Homogeneous vs. inhomogeneous coexistence of magnetic order and superconductivity probed by NMR in Co- and K-doped iron pnictides

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Abstract – In Ba(Fe0.95Co0.05)2As2 all of the 75As NMR intensity at the paramagnetic resonance position vanishes abruptly below T_{SDW}^{onset} = 56 K, indicating that magnetic (spin-density wave) order is present in all of the sample volume, despite bulk superconductivity below T_c = 15 K. The two phases thus coexist homogeneously at the microscopic scale. In Ba0.6K0.4Fe2As2, on the other hand, the signal loss below T_{SDW}^{onset} ≃ 75 K is not complete, revealing that magnetic order is bound to finite-size areas of the sample, while the remaining NMR signal shows a clear superconducting response below T_c = 37 K. Thus, the two phases are not homogeneously mixed, at least for this potassium concentration. For both samples, spatial electronic and/or magnetic inhomogeneity is shown to characterize the NMR properties in the normal state.

Introduction. – How long range magnetic order can coexist with bulk superconductivity is a central question in a number of unconventional superconductors. In both families of high temperature superconductors, the copper oxides and the “new” iron pnictides, the superconducting phase is obtained by adding charge carriers into a phase with antiferromagnetic order. Observation of phase coexistence in such a situation immediately raises two important questions. The first one is related to the intrinsic character of the coexistence. This question is obviously linked to a rather subtle issue in these off-stoichiometric materials: to which extent is chemical inhomogeneity of the samples intrinsic or not (i.e. unavoidable or not)? The next important question is: Do the phases overlap in space, or do they occupy mutually exclusive volumes? In short, on which length scale do the two phases coexist? This is an equally delicate problem because unambiguous direct experimental proofs are in most cases difficult to obtain, even for true local probes such as nuclear magnetic resonance (NMR), muon spin rotation (µSR) or scanning tunneling microscopy (STM). As a matter of fact, the debate is still going on in the cuprates (see [1] and references therein). In the iron pnictides, magnetic order (a spin-density wave state) has recently been found to coexist with superconductivity in several (but apparently not all) families, such as Ba1−xKxFe2As2 or Ba(Fe1−xCo)x2As2. Yet, a global picture of the conditions for this coexistence in the pnictides is still lacking. Because there is an important number of reports on this matter, we primarily refer the reader to the papers presenting phase diagrams of these systems, see [2–7] and references therein.

In this letter, we investigate single crystals of Ba0.6K0.4Fe2As2 and Ba(Fe1.95Co0.05)2As2 with 75As nuclear magnetic resonance (NMR). Although both of these samples exhibit coexistence of bulk superconductivity and spin-density wave (SDW) order, the contrasting
behaviors observed in their NMR properties shows that the coexistence occurs on different length scales in the two samples.

Experimental details and bulk properties. – Single crystals Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and Ba(Fe$_{1.95}$Co$_{0.05}$)$_2$As$_2$ (initial Co content of 0.07) were grown using a self-flux technique, as detailed elsewhere [8]. The magnetization was measured in a SQUID magnetometer in a 10 Oe magnetic field applied perpendicular to the c-axis after zero-field cooling. The in-plane resistivity was measured using standard four-probe method. $^{75}$As NMR experiments were performed with a home built pulsed spectrometer.

Figure 1 shows the temperature-dependent magnetic susceptibility $\chi$ and the superconducting transitions at $T_c$ for both samples. The values of onset $T_c$ are $\sim 37$ K for Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and 15 K for Ba(Fe$_{1.95}$Co$_{0.05}$)$_2$As$_2$, respectively. The same values of $T_c$ are obtained from measurements of the in-plane resistivity $\rho_{ab}$ (see fig. 3(a)). These values of $T_c$ are in agreement with the literature values for similar K [9,10] or Co [5,7,11–13] contents. The diamagnetic susceptibility saturates at low temperatures. Using $\chi$ values at 2 K, the superconducting volume fraction is estimated to be nearly 100% for both Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and Ba(Fe$_{1.95}$Co$_{0.05}$)$_2$As$_2$.

