Quantum oscillations probe the normal electronic states of novel superconductors

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In 2008, new classes of high-temperature superconductors containing iron have been discovered. These iron pnictides offer a new area of exploration and understanding of superconductivity. Quantum oscillations is a bulk probe that allows us to map out the full Fermi surface of a superconducting system in its normal metallic state. These oscillations are determined by the Landau quantization in high magnetic fields and are usually observed at very low temperatures and in very clean samples. By knowing the exact nature of the quasi-particles in the normal state and the degree of electronic correlations, one can simplify and restrict theoretical models required to understand the pairing mechanism in superconductors. I will discuss the current understanding of the Fermi surface studies in iron-based superconductors as determined from quantum oscillations.

Keywords: quantum oscillations; Fermi surface; high $T_c$ superconductivity

1. Introduction

One of the many fascinating manifestations of strong correlations in materials is the presence of a condensate superconducting (SC) state in which all the electrons collapse into a unique electronic state for which the electrical current feels no resistance. Superconductivity was found in elemental materials such as lead and tin a long time ago, but it was not until 1986 with the discovery of high-temperature superconductivity in copper oxides that the dream of making these materials useful inspired and challenged many generations of physicists.

Unconventional superconductors are those in which superconductivity arises from direct electron–electron interactions, as contrasted to the conventional indirect interaction via phonons, found in elemental materials or more recently in MgB$_2$. Direct interactions due to many body effects often favour higher (compared with isotropic $s$-wave) angular momentum pairing (like $p$-wave or $d$-wave), whereas the onsite Coulomb repulsion and spin fluctuations often play a key role.
role in stabilizing an unconventional $d$-wave SC state in cuprates. A completely new class of high-temperature superconductors containing iron coordinated with pnictogen atoms (such as As or P), called iron pnictides, was discovered in 2008, and their pairing symmetry is still under investigation. It is not yet clear whether the mechanism for superconductivity in these iron-based superconductors is closely connected to that in cuprates or whether a new route to high-temperature superconductivity has been found.

In this paper, I will review the recent experimental developments in the study of the electronic properties of iron pnictides, highlighting the role of the Fermi surface topology and the effects of many-body interactions in different materials belonging to different classes of iron pnictides. The body of the paper concentrates on the various parameters that can be determined experimentally in the normal metallic state stabilized at high magnetic field and which can help to understand superconductivity in these novel materials.

(a) Iron-based superconductors

The first report of superconductivity in an iron-based material was in LaFePO, which has a relatively low transition temperature, $T_c \sim 6 \text{K}$ (Kamihara et al. 2006). Based on the same crystallographic structure and replacing the pnictogen P with As, high $T_c$ superconductivity was found in the fluoride-doped LaFeAsO ($T_c \sim 26 \text{K}$; Kamihara et al. 2008). This work sparked intense experimental and theoretical work to search for new materials that shared similar structural characteristics, and the highest transition temperature of 55K was found in F-doped SmFeAsO (Ren et al. 2008). Stabilization of an SC phase in systems with iron was mostly unexpected as iron, because of its strong ferromagnetic properties, is generally expected to disrupt a conventional pairing mechanism. The basic structural features of these materials is the presence of square planar sheets of Fe ions coordinated tetrahedrally by pnictogens (such as As or P) or chalcogens (Se, Te and S). A variety of compounds are obtained by sandwiching the FeAs layers (made up of FeAs$_4$ tetrahedra) with various ionic layers, such as LaO (as in the case of 1111 compounds, LaO$_{1-x}$F$_x$FeAs) or Ba (in the case of 122 compounds, Ba$_{1-x}$K$_x$Fe$_2$As$_2$), as shown in figure 1b,c. Besides these compounds, superconductivity has been found by intercalating deficient Li or Na between FeAs layers (111 compounds) or by van der Waals gaps in chalcogenites (11 compounds, Fe(Se$_x$Te$_{1-x}$)); the latter group do not contain arsenic and may be the most suitable for practical applications. Interestingly, the highest $T_c$ is found when the FeAs$_4$ tetrahedron has a regular shape, so it is clear that the structural details are important in achieving the largest $T_c$ in the iron-based superconductors. For a general view on this new area of research, see a recent review by Ishida et al. (2009).

