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Coexistence and Competition of the Short-Range Incommensurate Antiferromagnetic Order with the Superconducting State of BaFe$_{2-x}$Ni$_x$As$_2$

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Superconductivity in the iron pnictides develops near antiferromagnetism, and the antiferromagnetic (AF) phase appears to overlap with the superconducting phase in some materials such as BaFe$_{2-x}$T$_x$As$_2$ (where $T =$ Co or Ni). Here we use neutron scattering to demonstrate that genuine long-range AF order and superconductivity do not coexist in BaFe$_{2-x}$Ni$_x$As$_2$ near optimal superconductivity. In addition, we find a first-order-like AF-to-superconductivity phase transition with no evidence for a magnetic quantum critical point. Instead, the data reveal that incommensurate short-range AF order coexists and competes with superconductivity, where the AF spin correlation length is comparable to the superconducting coherence length.

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High-temperature superconductivity (high-$T_c$) in iron pnictides arises at the border of antiferromagnetism [1–3]. Since magnetic excitations may be responsible for electron pairing and superconductivity [4–7], it is essential to understand the doping and temperature dependence of the antiferromagnetic (AF) spin correlations. For electron-doped iron pnictides such as BaFe$_{2-x}$T$_x$As$_2$ (where $T =$ Co or Ni), the Néel temperature ($T_N$) of the system decreases gradually with increasing electron-doping level $x$, and the AF phase appears to overlap with the superconducting phase [8–10]. This raises the question concerning the role of quantum criticality [11] and the coexisting AF order and superconductivity to the superconducting pairing mechanism [12,13]. Here we use neutron scattering and transport measurements to show that genuine long-range AF order does not coexist with superconductivity in BaFe$_{2-x}$Ni$_x$As$_2$ near optimal doping. With increasing $x$, the static AF order in BaFe$_{2-x}$Ni$_x$As$_2$ changes abruptly from a commensurate wave vector for $x = 0.085$ to an incommensurate wave vector with short-range order for $x = 0.092, 0.096$. While the ordered moment decreases smoothly from $x = 0.085$ to 0.096, the Néel temperature ($T_N$) changes slowly from $\sim 47$ K for $x = 0.085$ to $\sim 35$ K for $x = 0.096$ before vanishing at $x = 0.1$. In addition, we find that the short-range incommensurate AF order directly competes with superconductivity, and there is no evidence for a conventional magnetic quantum phase transition between the two phases. Therefore, the presence of microscopic coexisting long-range AF and superconducting phases and a magnetic quantum critical point (QCP) between the AF and superconducting phase are not essential for superconductivity in the BaFe$_{2-x}$T$_x$As$_2$ family of materials.

In earlier neutron and x-ray scattering work on BaFe$_{2-x}$T$_x$As$_2$, the competition between coexisting superconductivity and antiferromagnetism was inferred from the reduction of the magnetic Bragg peak intensity below $T_c$ [14–17]. However, muon spin rotation (µSR) experiments on underdoped BaFe$_{1.89}$Co$_{0.11}$As$_2$ suggest an incommensurate spin density wave below $T_{\text{max}} = 32$ K with a reduced ordered magnetic moment below $T_c = 21.7$ K [19]. Neutron scattering reveals that the commensurate AF order at the wave vector $Q = (0.5, 0.5, 1)$ becomes transversely incommensurate at $Q = (0.5 - \delta, 0.5 + \delta, 1)$ [inset in Fig. 1(a)] for BaFe$_{2-x}$Co$_x$As$_2$ with $0.12 < x < 0.12$ [20].

We carried out systematic neutron scattering experiments on BaFe$_{2-x}$Ni$_x$As$_2$ using C-5, Rita-2, and BT-7 triple-axis spectrometers at the Canadian Neutron Beam Center, Paul Scherrer Institute, and NIST Center for Neutron Research, respectively. For C-5 and BT-7 thermal triple-axis spectrometers, the final neutron energies were set to $E_f = 14.56$ and $E_f = 13.8$ meV, respectively, with pyrolytic graphite as monochromator, analyzer, and filters. For Rita-2 measurements, the final energy was

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FIG. 1 (color online). (a) Electronic phase diagram of BaFe$_{2-x}$Ni$_x$As$_2$ as a function of $x$. The long-range commensurate AF (C-AF) order changes into short-range incommensurate AF (IC-AF) order for $x = 0.085$–0.096. The optimal superconductivity occurs at $x = 0.1$, where the static AF order is suppressed [22]. The inset shows the C-AF and IC-AF positions in reciprocal space in tetragonal notation, where $\delta = \epsilon/\sqrt{2}$.