NMR spectra. – $^{75}$As NMR spectra are presented in fig. 2 with quantitative information included in the caption. For both Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ (hereafter abbreviated as [Ba/K]) and Ba(Fe$_{0.95}$Co$_{0.05}$)$_2$As$_2$ (hereafter [Fe/Co]), the quadrupole parameters and the full width at half-maximum (FWHM) of the NMR lines appears to be comparable to the best data published, confirming that self-flux grown crystals are considerably cleaner than Sn-flux ones (for comparisons, see [14–17] and [18,19], respectively).

NMR intensity at high temperature. – A central result of the present work is the $T$-dependence of the total $^{75}$As NMR intensity $I_{\mathrm{NMR}}$ (fig. 3(b)), which is proportional to the number of nuclei contributing to the signal. For both samples, this intensity decreases moderately with $T$ below $\sim 200$ K. Park et al. claim the occurrence of magnetic order in $\sim 21\%$ (at 300 K) to 26% (70 K) of their Ba$_{1-x}$K$_x$Fe$_2$As$_2$ sample [20]. A similar phenomenon cannot be excluded here as it could indeed cause part of the NMR signal to disappear. However, the $T$ dependence of our NMR intensity is stronger than the $T$ variation of their magnetic volume fraction. Furthermore, it is also likely that the penetration of the radiofrequency is limited by the skin effect in our crystals with a few hundreds micron thickness: The relative change in $\sqrt{\rho_{ab}}$ (which is proportional to the skin depth $\delta$) is 15% for [Fe/Co] and 45% for [Ba/K], between 180 K and 70 K. These numbers are comparable to the relative signal loss which amounts to 25% and 45%, respectively. Therefore,
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Fig. 3: (Colour on-line) (a) In-plane resistivity of the K- and Co-doped samples. Inset: $\rho_{ab}$ minimum at 62 K for the [Ba/Co] sample (SDW transition). (b) $^{75}$As NMR intensity (integrated over the full width of the central lines and normalized by a factor $T$ accounting for the Curie dependence of the nuclear magnetization). No $T_2$ correction was necessary as $T_2$ is always much longer than the delay separating the two pulses of the spin-echo sequence. Inset: $dI_{\text{NMR}}/dT$ data for [Ba/K]. The continuous lines are guides to the eye. (c) Width (FWHM) of the $^{75}$As NMR central lines shown in fig. 2. The solid lines are fits to $A + b/(T + \theta)$, with $a = 57(2)$ kHz and $\theta = -38(2)$ for [Ba/K] ($T \geq 52$ K) and $a = 29(2)$ kHz and $\theta = -36(2)$ for [Fe/Co]. (d) Spin-lattice relaxation rate $T_1^{-1}$. (e) Same $T_1^{-1}$ data as in (d), divided by $T$. In panels (c), (d) and (e), the dashed lines represent the data for [Fe/Co] multiplied by an appropriate factor in order to match the [Ba/K] data about 175 K.

a significant part, if not all, of the smooth decrease of the NMR signal intensity is likely due to the skin effect in these metallic single crystals. Upon decreasing $T$ further, the NMR intensity for the two samples clearly displays different trends, which we discuss now.

**Phase coexistence** in Ba(Fe$_{1.95}$Co$_{0.05}$)$_2$As$_2$. – For [Fe/Co], the signal intensity $^{75}I_{\text{NMR}}$ drops abruptly to almost zero below $\sim 56$ K, i.e. far above $T_c$. In the same temperature range, $\rho_{ab}$ shows a clear upturn attributed to the appearance of a SDW phase in previous works [5,7,21]. In principle, in the SDW state, the central NMR line splits and/or broadens. So, most, if not all, of the signal shifts away from from the paramagnetic resonance frequency $\nu_0 = \gamma H_{\text{ext}}$, where $H_{\text{ext}}$ is the applied external field. In this sample, despite broad magnetic field sweeps and the presence of a very small residual intensity, no well-defined NMR signal could be measured below 50 K. This result is not surprising since extreme $^{75}$As line broadening is already visible for a Co doping of $x = 0.04$, as reported by Ning et al. [22]. Hence, the signal is “lost” and the ordered phase could not be characterized further, except for determination of the transition temperature $T_{SDW} \approx 52 \pm 3$ K, defined as the point at which the NMR signal has decreased by 50%, with the error bars denoting the width of the transition.

