# Superconductivity in $Ln$FePO ($Ln$ = La, Pr and Nd) single crystals

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**Abstract.** Single crystals of the compounds LaFePO, PrFePO and NdFePO have been prepared by means of a flux growth technique and studied by electrical resistivity, magnetic susceptibility and specific heat measurements. We have found that PrFePO and NdFePO display superconductivity with values of the superconducting critical temperature $T_c$ of 3.2 and 3.1 K, respectively. The effect of annealing on the properties of LaFePO, PrFePO and NdFePO is also reported. The $Ln$FePO ($Ln$ = lanthanide) compounds are isostructural with the $Ln$FeAsO$_{1-x}$F$_x$ compounds that become superconducting with $T_c$ values as high as 55 K for $Ln$ = Sm. A systematic comparison of the occurrence of superconductivity in the series $Ln$FePO and $Ln$FeAsO$_{1-x}$F$_x$ points to a possible difference in the origin of the superconductivity in these two series of compounds.

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## 1. Introduction

Although the rare-earth transition metal phosphide oxides $Ln$FePO, where $Ln$ is a lanthanide, were first synthesized in 1995 [1], it was not until 2006 [2] that superconductivity near 5 K was discovered in LaFePO. The subsequent report of superconducting critical temperature $T_c$ values near 26 K in the related, fluorine-doped compound LaFeAsO$_{1-x}$F$_x$ [3] resulted in a great deal of excitement and many publications on what is now recognized as a new class of Fe-based high-temperature superconductors. Several different types of doping have been found to induce superconductivity in these compounds including substituting F for O [3]–[9], Co for Fe [10], Sr for La [11], Th for Gd [12] and also the introduction of oxygen vacancies [9, 13]. Materials with related structures that include the same type of Fe–$Pn$ planes, where $Pn$ is a pnictide, such as Ba$_{1-x}$K$_x$Fe$_2$As$_2$ [14] and LiFeAs [15] have also been found to exhibit similar physics including relatively high-temperature superconductivity. Clearly, there exists an enormous phase space of potential Fe–$Pn$ superconductors. The vast majority of work has focused on the arsenic-based versions of these compounds since, thus far, they exhibit the highest $T_c$ values, with the record high $T_c$ near 55 K for SmFeAsO$_{1-x}$F$_x$ [8] and SmFeAsO$_{1-\delta}$ [13], and 56 K for Gd$_{1-x}$Th$_x$FeAsO [12]. Given the toxic nature of arsenic, it would be highly desirable to discover similarly high $T_c$ values in less toxic P-, Sb- or Bi-based versions of these compounds. However, despite the fact that replacing La with the lanthanides Ce, Pr, Nd, Sm or Gd in the As-based oxypnictides leads to a near doubling of $T_c$, there appears to be a striking lack of data on the corresponding phosphorus-based versions of these compounds. Although LaFePO has received substantial attention, SmFePO was recently been reported to be superconducting [16], and CeFePO remains non-superconducting down to 400 mK [17], the compounds $Ln$FePO with $Ln =$ Pr, Nd and Gd do not yet appear to have been scrutinized for the occurrence of superconductivity.

The undoped parent compounds, $Ln$FeAsO, exhibit a spin density wave (SDW) and structural instability near 150 K, remain metallic to low temperatures, and only display super-conductivity when the SDW is suppressed towards zero temperature either through doping or pressure [18]. In contrast, the phosphorus-based analogues LaFePO and SmFePO [16] do not manifest a SDW transition and appear to develop a superconducting state in the undoped form at ambient pressure. Three key questions are whether the mechanism of superconductivity is the same in the P- and As-based compounds, whether the P-based versions of these compounds indeed exhibit superconductivity in the undoped form or only in samples that are in fact of the form $Ln$FePO$_{1-\delta}$, and to what degree sample quality affects the superconducting properties.

For LaFePO, values of $T_c$ that range from 3 K [2] to 7 K [19] have been reported. Under pressure, we found that the $T_c$ of LaFePO reaches nearly 14 K at $\sim$110 kbar [20]. However, in a recent study of polycrystalline materials, it was concluded that stoichiometric LaFePO is metallic but non-superconducting [21] at temperatures as low as 0.35 K. Our recent work on single-crystalline LaFePO [20] indicated $T_c$ values near 6 K as measured by electrical resistivity and magnetization, but the specific heat exhibited no discontinuity at $T_c$ leading us to propose that the superconductivity may be associated with oxygen vacancies that alter the carrier concentration in a small fraction of the sample, although superconductivity characterized by an unusually small gap value could not be ruled out. Yet, the superconductivity appeared to be associated with the ZrCuSiAs structure, since the upper critical field was anisotropic. However, in a recent study of single crystals of LaFePO [22], a specific heat anomaly roughly 60% of the expected Bardeen–Cooper–Schrieffer (BCS) value in magnitude at the $T_c \approx 6$ K was reported,

indicating that the superconductivity can be a bulk phenomenon in this material. These samples were grown using a slightly different method than the one we have employed, where $La_2O_3$ was used as the oxygen containing precursor rather than $Fe_2O_3$, as used in our growths. The variation in the reported data indicates that the $T_c$ value and superconducting fraction are sensitive to the details of the synthesis conditions.

In this paper, we report the results of electrical resistivity, magnetic susceptibility and specific heat measurements on single-crystal samples of LaFePO, PrFePO and NdFePO. All three compounds exhibit complete resistive superconducting transitions; i.e. the resistivity drops to a negligibly small value at low temperatures. However, as-grown crystals of PrFePO and NdFePO do not show superconducting transitions in the magnetic susceptibility and magnetic screening only develops after post-annealing the samples in flowing $O_2$ at 700 °C. Annealing in flowing $O_2$ at 700 °C for 24 h is also found to improve the superconductive properties of LaFePO.

## 2. Experimental details

Single crystals of LaFePO, PrFePO and NdFePO were grown from elements and elemental oxides with purities > 99.9% in a molten Sn:P flux. The growths took place over a 1 week period in quartz ampoules that were sealed with 75 Torr Ar at room temperature. The inner surface of each quartz ampoule was coated with carbon by a typical pyrolysis method. The starting materials were $Ln$, $Fe_2O_3$, P and Sn, which were combined in the molar ratios $9 : 3 : 6 : 80.5$, similar to previous reports [20, 23] for P-based oxypnictide single crystals. The $Fe_2O_3$ powder was dried for ~10 h at 300 °C before weighing. The ampoule was heated to 1135 °C at a rate of 35 °C h$^{-1}$ kept at this temperature for 96 h, and then rapidly cooled to 700 °C. After removing the majority of the flux by spinning the ampoules in a centrifuge, LaFePO, PrFePO and NdFePO single-crystal platelets of an isometric form with typical dimensions of ~$0.5 \times 0.5 \times 0.05$ mm$^3$ or smaller (particularly for the NdFePO crystals), were collected and cleaned in hydrochloric acid to remove the flux from the surface of the crystals prior to measurements. As previously reported [20], the platelets cleaved easily in the $ab$-plane and were notably malleable, in contrast to the cuprate superconductors. In order to explore the effects of annealing in oxygen, several batches of crystals were heated to 700 °C for 24 h under flowing $O_2$. Hereafter, these samples will be referred to as '$O_2$-annealed'.

