Incommensurate spin density wave in Co-doped BaFe$_2$As$_2$

P. Bonville$^{(a)}$, F. Rullier-Albenque, D. Colson and A. Forget

CEA, Centre de Saclay, DSM/IRAMIS/Service de Physique de l’Etat Condensé 91191 Gif-sur-Yvette, France, EU

received 16 December 2009; accepted in final form 16 March 2010
published online 19 April 2010

PACS 74.70.Xa – Pnictides and chalcogenides
PACS 75.30.Fv – Spin-density waves
PACS 76.80.+y – Mössbauer effect; other $\gamma$-ray spectroscopy

Abstract – $^{57}$Fe Mössbauer spectroscopy measurements are presented in the underdoped Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series for $x = 0.014$ ($T_c < 1.4$ K) and $x = 0.03$ and 0.045 ($T_c \approx 2$ and 12 K, respectively). The spectral shapes in the so-called spin density wave (SDW) phase are interpreted in terms of incommensurate modulation of the magnetic structure, and allow the shape of the modulation to be determined. In undoped BaFe$_2$As$_2$, the magnetic structure is commensurate, and we find that incommensurability is present at the lowest doping level ($x = 0.014$). As Co doping increases, the low-temperature modulation progressively loses its “squareness” and tends to a sine-wave. The same trend occurs for a given doping level, as temperature increases. We find that a magnetic hyperfine component persists far above the SDW transition, its intensity being progressively transferred to a paramagnetic component on heating.

Copyright © EPLA, 2010

Introduction. – Investigation of the magnetic properties of the newly discovered layered Fe-based pnictide superconductors [1] with a microscopic probe such as Mössbauer spectroscopy is of interest for (at least) two reasons: i) to determine the characteristics of the expected spin density wave (SDW) order and ii) to give experimental evidence concerning the problem of the interaction and/or local coexistence between superconductivity and magnetic ordering of the Fe moments. In the so-called 122 family with Ba, the parent (non-superconducting) compound is BaFe$_2$As$_2$ and doping with Co substituted for Fe has been shown to induce superconductivity at low doping levels [2]. In the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series, the phase diagram as a function of Co concentration $x$ is “bell-shaped”, with $T_c(x)$ presenting a maximum of 26 K for $x = 0.07$ [3,4]. Below this optimal concentration, the material shows apparently the persistence of an antiferromagnetic (AF) structure in the superconducting phase, the AF or spin density wave (SDW) transition temperature decreasing rapidly as $x$ increases. Neutron diffraction in the undoped compound BaFe$_2$As$_2$ [5] has determined the AF magnetic structure below $T_N \approx 143$ K to be a priori commensurate. $^{57}$Fe Mössbauer spectroscopy [6,7] and $^{75}$As NMR [8] in BaFe$_2$As$_2$ have confirmed the commensurability of the magnetic structure.

$^{(a)}$E-mail: pierre.bonville@cea.fr

Fig. 1: (Color online) Resistivity $\rho(T)$ vs. temperature for BaFe$_2$As$_2$ with Co dopings $x = 0.014$, 0.03 and 0.045 from ref. [4]. The data for $x = 0.014$ have been shifted by 100 $\mu\Omega\cdot$cm for clarity. The full arrows mark the inflexion point of $\rho(T)$, attributed to the onset of magnetic ordering ($T_{SDW}$), and the dash-dotted arrows the superconducting transition temperature.

In this work, we focus on the first problem evoked above: we performed a $^{57}$Fe Mössbauer study of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ in the underdoped region in order to investigate the SDW state. In our samples with Co doping $x = 0.014$, 0.03 and 0.045, the resistivity data show an inflexion point [4] respectively around 115 K, 92 K...
and 64 K (see fig. 1). According to neutron diffraction data in materials with similar Co dopings [9–11], this temperature corresponds to the SDW-paramagnetic transition. We find that the spectra in the magnetic phase have an unusual shape, which we interpret as due to an incommensurate modulation of the AF structure, i.e. to an incommensurate (IC) spin density wave. We also find that the magnetic hyperfine subspectrum persists far above $T_{\text{SDW}}$, i.e. that AF correlations are present up to $T_{\text{AF}} \approx 1.5 T_{\text{SDW}}$.