Nevertheless, the important point here is that the complete loss of NMR signal requires that every $^{75}$As nucleus has at least one magnetic Fe site (i.e. one site in a magnetically ordered region) among its four first neighbours, within the NMR time window of $\sim 1$ µs. Shifts due to longer range (dipolar) field from the more distant Fe sites can be ruled out since 1 µB creates a dipolar field as low as $\sim 0.2$ kOe at the next nearest As site (to be compared to the hyperfine field transferred from each first neighbour Fe sites of $\sim 6$ kOe/µB [23]). Thus, the magnetic phase must be present in all of the sample volume at any given time $t$. (Note that an apparent mixing due to space/time fluctuations between two macroscopically separated phases would produce very short spin-spin relaxation time $T_2$. This is incompatible with the data at lower $x$ values [22] which suggest that the signal is lost because of extreme broadening, not because of too short $T_2$). The presence of magnetic order over the whole sample volume is in agreement with conclusions drawn from NMR intensity data mentioned by Ahilan et al. [21] and from the µSR results of Bernhard et al. [24]. The coexistence has also been observed in neutron scattering [11–13]. The close values of $T_{SDW}$ in neutrons and NMR indicates the absence of probe-frequency dependence.

Since both magnetic order and superconductivity are present in the full sample volume probed by NMR, these two phases must “coexist homogeneously”, i.e. they are mixed at the microscopic (sub-nanometer) scale or even present on the same electronic sites.
Phase coexistence in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$. – For [Ba/K], close inspection of the intensity data (fig. 3(b)) reveals that $^{75}$I$_{NMR}$ decreases much more strongly below $\sim$ 75 K. We attribute this additional loss of signal to the presence of magnetic order below $T_{SDW} \simeq 75$ K. We note that for the same 40% potassium concentration, Fukazawa et al. roughly estimate 80 K $\leq T_{SDW} \leq 100$ K from the $T$ dependence of the NMR line width [14], while Mukhopadhyay et al. report a loss of NMR intensity below $\sim 75$ K in a single crystal containing a significant amount of Sn impurities [15].

The important point here is that $^{75}$I$_{NMR}$ remains finite down to the superconducting transition at $T_c$ and even below (where $^{75}$I$_{NMR}$ can no longer be reliably measured). The persistence of a well-defined NMR signal at the paramagnetic resonance frequency implies that a fraction of the nuclei is not coupled to any magnetic Fe site, even on the long time scale of NMR. Hence, magnetic order occurs only in finite-size regions of the sample. Regions without magnetic order are present at all temperatures below 37 K and these regions clearly appear superconducting from NMR, as expected from the full Meissner fraction of the sample. Indeed, a sharp drop of $1/T_1$ is observed below $T_c$ (fig. 3(d),e)), in agreement with other results for Ba$_{1-x}$K$_x$Fe$_2$As$_2$ where $1/T_1$ was fit with one [14] or two [17,25] gap functions. We also observed a sharp drop of the magnetic hyperfine shift $^{75}$K below $T_c$, indicating spin-singlet pairing (not shown).

In agreement with a number of other works [14,20,26–28], our results thus point to a more inhomogeneous phase coexistence in this K-doped sample than in [Fe/Co]. The reduced magnetic fraction probably explains why no upturn is observed in the resistivity of this sample. We point out that, since the signal does not completely disappear and no spectacular effect is seen in either the line width or the $T_1$ data (see below), only a careful estimate of the NMR intensity is able to reveal the signal loss and thus the presence of a magnetic state. This progressive (instead of abrupt) loss of signal at the paramagnetic resonance frequency is typical of situations where a significant electronic inhomogeneity is present, as we shall confirm below.

Spin dynamics above the magnetic transition. – For [Fe/Co], the spin-lattice relaxation rate divided by temperature ($T_1 T$)$^{-1}$, which is proportional to a weighted sum over wave vectors $q$ of the dynamic susceptibility $\chi''(q,\omega_{NMR})$, continuously increases on cooling down to $T_{SDW}$ (fig. 3(e)). From this point of view, spin dynamics above the transition appear similar to what is observed in Ba(Fe$_{0.9}$Co$_{0.1}$)$_2$As$_2$ for lower $x$ values, including $x=0$ [19,29,30]. Note that $^{75}$As nuclei are located on top of the center of the square formed by four Fe sites of the same plane, so they are weakly sensitive to fluctuations involving a transfer of wave vector $q_{x,y} = \pi/a$. This probably explains why the critical divergence in $1/T_1$, which is standard for most antiferromagnetic transitions, is absent here. Indeed, $1/T_1$ only increases by 10% from 100 K to 52 K.

