In noncentrosymmetric superconductors the absence of inversion symmetry in a crystal structure causes the appearance of an ASOC, which lifts the spin degeneracy that results in a possible admixture of spin-singlet and spin-triplet pairing states. ASOC thus leads to a spin–orbit band splitting $E_{SO}$ that is thought to have implications in the superconducting behavior, regardless of the electron pairing mechanism, when it is significantly larger than the superconducting energy scale $k_B T_c$ [1]. For instance, unconventional properties such as zeros in the superconducting gap function may appear in the presence of a strong ASOC. Our result also downplays LaPtSi as a good candidate for realizing time-reversal invariant topological superconductivity.

Keywords: superconductivity, spin–orbit coupling, noncentrosymmetric, topological

In noncentrosymmetric superconductors the absence of inversion symmetry in a crystal structure causes the appearance of an ASOC, which lifts the spin degeneracy that results in a possible admixture of spin-singlet and spin-triplet pairing states. ASOC thus leads to a spin–orbit band splitting $E_{SO}$ that is thought to have implications in the superconducting behavior, regardless of the electron pairing mechanism, when it is significantly larger than the superconducting energy scale $k_B T_c$ [1]. For instance, unconventional properties such as zeros in the superconducting gap function may appear in the presence of a strong ASOC. In this regard, line nodes in the superconducting gap function may appear in the presence of a strong ASOC. In this regard, line nodes in the superconducting gap structure of CePt$_3$Si [2, 3] and Li$_2$Pt$_3$B [4], both without inversion symmetry and with $E_{SO}/k_B T_c > 800$, were explained in terms of an admixture of spin states.

However, strong ASOC does not always imply unconventional behaviors. Noncentrosymmetric LaPt$_3$Si, with a larger $E_{SO}/k_B T_c$ than the one of isostructural CePt$_3$Si, has an isotropic energy gap structure consistent with a largely dominant s-wave pairing state [5]. This is a remarkable difference with respect to CePt$_3$Si, whose line nodes may be related to an antiferromagnetic (AFM) order coexisting with superconductivity or to strong electronic correlations [6] (both conditions absent in LaPt$_3$Si). While in most noncentrosymmetric superconductors $E_{SO} > k_B T_c$, only in a few $E_{SO}/k_B T_c > 100$: LaPdSi$_3$ [7], BaPtSi$_3$ [8], PbTaSe$_2$ [9], Th$_7$Fe$_3$ [10], CaIrSi$_3$ [11], and K$_2$Cr$_3$As$_3$ [12]. With the exception of K$_2$Cr$_3$As$_3$, all these superconductors have a very strong ASOC, are nonmagnetic, have weak electronic correlations, and possess an isotropic superconducting energy gap consistent with a highly dominant spin-singlet pairing state. As in LaPt$_3$Si, unconventional behaviors are not seen in these materials.

By now, there is mounting evidence that independently of the ASOC strength in noncentrosymmetric superconductors—as it happens in other superconducting families—the presence of magnetism seems to be essential for the emergence of unconventional behaviors (see later discussion below) [12–15].

The appearance of nodes in the energy gap of noncentrosymmetric superconductors leads to another implication of a strong ASOC: candidacy for hosting time-reversal invariant
nodal topological superconductivity [6, 16–19]. The proper balance between the spin-singlet and spin-triplet components of the mixed pairing states may lead to topologically nontrivial line nodes, as has been suggested for CePt3Si and Li3Pt2B among other noncentrosymmetric materials [19]. In the nodal topological superconductors the properties of the topologically protected (Majorana) surface states are related to the bulk nodal structure and the symmetries of the order parameter [19]. One should note that topological order can also appear in noncentrosymmetric superconductors with broken time-reversal symmetry (under the application of a magnetic field), in which case the topological phase is independent of the spin-triplet component of the mixed state [16, 20].

Predicted to have a very strong ASOC (130–255 meV) [21], the weakly correlated nonmagnetic superconductor LaPtSi \((T_c = 3.7 \text{ K})\) without inversion symmetry is a good prospect to deepen further into the influence of an ASOC on the superconducting properties of noncentrosymmetric compounds. For this purpose, it is quite relevant to study the gap structure and the symmetry of the order parameter. A previous work on specific heat in this compound suggested an exponential BCS-like behavior below 0.67 K \((0.18T_c)\) [21], indicative of a ruling spin-singlet component. However, due to the lack of information in the true low-temperature region (below 0.2Tc), the energy gap structure remains uncertain.