**Experimental and sample characterisation.**

The samples are single crystals prepared by the self-flux method, as described in ref. [4]. It was checked that Co doping is uniform and that superconductivity occurs in the bulk [12,13]. For the Mössbauer measurements, the crystals were finely ground. Powder samples made by solid-state reaction were also prepared, with $x = 0$ and 0.03, for comparison purposes. The spectra were recorded using a commercial $^{57}$Co$^{+}$:Rh $\gamma$-ray source mounted on an electromagnetic drive with linear velocity signal. Room temperature spectra ensured that no trace of FeAs (with a quadrupole splitting $\Delta E_Q = 0.69$ mm/s) was present.

In the high-temperature tetragonal phase (space group $I4/mmm$), the 4$d$ Fe site has fourfold symmetry ($4m2$). At low temperature, slightly above $T_{\text{SDW}}$, a small orthorhombic distortion takes place (space group $Fmmm$), and the local symmetry at the 8$f$ Fe site is lowered (222).

The $^{57}$Fe Mössbauer spectra at 4.2 K. – The spectra at 4.2 K in the three investigated compounds and in undoped $\text{BaFe}_2\text{As}_2$, are represented in fig. 2. In $\text{BaFe}_2\text{As}_2$, one observes a single magnetic hyperfine pattern, in agreement with ref. [7], with a hyperfine field $H_{hf} = 5.4(1)$ T. By contrast, the spectral shapes in the Co-doped compounds are rather far from this standard 6-line pattern. Saturation effects can be discarded since the resonant absorption is modest; for $x = 0.03$, where it amounts to 7%, we checked that an absorber with 2% absorption yields exactly the same spectrum. Texture effects are also negligible since a powder absorber (for $x = 0.03$) yields spectra quasi-identical with those of the single-crystal sample. The high statistics reached in these experiments allows us to distinguish fine details of the spectral shape, which is a prerequisite for the fits to be described below.

We interpret these unusual spectral shapes as due to a distribution of hyperfine fields arising from an IC modulated magnetic structure. Indeed, in this case, the $^{57}$Fe nuclei are submitted to hyperfine field values ranging from zero to a maximum value, and although the Mössbauer data cannot give access to the propagation vector $\mathbf{q}$, the shape of the distribution reflects the particular shape of the modulation. In order to describe the influence of the moment modulation on the spectral shape, we assume a collinear magnetic structure, with no ferromagnetic component, like in undoped BaFe$_2$As$_2$ where the Fe moments lie along the orthorhombic $a$ axis [5]. We also assume the hyperfine field is collinear with the Fe moment (see discussion below). Then, along the direction $OX$ parallel to the propagation vector $\mathbf{q}$, the modulation of the hyperfine field is defined in terms of a Fourier series as

$$H_{hf}(qX) = \sum_{k=0,n} h_{2k+1} \sin[(2k+1)qX],$$

(1)

where the $h_i$ are the odd Fourier coefficients of the modulation. The spectra are then fitted to a superposition of individual hyperfine 6-line patterns with discrete $H_{hf}$ values according to eq. (1) with a linear mesh along a period ($0 \leq qX \leq 2\pi$). The number of Fourier components in the fit is increased until a good reproduction of the lineshape is obtained. At 4.2 K, the very good fits shown in fig. 2 were performed with 6, 5 and 3 Fourier components for $x = 0.014$, 0.03 and 0.045, respectively. The resulting hyperfine field modulations are shown in fig. 3, and the values of the Fourier coefficients are given in table 1. The isomer shift at 4.2 K with respect to $\alpha$-Fe is 0.54(1) mm/s and a very small quadrupolar interaction with $\Delta E_Q \approx -0.04(2)$ mm/s is needed to reproduce the slight asymmetry of the spectra.