For [Ba/K], $(T_1 T)^{-1}$ (fig. 3(e)) shows a similar thermal variation as for [Fe/Co]. However, the plot of $T_1^{-1}$ vs. $T$ (fig. 3(d)) reveals an important difference (besides the plateau of $1/T_1$ between 60 and 40 K): There is a 30% increase of $1/T_1$ on cooling below $\sim 110$ K, much larger than for the Co-doped sample. Interestingly, for a slightly smaller K-doping value of $x=0.3$, Matano et al. report a bump in $(T_1 T)^{-1}$ vs. $T$ around 90 K, which they attribute to a structural (tetragonal to orthorhombic) transition because a small change of the quadrupole coupling is observed at the same temperature [17]. For $x=0.4$, on the other hand, Yashima et al. do not report any hump in $1/T_1$ [25] and Takeshita and Kadono report the absence of frozen magnetism [31]. At present, given both the uncertainties on the precise doping level of the different samples and the sharp changes in the electronic properties which probably occur close to $x=0.4$, it is difficult to comment on possible discrepancies as well as on the presence or absence of a structural lattice distortion associated with the onset of the SDW. It is also interesting to mention a recent study by Inosov et al. [32]: their single crystal of Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$, which also contains magnetic order in finite-size regions, does not break its tetragonal symmetry macroscopically, although local distortions are clearly observed. We speculate that remanent low energy lattice fluctuations failing to induce a long range crystallographic transition could be the origin of the fluctuations of the hyperfine field and/or of the electric field gradients, which enhance $T_1^{-1}$ above $T_{SDW}$.

Spatial inhomogeneity. – Around $\sim 200$ K, the $^{75}$As NMR line width, which reflects the distribution of magnetic hyperfine shift values $^{75}_A K$, is much larger for [Ba/K] than for [Fe/Co] (fig. 3(c)). The distribution of quadrupole frequencies (related to the electric field gradients at the $^{75}$As sites) is also significantly larger in the K-doped sample (fig. 2). Evidently, there should be a correlation between the more inhomogeneous mixing of the magnetic and superconducting phases in the K-doped sample and its larger electronic (and possibly structural) inhomogeneity. As can be inferred from the magnetisation data in fig. 1, the homogeneity of our sample is probably not optimal. However, considering the converging recent reports [20,21,24,26–28], it can safely be concluded that 40% potassium doping creates much more inhomogeneity/disorder in the FeAs layers than $\sim 5$% cobalt doping. Upon cooling, the NMR line broadens and follows a Curie-Weiss law for both samples (fig. 3(c)). This contrasts with the small linear decrease with $T$ of the mean value of the magnetic hyperfine shift $^{75}_A K$, which is proportional to the intrinsic (local) static spin susceptibility ($^{75}_A K$ data for our two samples are not shown but they are identical to published data). The opposite temperature dependence of the width and the position of the NMR
The most interesting result for this sample, however, is the fact that the line width remains almost constant below the superconducting transition. The absence of narrowing below $T_{SDW}$, and especially below $T_c$, suggests that the main source of broadening is present in the non-magnetic regions of the sample. A distribution of doping values appears unlikely since the NMR shift drops to zero as $T \to 0$ in the superconducting state. A plausible scenario is that the line is broadened by a (paramagnetic) staggered spin polarization, such as observed in Zn-doped YBa$_2$Cu$_3$O$_7$ [34–36] or in LSCO [37].