A typical phase diagram for the iron pnictides is shown in figure 1a. Without doping, most of the parent compounds are semimetallic, show universal long range magnetic order and show a tetragonal to orthorhombic/monoclinic structural transition at low temperatures. This is in contrast to the parent compounds of the cuprates, which are Mott insulators owing to strong electron–electron interactions. The magnetic order is a collinear AFM spin structure with a $(\pi, \pi)$ ordering wavevector in the folded Brillouin zone with two Fe ions per unit cell. The structural distortion follows closely the magnetic transitions and is
believed to play an important role in driving the magnetic transition. Doping with electrons or holes in the ionic layers (figure 1a), applied pressure and isoelectronic substitution (As for P) in the magnetic parent compounds suppress the magnetic and structural phase transitions and stabilize superconductivity (Ishida et al. 2009).

The origin of the magnetic order in the parent compounds is not yet clearly understood. In one scenario, the transition has an itinerant character driven by the nesting instability of the Fermi surface which consists of two electron and two hole sheets with similar $d_{xz}/d_{yz}$ orbital character. These sheets have approximately compensating cross sections and can be matched reasonably well if translated by $(\pi, \pi)$ for an arbitrary $k_z$ value (for an illustration, see figure 3d) (Chubukov et al. 2008; Kuroki et al. 2008; Mazin et al. 2008a,b). The fulfillment of such a nesting condition leads to a peak in the wavevector-dependent Lindhard susceptibility and, as the pnictides have a large density of states at the Fermi level, $N(E_F)$, and a strong Stoner enhancement, this results in a magnetic ordering instability. This is a spin density wave (SDW) instability of the Fermi surface driven by electrons at and near $E_F$ and may provide an explanation for the experimentally observed SDW order found in most of the undoped iron pnictides. Alternatively, a Heisenberg model with exchange interactions between localized spin moments (where moment formation is a result of onsite interactions) is proposed to explain the collinear AFM spin structure (Uhrig et al. 2009). Itinerant magnetism differs from local moment magnetism in that the physics involves the Fermi surface nesting, and understanding its exact topology is important in understanding the SC mechanism in iron pnictides.
The superconductivity emerging from these SDW compounds is theoretically proposed to be unconventional and mediated by AFM spin fluctuations. Such an SC state has an extended $s$-wave pairing with a sign reversal of the order parameter between different Fermi surface sheets, as the magnetic fluctuations, while too broad to induce a magnetic instability, are instrumental in stabilizing superconductivity (Chubukov et al. 2008; Kuroki et al. 2008; Mazin et al. 2008a,b). So far experiments show evidence for a more complex picture where the gap order parameter is not simply an $s_{\pm}$-wave but may also have line nodes (Fletcher et al. 2009) and thus the knowledge of the exact details of the Fermi surface that may favour one type of pairing over another is essential.

(b) Quantum oscillations

An electronic gas placed in a magnetic field has its energy levels quantized at values that depend on the strength of the magnetic field. By varying the magnetic field strength, nearly all measurable quantities will show oscillations periodic in $1/B$ (figure 2). Such quantum oscillations represent a canonical probe of the defining aspect of a metal, its Fermi surface. By providing the precise details of the Fermi surface in the normal metallic state and the effect of many-body interaction on the effective masses of the quasi-particles, quantum oscillations help to develop reliable theories for understanding superconductivity. In iron pnictides, the degree of nesting between the various Fermi sheets and the magnitude and anisotropy of the Fermi velocities is believed to be important for the paring mechanism (Kuroki et al. 2008; Mazin et al. 2008a,b). Conventional band structure calculations only include many-body effects at the mean field level; in strongly interacting systems, there can be substantial renormalization of the effective masses or Fermi velocities due to electron–phonon or electron–electron interactions, and this enhancement can be determined from quantum oscillations. Furthermore, quantum oscillations can provide unique access to the details of a Fermi surface which suffers reconstruction by breaking up a large Fermi surface into many small pockets due to structural or magnetic instabilities (such as charge density waves and SDWs).