The 4.2 K modulation is seen to depart more and more from “squaredness” (which occurs for $x = 0$) as $x$ increases;
Incommensurate spin density wave in Co-doped BaFe$_2$As$_2$

![Figure 3](image_url)  
Fig. 3: (Color online) Modulation of the hyperfine field along the direction of $q$ at 4.2 K in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ for $x = 0.014$, 0.03 and 0.045, derived from the Mössbauer spectra. Insert: variation with the Co concentration $x$ of the maximum hyperfine field value (circles); for $x = 0$, hyperfine field in BaFe$_2$As$_2$ (square). The dashed line is a guide for the eye.

| $x$  | $h_1$  | $h_3$  | $h_5$  | $h_7$  | $h_9$  | $h_{11}$ | $h_m$ |
|------|--------|--------|--------|--------|--------|----------|-------|
| 0.014| 5.45   | 2.41   | 1.75   | 0.24   | 1.24   | 0.55     | 6.06  |
| 0.03  | 5.24   | 0.44   | 0.45   | 0.21   | 0.25   | –        | 5.29  |
| 0.045 | 4.06   | –0.26  | 0.23   | –      | –      | –        | 4.55  |

for $x = 0.045$, the modulation is close to a pure sine-wave. This is reflected in the number of Fourier coefficients needed to reproduce the lineshape (see table 1), which decreases as $x$ increases. The maximum value of the hyperfine field at 4.2 K decreases as $x$ increases (see insert in fig. 3). For $x = 0.045$, it is 75% of the $x = 0.014$ value.

**Table 1**: In Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$: Fourier coefficients $h_{2k+1}$ and maximum value $h_m$ (in T) of the hyperfine field modulation at 4.2 K.

**Thermal variation of the Mössbauer spectra.** – The thermal variation of the spectra for $x = 0.014$, for which $T_{SDW} \simeq 115$ K (fig. 1), is shown in fig. 4. No important change occurs up to about 80 K, then the modulation changes shape, tending towards a pure sine-wave as temperature is further increased. A striking feature is observed when comparing fig. 2 and fig. 4: increasing the Co doping has the same effect on the modulation at 4.2 K as increasing the temperature for the $x = 0.014$ sample. The maximum value of the hyperfine field shows little thermal variation, as well as the main Fourier coefficient $h_1$. Above 115 K, a single line, characteristic of the paramagnetic phase, is present in the spectra and it grows on heating at the expense of the magnetic subspectrum (see red line in the 130 K spectrum in fig. 4). The latter actually persists in a rather large temperature range above $T_{SDW}$, up to 150 K at least. In this temperature range, very good fits of the spectra were obtained with two components: a single Lorentzian-shaped line and a magnetic subspectrum with a modulation identical to that of the 115 K spectrum. For this latter component, a common scaling factor of the Fourier coefficients was introduced in order to allow for a decrease of the modulation amplitude on heating; it remains above 0.9 up to the highest temperature. The thermal variation of the fraction of the single line derived from these fits is shown in fig. 5: a small hysteresis is observed and a unique line is recovered only above 150–160 K.

![Figure 4](image_url)  
Fig. 4: (Color online) Mössbauer absorption spectra on $^{57}$Fe at selected temperatures in BaFe$_2$As$_2$ with $x = 0.014$ Co doping. The lines are fits to an incommensurate modulation of hyperfine fields; the red subspectrum at 130 K is a single Lorentzian-shaped line.