**Conclusion and discussion**. – To sum up our results, Ba(Fe$_{1.95}$Co$_{0.05}$)$_2$As$_2$ and Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ both show the coexistence of bulk superconductivity with magnetic (SDW) order. Yet, the details appear different:

In Ba(Fe$_{1.95}$Co$_{0.05}$)$_2$As$_2$, the two phases coexist at the microscopic scale probed by NMR, a situation which is often referred to as “homogeneous mixing” in the literature. This implies either that both types of orders are simultaneously defined at each Fe site (owing to the multiple bands present at the Fermi level), or that they are mixed on the scale of one or two lattice spacings. A nanoscale coexistence involving superconducting islands (without magnetic order) of typical size defined by the coherence length $\xi \approx 2.8$ nm [38] appears to be unlikely. In this case, some paramagnetic NMR signal from regions as large as ten times the Fe-Fe distance should be observed.

In Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$, on the other hand, the magnetic regions do not occupy the full sample volume. In this sense, the coexistence might be qualified as “inhomogeneous”.

Both samples show some spatial inhomogeneity of their magnetic properties, already above the spin-density wave transition. It is not yet clear to what extent the inhomogeneous magnetisation in both systems is due to spatial variations of the electronic density or only of the spin polarization. The latter may itself be a precursor manifestation of the spin-density wave state or it may be caused by the magnetic screening of impurities/defects [15,34–36].

The dramatic effect of a small amount of impurities on the NMR line broadening already in the undoped material [29,30] is a strong indication that the extreme NMR broadening observed here and by Ning et al. [22] below the transition at $T_{SDW}$ is due fact that the spin-density wave state in superconducting samples is highly disordered/inhomogeneous.

Perhaps unexpectedly, the inhomogeneity is considerably stronger in the potassium-doped sample. Actually, the fact that substitutions at the Fe site, unlike substitutions at the Cu site in the cuprates, improves conductivity and even induces superconductivity is one of the most remarkable surprises of these new superconductors. It is impossible to fully understand the Ba$_{1-x}$K$_x$Fe$_2$As$_2$ system from the present NMR data only. The important inhomogeneity/disorder could be due to inhomogeneity of K$^+$ concentration and/or to a particularly strong impact of these ions on the local electronic structure in FeAs layers. No evidence for phase separation could be detected in the K-doped sample, and the single crystal exhibits...
100% Meissner fraction. Our NMR data thus seem to be in better agreement with the picture proposed by Rotter et al. [27] than with the pure phase separation picture of Park et al. [20]. We point out that $T_{SDW}$ vs. $x$ is extremely steep near $x = 0.4$. Phase separation or inhomogeneous coexistence could thus originate from K-doping inhomogeneity around this particular concentration. They might thus not reflect the properties at somewhat lower $x$ values. Said differently, Ba$_{1-x}$K$_x$Fe$_2$As$_2$ should perhaps be simply viewed as a disordered version of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$.

Because the magnetic transition temperature drops continuously to zero about the middle of the superconducting dome for Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, the phase diagram of these pnictides shows a clear analogy with some heavy fermion compounds (and possibly electron-doped cuprates [39]). The coexistence of magnetic order and superconductivity has been observed with NMR in several heavy fermions [40,41], the two phases being homogeneously mixed in some of them, separated in others. There is also some analogy between the present results (see also [42,43]) and the coexistence between magnetic order and superconductivity as seen by NMR in hole-doped cuprates (see [1,44] and references therein). On the other hand, the data reported here do not reveal the phase separation observed with NMR in 2D [45] and 1D [46] organic conductors. This correlates with the fact that these materials have a quite different phase diagram.

Clearly, more experimental and theoretical work is needed to clarify all aspects of the mixing of magnetic and superconducting phases in the pnictides. Nevertheless, their coexistence over a substantial portion of the phase diagram clearly emerges as a cornerstone of their physics.

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Additional remark: After the completion of this paper, we became aware of a recent NMR work (LAPLACE Y. et al., arXiv:0906.2125), with similar conclusions regarding the mixing of superconducting and spin-density wave orders at the microscopic scale for the cobalt-doped system. In their more strongly (6%) Co-doped single crystal ($T_{SDW} = 31$ K, $T_c = 22$ K), the average moment is strongly reduced and the NMR signal in the magnetic phase is severely broadened but remains observable, in contrast with our case.