The frequencies of the observed oscillations, $F$, provide very accurate measurements of the Fermi surface cross-sectional areas, $A_k$, via the Onsager relation, $F = (\hbar/2\pi e)A_k$. From the evolution of these frequencies as a function of the magnetic field orientation, one can construct a detailed three-dimensional picture of the shape and size of the Fermi surface (figure 2d).

The standard expression for the first harmonic of the oscillatory part of the magnetization (de Haas van Alphen effect (dHvA)) for a three-dimensional Fermi liquid is given by (Shoenberg 1984)

$$M_{\text{osc}} \propto CB^{3/2}R_D R_T R_S R_{SC} \sin \left( \frac{2\pi F}{B} + \varphi \right),$$  

(1.1)

where $F$ is the dHvA frequency, $C = |\partial^2 A_k/\partial k^2|^{-1/2}$ the curvature factor and $\varphi$ the phase. $R_D$, $R_T$ and $R_S$ are the damping factors from impurity scattering, temperature and spin splitting, respectively. $R_T = X/\sinh X$, where $X = (2\hbar^2 k_B m^* T)/(\hbar e B)$. Another damping term is the Dingle factor, $R_D = \exp(-\pi k_F/e B \ell)$, where $k_F$ is the orbitally averaged Fermi wavevector and $\ell$ is the inelastic quasi-particle mean free path. The effect of the electron spin is to

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split each Landau level into two (spin up and spin down) with the spin splitting term, $R_S$, given by \( \cos \left( \frac{\pi g m_B (1 + S)}{2 m_e} \right) \), where \( 1 + S \) is the orbitally averaged exchange-correlation (Stoner) enhancement factor. When $R_S = 0$, the spin-up and spin-down Fermi surfaces beat out of phase to produce a spin-zero minimum in the dHvA amplitude. In an SC state, the dHvA amplitude of oscillations suffers further exponential damping in a magnetic field, $R_{SC}$, which can be understood on the basis of the model of the quasi-particle scattering by the random vortex lattice with large SC (vortex) fluctuation around the mean field $H_{c2}$ (Maniv et al. 2001). Both the effect of the impurity scattering and the thermal smearing broaden the Landau levels (figure 2a), imposing stringent conditions for the observation of quantum oscillations only at low temperatures, in very pure samples and at high magnetic fields (which are often large enough to allow access to the normal state of superconductors).

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The effective mass of the quasi-particles on the various orbits, $m^*$, is determined by fitting the temperature-dependent amplitude of the oscillations to the conventional Lifshitz–Kosevich formalism (Shoenberg 1984; Springford & Wasserman 1996). The mass enhancement is given by the ratio $m^*/m_b$ between the effective mass and the calculated band mass and reflects the effects of both electron–phonon coupling and electron–electron interactions by $m^*/m_e = (1 + \lambda_{el-ph})(1 + \lambda_{el-el})$.

Quantum oscillations studies are performed at low temperatures (below $T < 4\text{K}$) and high magnetic steady and pulsed fields (up to $55\text{T}$) using a variety of techniques such as magnetization, torque magnetometry or magnetotransport and tunnel diode oscillator (Shubnikov–de Haas). Torque measurements using piezoresistive microcantilevers (Rossel et al. 1996) offer a clear advantage in the study of extremely small single crystals, as magnetic moments as small as $10^{-9} - 10^{-11} \text{emu}$ can be detected. The oscillatory part of the magnetic torque, $\tau_{osc} = -dM_{osc}/d\theta = -1/F(dF/d\theta)M_{||}B$, is determined by the Fermi surface anisotropy and thus vanishes near symmetry axes and for spherically symmetric Fermi surfaces. Since single crystals of relatively high quality can be grown in pnictides, especially in the 1111 and the 122 family, these materials have become quite popular for investigation of fundamental properties of iron pnictides including quantum oscillations studies.