![Figure 5](image_url)  
Fig. 5: (Color online) In BaFe$_2$As$_2$ with $x = 0.014$ Co doping, thermal variation of the fraction of the single-line component in the Mössbauer spectra, for increasing and decreasing temperature runs (left scale), and of the resistivity (right scale).
For the sample with $x = 0.03$, the thermal variation of the 5 Fourier components was studied in more detail (see fig. 6, top) and a similar trend is observed. The main component $h_1$ is an order of magnitude larger than the higher harmonics, and its variation with temperature is weak: it falls by about 20% between 4.2 and 90 K, which is close to $T_{SDW}$ (see fig. 1). The higher harmonics are constant up to 60 K, then they drop and $h_3$ becomes negative and almost opposite to $h_5$, the other two harmonics being smaller. In terms of the shape of the modulation, it does not change up to about 60 K, and on further heating it evolves smoothly towards an almost pure sine-wave at 85 K. The spectrum at 85 K for $x = 0.03$ is very similar to the 4.2 K spectrum for $x = 0.045$, illustrating the above-mentioned trend that increasing $x$ at 4.2 K has the same effect on the shape of the modulation as increasing $T$ for a given $x$. Above 90 K, i.e. above $T_{SDW}$, a coexistence region is present, like in the sample with $x = 0.014$. The thermal variations of the fraction of the single line and of the resistivity are represented in fig. 6, bottom. Above 115 K, the two components of the Mössbauer spectra cannot be distinguished, but the coexistence region probably extends up to 130–140 K.

For $x = 0.045$, the modulation remains unchanged up to about 60 K, close to $T_{SDW}$, then a single line grows in the spectrum on further heating. However, due to the lack of resolution of the spectra, no quantitative assessment of the fraction of single line can be done. For this doping level, the spectrum at 4.2 K belongs to the superconducting phase, but we postpone a discussion of the mixed phase (superconducting/SDW) to a future publication.

According to the neutron diffraction data [9–11], the transition to a long-range ordered SDW state occurs at $T_{SDW}$. Actually, this transition is not “seen” in the spectra of our underdoped samples; rather, above $T_{SDW}$, a paramagnetic component (single line) appears and coexists with the magnetic hyperfine component. The latter progressively dwindles as temperature increases, its (maximum) hyperfine field decreases slowly on heating, and so does the Fe moment (see discussion below). We also observe a small hysteresis (for $x = 0.014$). This points to the persistence of AF correlations, probably short range and dynamic, far above $T_{SDW}$. We estimate that a “fully paramagnetic” phase is recovered around $T_{AF} \sim 1.5 T_{SDW}$. This behaviour could be linked with the strong bidimensional character of the magnetic interactions in the Fe layers [14,15].

As to the structural transition which, in the Co-doped compounds, occurs at a temperature higher than $T_{SDW}$ [9,11], nothing can be said from the Mössbauer data due to the very weak quadrupolar interaction in these compounds.

**Discussion.**

**Disorder induced by Co substitution.** Since these materials are (weakly) substituted compounds, one may wonder whether the observed lineshapes, for which a distribution of hyperfine fields is clearly present, could be accounted for by some disorder-induced spread in the hyperfine field values. In the layered structure of the pnictides, a Fe atom has 4 in-plane nearest neighbors, and for Co dopings $x = 0.03$ and 0.045, it results that respectively 12% and 18% Fe atoms have one Co atom as nearest neighbour. Assuming that the hyperfine field is different for a Fe atom with 4 Fe and with 1 Co - 3 Fe as nearest neighbors, then the corresponding Mössbauer spectrum would show a two peak hyperfine field distribution with, for instance for $x = 0.03$, relative weights of 88 and 12%. The distribution associated with the 4.2 K modulation for $x = 0.03$ is shown in fig. 7: it presents 3 peaks, each with 25–30% relative intensity, which therefore cannot be due to the above hypothesis of different environments of a Fe atom. The hyperfine fields of Fe atoms with 4 Fe or 1 Co - 3 Fe are probably very close due to the delocalised nature of the 3d electrons.