X-ray powder diffraction measurements were made using a diffractometer with a non-monochromated Cu K$\alpha$ source to check the purity and crystal structure of the LaFePO and PrFePO single crystals. Due to a small batch yield, x-ray diffraction measurements were not made for the NdFePO crystals. As reported previously, the crystals were difficult to grind into a fine powder as a result of their malleability. Thus, the powder diffraction patterns for $Ln =$ La and Pr crystals were generated from a collection of several crystals that were cut into small pieces using a razor blade and then ground into a coarse powder using a mortar and pestle. The XRD results revealed diffraction patterns that are consistent with those reported previously [1]. Chemical analysis measurements were also made using an FEI Company Model 600 scanning electron microscope which revealed that the stoichiometry for the crystals was consistent with the ratio $1 : 1 : 1 : 1$ for $Ln :$ Fe : P : O where $Ln =$ La, Pr, Nd.

Electrical resistivity $\rho(T)$ measurements were performed in a four-wire configuration with the current in the $ab$-plane, at temperatures $T = 1.1$–300 K using a conventional $^4$He cryostat and a Quantum Design Physical Properties Measurement System (PPMS). Due to the small size

of the crystal samples and uncertainties in the placement of the leads, the absolute resistivity values are accurate only to $\sim\pm 50\%$. Specific heat $C(T)$ measurements were made for 2–300 K for LaFePO and PrFePO crystals in a quantum design PPMS semiadiabatic calorimeter using a heat-pulse technique. The specimens for specific heat measurements were attached to a sapphire platform with a small amount of Apiezon N grease and were composed of several hundred single crystals for which the mass $m = 13.06$ mg (La unannealed) 8.93 mg (Pr unannealed), and 6.32 mg (Pr $O_2$-annealed). Dc magnetization $M(T, H)$ measurements were made using a Quantum Design Magnetic Properties Measurement System (MPMS) in order to probe both the superconducting and normal state properties of the single-crystal platelets. For the normal state measurements at room temperature, the LaFePO and PrFePO specimens studied were the same as those used for specific heat measurements and were mounted in cotton packed gelatin capsules. For NdFePO, the normal state measurements were made using a single crystal ($m = 0.0125$ mg) that was mounted on a piece of tape with the $ab$-plane perpendicular to the applied magnetic field. To study the superconducting state, individual single-crystal specimens were mounted with the $ab$-plane perpendicular to the magnetic field. Multiple single-crystal platelets were each individually measured for 2–10 K and $H = 5$ Oe under both zero-field cooled (ZFC) and field-cooled (FC) conditions in order to characterize batch homogeneity via variation in $T_c$, which was found to be minimal.

## 3. Results

The electrical resistivity data for unannealed $Ln$FePO ($Ln = $ La, Pr and Nd), shown in figure 1, reveal metallic behavior where $\rho(T)$ decreases with decreasing $T$ until the onset of the zero resistance state at the superconducting transition temperatures $T_c \sim 6.6$, 3.2 and 3.1 K for $Ln = $ La, Pr and Nd, respectively. The transition temperatures are defined as the $T$ where $\rho(T)$ drops to 50% of the extrapolated normal state value. The transition widths are taken as the difference in the temperatures where $\rho(T)$ drops to 10% and 90% of the extrapolated normal state value. For 100–300 K, the $\rho(T)$ data have approximately linear $T$ dependences which evolve into quadratic forms for $T \sim 10$–100 K, as shown in the right inset to figure 1. Fits over this temperature range show that the data are well described by the expression

$$\rho(T) = \rho_0 + AT^2. \tag{1}$$

Additionally, the residual resistivity ratios RRR $= \rho(300 \text{ K})/\rho(0)$ for unannealed samples are large, reflecting the high quality of the crystals. The results from fits to the $\rho(T)$ data are given in table 1.

Specific heat divided by temperature $C/T$ versus $T$ data for unannealed LaFePO and PrFePO and $O_2$-annealed PrFePO are shown in figure 2. From room $T$, the unannealed $Ln$FePO ($Ln = $ La and Pr) specimens exhibit weak increases in $C/T$ with decreasing $T$ that are followed by broad maxima near 110 K (La) and 90 K (Pr). Below its maximum, $C/T$ for LaFePO continues to decrease with decreasing $T$ and is described for $2 \text{ K} < T < 8 \text{ K}$ by a sum of electronic and lattice terms,

$$C/T = \gamma + \beta T^2 \tag{2}$$

yielding an electronic specific heat coefficient $\gamma = 12.7$ mJ mol$^{-1}$ K$^{-2}$ and $\beta = r 1944(1/\Theta_D)^3$ J mol$^{-1}$ K$^{-1}$, which gives a Debye temperature $\Theta_D = 427$ K.

In contrast to results for LaFePO, $C/T$ versus $T$ data for PrFePO specimens exhibit a trough–peak structure with minima near 27 and 32 K and maxima near 14.5 and 15.5 K
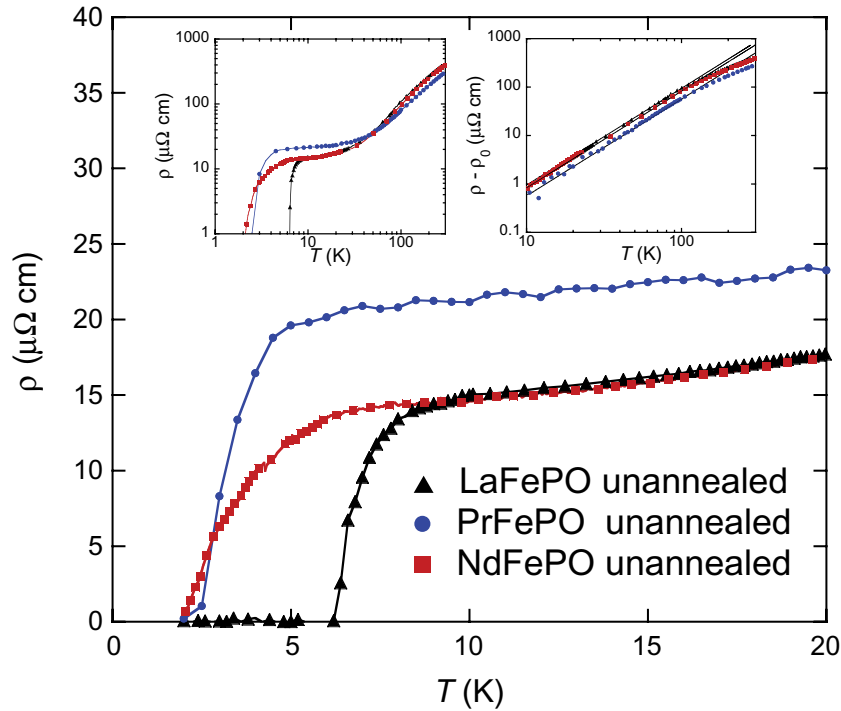
**Figure 1.** Electrical resistivity $\rho$ versus temperature $T$ measured in the *ab*-plane for unannealed single crystals of LaFePO, PrFePO and NdFePO. Left inset: log–log plot of $\rho$ versus $T$ over the entire measured temperature range. Right inset: log–log plot of $\rho$–$\rho_0$ versus $T$. The solid lines are fits to the data, which demonstrate the $T^2$ behavior for 10–100 K.

