained from the lowest-Landau-level scaling analysis virtually coincide with values of \( T_c(H) \) (lower inset of figure 3b)). This result evidences the importance of LLL fluctuations in \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \). Importantly, the enhanced diamagnetic signal observed above \( T_c(H) \) in \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \) is much higher than those expected from Gaussian fluctuations, is very likely to be related to the strength of the spin-triplet admixture in the order parameter, due to Pt, which enhances the asymmetric spin–orbit-coupling when added (by substitution) to the \( \text{Li}_2\text{Pd}_3\text{B} \) system. It should be noted that a similar scenario occurs in high-\( T_c \) superconductors where phase fluctuations near \( T_c(H) \) are accompanied by enhanced amplitude fluctuations near and above \( T_c(H) \) [24, 10]. We also mention that we applied the same LLL scaling approach on the reversible data of \( \text{Li}_2\text{Pd}_3\text{B} \) (not shown) producing a poor collapsing of the curves, which somehow agrees with the observation that the fluctuation magnetization above \( T_c(H) \) in this system is well explained in terms of Gaussian fluctuations, as addressed above.

4. Conclusions

Our work presents phase and fluctuation analysis results deduced from the experimental reversible magnetization data measured on the \( \text{Li}_2(\text{Pd}_{1-x}\text{Pt}_x)_3\text{B}, x = 0 \) and 0.2 non-centro-symmetric superconducting system. Results point to the existence of line nodes in the order parameter of the \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \) and a pure \( s \)-wave for the \( \text{Li}_2\text{Pd}_3\text{B} \) sample as for Nb, confirming similar conclusions obtained from penetration depth, specific heat and Knight shift measurements [4, 5]. The study also supports the idea that the strength of the spin-triplet admixture in the order parameter of \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \) plays an important role in the amplitude and phase fluctuations near \( T_c(H) \). Diamagnetic fluctuations observed above \( T_c(H) \) in \( \text{Li}_2\text{Pd}_3\text{B} \) can be well explained by Gaussian fluctuations, while for \( \text{Li}_2(\text{Pd}_{0.8}\text{Pt}_{0.2})_2\text{B} \) the diamagnetic signals above \( T_c(H) \) for higher fields are much higher than the values expected by Gaussian fluctuations and are probably well explained by critical three-dimensional LLL fluctuations. Amplitude and phase fluctuation scaling analysis of the experimental magnetization data turns out to be a convenient and relatively simple method to study unconventional systems as in this case of the non-centro-symmetric superconductors showing particular non-\( s \)-wave features.

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