(b) The Ni-doping dependence of the in-plane AF spin-spin correlation length. For $x = 0.096$, we have $\xi_{\perp}^{AF} = 66$ Å and the superconducting coherence length $\xi_{SC} \approx 27$ Å [40].

c) The doping dependence of the ordered magnetic moment $M$ [23].

d) Temperature dependence of the magnetic order parameter at $Q = (0.5, 0.5, 1)$ and $(0.5, 0.5, 3)$ AF Bragg positions for $x = 0.03, 0.065,$ and (e) $x = 0.085, 0.092, 0.096$.

$E_f = 4.6$ meV and a cooled Be filter was additionally used as a filter. High-quality single crystals were grown by FeAs self-flux method as described previously [21]. We define the wave vector $Q$ at $(q_x, q_y, q_z)$ as $(H, K, L) = (q_x/a/2\pi, q_y/b/2\pi, q_z/c/2\pi)$ reciprocal lattice units (rlu) using the tetragonal unit cell, where $a = b = 3.96$ Å, and $c = 12.77$ Å.

Figure 1(a) shows the electronic phase diagram of BaFe$_{2-x}$Ni$_x$As$_2$ as a function of Ni doping $x$ as determined from our neutron scattering experiments, where the commensurate-to-incommensurate AF phase transition occurs between $x = 0.085$ and 0.092. Figures 1(b)–1(e) show the Ni-doping dependence of the spin correlation length, moment, and magnetic order parameters, respectively. While the Néel temperatures decrease gradually with increasing $x$ for $0 \leq x \leq 0.065$ as shown in Fig. 1(d) [14–18], they decrease rather slowly for $x = 0.085, 0.092, 0.096$ before vanishing abruptly at $x = 0.1$ [Figs. 1(a) and 1(e)] [22]. For comparison, the ordered moment decreases smoothly to zero with increasing $x$ at 0.1 [Fig. 1(c)], consistent with the presence of a magnetic QCP [11]. However, the static spin correlation length, which is instrumental resolution limited for $x < 0.085$, decreases abruptly for samples with incommensurate AF order [Fig. 1(b)] [23]. This is contrary to the magnetic QCP in CeFeAs$_{1-x}$P$_x$O, where the commensurate AF order is resolution-limited at all $x$ as the ordered moment vanishes with $x \rightarrow 0.4$ [24].

To demonstrate the doping evolution of the AF order through the commensurate-to-incommensurate AF phase transition, we summarize in Fig. 2 longitudinal and transverse scans along the $[H, H, 6H]$ and $[H, 1-H, 3]$ directions for $x = 0.085, 0.092,$ and 0.096 at different temperatures, where the solid red lines indicate the instrumental resolution. For $x = 0.085$, the scattering is commensurate along both the longitudinal and transverse directions but not instrumental resolution limited [Figs. 2(a) and 2(b)]. Furthermore, the line shape of the transverse scan is not a

FIG. 2 (color online). Temperature and wave vector dependence of the C-AF and IC-AF scattering for BaFe$_{2-x}$Ni$_x$As$_2$ with $x = 0.085, 0.092,$ and 0.096. Samples are aligned in the $[H, H, 6H]$ and $[H, 1-H, 3]$ scattering plane. The solid red lines are the instrumental resolutions obtained using $\frac{A}{2}$ scattering from the (1, 1, 6) nuclear Bragg peak above $T_N$ without filter. Data in (a)–(d) are collected on C-5, (a),(b) Longitudinal and transverse scans at different temperatures through the $(0.5, 0.5, 3)$ AF Bragg peak for $x = 0.085$. The scattering is commensurate in both directions but not instrumental resolution limited. The solid lines in transverse scans are Lorentzian fits to the data. (c),(d) Identical scans using the same experimental setup for $x = 0.092$, which show clear incommensurate scattering along the transverse direction. (e),(f) Longitudinal and transverse scans for $x = 0.096$ at $Q = (0.5, 0.5, 3)$ collected on Rita-2. The solid horizontal bars are the calculated instrumental resolution, determined by the supermirror guide before the monochromator, the 80° collimation, the radial collimator of the Be filter (about 150°), the neutron-absorbing guide after the analyzer (effective collimation of 40°), and a sample mosaic spread of $\sim 15°$. Insets show the color images of incommensurate peaks centered around $Q = (0.5, 0.5, 3)$ and the scan directions at 2 K.
Gaussian but can be fit with a Lorentzian. Figures 2(c) and 2(d) show identical scans using the same instrument for the $x = 0.092$ sample. Here, we find broad commensurate scattering in the longitudinal direction and clear incommensurate peaks in the transverse direction. Figures 2(e) and 2(f) plot longitudinal and transverse scans along the aforementioned directions for the $x = 0.096$ sample. Converting these widths into real space [23], we find that the static spin correlation length along the longitudinal direction is only $62 \pm 5 \text{Å}$, while it is $81 \pm 15 \text{Å}$ and $249 \pm 35 \text{Å}$ for the $x = 0.092$ and 0.085 samples, respectively.