**Table 1.** A summary of results from electrical resistivity measurements for the compounds $Ln$FePO where $Ln =$ La, Pr and Nd. The listed quantities are defined in the text and are abbreviated as the following: superconducting transition temperature $T_c$, width of the superconducting transition $\Delta T_c$(K), residual resistivity $\rho_0$ (equation (1)), quadratic coefficient $A$ (equation (1)) and RRR $= \rho_{300\,K}/\rho_0$.

| $Ln$ | $T_c$ (K) | $\Delta T_c$ (K) | $\rho_0(\mu\Omega\,\mathrm{cm})$ | $A(\mu\Omega\,\mathrm{cm}\,\mathrm{K}^{-2}) \times 10^{-3}$ | RRR |
|---|---|---|---|---|---|
| La | 6.6 | 1.3 | 14.0 | 9.46 | 32 |
| Pr | 3.2 | 2.0 | 21.0 | 5.66 | 14 |
| Nd | 3.1 | 3.1 | 13.9 | 8.28 | 28 |

for unannealed and $O_2$-annealed samples, respectively. This type of behavior is indicative of crystalline electric field (CEF) splitting of energy levels of the $Pr^{3+}$ ions, which appears in specific heat data as a so-called 'Schottky anomaly'. Thus, for $2\,\mathrm{K} < T < 45\,\mathrm{K}$, the $C(T)/T$ data for both unannealed and $O_2$-annealed PrFePO specimens were fit by an expression that includes electronic, lattice and Schottky terms given by

$$C/T = \gamma + \beta T^2 + \alpha C_{\mathrm{Sch}}/T, \tag{3}$$
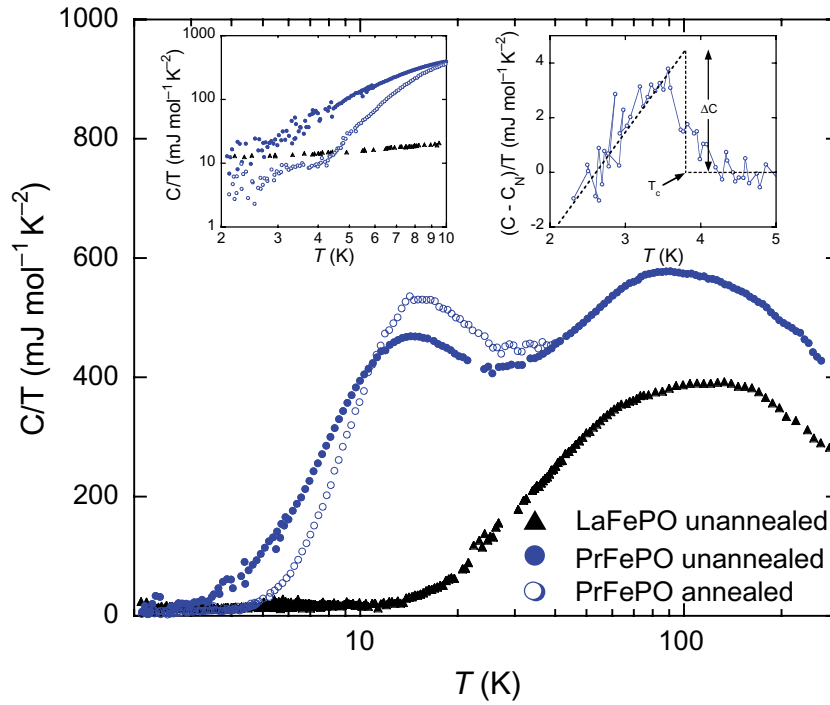
**Figure 2.** Linear–log plot of specific heat divided by temperature $C/T$ versus temperature $T$ for unannealed LaFePO, unannealed PrFePO and $O_2$-annealed PrFePO. Left inset: log–log $C/T$ versus $T$ plot for unannealed LaFePO, unannealed PrFePO and $O_2$-annealed PrFePO at low $T$. For $O_2$-annealed PrFePO, a broad jump is seen near $T_c = 3.6$ K. Right inset: $C/T$ versus $T$ plot where the normal state electronic contribution has been subtracted, revealing the jump associated with the superconducting transition. The dotted line represents an equal entropy construction that was used to determine the value of $T_c$ and the size of the jump $\Delta C$.

where $\gamma$ is the electronic specific heat coefficient and $\beta T^2$ represents the lattice contribution to the specific heat. The term $C_{\mathrm{Sch}}(T)$ is the Schottky specific heat anomaly for a two-level system arising from the energy difference between the CEF ground state and the first excited state, scaled by a factor $\alpha$, and is given by

$$C_{\mathrm{Sch}}(T) = R \left( \frac{\delta}{T} \right)^2 \frac{g_0}{g_1} \frac{\exp(\delta)/T}{[1 + (g_0/g_1) \exp(\delta/T)]^2}, \tag{4}$$