2. Fermi surface in a paramagnetic phase

(a) Quasi-two-dimensional 1111 systems

The iron phosphide superconductor, LaFePO, has a low SC transition of $T_c \sim 6\text{K}$ and a correspondingly low value of the upper critical field required to suppress superconductivity ($\mu_0H_{c2} \simeq 7$ for $H||ab$ plane; Coldea et al. 2008), being an ideal candidate for quantum oscillations studies. LaFePO is isostructural to the parent arsenide compound LaFeAsO (figure 1b; P and As are isoelectronic with As having a larger ionic radius). At high temperatures in the tetragonal phase, the two materials are predicted to have very similar electronic structures; however, they have very different magnetic ground states as the phosphides are non-magnetic and do not show any structural transitions (J. G. Analytis et al. 2008, unpublished data). In phosphides, the pnictogen (P) ions are closer to the Fe planes and the Fe–P bond angles depart substantially from those of a regular FeP$_4$ tetrahedron (Lee et al. 2008) and this may also lead to much broader bands when compared with the arsenides, so it is expected that the effect of many-body correlations will be reduced (Malaeb et al. 2008).

The Fermi surface of LaFePO, shown in figure 3a, consists of five different sheets (as five Fe $d$ bands are crossing the Fermi level and the hybridization with pnictogen is modest); four of them have a cylindrical shape, being mostly weakly dispersive along the $c$-direction; two hole cylinders are centred at the zone centre, $\Gamma$, and two electron cylinders at the zone corner and are primarily derived from Fe $d_{xz}$ and $d_{yz}$ orbitals (Lebègue 2007). In addition, there is a three-dimensional sheet derived from a heavy hole section which consists of a distorted sphere centred at the Z high-symmetry point. This spherical sheet corresponds to the band crossing the Fermi level along the $\Gamma$–Z direction and has mostly Fe $d_{z^2}$ character. The Fermi surface of LaFeAsO in the non-magnetic phase (Mazin et al. 2008a,b).
Figure 3. The Fermi surface of (a) SC LaFePO ($T_c \sim 6$ K), (b) metallic SrFe$_2$P$_2$ ($c/a = 3.04$) and (c) CaFe$_2$P$_2$ ($c/a = 2.65$) (LDA calculations were performed using experimental lattice parameters, as reported in detail by Coldea et al. (2008, 2009) and Analytis et al. (2009b). The corresponding cross sections of the Fermi surface at $k_z = 0$ ($\Gamma$ point) when the magnetic field is along the [0 0 1] direction is shown in (d–f), respectively. The arrow indicates the nesting vector along the ($\pi$, $\pi$) direction between the electron and hole pockets. The solid line delimits the first Brillouin zone.

has features similar to those of LaFePO except for the small three-dimensional electron pocket centred at Z whose presence is very sensitive to the position of the pnictogen height above the iron plane (figure 3a). LaFePO is a compensated metal as the number of electrons is equal to the number of holes, similar to the undoped parent arsenides.

Quantum oscillations were observed in the normal state of superconducting LaFePO, as shown in figure 2b,c. The observed frequencies correspond to a fraction varying between 2.8 and 9 per cent of the basal plane area of the Brillouin zone (Coldea et al. 2008). To identify the exact location of the observed frequencies, angular-dependent data provide information on the shape of the quasi-two-dimensional cylinders (figure 2d). The frequencies of the extremal dHvA orbits (figure 2c) obtained from the calculated band structure are compared with the experimental data. The shape and the angular dispersion of the $\beta$ orbits closely resemble those expected from the outer electron cylinder in both frequency and curvature, whereas the $\alpha$ orbits are similar to those of the inner electron cylinder (figure 2d; Coldea et al. 2008).