Figures 3(a)–3(c) show the detailed temperature dependence of the transverse scans at zero and a field of 14.8 T. At zero field, transverse scans are featureless at $T = 40$ K ($>T_N$) but show broad peaks indicative of incommensurate AF short-range order below $T_N = 35$ K. At $T = 20$ K just above $T_c$, the peak intensity continues to increase, but decreases upon further cooling to 2 K [Fig. 3(a)]. These results are consistent with earlier work on BaFe$_{2-x}$Co$_x$As$_2$ [20].

Upon applying a 14.8 T field aligned at $\sim 37^\circ$ out of the FeAs plane [Fig. 3(b)], we see that the broad peak at zero field and 2 K increases in intensity and becomes two clear incommensurate peaks centered at $Q = (0.5 - \delta, 0.5 + \delta, 3)$ with $\delta = 0.018 \pm 0.002$ rlu. For a temperature just above $T_c$ at 25 K, the broad peaks appear to merge into a single commensurate peak centered at $Q = (0.5, 0.5, 3)$ [Fig. 3(c)]. To determine the net effect of a 14.8 T field on the incommensurate AF order, we show in Fig. 3(d) the field-on minus field-off difference plots. At $T = 2$ K, the effect of a field is to induce clear incommensurate peaks, different from the field effect on superconducting BaFe$_{2-x}$Ni$_x$As$_2$ with lower $x$ [18]. At a temperature ($T = 25$ K) just above $T_c$, the effect of a field appears to be opposite and suppresses the incommensurate AF order. Figure 3(e) shows the temperature dependence of the scattering at the incommensurate position at zero and 14.8 T. At zero field, the data reveal a clear suppression of the magnetic intensity at $T_c$. A 14.8 T field reduces $T_c$ from 19 to 15 K and enhances the incommensurate AF order. The intensity of the incommensurate AF scattering increases linearly with increasing field, consistent with the field-induced reduction in the superconducting transition temperature as determined from resistivity measurements [Fig. 3(f)]. However, the line-widths of the incommensurate peaks remain unchanged at 2 K [Fig. 3(b)]. Therefore, superconductivity competes with the short-range incommensurate AF order instead of the long-range AF order.

In transport and nuclear magnetic resonance (NMR) experiments on isoelectronic BaFe$_2$(As$_{1-x}$P)$_x$ [25–28], a magnetic QCP has been identified at $x = 0.33$, which is believed to play an important role in the superconductivity of these materials [11]. For BaFe$_{2-x}$Co$_x$As$_2$, recent systematic ultrasonic measurements [29] suggest the presence of a structural QCP near optimal superconductivity, where the structural distortion associated with the static AF order vanishes. These results are consistent with NMR measurements, where the strength of the paramagnetic spin fluctuations diverges for Co concentration near optimal superconductivity [30]. If Ni doping in BaFe$_2$As$_2$ is equivalent to twice the Co doping [31], one should also expect a structural and magnetic QCP near optimal superconductivity for BaFe$_{2-x}$Ni$_x$As$_2$. Since the incommensurate AF spin correlations for the $x = 0.092, 0.096$ samples clearly do not increase with decreasing temperature, it is...
difficult to reconcile this result with a magnetic QCP, where one expects a diverging spin-spin correlation length as $T \rightarrow 0$ K. Furthermore, the Néel temperature of BaFe$_{2-x}$Ni$_x$As$_2$ suddenly vanishes at $x = 0.1$ from $T_N \sim 35$ K for $x = 0.096$. Therefore, instead of a magnetic QCP, the incommensurate AF order-to-superconductivity phase transition in BaFe$_{2-x}$Ni$_x$As$_2$ appears to be first order, much like that of the LaFeAsO$_{1-x}$F$_{x}$ family of materials [32].