where $\delta$ is the energy difference in units of K between the two levels, and $g_0$ and $g_1$ are the degeneracies of the ground state and first excited state [24]. The crystal structure of PrFePO belongs to the $p4/nmm$ space group, with $Pr^{3+}$ ions at the points of a tetragonal unit cell [1]. The energy level scheme for a Pr ion for the tetragonal symmetry CEF Hamiltonian contains five singlets and two doublets [25]. As shown in figure 3, the best fit to the data suggests that both the ground state and first excited states are non-magnetic singlets. It is also clear that, for unannealed specimens, equation (3) overestimates the value of $\gamma$. In contrast, the $C(T)/T$ data for $O_2$-annealed samples are fit extremely well for $2\,\mathrm{K} < T < 45\,\mathrm{K}$ and $\gamma$ is only slightly overestimated. These results suggest that for the unannealed sample, there are a range of CEF
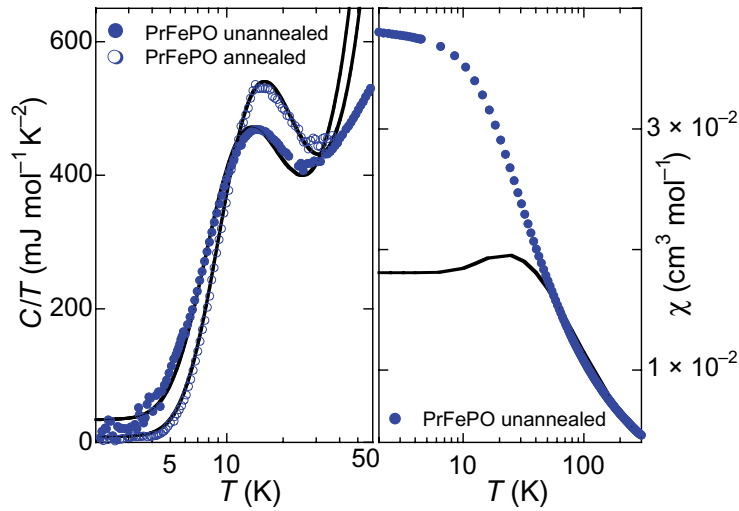
**Figure 3.** Left panel: specific heat divided by temperature $C/T$ versus $T$ for unannealed and $O_2$-annealed PrFePO. The solid lines are fits to the data using equation (3). Right panel: magnetic susceptibility $\chi(T) = M/H$ data for unannealed PrFePO. The solid line is a fit to the data using equation (7).

**Table 2.** A summary of results from specific heat measurements for the compounds $Ln$FePO where $Ln =$ La, Pr. For $\gamma$, both the extrapolated $T = 0$ K value and the results from CEF fits (equation (3)) are reported. The additional parameters from fits to the data using equation (3) are the coefficient $\beta$ of the phonon contribution, the splitting of the ground and first excited states by the CEF $\delta$ (K), and the fitting parameter $\alpha$.

| $Ln$ | $\gamma$ (mJ mol$^{-1}$ K$^{-2}$) | $\gamma_{\text{CEF}}$ (mJ mol$^{-1}$ K$^{-2}$) | $\beta$ (mJ mol$^{-1}$ K$^{-4}$) | $\delta$ (K) | $\alpha$ |
|---|---|---|---|---|---|
| La unannealed | 12.7 | – | 0.10 | – | – |
| Pr unannealed | 10 | 33 | 0.28 | 41.2 | 1.57 |
| Pr $O_2$-annealed | 3 | 7.3 | 0.22 | 48.4 | 2.27 |

energy level splittings which broaden the Schottky peak and render equation (3) too simple an expression to adequately describe the data. It is possible that a range of CEF energy splittings could arise as the result of crystalline disorder which would introduce variation in the local charge distribution around individual Pr ions. Thus, it seems likely that $O_2$-annealing reduces the spread of CEF energy level splittings, resulting in a sharper Schottky peak and a better CEF fit for $O_2$-annealed samples. For the unannealed and $O_2$-annealed PrFePO samples, the splitting between the ground state and the first excited state is 41.2 and 48.4 K, respectively. The remaining fit parameters are summarized in table 2.

As shown in the left inset to figure 2, $\gamma$ approaches 12.7 and 10 mJ mol$^{-1}$ K$^{-2}$ for unannealed LaFePO and PrFePO, respectively, and 3 mJ mol$^{-1}$ K$^{-2}$ for $O_2$-annealed PrFePO, as $T$ goes to zero. For both unannealed LaFePO and PrFePO, there is no detectable jump in the specific heat near the superconducting transition temperatures inferred from $\rho(T)$. In contrast, the $O_2$-annealed PrFePO specimen shows a broad jump at low $T$. In order to determine $T_c$

and the size of the specific heat jump $\Delta C$ for $O_2$-annealed PrFePO, the normal state terms were subtracted from $C/T$ near the discontinuity, resulting in the curve shown in the right inset to figure 2. The parameters, $T_c$ and $\Delta C$ were then determined by applying an equal entropy construction, as shown by the dashed line in the right inset to figure 2. In agreement with $\rho(T)$ for unannealed samples, $T_c = 3.6\,\text{K}$. Interestingly, the specific heat jump $\Delta C = 15.1\,\text{mJ}\,\text{mol}^{-1}\,\text{K}^{-1}$ is nearly 100% of the value expected for a weak-coupling conventional BCS superconductor, given by $\Delta C = 1.52\gamma T_c = 16.4\,\text{mJ}\,\text{mol}^{-1}\,\text{K}^{-1}$ if $\gamma$ is the extrapolated value of $3\,\text{mJ}\,\text{mol}^{-1}\,\text{K}^{-2}$ and $T_c = 3.6\,\text{K}$ [26]. In comparison, unannealed LaFePO and PrFePO are expected to show $\Delta C = 127.4$ and $54.7\,\text{mJ}\,\text{mol}^{-1}\,\text{K}^{-1}$, respectively. By comparing the expected specific heat jumps with the scatter in the $C(T)$ data for the unannealed samples, it appears that at most $\sim$40% of the bulk is superconducting for the unannealed samples.

The normal state $\chi(T)$ data for unannealed LaFePO, PrFePO and NdFePO are shown in figure 4. Near $\sim$220 K, $\chi(T)$ increases strongly with decreasing $T$ for LaFePO and NdFePO. This temperature dependence is similar to that of the compound $Fe_2P$ [27], which may be present as inclusions or surface impurities. We estimate that our observed magnetic susceptibility is consistent with 1–2% $Fe_2P$ impurity for both LaFePO and NdFePO. Interestingly, the $\chi(T)$ data for PrFePO show no such feature. With decreasing $T$, $\chi(T)$ for LaFePO increases gradually and exhibits a low $T$ upturn which persists down to 2 K. This behavior is not typical for $Fe_2P$, and is either intrinsic to LaFePO or due to a small concentration of some other paramagnetic impurity. For unannealed NdFePO, $\chi(T)$ is consistent with Curie–Weiss behavior for $Nd^{3+}$ ions for $2\,\text{K} < T < 150\,\text{K}$, where the magnetic contribution from the magnetic ordering at 220 K appears to be constant. For this $T$ range, $\chi(T)$ can be described by a sum of a constant term and Curie–Weiss function and is given by the expression

$$\chi(T) = \chi_0 + C/(T - \Theta), \tag{5}$$

where $\chi_0 = 0.039\,\text{cm}^3\,\text{mol}^{-1}$, $C = 1.33\,\text{cm}^3\,\text{K}\,\text{mol}^{-1}$ and $\theta = -8.1\,\text{K}$. The $\chi_0$ term is unusually large and it seems likely that it may be attributed to the magnetic contribution of the impurity phase. From the Curie constant $C$, it appears that the effective magnetic moment for the Nd ions is $3.26\,\mu_B$, which is reasonably close to the value expected for $Nd^{3+}$ ions according to Hund's rules ($\mu_{\text{eff}} = 3.62\,\mu_B$ for $Nd^{3+}$). Lastly, the negative Curie–Weiss temperature indicates antiferromagnetic spin correlations for the Nd ions.

