The competition and/or coexistence between different electronic orders is a central issue in the physics of strongly correlated systems and in particular in the physics of unconventional or electronic driven superconductivity. The recently discovered iron-pnictides high temperature superconductors provide an interesting case to study the coexistence and/or competition between spin-density-wave (SDW) and SC orders. The delicate balance between both orders in the pnictides is exemplified by two facts: superconductivity in iron-pnictides only arises when the SDW order is significantly weakened, and yet there is a growing theoretical consensus that both orders are driven by interband interactions [1–3]. The predominance of interband interactions naturally leads to a superconducting order parameter that switches sign between different electronic bands [1, 2], which contrary to a regular s-wave gap, favors the coexistence between SDW and SC orders [4, 5].

Electron doped Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\) (Co-Ba122) is a particularly suitable system to study the interplay between both orders because Co doping can be used to tune SDW and SC orders presumably by changing the respective size of the Fermi surface sheets and the corresponding nesting properties. In addition, there are strong evidences that both SDW and SC orders coexist spatially over a finite range of doping [6]. Recent neutron scattering measurements have shown a sizable reduction of the Fe magnetic moment upon entering the superconducting state that most likely results from a competition between the two orders for low energy electronic states [7, 8]. Up to now however, the impact of the SDW order on the superconducting properties themselves such as the gap amplitude and anisotropies has not been experimentally addressed.

Here we report doping dependent electronic Raman scattering measurements on iron-pnictide superconductor Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\) single crystals. The B\(_{2g}\) Raman spectrum at optimal doping is consistent with a strongly anisotropic gap on the electron pocket. Upon entering the coexistence region between superconducting (SC) and spin-density-wave (SDW) orders, the effective pairing energy scale is strongly reduced. Our results are interpreted in terms of a competition between SC and SDW orders for electronic states at the Fermi level. Our findings advocate for a strong connection between the SC and SDW gaps anisotropies which are both linked to interband interactions.
All $B_{2g}$ responses display a distinctive pair-breaking peak in the superconducting state but its overall intensity varies significantly with doping. The weaker superconducting responses for $x=0.075$ and $x=0.10$ do not allow a reliable extraction of the gap anisotropy as performed in the $x=0.065$ case. However, the sizable intensities well below $2\Delta_{\text{max}}$ are consistent with a significant gap anisotropy, possibly including nodes (see later for a discussion of the $x=0.06$ and $x=0.055$ cases). The doping dependence of the pair-breaking peak integrated intensity, which is proportional to the Cooper pair density in the BCS framework \([21]\), is sharply peaked at $x=0.065$ (see Fig.1b). The suppression of the Cooper pair density away from optimal doping is in agreement with specific heat measurements which report a similar behavior for the specific heat jump across $T_c$ \([22]\). This effect cannot be simply linked with disorder as one would naively expect because the residual resistivity extracted from transport measurements does not vary significantly over the corresponding doping range \([3]\). All $B_{2g}$ crystals display $\Gamma$ symmetry for all dopings; weak and broad pair-breaking peaks were observed between 100 and $180\, \text{cm}^{-1}$ in the $A_{1g}$ channel \([11]\). The $B_{2g}$ Raman responses, well below and slightly above $T_c$, are displayed in Fig.2a, as a function of doping. No pair-breaking peak was observed in $B_{1g}$ symmetry for all dopings; no magnetic SDW transition \((x=0.065)$ (see Fig.2b). The suppression of the Cooper pair density away from optimal doping is in agreement with specific heat measurements which report a similar behavior for the specific heat jump across $T_c$. This effect cannot be simply linked with disorder as one would naively expect because the residual resistivity extracted from transport measurements does not vary significantly over the corresponding doping range. In the same manner, it cannot be simply linked to the $T_c$ itself since the strong changes in Cooper pair density reported here correspond to relatively modest changes in $T_c$ (see for example $x=0.065$, $T_c=24.7\, \text{K}$ and $x=0.075$, $T_c=23.5\, \text{K}$). Rather it is highly suggestive of a strong link between the Cooper pair density and the proximity of the critical doping where the SDW phase disappears.

The way the superconducting response is suppressed differs drastically between underdoped crystals, where SDW and SC coexist, and overdoped crystals with only the SC phase. While the SC response remains dominated by the main pair-breaking peak centered around $T_c$, within our experimental accuracy (inset of Fig.1). In Fig.1b is shown a zoom of the SC Raman response $\chi''$ below $100\, \text{cm}^{-1}$ and down to $8\, \text{cm}^{-1}$, at two different excitation wavelengths, $\lambda = 514.52\, \text{nm}$ and $647.1\, \text{nm}$. Both responses are essentially identical and display considerable spectral weight below the main pair-breaking peak with a weak downward bend below $20\, \text{cm}^{-1}$. The low energy part of the spectrum can be linked to an anisotropic s-wave gap around the M electron pocket, as drawn schematically in Fig.1c. This picture is in agreement with thermal conductivity and penetration depth measurements where significant gap anisotropy was reported in Co-Ba122 \([15, 16]\) and is consistent with calculations based on spin-fluctuations mediated superconductivity \([17, 18]\). Reasonably good fits of the low energy spectrum are obtained using the standard BCS Raman response \([19]\) with a phenomenological broadening $\gamma$ and an in-plane anisotropy of the gap, $\Delta(\phi) = \Delta_{\text{max}}\cos(2\phi)$, with $a = 1.35\ (\pm 0.1)$ (see Fig.1b) yielding deep minima in the gap function $\Delta_{\text{max}} = 7\ (\pm 2)\ \Delta_{\text{min}}$.

