Emergence of Orbital Nematicity in the Tetragonal Phase of BaFe$_2$(As$_{1-x}$P$_x$)$_2$

Tetsuya Iye$^{1,2}$*, Marc-Henri Julien$^1$,†, Hadrien Mayaffre$^1$, Mladen Horvat$c$i$^1$, Claude Berthier$^1$, Kenji Ishida$^{2,3}$, Hiroaki Ikeda$^2$, Shigeru Kasahara$^2$, Takasada Shibuchi$^2$, and Yuji Matsuda$^3$

$^1$Laboratoire National des Champs Magnétiques Intenses, LNCMI - CNRS (UPR3228), UJF, UPS and INSA, BP 166, 38042 Grenoble Cedex 9, France
$^2$Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

We report on $^{75}$As-NMR measurements in single crystalline BaFe$_2$(As$_{0.96}$P$_{0.04}$)$_2$ for magnetic fields parallel to the orthorhombic [110]$_o$ and [100]$_o$ directions above the structural transition temperature $T_S \simeq 121$ K. A large difference in the linewidth between the two field directions reveals in-plane anisotropy of the electric field gradient, even in the tetragonal phase. This provides microscopic evidence of population imbalance between As-4$p_z$ and 4$p_x$ orbitals, which reaches $|n_z - n_x| / (n_x + n_z) \sim 15$% at $T \rightarrow T_S$ and is a natural consequence of the orbital ordering of Fe-3$d_{yz}$ and 3$d_{zx}$ electrons. Surprisingly, this orbital polarization is found to be already static near room temperature, suggesting that it arises from the pinning of anisotropic orbital fluctuations by disorder. The effect is found to be stronger below $\sim 160$ K, which coincides with the appearance of nematicity in previous torque and photoemission measurements. These results impose strong constraints on microscopic models of the nematic state.

The relationships among spin, orbital, and lattice degrees of freedom are a central issue in iron pnictides since fluctuations in these channels are potentially at the origin of high-$T_c$ superconductivity. The problem is best illustrated by the presence of two interrelated structural and magnetic transitions, at temperatures $T_S$ and $T_N$, respectively, which both disappear near the optimal $T_c$ in most pnictides.$^1$ Although the tetragonal-to-orthorhombic transition slightly precedes (or coincides with) the antiferromagnetic (AFM) transition, the latter is not necessarily a consequence of the former: whether the orthorhombic distortion is driven by magnetic or orbital fluctuations has been the subject of continuing debate$^5$ (see Ref. 5 and references therein). Furthermore, the tetragonal phase above $T_S$ turns out to be unconventional: various electronic properties have been found to break the fourfold symmetry of the Fe-As planes.$^6$–$^{25}$ The relative role and the microscopic origin of the spin and orbital instabilities leading to such an “electronic nematic state” are also controversial.$^{23}$,$^{26}$–$^{37}$ Actually, because magnetic and orbital degrees of freedom are entangled and most likely cooperate,$^{38}$ it is challenging to determine which one, if any, is dominant. While both the magnetic and orbital scenarios find support in experiments$^3$,$^5$,$^6$,$^14$,$^20$,$^39$–$^{43}$ the nematic state remains puzzling.

Here, we report on NMR measurements above $T_S$ in underdoped BaFe$_2$(As$_{0.96}$P$_{0.04}$)$_2$. We demonstrate that orbital polarization of the As-4$p$ orbitals, related to Fe-3$d$ polarization, is present within electronic domains in the tetragonal phase, even without any applied uniaxial stress. We estimate the magnitude of this polarization and show that it is static.

We further reveal an unanticipated temperature dependence: while the onset of the nematic state, as inferred from torque and photoemission experiments,$^{22}$,$^{24}$ is manifested by an upturn near 160 K in our linewidth data, static orbital polarization is found to be already present at much higher temperatures. This suggests that static short-range orbital order is first nucleated around defects and that its evolution towards longer-range order is directly involved in the manifestation of nematicity at the macroscopic scale.

Single-crystalline BaFe$_2$(As$_{0.96}$P$_{0.04}$)$_2$ was synthesized by the conventional self-flux method.$^{44}$ Edges of the crystal were cut along [110]$_o$ in the orthorhombic notation (As-Fe direction), [100]$_o$ (Fe-Fe direction), and [110]$_o$ [see Fig. 1(a)] and the resulting dimensions of the crystal were 2.0 $\times$ 1.4 $\times$ 0.25 mm$^3$. For the following NMR measurements, the field was parallel to the $ab$-plane to within $\pm 1^\circ$. $^{75}$As-NMR spectra were obtained by sweeping the frequency in a fixed field of 15 and 6 T. The structural transition at $T_S \simeq 121$ K was determined from a kink in the resistivity measured on a crystal from the same batch while the magnetic ordering at $T_N \simeq 121$ K was determined from the sharp drop in the NMR signal intensity, signifying the simultaneous structural and magnetic transition $T_S = T_N$.