Similarly, $\chi(T)$ for unannealed PrFePO shows behavior that is consistent with Curie–Weiss behavior for $50\,\text{K} < T < 300\,\text{K}$ and is described by equation (5), where $\chi_0 = 0$, $C = 1.58\,\text{cm}^3\,\text{K}\,\text{mol}^{-1}$ and $\Theta = -46.7\,\text{K}$. Again, the Curie constant yields a reasonable value of $\mu_{\text{eff}} = 3.55\,\mu_B$ ($\mu_{\text{eff}} = 3.58\,\mu_B$ for $Pr^{3+}$ according to Hund's rules), while the large negative Curie–Weiss temperature indicates antiferromagnetic spin correlations for the Pr ions. For $T < 50\,\text{K}$, $\chi(T)$ is suppressed from Curie–Weiss behavior and saturates to a constant value with decreasing $T$. This result is consistent with the ground and first excited states being non-magnetic singlets, between which the energy splitting is close to 41 K as inferred from the fit to the Schottky anomaly in the $C(T)/T$ data. In order to describe the effect of CEF splitting on $\chi(T)$, a CEF fitting scheme is considered. As mentioned above, the crystal structure of PrFePO belongs to the $p4/nmm$ space group, with $Pr^{3+}$ ions at the points of a tetragonal unit cell. The CEF Hamiltonian of the Pr ions has the form

$$\mathcal{H}_{\text{CEF}} = B_2^0 O_2^0 + B_4^0 O_4^0 + 5 B_4^0 O_4^4 + B_6^0 O_6^0 - 21 B_6^0 O_6^4, \tag{6}$$

where $O_2^0$, $O_4^0$, $O_4^4$, $O_6^0$ and $O_6^4$ are Stevens operators for the $J = 4$ manifold and the $B$'s are parameters determined from experiment. The CEF Hamiltonian $\mathcal{H}_{\text{CEF}}$ splits the $J = 4$ Hund's
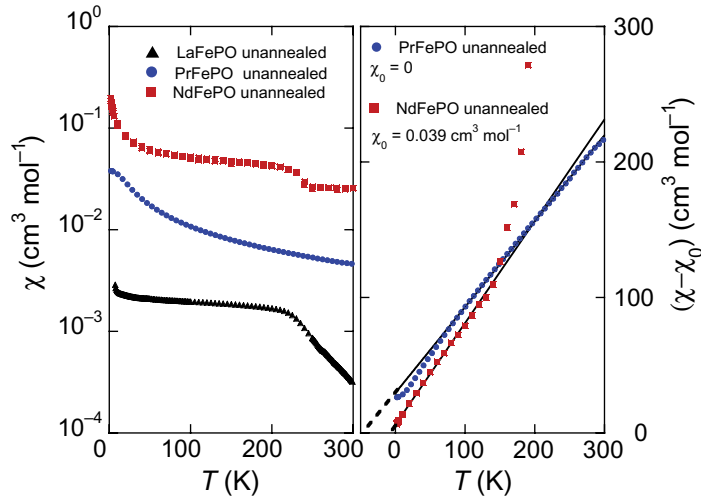
**Figure 4.** Left panel: magnetic susceptibility $\chi(T) = M/H$ versus $T$ for $Ln$FePO ($Ln$ = La, Pr, Nd) data. Right panel: inverse magnetic susceptibility $\chi^{-1}$ versus $T$ for $Ln$FePO ($Ln$ = Pr, Nd). The straight lines are fits to the data using modified Curie–Weiss expressions, as given by equation (5).

rule multiplet of $Pr^{3+}$ into five singlets and two doublets. In the presence of an external magnetic field, the Zeeman interaction mixes and splits the CEF energy levels and the magnetic susceptibility is given by [28]

$$\chi_{\mathrm{CEF}} = \frac{\sum_n \left[ \left(E_n^{(1)}\right)^2 / kT - 2E_n^{(2)} \right] \exp\left(-E_n^{(0)}/kT\right)}{\sum_n \exp\left(-E_n^{(0)}/kT\right)}, \tag{7}$$

where the $E_n^{(0)}$ are the unperturbed cubic CEF levels, $E_n^{(1)} = \mu_{\mathrm{B}} g \langle \phi_n | J | \phi_n \rangle$ with $\phi$ the CEF wave functions and $g$ the Landé $g$-factor, and

$$E_n^{(2)} = \sum_{n' \neq n} \mu_{\mathrm{B}}^2 g^2 \frac{|\langle \phi_n | J | \phi_n' \rangle|^2}{E_n^{(0)} - E_{n'}^{(0)}}. \tag{8}$$

In the molecular-field approximation, the measured magnetic susceptibility $\chi$ is given by $\chi = \chi_{\mathrm{CEF}}/(1 - \lambda \chi_{\mathrm{CEF}})$, where $\lambda$ is the molecular field parameter that describes exchange interactions between $Pr^{3+}$ ions [29]. Our best fit is shown as the solid curve in figure 3 where it is apparent that the CEF fit only describes the data qualitatively. The CEF fit parameters are $B_2^0 = -1.1$ meV, $B_4^0 = 0.0001$ meV, $B_4^4 = 0.0082$ meV, $B_6^0 = -0.0030$ meV, $B_6^4 = -0.0148$ meV and $\lambda = -18.4$ mol emu$^{-1}$. This set of CEF parameters suggests the energy separation between the ground and first excited states is 44.3 K, and both ground and first excited states are singlets, in good agreement with the specific heat data.

