$^{75}$As NMR Observation of Anisotropic Spin Fluctuations in the 
Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ Superconductor ($T_c = 22$ K)

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The recent discovery of iron-pnictide superconductors with transition temperatures as high as $T_c \sim 55$ K has attracted a huge amount of attention.$^{1-4}$ A prototypical parent compound of the iron-pnictide superconductors, BaFe$_2$As$_2$, is an itinerant antiferromagnet, and displays a first order Spin Density Wave (SDW) transition at $T_{SDW} \sim 135$ K accompanied by a simultaneous tetragonal-orthorhombic structural phase transition.$^5, 6$ In a recent paper,$^7$ Kitagawa et al. reported a comprehensive $^{75}$As NMR investigation of the parent compound BaFe$_2$As$_2$, and proposed a stripe antiferromagnetic spin structure below $T_{SDW}$. They also showed the growth of anisotropic spin fluctuations at $^{75}$As sites between $ab$- and $c$-axis orientations in the paramagnetic state above $T_{SDW}$. In this short note, we will demonstrate that analogous anisotropy of paramagnetic spin fluctuations grows with decreasing temperature in the optimally electron-doped superconductor Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ ($T_c = 22$ K) when short-range antiferromagnetic correlations develop toward $T_c$.

In Fig. 1(a), we show the $^{75}$As nuclear spin-lattice relaxation rate divided by temperature, $^{75} (\frac{1}{T_1T})_{ab}$, for Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ with an external magnetic field $B_{ext} = 7.7$ Tesla applied within the $ab$-plane. For comparison, we also reproduce $^{75} (\frac{1}{T_1T})c$ with $B_{ext}$ applied along the $c$-axis from our earlier report.$^8$ Compared with the case of BaFe$_2$As$_2$ in [7], the overall magnitude of $^{75} (\frac{1}{T_1T})$ in the paramagnetic state is suppressed by Co doping for both orientations. We refer readers to our previous studies$^8, 9$ for a systematic investigation of the Co doping effects on the static and dynamic susceptibilities. Our results in Fig. 1(a) show that the enhancement of $^{75} (\frac{1}{T_1T})$ toward $T_c$ is stronger for $^{75} (\frac{1}{T_1T})_{ab}$ than for $^{75} (\frac{1}{T_1T})_c$. This behavior in Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ is qualitatively similar to that of the undoped parent compound BaFe$_2$As$_2$ above $T_{SDW}$.$^7$

In general, $^{75} (\frac{1}{T_1T})$ probes spin fluctuations within the plane perpendicular to the quantization axis set by $B_{ext}$. 


\[
\frac{1}{T(1)}_c \propto \sum_q |A_\alpha(q)|^2 \frac{\chi_\alpha''(q,f)}{f} + \sum_q |A_b(q)|^2 \frac{\chi_b''(q,f)}{f} \tag{1a}
\]
\[
\propto 2 \sum_q |A_a(q)|^2 \frac{\chi_a''(q,f)}{f}, \tag{1b}
\]
\[
\frac{1}{T|c|^2} \propto \sum_q |A_a(q)|^2 \frac{\chi_a''(q,f)}{f} + \sum_q |A_c(q)|^2 \frac{\chi_c''(q,f)}{f}, \tag{1c}
\]
where \( |A_\alpha(q)|^2 \) (\( \alpha = a, b, c \)) and \( \chi_\alpha''(q,f) \) are the wave-vector \( q \)-dependent hyperfine form factor and the dynamical spin susceptibility at NMR frequency \( f \), respectively. We assume \( |A_\alpha(q)|^2 \) and \( \chi_\alpha''(q,f) \) are isotropic within the \( ab \)-plane in the tetragonal phase. Thus stronger enhancement of \( 75(\frac{1}{T|c|^2})_{ab} \) toward \( T_c \) indicates that spin fluctuations are enhanced at \( 75 \) As sites more strongly toward \( T_c \) along the \( c \)-axis than within the \( ab \)-plane. We define the anisotropy, \( R \), from Eqs. (1b) and (1c) as,

\[
R = \frac{\sum_q |A_c(q)|^2 \chi_c''(q,f)}{\sum_q |A_\alpha(q)|^2 \chi_\alpha''(q,f)} = \frac{(\frac{1}{T|c|^2})_{ab} - \frac{1}{2}(\frac{1}{T|c|^2})_c}{\frac{1}{2}(\frac{1}{T|c|^2})_c}, \tag{2}
\]

We plot \( R \) in Fig. 1(b). \( R \) continuously increases with decreasing temperature toward \( T_c \). Since the magnitudes of the hyperfine form factors are comparable \(^7\) and temperature independent, the observed temperature dependence of \( R \) reflects that of the spin fluctuations. For comparison, we also estimate \( R \) for the parent compound from the data reported in \(^7\) as shown in Fig. 1(b). The magnitudes of \( R \) for the two compounds are comparable toward the ordering temperatures. The anisotropy \( R \) below \( T_c \) can, in principle, provide valuable information about the pairing state,\(^10\) but it is beyond the scope of this short note.

In Fig. 2, we present \(^{59}(\frac{1}{T|c|^2})_{ab} \) for Ba(Fe\(_{0.92}\)Co\(_{0.08}\))\(_2\)As\(_2\) with \( B_{ext} \) applied within the \( ab \)-plane. We also present \(^{59}(\frac{1}{T|c|^2})_c \) for comparison.\(^8\) \(^{59}(\frac{1}{T|c|^2})_c \) levels off below \( \sim 100 \) K down to \( T_c \), while \(^{59}(\frac{1}{T|c|^2})_{ab} \) is enhanced slightly toward \( T_c \). This finding provides additional proof that the spin fluctuations are anisotropic. The presence of the orbital contributions to \( \frac{1}{T|c|^2} \)\(^11\) of \(^{59}\)Co makes it difficult to estimate \( R \). The difference between the temperature dependences of \( 75(\frac{1}{T|c|^2}) \) and \(^{59}(\frac{1}{T|c|^2}) \) suggest that different areas in the Brillouin Zone have a different temperature dependence for spin fluctuations, and that the hyperfine form factors filter out the different regions for \( 75 \) As and \(^{59}\)Co. Alternatively, because of the itinerant nature of electrons, the local spin density at \( 75 \) As and \(^{59}\)Co sites may display different behaviors.

In conclusion, we have demonstrated that the anisotropy \( R \) of the paramagnetic spin fluctuations grows toward \( T_c \) at \( 75 \) As sites in the superconductor Ba(Fe\(_{0.92}\)Co\(_{0.08}\))\(_2\)As\(_2\), with stronger spin fluctuations along the \( c \)-axis. Our finding is in remarkable contrast with the case of high \( T_c \) cuprates, where \( R \) is independent of temperature above \( T_c \).\(^10\)

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Fig. 1. (Color Online). (a) The temperature dependence of $\frac{1}{T} \frac{1}{T_1}$ with external field $B_{ext} = 7.7$ Tesla applied within the $ab$-plane (■) and along the $c$-axis (●) in Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$. (b) The temperature dependence of the anisotropy of spin fluctuations $R$ for the superconductor Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ (◇), and BaFe$_2$As$_2$ (△) (estimated from [7], $T_{SDW} = 135$ K). The dashed line marks $T_c$.

Fig. 2. (Color Online). $^{59}(\frac{1}{T} \frac{1}{T_1})$ with external field $B_{ext}$ applied within the $ab$-plane (■) and along the $c$-axis (●) for the superconductor Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$. The dashed line marks $T_c$. 

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