Quantum oscillations have a net advantage over surface-sensitive probes, like APRES, especially because, as seen in LaFePO, the cleaved plane investigated can be electrically charged (Lu et al. 2008). In the case of complicated or a large number of Fermi surface sheets, the quantum oscillations cannot determine experimentally the exact k-space location of the observed Fermi surface orbits,
and relies on comparison with band structure calculations. In order to match the calculated band structure predictions with the experimental data, small rigid shifts of the electron and hole bands were necessary in LaFePO (by conserving the number of electrons and holes in a compensated metal; Coldea et al. 2008; Carrington et al. 2009). The band shifting leads to a shrinking of both electron and hole sheets when compared with band structure predictions. This shrinking has been suggested to be a natural consequence of the strong particle–hole asymmetry of electronic bands in pnictides. It also provides indirect experimental evidence of dominant interband over intraband scattering, as a direct consequence of the coupling to a bosonic mode (Ortenzi et al. 2009).

A two-dimensional cut of the Fermi surface at the \( \Gamma \) point in the two-dimensional conducting plane shows that in LaFePO the size of the electron pockets at the corner of the Brillouin zone has shape and size similar to those of the hole pockets located at the centre of the zone (figure 3d) and could be nested with a wavevector \((\pi, \pi)\). Nesting requires a perfect match between the size and the Fermi surface topology of the electron and hole pockets and this could stabilize an SDW. LaFePO is non-magnetic but may be close to fulfilling a nesting condition. There is also a small three-dimensional pocket centred at \( Z \) (figure 3) not observed experimentally in torque measurements and it is not clear whether it plays any role (Coldea et al. 2008; Carrington et al. 2009). Moreover, the symmetry of the order parameters in LaFePO is expected to have line nodes (Fletcher et al. 2009), suggesting that the predicted \( s_{\pm} \)-wave type of symmetry (Mazin et al. 2008a,b) may not be applicable to all iron-based superconductors.

The effective masses in LaFePO have been found to be enhanced by a factor of 2 when compared with band structure calculations (Coldea et al. 2008). This value suggests that LaFePO is a moderately correlated system with a Fermi surface which can be described by band structure calculations. Similar mass enhancement, when compared with the bare band mass, was found also in ARPES and optical studies (Lu et al. 2008; Qazilbash et al. 2009). Despite the absence of a Mott transition the electronic many-body effects are believed to be important in iron pnictides.

(b) Quasi-three-dimensional 122 systems

The Fermi surface of the 122 phosphides of type AFe\(_2\)As\(_2\) (A = Ba, Sr and Ca) is likely to be different from that of LaFePO; by replacing an LaO spacing layer by a single alkali ion such as Ba, the distance between the active Fe–P layers is expected to be much smaller (whereas the interlayer Fe–Fe distance is approximately 2.2 Å smaller in BaFe\(_2\)As\(_2\) than in LaOFeAs, as shown in figure 1b,c). This reduction in the two dimensionality leads to a significant c-axis dispersion of the Fermi surface. Phosphites belonging to the 122 class of iron pnictides are metallic and non-magnetic and their Fermi surface was measured directly by quantum oscillations (Analytis et al. 2009b; Coldea et al. 2009). A good qualitative agreement with band structure calculations in SrFe\(_2\)P\(_2\) (Analytis et al. 2009b) was found, but certain bands shifts were necessary to obtain an exact agreement. The shift of the bands necessary to finely tune the band structure calculations to the experimental data led to smaller electron and hole sheets, as seen before in LaFePO. Shrinking of the electronic sheets was also found approaching the maximum \( T_c \) in BaFe\(_2\)(As\(_{1-x}\)P\(_x\))\(_2\) from quantum oscillations.
measurements (Shishido et al. 2010) and also in BaFe$_{1-x}$Co$_x$As$_2$ from ARPES studies (Brouet et al. 2009). This tendency towards shrinking of the Fermi surface sheets in relation to the band structure calculations is not caused by simple band renormalization effects and seems to be a more general feature of iron pnictides, reflecting the domination of the interband interactions over interband ones, and/or the important role of spin fluctuations which may also be responsible for the pairing mechanism (Ortenzi et al. 2009).