In an effort to determine whether the superconductivity is a bulk phenomenon, ZFC and FC measurements of the magnetic susceptibility were made in a field of 5 Oe for unannealed and $O_2$-annealed LaFePO, PrFePO and NdFePO crystals. It should be noted at the outset that the values of $M$(emu g$^{-1}$) are accurate to roughly $\pm 15\%$ due to uncertainties in mass and geometry of the small crystals. A plot of the ZFC and FC magnetic susceptibility through the superconducting transition temperatures observed in $\rho(T)$ is shown in figure 5. For unannealed
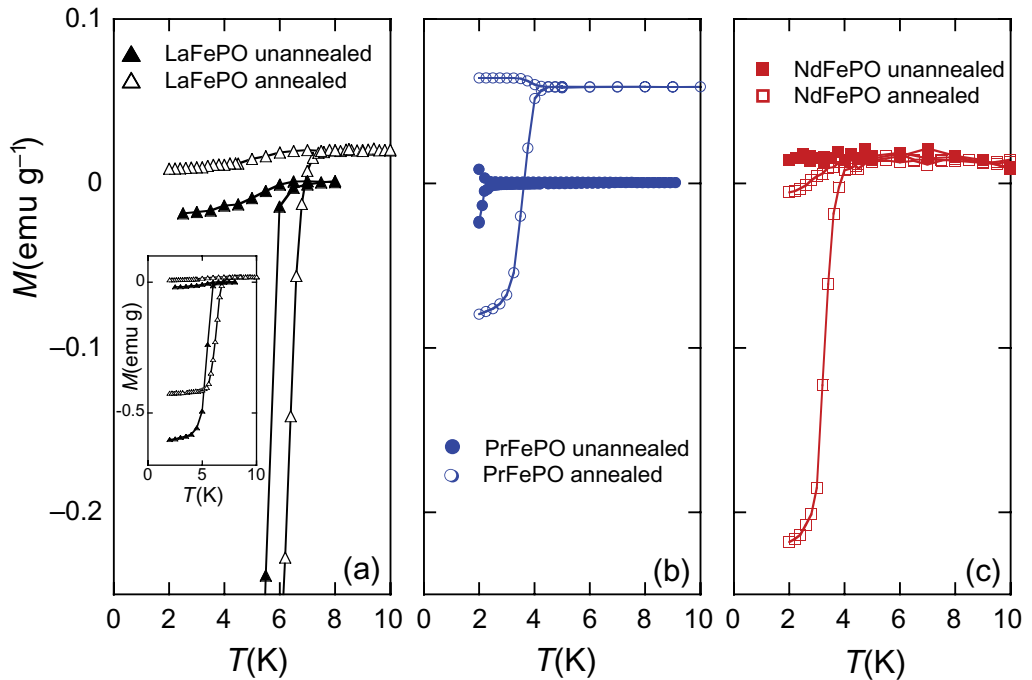
**Figure 5.** Left panel: magnetization $M(T)$ data for $H = 5$ Oe for unannealed and $O_2$-annealed LaFePO samples. Center panel: magnetization $M(T)$ data for $H = 5$ Oe for unannealed and $O_2$-annealed PrFePO samples. Right panel: magnetization $M(T)$ data for $H = 5$ Oe for unannealed and $O_2$-annealed NdFePO samples.

LaFePO, the onset temperature for LaFePO is near 6.0 K. With $O_2$-annealing, $T_c$ increases to a value near 7.0 K. For both the unannealed and $O_2$-annealed cases, the FC data return to $\sim$5% of the ZFC values. It also appears that the normal state magnetization is slightly enhanced for the $O_2$-annealed samples. Unannealed PrFePO shows a weak superconducting transition near 2 K for ZFC measurements and the FC measurement reveals a weak upturn in the magnetization below $T_c$. Although this feature is anomalous for typical superconductors, it has been repeatedly observed for these crystals. With annealing, PrFePO develops a pronounced superconducting transition with an onset near $T_c = 4.4$ K which is again accompanied by the anomalous low $T$ upturn in the FC measurement. Interestingly, the normal state magnetization is markedly enhanced for the $O_2$-annealed samples. A comparison of our specific heat, magnetic susceptibility and resistivity measurements on PrFePO is shown in figure 6. Unannealed NdFePO shows no evidence for a superconducting transition down to 2 K. Again, $O_2$-annealing promotes superconductivity, yielding an onset temperature $T_c = 4.4$ K. For $O_2$-annealed NdFePO, the FC data return to $\sim$3% of the ZFC values. Also, there is no offset in the normal state magnetization as the result of $O_2$-annealing. Thus, it is evident that $O_2$-annealing acts to promote the superconducting state for LaFePO, PrFePO and NdFePO, although it is unclear what the overall effect of $O_2$-annealing is on the normal state behavior. Additionally, the small recovery of the diamagnetic signal on field cooling indicates either that the material shows strong vortex pinning or that the superconductivity is not a bulk phenomenon. Further studies are required to make this distinction.
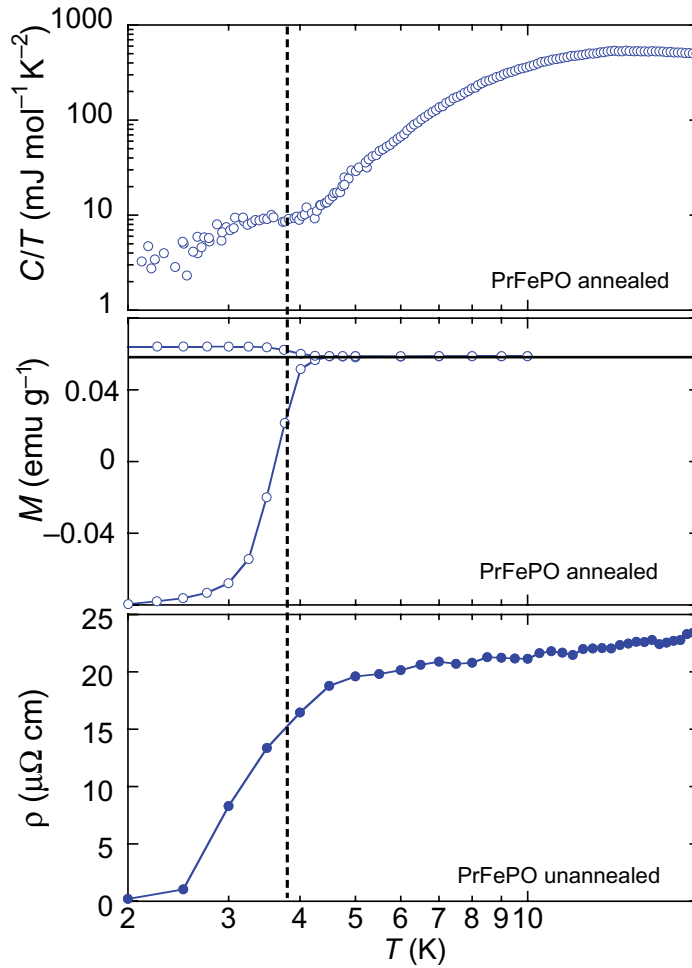
**Figure 6.** A comparison of the electrical resistivity $\rho$ versus $T$ data for unannealed PrFePO samples with specific heat divided temperature $C/T$ versus $T$ and magnetization $M$ versus $T$ for $O_2$-annealed PrFePO showing the agreement in $T_c$ among the measurements.