**Other evidences for incommensurability.** An incommensurability of the AF magnetic order in Co-underdoped BaFe$_2$As$_2$ has been inferred by NMR measurements [12,16] from the anisotropy of the line broadening. The IC wave vector was estimated in ref. [12] to depart only slightly (by a few percent) from the commensurate value $q = (101)$ in the orthorhombic cell. μSR data in a sample with $x = 0.04$ [17] can also be interpreted in terms of an
Indeed, the magnetic susceptibility has been found (from neutron diffraction data). The positions of the peaks near 2.8 and 4.3 T correspond to the quasi-plateaus of the modulation, and the (unphysical) divergence to the maximum hyperfine field where $dH_{hf}/dqX = 0$ (see fig. 3). Insert: integrated weight.

IC magnetic structure. The neutron diffraction measurements [9–11] did not report any incommensurability, but the resolution in $q$-space is probably not sufficient for this purpose; we note that neither the $(a, b)$ orthorhombic splitting could be resolved in these experiments as well. In LaOFeAs, a calculation of the Lindhardt response function $\chi_0(q)$ was performed for the undoped system and for the system with $x = 0.1$ Fe doping [18]. It is shown that F doping shifts the maximum of $\chi_0(q)$ from the $M$-point of the Brillouin zone to an IC $q$-vector, inducing thus an IC magnetic structure. The appearance of an IC SDW upon doping is also predicted in ref. [19]. In view of the similarities between the 1111 and 122 families of pnictides, these results could also hold for the latter family, accounting for the fact that a very small doping level ($x = 0.014$) is enough to push the material towards an IC SDW.

The hyperfine constant and the Fe moment. The saturated hyperfine field in BaFe$_2$As$_2$ is 5.4 T [7] and the maximum hyperfine field at 4.2 K in the Co-doped compounds has comparable magnitude (see insert of fig. 3). These are unusually small values for Fe, even in an itinerant magnet. In intermetallic compounds, it is usually assumed that the Fermi contact interaction with $s$-electrons is the dominant hyperfine coupling, implying that the Fe moment $m$ is proportional to the hyperfine field $H_{hf}$ [20]. This is true in $\alpha$-Fe, with a hyperfine constant $C_{hf} = H_{hf}/m \approx 15$ T/$\mu_B$, and in a number of other intermetallics with similar $C_{hf}$ value. In the 122 family of isostructural pnictides, the ratios of hyperfine field and moment are smaller and present rather scattered values (see table 2, where the moment is taken from neutron diffraction data). A strict proportionality between moment and hyperfine field can be however questioned in the pnictides. Indeed, the magnetic susceptibility has been found to be anisotropic ($\chi_\perp/\chi_\parallel \approx 1.5–2$) both in undoped BaFe$_2$As$_2$ [14] and in Co-doped compounds [25]. This is a hint to the presence of an “unquenched” orbital moment at the Fe site. This implies a probably small, but non-zero contribution of the $d$-orbitals to the hyperfine field, with a sign opposite to that of the Fermi contact field. Then, like in Fe$^{2+}$ compounds [26], the hyperfine field is no longer strictly proportional to the moment. The hyperfine field modulation then would not reflect exactly that of the Fe moment.

However, assuming as a first good approximation that proportionality holds in the Ba(Fe$_{1−x}$Co$_x$)$_2$As$_2$ series with the same constant as in BaFe$_2$As$_2$, then the maximum Fe moment of the modulation at 4.2 K would be 0.96, 0.84 and 0.72 $\mu_B$ for $x = 0.014$, 0.03 and $x = 0.045$, respectively.