Here, we present measurements of the magnetic penetration depth of LaPtSi down to 0.02Tc. A conventional s-wave behavior was observed, which firmly establishes the dominance of the fully gapped spin-singlet component of the parity mixing in LaPtSi. In light of this result, we discuss further the role of the ASOC in the appearance of unconventional behaviors by comparing all previous relevant findings.

Polycrystalline LaPtSi was grown by arc melting the stoichiometric amounts of pure metal ingots under Ti-gettered argon and annealing under vacuum in sealed quartz ampoules at 800 °C for one week [21]. An x-ray analysis ensures the sample purity since no other phases were observed [21]. A sample was cut to the dimensions \(0.39 \times 0.25 \times 0.25 \text{ mm}^3\) and then polished with aluminum oxide to minimize surface irregularities. It is worth noting that LaPtSi is highly fragile, which makes it difficult to obtain the appropriate dimensions without leaving out irregularities.

Penetration-depth measurements down to around 50 mK were carried out using a self-inductive technique based on a 13.5 MHz tunnel-diode oscillator [2]. The oscillator circuit had a noise level of less than one part in \(10^9\) and a very low drift. A LaPtSi sample was placed inside the probing coil using a single-crystal sapphire rod, the other end of which was thermally connected to the mixing chamber of a dilution refrigerator. The test coil and the other parts of the oscillator circuit were maintained at a fixed temperature. The magnitude of the ac magnetic field was estimated to be less than 5 mOe and the dc field at the sample was reduced to around 1 mOe. A change in the penetration depth causes a variation in the susceptibility \(\chi\) of the sample and hence in the sample-coil inductance, which in turn shifts the measured frequency of the oscillator from a reference value \(f(T) - f(T_{\text{min}}) = G\chi(T) - \chi(T_{\text{min}})\).

\[\Delta\lambda(T) = \Delta\lambda(T_{\text{min}}),\]

Here \(T_{\text{min}}\) is the lowest temperature of the experiment and \(\chi\) is a function of \(\lambda\). \(G\) is a constant factor calculated by measuring a sample of known behavior and of the same dimensions of the test sample. Up to \(T \sim 0.99T_c\), the deviation of the penetration depth from the lowest measured temperature, \(\Delta \lambda(T) = \lambda(T) - \lambda(T_{\text{min}})\), was obtained from the change in the measured resonance frequency \(\Delta f(T) : \Delta f(T) = G\Delta \lambda(T)\).

The main panel of figure 1 shows the low-temperature variation of the magnetic penetration depth \(\Delta \lambda(T)\) normalized to \(\Delta \lambda_{\text{max}}\), defined as the total penetration-depth shift from \(T_c\) down to the lowest temperature. The inset of figure 1 shows the entire superconducting region and a photomicrograph of the sample. The transition temperature \(T_c = 3.7 \text{ K}\) was taken at the onset of the diamagnetic transition, in good agreement with a previous report on resistivity and heat-capacity measurements [21]. The small irregular behavior around 3 K may be due to surface irregularities (see micrograph in the inset of figure 1). In LaPtSi samples, the \(\Delta \lambda/\Delta \lambda_{\text{max}}\) data errors in a single run are less than \(0.05 \times 10^{-2}\) and the different runs deviate from each other in less than \(0.1 \times 10^{-2}\). The errors of experimental data are thus very small, so in figure 1 the error bars can be considered the size of the dots.

In figure 1 it is observed that the experimental data flatten out below 0.2Tc, as expected for a superconductor with an isotropic energy gap. LaPtSi is a dirty type-II superconductor [22], since the coherence length \(\xi_{\parallel}(0) = 338 \text{ Å}\) is much larger than the mean free path \(l = 43 \text{ Å}\). We fitted the experimental data to clean and dirty s-wave models up to 0.5Tc. We used the low-temperature approximations of the clean local BCS model

\[\Delta \lambda(T)_{\text{clean}} \propto \sqrt{\frac{\pi \Delta_0}{2k_B T}} \exp(-\Delta_0/k_BT),\]

(1)

where \(\Delta_0\) is the zero-temperature energy gap and \(k_B\) is the Boltzmann constant, and the dirty local s-wave model [23].

Figure 1. Magnetic penetration depth of LaPtSi in the low-temperature regime fitted to clean and dirty local s-wave models. The inset shows the complete temperature behavior of the penetration depth and a photomicrograph of the sample. The experimental error bars correspond to the size of the dots (see text).
It is obvious from figure 1 that the dirty local s-wave model fits the data better than the clean model, reaffirming the dirty condition of this superconductor. The dirty model yields a zero-temperature energy gap $\Delta_0 = 1.73 k_B T_c$, which is very similar to the standard BCS value ($\Delta_0 = 1.76 k_B T_c$). Thus, our results indicate that LaPtSi can be described in terms of s-wave superconductivity with an isotropic energy gap, confirming early heat-capacity measurements [21].