## 4. Discussion

An important question for understanding the Fe–$Pn$ superconductors is how the magnetism associated with the $Ln$ ion influences the superconductivity. For conventional superconductors, it is expected that $T_c$ values are suppressed by the introduction of magnetic ions, as is observed for the well-known case of de Gennes' scaling in BCS superconductors [30, 31]. Interestingly, both the series $Ln$FeAsO$_{1-x}$F$_x$ and $Ln$FeAsO$_{1-\delta}$ display an increase in the maximum $T_c$ values on replacing La with magnetic $Ln$ ions [3]–[8]. This result, together with the apparent suppression of a SDW that is correlated with the appearance of superconductivity, has led to the suggestion that the superconductivity exhibited by these compounds is unconventional in the sense that it is promoted by magnetic interactions [32]. In contrast, for the series $Ln$FePO, the $T_c$ values decrease upon replacing La with Pr, Nd, or Sm, as could be expected for a conventional superconductor in the presence of magnetic pairbreaking interactions. For the purpose of comparison, the evolution of $T_c$ versus $Ln$ for the series $Ln$FeAsO$_{1-x}$F$_x$, $Ln$FeAsO$_{1-\delta}$ and
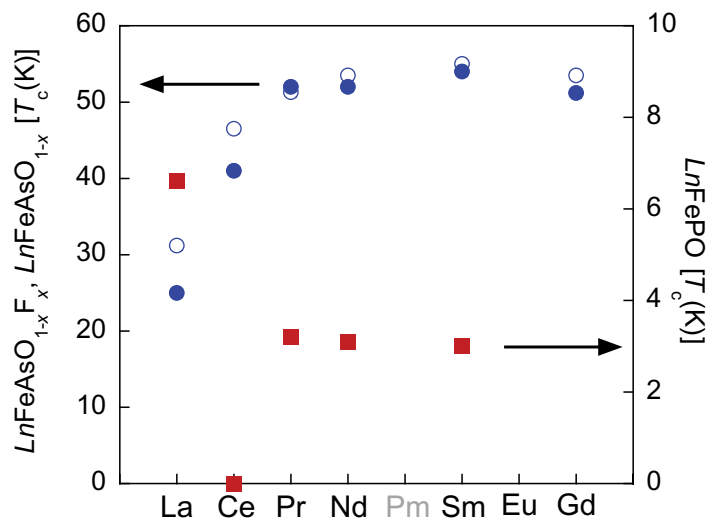
**Figure 7.** A comparison of the evolution of the superconducting transition temperature $T_c$ versus lanthanide $Ln$ for the series $Ln$FePO with $Ln =$ La, Ce [17], Pr, Nd, Sm [16] (solid squares), the optimally fluorine doped compounds $Ln$FeAsO$_{1-x}$F$_x$ with $Ln =$ La [3], Ce [4], Pr [5], Nd [6], Sm [8] and Gd [9] (solid circles), and the oxygen deficient compounds $Ln$FeAsO$_{1-\delta}$ [9] (open circles).

$Ln$FePO is shown in figure 7. While one should be careful when comparing systematics between undoped $Ln$FePO and optimally doped $Ln$FeAsO$_{1-x}$F$_x$ and $Ln$FeAsO$_{1-\delta}$ samples, the opposite effects of magnetic ion substitution could be taken as evidence for a difference between the P- and As-based compounds in the mechanism of superconductivity. The point of view that the superconductivity for the series $Ln$FePO is BCS-like is supported by the lack of anomalous behavior in the electrical resistivity, magnetic susceptibility and specific heat.

Another important question for understanding the Fe–$Pn$ superconductors is how sample quality affects the superconductivity. Broadly speaking, sample quality can be defined as either crystalline or chemical homogeneity, each of which has the potential to affect the physical properties in unique ways. It has been noted [33] that among several samples of undoped LaFePO, those with the lowest residual resistivities display the highest $T_c$ values. A correlation between low residual resistivity and high $T_c$ has also been observed in SmFePO [16]. This trend could derive from several possible differences among the samples, including lattice disorder, oxygen vacancy-induced changes in the carrier density, or oxygen vacancy-induced changes in the lattice parameters. Our measurements for LaFePO, PrFePO and NdFePO, which clearly show that O$_2$-annealing promotes the superconducting state, suggest a correlation between sample quality and higher $T_c$ values. This is shown in figure 6 for PrFePO where electrical resistivity for unannealed samples, magnetization data for O$_2$-annealed samples and specific heat data for O$_2$-annealed samples are compared. Comparison of magnetization data for unannealed and O$_2$-annealed samples also show that superconductivity is promoted by O$_2$-annealing (figure 5). In general, annealing tends to improve crystalline quality by allowing disorder in the lattice to relax, in addition to reducing possible chemical inhomogeneity. On the other hand, annealing can also promote phase separation. For this reason, although it seems reasonable to correlate crystalline quality with an enhancement of the superconducting state,

it is still necessary to carry out a more systematic study of the effect of annealing in these compounds. Furthermore, we note that it may be possible to improve the superconducting properties of the Fe–As compounds by synthesizing high-quality single-crystal specimens.

## 5. Concluding remarks

We have reported results for single crystals of the compounds LaFePO, PrFePO and NdFePO, which were prepared by means of a flux growth technique. Measurements of electrical resistivity, magnetic susceptibility and specific heat reveal metallic behavior for unannealed samples, which evolves into a superconducting state at low $T$ in $Ln = \mathrm{La}$ ($T_c = 6.6\,\mathrm{K}$), $Ln = \mathrm{Pr}$ ($T_c = 3.2\,\mathrm{K}$) and $Ln = \mathrm{Nd}$ ($T_c = 3.1\,\mathrm{K}$). The effect of annealing in flowing $O_2$ at $700\,^{\circ}\mathrm{C}$ for 24 h was also studied and found to enhance the superconducting properties. Although it seems likely that the positive effect of $O_2$-annealing on the superconducting properties is due to improved crystallinity and chemical homogeneity, further research will be required to support this conclusion. Finally, the evolution of $T_c$ with $Ln$ ion for the P- and As-based $Ln\mathrm{Fe}Pn\mathrm{O}$ compounds appears to be in opposite directions: $T_c$ increases as $Ln$ is varied from La to Sm for $Pn = \mathrm{As}$ and decreases as $Ln$ is varied from La to Sm for $Pn = \mathrm{P}$. This suggests that the mechanism of the superconductivity in these two series of compounds may be different; i.e. the superconductivity may be unconventional for the arsenides and conventional for the phosphides.