REFERENCES

[1] MITROVIĆ V. et al., Phys. Rev. B, 78 (2008) 014504.
[2] ZHIAO J. et al., Nat. Mater., 7 (2008) 953.
[3] LUEKENS H. et al., Nat. Mater., 8 (2009) 305.
[4] DREW A. J. et al., Nat. Mater., 8 (2009) 310.
[5] NI N. et al., Phys. Rev. B, 78 (2008) 214515.
[6] CHEN H. et al., EPL, 85 (2009) 17006.
[7] CHU J.-H., ANALYTIS J. G., KUCHARCZYK C. and FISHER I. R., Phys. Rev. B, 79 (2009) 014506.
[8] CHEN G. F. et al., Phys. Rev. B, 78 (2008) 224512.
[9] ROTTER M. et al., Angew. Chem., Int. Ed., 47 (2008) 7949.
[10] LI G. et al., Phys. Rev. Lett., 101 (2008) 107004.
[11] LESTER C. et al., Phys. Rev. B, 79 (2009) 144523.
[12] PRATT D. K. et al., arXiv:0903.2833 (2009).
[13] CHRISTIANSON A. D. et al., arXiv:0904.0767, to be published in Phys. Rev. Lett.
[14] FUKAZAWA H. et al., J. Phys. Soc. Jpn., 78 (2009) 033704.
[15] MUKHOPADHYAY S. et al., New. J. Phys., 11 (2009) 055002.
[16] MUKUDA H. et al., arXiv:0901.4607 (2009).
[17] MATANO K. et al., arXiv:0903.5098 (2009).
[18] NING F. L. et al., J. Phys. Soc. Jpn., 77 (2008) 103705.
[19] NING F. L. et al., J. Phys. Soc. Jpn., 78 (2009) 013711.
[20] PARK J. T. et al., Phys. Rev. Lett., 102 (2009) 117006.
[21] AHILAN K. et al., J. Phys.: Condens. Matter, 20 (2008) 472201.
[22] NING F. L. et al., Phys. Rev. B, 79 (2009) 140506.
[23] GRAFE H.-J. et al., Phys. Rev. Lett., 101 (2008) 047003.
[24] BERNHARD C. et al., New J. Phys., 11 (2009) 055050.
[25] YASHIMA M. et al., arXiv:0905.1896 (2009).
[26] ACZEL A. A. et al., Phys. Rev. B, 78 (2008) 214503.
[27] ROTTER M. et al., New. J. Phys., 11 (2009) 025014.
[28] GOKO T. et al., Phys. Rev. B, 80 (2009) 024508.
[29] KITAGAWA K. et al., J. Phys. Soc. Jpn., 77 (2008) 114709.
[30] BAEK S.-H. et al., Phys. Rev. B, 78 (2008) 212509.
[31] TAKESHITA S. and KADONO, New J. Phys., 11 (2009) 035006.
[32] INOSOV D. S. et al., Phys. Rev. B, 79 (2009) 224503.
[33] MASSEE F. et al., Phys. Rev. B, 79 (2009) 220517(R).
[34] JULIEN M.-H. et al., Phys. Rev. Lett., 84 (2000) 3422.
[35] OUAZI S. et al., Phys. Rev. Lett., 96 (2006) 127005.
[36] ALLOLU H., BOBROFF J., GABAY M. and HIRSCHFELD P. J., Rev. Mod. Phys., 81 (2009) 45.
[37] JULIEN M.-H. et al., Phys. Rev. Lett., 83 (1999) 604.
[38] YIN Y. et al., Phys. Rev. Lett., 102 (2009) 097002.
[39] ARMITAGE P. N., FOURNIER P. and GREENE R. L., arXiv:0906.2931 (2009).
[40] KITAOKA Y. et al., J. Phys. Chem. Solids, 63 (2002) 1141.
[41] CURRO N. J., Rep. Prog. Phys., 72 (2009) 026502.
[42] NAKAI Y. et al., Phys. Rev. Lett., 101 (2008) 077006.
[43] JULIEN M.-H., J. Phys. Soc. Jpn., 77 (2008) 125002.
[44] JULIEN M.-H., Physica B, 329-333 (2003) 693.
[45] LÉFEBVRE S. et al., Phys. Rev. Lett., 85 (2000) 5420.
[46] LEE I. J. et al., Phys. Rev. Lett., 94 (2005) 197001.