In regard to the possible pairing mixed states, our results indicate that the spin-singlet component is predominant in LaPtSi as well, in clear concordance with other noncentrosymmetric compounds with very strong ASOC that show conventional behaviors.

Table 1 shows a list of noncentrosymmetric compounds organized according to their $E_{SO}/k_B T_c$ strengths. Each material was selected following the criterion that either its ratio $E_{SO}/k_B T_c > 500$ or its energy gap has been found to possess nodes. It is notable that in general superconductors with an estimated strong ASOC display a conventional behavior unless magnetic order is present. Among the standard BCS superconductors are the nonmagnetic systems LaPtSi, BaPt$_3$Si, PbTaSe$_2$, LaPdSi$_3$, CaIrSi$_3$, Th$_3$Fe$_3$, and LaPtSi. Unconventional superconducting behaviors appear independently of the ASOC strength and in connection with a magnetic instability. Such is the case of CePt$_3$Si, K$_2$Cr$_3$As$_3$, CeRhSi$_3$, CeIrSi$_3$, and LaNiC$_2$ (recently found to have a magnetic phase at finite pressures [14]).

Nonmagnetic Li$_2$Pt$_3$B seems to be at odds with this pattern, since line nodes in the energy gap have been found in magnetic penetration-depth [4] and heat-capacity [31, 32] measurements. Y$_2$C$_3$ may also be in conflict, although the two results reported so far in this compound are contrasting. Penetration depth indicates line nodes [43], whereas heat capacity suggests an isotropic energy gap [42].

We emphasize here that the exclusive presence of a strong ASOC does not seem to be sufficient to cause any exotic superconducting behavior. However, this in no way implies that ASOC should be left out in all analyses. It is possible that ASOC can relate or couple in some way with any other relevant interaction to yield unconventional behaviors. As we expose here, it appears that a connection with magnetism leads to exotic superconductivity. It is likely that the presence of magnetic instabilities enhances the spin-triplet component of the parity mixing due to ASOC [6, 44].

With regard to topological order, our result of a fully gapped LaPtSi discards this compound as a candidate for a time-reversal symmetric topological superconductor. Notwithstanding, LaPtSi can still be considered a prospect for topological order under the application of an external magnetic field [16, 20]. It looks like good noncentrosymmetric candidates for nodal topological superconductivity would be those that have a nearby magnetic instability rather than a strong ASOC.

We performed magnetic penetration-depth measurements in noncentrosymmetric LaPtSi down to 0.02$T_c$. We observed an s-wave BCS-like behavior in the local dirty limit. Our result reasserts that a strong ASOC does not seem to have the sole responsibility for unconventional behaviors in noncentrosymmetric materials. In these compounds as well, widely accepted results point to the need for proximity to a magnetic instability for the appearance of unconventional superconducting behaviors. The fully gapped state rules out LaPtSi as a good candidate for hosting time-reversal invariant nodal topological superconductivity, which may be more realizable in noncentrosymmetric compounds with some kind of magnetism.
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References