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## References

[1] Zimmer B I, Jeitschko W, Albering J H, Glaum R and Reehuis M 1995 The rare earth transition metal phosphide oxides LnFePO, LnRuPO and LnCoPO with ZrCuSiAs type structure *J. Alloys Compd.* **229** 238
[2] Kamihara Y, Hiramatsu H, Hirano M, Kawamura R, Yanagi H, Kamiya T and Hosono H 2006 Iron-based layered superconductor: LaOFeP *J. Am. Chem. Soc.* **128** 10012
[3] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 Iron-based layered superconductor La[O$_{1-x}$F$_x$]FeAs ($x = 0.05$–0.12) with $T_c = 26\,\mathrm{K}$ *J. Am. Chem. Soc.* **130** 3296
[4] Chen G F, Li Z, Wu D, Li G, Hu Z, Dong J, Zheng P, Luo J L and Wang N L 2008 Superconductivity at 41 K and its competition with spin-density-wave instability in layered CeO$_{1-x}$F$_x$FeAs *Phys. Rev. Lett.* **100** 247002
[5] Ren Z A, Yang J, Lu W, Yi W, Che G C, Dong X L, Sun L L and Zhao Z-X 2008 Superconductivity at 52 K in iron based F doped layered quaternary compound Pr[O$_{1-x}$F$_x$]FeAs *Mater. Res. Innov.* **12** 105
[6] Ren Z-A *et al* 2008 Superconductivity in the iron-based F-doped layered quaternary compound Nd[O$_{1-x}$F$_x$]FeAs *Europhys. Lett.* **82** 57002
[7] Chen X H, Wu T, Liu R H, Chen H and Fang D F 2008 Superconductivity at 43 K in SmFeAsO$_{1-x}$F$_x$ *Nature* **453** 761

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[8] Ren Z A, Lu W, Yang J, Yi W, Shen X L, Li Z C, Che G C, Dong X L, Sun L L, Zhou F and Zhao Z X 2008 Superconductivity at 55 K in iron-based F-doped layered quaternary compound Sm[$O_{1-x}F_x$]FeAs *Chin. Phys. Lett.* **25** 2215

[9] Yang J, Li Z-C, Lu W, Yi W, Shen X-L, Ren Z-A, Che G-C, Dong X-L, Sun L-L, Zhou F and Zhao Z-X 2008 Superconductivity at 53.5 K in GdFeAsO$_{1-\delta}$ *Supercond. Sci. Technol.* **21** 082001

[10] Sefat A S, Huq A, McGuire M A, Jin R, Sales B C, Mandrus D, Cranswick L M D, Stephens P W and Stone K H 2008 Superconductivity in LaFe$_{1-x}$Co$_x$AsO *Phys. Rev.* B **78** 104505

[11] Wen H-H, Mu G, Fang L, Yang H and Zhu Y 2008 Superconductivity at 25 K in hole-doped (La$_{1-x}$Sr$_x$)OFeAs *Europhys. Lett.* **82** 17009

[12] Wang C *et al* 2008 Thorium-doping-induced superconductivity up to 56 K in Gd$_{1-x}$Th$_x$FeAsO *Europhys. Lett.* **83** 67006

[13] Ren Z-A *et al* 2008 Superconductivity and phase diagram in iron-based arsenic-oxides ReFeAsO$_{1-\delta}$ (Re = rare-earth metal) without fluorine doping *Europhys. Lett.* **83** 17002

[14] Rotter M, Tegel M and Johrendt D 2008 Superconductivity at 38 K in the iron arsenide (Ba$_{1-x}$K$_x$)Fe$_2$As$_2$ *Phys. Rev. Lett.* **101** 107006

[15] Tapp J H, Tang Z, Lv B, Sasmal K, Lorenz B, Chu P C W and Guloy A M 2008 LiFeAs: an intrinsic FeAs-based superconductor with $T_c = 18$ K *Phys. Rev.* B **78** 060505

[16] Kamihara Y, Hiramatsu H, Hirano M, Kobayashi Y, Kitao S, Higashitaniguchi S, Yoda Y, Seto M and Hosono H 2008 Coexistence of superconductivity and antiferromagetic ordering in the layered superconductor SmFePO *Phys. Rev.* B **78** 184512

[17] Bruning E M, Krellner C, Baenitz M, Jesche A, Steglich F and Geibel C 2008 CeFePO: A heavy fermion metal with ferromagnetic correlations *Phys. Rev. Lett.* **101** 117206

[18] Okada H, Igawa K, Takahashi H, Kamihara Y, Hirano M, Hosono H, Matsubayashi K and Uwatoko Y 2008 Superconductivity under high pressure in LaFeAsO *J. Phys. Soc. Japan* **77** 113712

[19] Tegel M, Schellenberg I, Pöttgen R and Johrendt D 2008 A $^{57}$Fe Moessbauer spectroscopy study of the 7 K superconductor LaFePO *Z. Naturforsch.* B **63** 1057

[20] Hamlin J J, Baumbach R E, Zocco D A, Sayles T A and Maple M B 2008 Superconductivity in single crystals of LaFePO *J. Phys.: Condens. Matter* **20** 365220

[21] McQueen T M, Regulacio M, Williams A J, Huang Q, Lynn J W, Hor Y S, West D V, Green M A and Cava R J 2008 Intrinsic properties of stoichiometric LaOFeP *Phys. Rev.* B **78** 024521

[22] Analytis J G, Chu J H, Erickson A S, Kucharczyk C, Serafin A, Carrington A, Cox C, Kauzlarich S M, Hope H and Fisher I R 2008 Bulk superconductivity and disorder in single crystals of LaFePO arXiv:0810.5368

[23] Krellner C and Geibel C 2008 Single crystal growth and anisotropy of CeRuPO *J. Cryst. Growth* **310** 1875

[24] Gopal E S R 1966 *Specific Heat at Low Temperatures* (New York: Plenum)

[25] Michalski R, Ropka Z and Radwanski R J 2000 Crystal-field interactions in PrRu$_2$Si$_2$ *J. Phys.: Condens. Matter* **12** 7609

[26] Bardeen J, Cooper L N and Schrieffer J R 1957 Theory of superconductivity *Phys. Rev.* **108** 1175

[27] Bellavance D, Mikkelsen J and Wold A 1970 Preparation and properties of Fe$_2$P *J. Solid State Chem.* **2** 285

[28] van Vleck J H 1932 *The Theory of Electric and Magnetic Susceptibility* (Oxford: Oxford University Press)

[29] Murao T and Matsubara T 1957 On the magnetic properties of cubic cerium *Prog. Theor. Phys.* **18** 215

[30] De Gennes P G 1962 Interactions indirectes entre couches 4f dans les metaux de terres rares *J. Phys. Radium* **23** 510

[31] Maple M B, DeLong L E and Sales B C 1978 *Handbook on the Physics and Chemistry of Rare Earths* (Amsterdam: North-Holland) chapter 11, p 797

[32] Drew A J *et al* 2008 Coexistence of magnetic fluctuations and superconductivity in the pnictide high temperature superconductor SmFeAsO$_{1-x}$F$_x$ measured by muon spin rotation *Phys. Rev. Lett.* **101** 097010

[33] Kamihara Y, Hirano M, Yanagi H, Kamiya T, Saitoh Y, Ikenaga E, Kobayashi K and Hosono H 2008 Electromagnetic properties and electronic structure of the iron-based layered superconductor LaFePO *Phys. Rev.* B **77** 214515