The Fermi surface characteristics of ternary phosphides with different divalent ions between the Fe–P layers (or c/a ratio) is shown in figure 3b,c. The shape of the electron pockets in ternary compounds deviates from that of a simple warped cylinder along the c-axis, as found in LaFePO, and it can be parametrized by considering that the Fermi wavevector is modulated by both a complex in-plane and interplane dispersion, similar to what was proposed for the quasi-two-dimensional Sr$_2$RuO$_4$ (Bergemann et al. 2000) and Tl$_2$Ba$_2$CuO$_{6+d}$ (Analytis et al. 2007). By replacing Sr (c/a = 3.04) with a smaller Ca (c/a = 2.65), the Fermi surface suffers a major topological change (Coldea et al. 2009), having only one electronic band remaining, which is significantly warped, and the system can be clearly viewed as three-dimensional (having a larger contribution from the interlayer dispersion term, when compared with SrFe$_2$As$_2$). The hole pockets also change the size and shape when reducing the size of the spacing layer (from LaO to Ca). The study of CaFe$_2$P$_2$ provides access to the non-magnetic collapsed tetragonal phase of CaFe$_2$As$_2$, which can be accessed only under pressure, suggesting that isoelectronic substitution of As for P or chemical pressure in iron pnictides is equivalent to the applied pressure. The Fermi surface of CaFe$_2$P$_2$ may be relevant to other systems in which, owing to the small size of the spacer layer, the Fe–As bonding weakens and the (inter- and intraplanar) As–As bonding gets stronger.

Quantum oscillations establish experimentally that the Fermi surface of iron pnictides becomes more three-dimensional by reducing the spacing between the active Fe layers; consequently, this evolution from a quasi-two-dimensional Fermi surface, like that of LaFePO, to one that is quasi-three-dimensional in SrFe$_2$P$_2$ and three-dimensional in CaFe$_2$P$_2$ can explain the changes in the anisotropy of the electronic properties. Moreover, this can also explain the anisotropy of the upper critical field in iron pnictides (Yin et al. 2008; Singleton et al. 2009), as the corrugations of the Fermi surface are sufficient to permit circulating currents at all field orientations. Compared with the cuprates or organic superconductors, iron pnictides, including the 1111 systems, are substantially less anisotropic. This relatively low anisotropy is of potential practical importance. In particular, flux pinning is an important issue in applications of superconductivity, and this is greatly facilitated in low-anisotropy materials.

A comparison between cross sections of the Fermi surface at the centre of the Brillouin zone is shown in figure 3d–f. The effect of Fermi surface corrugation is to reduce the nesting of the cylindrical electron and hole sheets. While in LaFePO the in-plane geometrical nesting between the electron and hole sheets along the (π, π) direction is likely to be possible in SrFe$_2$P$_2$, this nesting is strongly inhibited because of the variation in size of the electron and hole pockets, whereas in CaFe$_2$P$_2$ it is completely excluded. One possible avenue for good nesting could exist only in a limited $k_z$ range, owing to the strong dispersion of the electronic bands along this direction, and this needs to be further explored.

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The torque signal in the quantum oscillations experiments in iron phosphides and SC As-substituted iron phosphides (Shishido et al. 2010) is dominated by the contribution from the electronic pockets (figure 2c). In LaFePO, SrFe$_2$P$_2$ and CaFe$_2$P$_2$, the mean free paths of electrons are at least a factor of 2 larger than those of the holes, which may be caused by differences in the orbital character between the electron and hole sheets (Analytis et al. 2009b; Coldea et al. 2009). Furthermore, for the same electron sheet, the mean free path varies along $k_z$, suggesting possibly anisotropy in scattering, which may be relevant for understanding the presence of line nodes in some of the iron pnictides (Fletcher et al. 2009). The Hall effect data in the paramagnetic (PM) state of BaFe$_2$As$_2$ also suggest that electron bands have a higher mobility than the hole bands (Fang et al. 2009), and at low temperatures, in the magnetic state, hole mobility is suppressed when compared with that of electrons, suggesting that hole localization may be promoted by spin fluctuations (Fang et al. 2009).