[1] Frigeri P A, Agterberg D F, Koga A and Sigrist M 2004 Phys. Rev. Lett. 92 097001
[2] Bonalde I, Brämer-Escamilla W and Bauer E 2005 Phys. Rev. Lett. 94 207002
[3] Hayashi N, Wakabayashi K, Frigeri P A and Sigrist M 2006 Phys. Rev. B 73 024504
[4] Yuan H Q, Agterberg D F, Hayashi N, Badica P, Vandervelde D, Togano K, Sigrist M and Salamon M B 2006 Phys. Rev. Lett. 97 017006
[5] Ribeiro R L, Bonalde I, Haga Y, Settai R and Ōnuki Y 2009 J. Phys. Soc. Japan 78 115002
[6] Fujimoto S 2006 J. Phys. Soc. Japan 75 083704
[7] Smidman M, Hillier A D, Adroja D T, Lees M R, Anand V K, Singh R P, Smith R I, Paul D M and Balakrishnan G 2014 Phys. Rev. B 89 094509
[8] Ribeiro R, Carabalbo R, Rogl P, Bauer E and Bonalde I 2014 J. Phys.: Condens. Matter 26 235701
[9] Pang G M, Smidman M, Zhao L X, Wang Y F, Weng Z F, Che L Q, Chen Y, Lu X, Chen G F and Yuan H Q 2016 Phys. Rev. B 93 060506
[10] Sereni J G, Nieva G L, Huber J G and Delong I E 1994 Physica C 230 159–62
[11] Singh R P, Hillier A D, Chowdhury D, Barker J A T, Paul D M, Lees M R and Balakrishnan G 2014 Phys. Rev. B 90 104504
[12] Pang G M et al 2016 J. Magn. Magn. Mater. 400 84–7
[13] Bauer E and Sigrist M (ed) 2012 Non-Centrosymmetric Superconductors: Introduction and Overview (Lecture Notes in Physics vol 847) (Berlin: Springer)
[14] Landaeja J F, Subero D, Machado P, Honda F and Bonalde I 2017 Phys. Rev. B 96 174515
[15] Landaeja J F, Subero D, Catalá D, Taylor S V, Kimura N, Settai R, Ōnuki Y, Sigrist M and Bonalde I 2018 Phys. Rev. B 97 104513
[16] Sato M and Fujimoto S 2009 Phys. Rev. B 79 094504
[17] Schnyder A P and Ryu S 2011 Phys. Rev. B 84 060504
[18] Schnyder A P, Brydon P M R and Timm C 2012 Phys. Rev. B 85 024522
[19] Schnyder A P and Brydon P M R 2015 J. Phys.: Condens. Matter 27 243201
[20] Ghosh P, Sau J D, Tewari S and Sarma S D 2010 Phys. Rev. B 82 184525
[21] Kneidinger F, Michor H, Sidorenko A, Bauer E, Zeiringr I, Rogl P, Blaas-Schemmer C, Reith D and Podloucky R 2013 Phys. Rev. B 88 104508
[22] Ramakrishnan S, Ghosh K, Chinchure A D, Marathe V R and Chandra G 1995 Phys. Rev. B 52 6784–95
[23] Tinkham M 1996 Introduction to Superconductivity (International Series in Pure and Applied Physics) (Berlin: McGraw-Hill)
[24] Ōnuki Y and Settai R 2012 Non-centrosymmetric Superconductors: Introduction and Overview (Lecture Notes in Physics vol 847) ed E Bauer and M Sigrist (Berlin: Springer) pp 81–125
[25] Samokhin K V, Zijlstra E S and Bose S K 2004 Phys. Rev. B 69 094514
[26] Bauer E et al 2009 Phys. Rev. B 80 064504
[27] Ali M N, Gibson Q D, Klimczuk T and Cava R J 2014 Phys. Rev. B 89 020505
[28] Buan G et al 2016 Nat. Commun. 7 10556
[29] Winiarski M and Samels-Czekala M 2015 Intermetallics 56 44–7
[30] Lee K W and Pickett W E 2005 Phys. Rev. B 72 174505
[31] Takeya H, ElMassalami M, Kasahara S and Hirata K 2007 Phys. Rev. B 76 104506
[32] Eguchi G, Peets D C, Kriener M, Yonezawa S, Bao G, Harada S, Inada Y, Zheng G Q and Maeno Y 2013 Phys. Rev. B 87 161203
[33] Uzunok H Y, Ipsara E, Tütüncü H M, Srivastava G P and Basoğlu A 2016 J. Alloys Compd. 681 205–11
[34] Sahakyan M and Tran V H 2017 Phil. Mag. 97 957–66
[35] Jiang H, Cao G and Cao C 2015 Sci. Rep. 5 16054
[36] Terashima T, Kimata M, Uji S, Sugawara T, Kimura N, Aoki H and Harima H 2008 Phys. Rev. B 78 205107
[37] Hirose Y et al 2012 J. Phys. Soc. Japan 81 113703
[38] Lee W H, Zeng H K, Yao Y D and Chen Y Y 1996 Physica C 266 138–42
[39] Bonalde I, Ribeiro R L, Syu K J, Sung H H and Lee W H 2011 New J. Phys. 13 123022
[40] Mukuha H, Fujii T, Ohara T, Harada A, Yashima M, Kitaoka Y, Okuda Y, Settai R and Ōnuki Y 2008 Phys. Rev. Lett. 100 107003
[41] Nishikayama Y, Shishidou T and Oguchi T 2007 J. Phys. Soc. Japan 76 064714
[42] Akutagawa S and Akimitsu J 2006 Sci. Technol. Adv. Mater. 7 2–5
[43] Chen J, Salamon M B, Akutagawa S, Akimitsu J, Singleton J, Zhang J L, Jiao L and Yuan H Q 2011 Phys. Rev. B 83 144529
[44] Yanase Y and Sigrist M 2007 J. Phys. Soc. Japan 76 043712