An equally good fit was obtained by invoking a strong $k_z$ dependence of the gap (see Fig.1c) instead of the in-plane anisotropy used above. Recent $c$-axis thermal conductivity data on Co-Ba122 suggest a strong $k_z$ dependence of the superconducting gap. However, this dependence most likely arises from the 3D hole Fermi surface centered around $\Gamma$ \([20]\) and not the 2D electron pocket which is probed in $B_{2g}$ symmetry. We note that because of the presence of two electron pockets in the reduced Brillouin zone, a two gaps scenario cannot be ruled out. Indeed, a satisfactory fit of the data could also be performed using two isotropic gaps $\Delta_1$, $\Delta_2$ with $\Delta_2 \sim 4\Delta_1$ but with a rather large lifetime broadening, $\gamma = 0.3\Delta_2$ (see Fig.1d).

We now turn to the evolution of the superconducting response with varying doping and in particular across the SDW transition. While no magnetic transition is observed above $T_c$ for $x=0.065\ (T_c=24.7\, \text{K})$, $0.075\ (T_c=23.5\, \text{K})$ and $0.10\ (T_c=20\, \text{K})$, the $x=0.06\ (T_c=22\, \text{K})$ and $x=0.055\ (T_c=20.5\, \text{K})$ crystals display magnetic SDW transition \((T_N)\) at $41\, \text{K}$ and $31\, \text{K}$ respectively (see the phase diagram in Fig.2b) \([6, 9]\). The $B_{2g}$ Cooper pairs density away from optimal doping is in agreement with specific heat measurements which report a similar behavior for the specific heat jump across $T_c$. This effect cannot be simply linked with disorder as one would naively expect because the residual resistivity extracted from transport measurements does not vary significantly over the corresponding doping range. In the same manner, it cannot be simply linked to the $T_c$ itself since the strong changes in Cooper pair density reported here correspond to relatively modest changes in $T_c$. This effect cannot be simply linked with disorder as one would naively expect because the residual resistivity extracted from transport measurements does not vary significantly over the corresponding doping range. In the same manner, it cannot be simply linked to the $T_c$ itself since the strong changes in Cooper pair density reported here correspond to relatively modest changes in $T_c$. Rather it is highly suggestive of a strong link between the Cooper pair density and the proximity of the critical doping where the SDW phase disappears.
The SDW transition has also a strong impact on the normal state Raman continuum. Figure 3a shows temperature dependent measurements in the normal state for different dopings $x = 0$, $x = 0.045$, $x = 0.065$, $x = 0.075$ in the $B_{2g}$ symmetry. The Raman continuum intensity displays a systematic increase at low energy around the magneto-structural transition temperature (shown in dashed lines in Fig 3a) for the $x=0$ and $x=0.045$ crystals before disappearing at lower temperatures. It is also observed for the $x=0.065$ crystals where no magneto-structural transition is observed above $T_c$, but is essentially absent for $x=0.075$ and $x=0.10$ (not shown). A similar Quasi Elastic Peak (QEP) was observed in the Raman spectra of undoped Sr(FeAs)$_2$ [26]. At higher energy and for $x=0$, there is a strong suppression of the Raman intensity below 400 cm$^{-1}$ below $T_N$ which is linked to the opening of the SDW gap (see Fig 3b) in agreement with optical conductivity measure-
The effective pairing scale is strongly reduced upon entering the SDW-SC coexistence phase. It is interpreted as a consequence of the competition between the SC and the SDW orders. Our study illustrates the delicate interplay between magnetism and superconductivity which seems to be a generic feature of iron-pnictide superconductors.

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The QEP was analyzed using a Lorentzian lineshape of the form
\[ I(\omega) \sim \frac{1}{1+n(\omega, T)} \]
where \( n(\omega, T) \) is the Bose factor and \( \gamma \) the width at half-maximum. As shown in Fig.3, the QEP intensity is maximum at the transition for \( x=0 \) and \( x=0.045 \) suggesting it originates from magnetic energy fluctuations as observed in magnetic insulators close to \( T_N \) [28]. In the case of iron-pnictides, the presence of fluctuating magnetic domains above the transition could also give rise to the observed QEP [29].

In conclusion, we have reported a doping dependent study of the superconducting gap in \( \text{Ba(Fe}_{1-x}\text{Co}_x)_2\text{As}_2 \). The effective pairing scale is strongly reduced upon entering the SDW-SC coexistence phase. It is interpreted as a consequence of the competition between the SC and the SDW orders. Our study illustrates the delicate interplay between magnetism and superconductivity which seems to be a generic feature of iron-pnictide superconductors.
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