The relevance of electron–electron interactions can be obtained by comparing the quasi-particle mass enhancement in relation to the band mass, $m^*/m_b$, and accounting for the electron–phonon coupling. The values corresponding to the averaged electron sheets between different compounds vary from 2.38 in SC LaFePO (Coldea et al. 2008) to 1.85 in SrFe$_2$P$_2$ (Analytis et al. 2009b) and 1.5 in both CaFe$_2$P$_2$ (Coldea et al. 2009) and BaFe$_2$P$_2$ (Shishido et al. 2010). It is worth emphasizing that in the three-dimensional CaFe$_2$P$_2$ the enhancement is the same for both electron and hole sheets. The conventional electron–phonon coupling for CaFe$_2$As$_2$ in a non-magnetic, collapsed tetragonal phase is calculated to be $\lambda_{el-ph} \sim 0.23$ (Yildirim 2009), and it can be considered as a good approximation for the non-magnetic phosphites that share similar structures and are isoelectronic to arsenides. Thus, the mass enhancement, $1 + \lambda_{el-ph} = 1.23$, is probably due to a conventional electron–phonon coupling; the many-body interactions, however, could be responsible for a further enhancement of the electron–phonon interaction owing to the strong polarization of the pnictogen ions (M. Kulic & A. Haghighirad 2009, unpublished data). While linear electron–phonon coupling in the non-magnetic phase is calculated to be weak, strong magneto-phonon coupling is believed to be very strong (in LaFeAsO, the Fe moment changes at a rate of 6.8 $\mu_B/$Å as the Fe–As distance is varied by changing the As layer height) (Yin et al. 2008). Assuming that the mass enhancement of $m^*/m_b \sim 1.5$ in non-magnetic phosphides is mainly an effect of the interaction with the lattice, the further enhancement seen in the SC LaFePO could suggest a significant contribution from electron–electron interactions ($\lambda_{el-el} \sim 0.8 - 1$) and it may reflect the large degree of nestability of this compound and its tendency towards magnetic instabilities.

3. Fermi surface in an AFM phase

In an AFM phase, the lattice periodicity is changed owing to the presence of an additional periodicity introduced by the magnetic order which leads to a Fermi surface reconstruction. Band structure calculations considering the AFM Brillouin zone have been reported by Analytis et al. (2009a,b) using the LDA + $U$ methodology with a negative value for $U$ in order to suppress the value of the magnetic moment, as LDA significantly overestimated the value of the

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moment. Although most of the Fermi surface is gapped by the SDW in the magnetic pnictides, there are remaining carriers; this is in contrast to cuprates, where the undoped materials are AFM Mott insulators. The Fermi surface of the AFM BaFe$_2$As$_2$ is represented by electron and hole ellipsoids and two tiny electron and hole pockets originated from Dirac-like crossing of the bands (Analytis et al. 2009a,b).

ARPES data in the SDW phase on BaFe$_2$As$_2$ (P. Richard et al. 2009, unpublished data) confirm the presence of these tiny pockets as originating from an anisotropic Dirac cone. This cone is located away from high-symmetry points and formed by bands that are gapped away from the cone. As the cone’s apex is located very near the Fermi level this will lead to the formation of tiny FS pockets which are very sensitive to structural and magnetic effects, less than 0.05 per cent of the PM Brillouin zone (Analytis et al. 2009a,b). Quantum oscillations studies (Harrison & Sebastian 2009) suggest the existence of these tiny pockets as a signature for nodal SDW. It is not clear at the moment whether these tiny pockets with high velocity play a major role in the superconductivity of the iron pnictides as their presence is strongly affected by the changes in the lattice and magnetism and the details of theoretical models.