Thermal variation of the moment and nature of the SDW transition. In the neutron diffraction studies of the series Ba(Fe$_{1−x}$Co$_x$)$_2$As$_2$ [5,9–11], the integrated intensity of the magnetic Bragg peaks continuously drops towards zero as temperature is increased towards $T_{SDW}$. This behaviour is in contrast with the $^{75}$As NMR work in BaFe$_2$As$_2$ [8], where the transferred hyperfine field at the As nucleus shows a weak thermal variation and it was concluded that the SDW transition is first order. A similar discrepancy is observed in the present work in Co-doped materials, where the main Fourier component $h_1$ of the modulation retains a sizeable value at $T_{SDW}$ (see fig. 6, top). However, a correct comparison with the neutron data must take into account the fact that the intensity of a magnetic Bragg peak is proportional to the square of the magnetic moment. In case of a modulated structure with Fourier coefficients $m_{2k+1}$, it should scale with $(m^2)$, where the brackets denote an average over a period of the moment modulation:

$$\langle m^2(x,T) \rangle = \frac{1}{2} \sum_{k=0,n} m_{2k+1}^2(x,T) \propto \frac{1}{2} \sum_{k=0,n} h_{2k+1}^2(x,T).$$

(2)

Figure 8 shows the thermal variations of $\langle m^2(x,T) \rangle$ (from the $h_{2k+1}(x,T)$ values determined by Mössbauer spectroscopy) for $x = 0.03$ and of the intensity of a magnetic Bragg peak for $x = 0.04$ [10]. The $\langle m^2 \rangle$ value is reduced by half at $T_{SDW}$, in disagreement with the neutron data. Similar behaviours occur for $x = 0.014$ and 0.045. It can thus be concluded that the SDW transition in the Ba(Fe$_{1−x}$Co$_x$)$_2$As$_2$ series, as observed with the Mössbauer local probe, also presents a strong first-order character.

Comparing the moment values obtained from the neutron data [11] for $x = 0.025$ and 0.045 with the Mössbauer results is more difficult since, in the scaling

### Table 2: Saturated Fe moment $m$ and hyperfine field $H_{hf}$, and the ratio $r = H_{hf}/m$ in $\alpha$Fe$_2$As$_2$ for $\alpha$ = Ba, Ca and Sr.

| $\alpha$ | Ba | Ca | Sr |
|---|---|---|---|
| $m$ ($\mu_B$) | 0.87 [5] | 0.80 [21] | 1.0 [22] |
| $H_{hf}$ (T) | 5.4 [6] | 10 [23] | 8.9 [24] |
| $r$ ($T/\mu_B$) | 6.3 | 12.5 | 8.9 |

Fig. 7: (Color online) Hyperfine field distribution associated with the hyperfine field modulation at 4.2 K for the $x = 0.03$ sample (see table 1). The positions of the peaks near 2.8 and 4.3 T correspond to the quasi-plateaus of the modulation, and the (unphysical) divergence to the maximum hyperfine field where $dH_{hf}/dqX = 0$ (see fig. 3). Insert: integrated weight.
of the neutron Bragg intensity, it was assumed that the magnetic structure is identical to that of \(\text{BaFe}_2\text{As}_2\), \textit{i.e.} commensurate with the lattice spacings. The mean saturated Fe moment value \(m_s\) obtained from neutron diffraction should be compared with

\[
m_s(x) = \sqrt{\langle m^2(x, T = 4.2\, K) \rangle}.
\]

Assuming proportionality between hyperfine field and moment, and using the Mössbauer derived values for \(h_{2k+1}(x, T = 4.2\, K)\), one gets: \(m_s = 0.70, 0.59\) and \(0.45\, \mu_B\) resp. for \(x = 0.014, 0.03\) and \(0.045\). This must be compared with \(m_s = 0.35\) and \(0.17\, \mu_B\) resp. for \(x = 0.025\) and \(0.045\) derived from the neutron data in ref. [11].

Further work is needed to resolve the disagreement between local probe and neutron diffraction data about the Fe moment variation with temperature and Co doping.