If there is a magnetic QCP in the phase diagram of BaFe$_{2-x}$Ni$_x$As$_2$ near $x = 0.10$ where the static long-range AF order vanishes [22], the temperature dependence of the resistivity $\rho = \rho_0 + AT^n$ should have an exponent $n = 1$ near $x = 0.1$ within a single band model similar to that of BaFe$_2$(As$_{1-x}$P$_x$)$_2$ at $x = 0.33$ [28]. Figure 4 shows the electron-doping dependence of the resistivity exponent $n$ obtained by fitting the temperature dependence of the resistivity of BaFe$_{2-x}$Ni$_x$As$_2$ [21,33]. The resistivity exponents show a broad minimum with $n = 1.5$ near $x = 0.15$. Similar analysis on the in-plane resistivity data of BaFe$_{2-x}$Co$_x$As$_2$ in the normal state also yielded minimum $n$ in the overdoped region, clearly different from that for BaFe$_2$(As$_{1-x}$P$_x$)$_2$ [28]. Therefore, our data suggest no magnetic QCP near the boundary of AF and superconducting phases in BaFe$_{2-x}$As$_2$. This is consistent with the more accurate two-band analysis of the normal state resistivity for BaFe$_{2-x}$As$_2$ [34,35], where a Fermi liquidlike coefficient $n = 2$ was found for optimally doped BaFe$_{2-x}$As$_2$, again suggesting no QCP near optimal superconductivity.

The observation of competing static short-range incommensurate AF order with superconductivity and the first-order-like AF-to-superconductivity phase transition raises the question concerning how AF order microscopically coexists with superconductivity in Fe-based superconductors [18]. In a recent $^{57}$Fe Mössbauer spectroscopy study of BaFe$_{2-x}$Ni$_x$As$_2$, a small reduction in magnetic hyperfine field below $T_c$ was found for the $x = 0.085$ sample [36]. Although such measurements suggest coexisting AF order and superconductivity on a length scale of $\sim 27$ Å [36], Mössbauer spectroscopy cannot provide a precise length scale of the AF spin correlations and their doping dependence. For comparison, our data show that AF order at this doping level is commensurate with a correlation length of $\sim 250$ Å [Figs. 1(b) and 2(a)]. For hole-doped Ba$_{1-x}$K$_x$Fe$_2$As$_2$, $\mu$SR [37] and neutron powder diffraction [38,39] measurements have suggested microscopic coexisting AF and superconducting phases in the underdoped regime. However, these measurements did not probe the region of the phase diagram close to optimal superconductivity and were unable to provide a length scale for the AF order that coexists with the superconductivity. From Figs. 1–3, we see that the static incommensurate AF order competing with superconductivity has a spin-spin correlation length of $\sim 60$ Å. This means that the incommensurate AF order has a similar length scale to the superconducting coherence length ($\sim 27$ Å) [40] and that, near optimal doping, there is no long-range AF order coexisting with superconductivity. Instead, our data can be understood in two scenarios: first, the two orders coexist microscopically and homogeneously and compete for the same itinerant electrons [12,13], such that superconductivity occurs at the expense of the static AF order. When a magnetic field is applied, the superconducting gap $\Delta(B)$ and $T_c$ decrease with increasing field via $\Delta(B)/\Delta(0) = T_c(B)/T_c(0) = \sqrt{1 - B/B_c}$ [41]. In the low-field limit, we have $B/B_c \approx \Delta T_c/T_c(0)$. Therefore, the field-induced AF order should be proportional to the field-induced reduction in $T_c$, consistent with the data in Fig. 3(f). Alternatively, the competition is mesoscopic: phase separation occurs with superconducting and nonsuperconducting, AF-ordered nanoregions of length scale $\sim 60$ Å. In this picture, the superconducting electrons do not directly contribute to the static AF order, and superconductivity only affects the AF order through a proximity effect. Here, one can imagine that the field-induced nonsuperconducting vortices have incommensurate AF order, much like field-induced AF vortices in some copper oxide superconductors [42]. This is also consistent with the first-order-like AF to superconductivity transition with increasing $x$. Since our neutron diffraction measurements of the bulk of the sample cannot resolve superconducting from nonsuperconducting parts of the sample, we find both scenarios are consistent with our observation of short-range AF order with superconductivity near optimal doping.

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