Quantum oscillations studies in (Ba/Sr/Ca)Fe$_2$As$_2$ (Sebastian et al. 2008; Analytis et al. 2009a,b; Harrison et al. 2009) only observe small pockets, which occupy 3 per cent of the PM Brillouin zone when compared with the large sheets of the non-reconstructed Fermi surface, which occupies 15 per cent of the PM Brillouin (figure 4). These results are in agreement with the presence of a Fermi surface reconstruction and opening of an SDW gap, but the size of the largest observed pocket is half the size of that predicted for the larger ellipsoid areas. However, as the band structure calculations in the magnetic phase of the iron pnictides cannot clearly account for the experimentally observed magnetic moments at this point, any direct association should be made with caution until all the predicted pockets are observed.

As in other new areas of research, the quality of the sample always requires time to be improved. In this respect, the research on iron pnictides has been done at such a high pace because various tools and experimental techniques developed...
for cuprates were already available. In the AFM phase, only small pockets were observed, which would be consistent with a Fermi surface reconstruction, and, at this point, it is not clear whether possible crystal twining may impede the observation of other pockets in the underdoped region.

4. Future prospects

The discovery of new materials based on iron tetrahedrally coordinated with pnictides or chalcogenites has raised the expectation that novel materials with even higher transition temperatures than iron-based superconductors or cuprates may be in our reach. One possible scenario relies on identifying structures in which the electronically active layers are isolated to provide enough density of carriers at the Fermi level to drive the systems towards magnetic instability, which can then be easily tuned to suppress the magnetism and stabilize a superconductive state.

One of the key ingredients to understanding high-temperature superconductivity in pnictides and in cuprates could be linked to understanding the evolution of the Fermi surface topology from a reconstructed Fermi surface in the AFM (underdoped) phase to a large Fermi surface (overdoped phase). By varying an external parameter (pressure, doping or a magnetic field), a second-order quantum phase transition, or a quantum critical point under the SC dome, may separate a PM Fermi liquid regime from the magnetically ordered state. Quantum oscillations measurements are ideally suited to access a quantum critical point as a function of a tuning parameter as they provide the effective mass of the elementary fermionic excitations that can be traced across the quantum critical point. In pnictides, a possible way to access such a critical point under the SC dome is through an isovalent substitution of phosphorus at the arsenic site (Dai et al. 2009) in BaFe$_2$As$_2$ and quantum oscillations indeed suggest an increase in the effective masses and nesting between the electron and hole pockets upon approaching the maximum $T_c$ (Shishido et al. 2010; J. G. Analytis, J.-H. Chu, R. D. McDonald, S. C. Riggs & I. R. Fisher 2010, unpublished data). Further studies to follow the detailed topological changes of the Fermi surface across the whole phase diagram will establish the relevant role played by the itinerant electrons in iron pnictides and will provide additional experimental guides for the further theoretical models concerning these materials.

In conclusion, the quantum oscillations studies on iron phosphides provide a unique access to the Fermi surface of two classes of iron-based superconductors. These systems do not show magnetic order, despite the fact that they have similar calculated Fermi surfaces in the tetragonal phase at high temperatures. While nesting may be important in stabilizing an SC state with low $T_c$ (like LaFePO), the high $T_c$ values observed in arsenides in the proximity of magnetic order suggest that spin fluctuations are also essential (Dai et al. 2009). Lower dimensional systems with an even larger spacer between Fe–As layers may further enhance these fluctuations and may possibly stabilize superconductivity at temperatures even higher than 55 K.

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Born in Transylvania, Romania, Amalia Coldea read physics at the Babes-Bolyai University, Cluj-Napoca, and graduated with an MSc with first class honours. She continued her studies at the University of Oxford, where she investigated colossal magnetoresistive materials and obtained her PhD in 2001. Later she continued as a postdoctoral researcher in Oxford, working on quantum oscillations in organic superconductors. In September 2005, she took up a Royal Society Dorothy Hodgkin Fellowship at the University of Bristol and, since January 2010, has been based at the University of Oxford. Her current field of research is quantum oscillations in iron-based superconductors and metallic systems on magnetically frustrated geometries. Amalia is married to Radu Coldea and they have two children, Victor and Sandra.