**Conclusions.** – \(^{57}\text{Fe}\) Mössbauer absorption spectra have been measured in the \(\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2\) series for \(x = 0.014, 0.03\) and \(0.045\). In all the samples, unusual magnetic hyperfine lineshapes are observed from \(4.2\, K\) to \(T_{\text{SDW}}\). They are interpreted in terms of a continuous modulation of hyperfine fields at the Fe sites arising from an incommensurate electronic SDW state. Incommensurability is present at the lowest doping level, \textit{i.e.} for \(x = 0.014\), while the magnetic structure in \(\text{BaFe}_2\text{As}_2\) is commensurate. Above \(T_{\text{SDW}}\), we do not observe a purely paramagnetic signal, but a coexistence of magnetic hyperfine and paramagnetic subspectra in a large temperature range, up to \(T_{\text{AF}} \sim 1.5\, T_{\text{SDW}}\) approximately for all samples. We believe this is due to the persistence of AF short-range correlated regions, probably dynamic, well above the SDW transition, which is found to have a strong first-order character. Our analysis of the hyperfine field modulations as a function of \(x\) shows that magnetism is not strongly depleted as doping increases, \textit{i.e.} the mean Fe moment or the maximum of the modulation does not decrease with \(x\) as rapidly as inferred from neutron diffraction data. We believe the incommensurability of the magnetic structure has not been evidenced by neutron scattering up to now due to the probable very small value of the incommensurate component(s) of the SDW wave vector. This makes Mössbauer spectroscopy a valuable tool to investigate these structures: although the propagation vector cannot be obtained with this technique, the spectral shape is sensitive to minute incommensurabilities.

***

We thank J. BOBROFF and H. ALLOUL for fruitful discussions.

**REFERENCES**

[1] KAMHARA Y. et al., J. Am. Chem. Soc., 130 (2008) 3296.
[2] SEFAT A. S. et al., Phys. Rev. Lett., 101 (2008) 117004.
[3] CHU J. H. et al., Phys. Rev. B, 79 (2009) 014506.
[4] RULLIER-ALBENQUE F., COLSON D., FORGET A. and ALLOUL H., Phys. Rev. Lett., 103 (2009) 057001.
[5] HUANG Q. et al., Phys. Rev. Lett., 101 (2008) 257003.
[6] ROTTIER. M. et al., Phys. Rev. B, 78 (2008) 020503.
[7] ROTTIER M. et al., New J. Phys., 11 (2009) 025014.
[8] KITAGAWA K. et al., J. Phys. Soc. Jpn., 77 (2008) 114709.
[9] PRATT D. K. et al., Phys. Rev. Lett., 103 (2009) 087001.
[10] CHRISTIANSON A. D. et al., Phys. Rev. Lett., 103 (2009) 087002.
[11] LESTER C. et al., Phys. Rev. B, 79 (2009) 144523.
[12] LAPLACE Y. et al., Phys. Rev. B, 80 (2009) 140501(R).
[13] LAPLACE Y. et al., Eur. Phys. J. B, 73 (2010) 161.
[14] WANG X. F. et al., Phys. Rev. Lett., 102 (2009) 117005.
[15] ZHANG G. M. et al., EPL, 86 (2009) 37006.
[16] NING F. L. et al., Phys. Rev. B, 79 (2009) 140506(R).
[17] BERNHARD C. et al., New J. Phys., 11 (2009) 055050.
[18] DONG J. et al., EPL, 83 (2008) 27006.
[19] CVETKOVIC V. and TESANOVIC Z., Phys. Rev. B, 80 (2009) 024512.
[20] FREEMAN A. J. and WATSON R. E., in *Magnetism*, edited by RADO G. T. and SUH H., Vol. IIA (Academic, New York) 1965, p. 167.
[21] GOLDMAN A. I. et al., Phys. Rev. B, 78 (2008) 100506.
[22] KANEKO K. et al., Phys. Rev. B, 78 (2008) 212502.
[23] KUMAR K. et al., Phys. Rev. B, 79 (2009) 012504.
[24] TEGEL M. et al., J. Phys.: Condens. Matter, 20 (2008) 452201.
[25] RULLIER-ALBENQUE F., private communication (2009).
[26] HARTMANN-BOUTRON F. and IMBERT P., J. Appl. Phys., 39 (1968) 775.