Since $^{75}$As nuclei have spin $I = 3/2$, the spectrum shows three lines corresponding to the transitions $I_z = m \leftrightarrow m - 1$ ($m = \pm 1/2, 3/2$) at the frequencies $f_{m-m-1}(\theta, \phi) = (\gamma / 2\pi)\mu_B H [1 + K(\theta, \phi)] + (m - 1/2)\gamma\nu(\theta, \phi) + (2^{nd}\text{-order quadrupolar correction})$, where $(\theta, \phi)$ indicates polar and azimuthal angles of the applied field in the orthorhombic basis $(\alpha_0, \beta_0, \gamma)$, $\gamma / 2\pi = 7.2919$ MHz/T is the $^{75}$As gyromagnetic ratio, and $K(\theta, \phi)$ represents the Knight shift, which is proportional to the magnetic susceptibility $\chi(q = 0)
The angular dependence of the quadrupole frequency \( v_q \) is expressed as

\[
v_q(\theta, \phi) = \left( v_c/2 \right)(m - 1)(3 \cos^2 \theta - 1 - \eta \sin^2 \theta \cos 2\phi),
\]

where \( v_c \) is proportional to the diagonal components of the electric field gradient (EFG) tensor.

\[ V_{aa} \equiv \partial^2 V/\partial r^2, v_c = eV_{aa}Q/2h \]

\[ (\alpha = a, b, c) \]

The in-plane EFG anisotropy is defined as \( \eta \equiv |V_{aa} - V_{bb}|/|V_{cc}| = |v_a - v_b|/|v_c| \]

with \( v_a + v_b + v_c = 0 \). Therefore, \( \eta = 0 \) in a local tetragonal environment.

Small additional peaks observed in the tail of the central line are attributed to those As sites (hereafter called As\(_{1}\)) having one P dopant among their four nearest neighbors (NNs). The As\(_{1}\) resonance splits into two peaks for \( H || [110]_o \) because As\(_{1}^{[100]}_1 \) and As\(_{1}^{[010]}_1 \) sites [defined in Fig. 1(a)] are inequivalent, while they are equivalent for \( H || [110]_o \) and \( [1\bar{1}0]_o \). In Ba\((Fe_{1-x}Co_x)\)\(_2\)As\(_2\), NNs to Co dopants produce similar peaks.\(^2,46,47\) The angle dependence of the resonance frequency of the As\(_{1}\) center peak is reproduced with the parameters \( |v_c| = 5 \text{ MHz}, \eta = 0.24, \) and \( \delta = 30^\circ \), where \( \delta \) is the tilt angle of the principal axis (c-axis) of the EFG from the crystalline c-axis [Fig. 1(b)] to [100]. The Knight shift of As\(_{1}\) is assumed to be the same as that of As\(_{0}\). These parameters enable us to estimate the positions of the As\(_{1}\) satellite peaks [Fig. 1(c)]. As seen in the satellite peaks for \( H || [100]_o \), weak and broad tails are observed. We consider that the broad tails arise from the As\(_{0}\) site next to As\(_{1}\) in the doped P and As\(_{1}\) directions, since these tails have the same angle dependence as the As\(_{1}\) site. It is clear from Fig. 1(c) that the central part of each satellite signal essentially arises from the As\(_{0}\) sites where the effect of the P-dopant is small.

Below, we discuss the electronic state of the As\(_{0}\) sites by analyzing two quantities: (i) the absolute value of their quadrupole frequency \( |v| \), directly determined from half of the separation between the high- and low-frequency satellites \( v(\phi) = [f_+ - f_-]/2 = |v||1 + \eta \cos 2\phi|/2 \), (ii) the distribution of quadrupole frequencies \( \Delta v/|v| \), where \( \Delta v \) is the full-width at half-maximum obtained by the Gaussian fit of the As\(_{0}\) satellite peak.

The central observation of our study is shown in Figs. 2(a) and 2(b). While the values of \( |v| \) are almost identical for \( H || [110]_o \) and for \( H || [100]_o \), the values of \( \Delta v/|v| \) for these two orientations are different and, most importantly, this difference increases on cooling. The difference in the linewidth is independent of the analysis procedure. The contrasting behavior between \( H || [110]_o \) and \( H || [100]_o \) is also observed in the linewidth of the 75 As-NMR center-line arising from the As\(_{0}\) site measured at 6 T, as shown in Fig. 3. We investigated the origin of the linewidth difference from the field dependence of the linewidth, and confirmed that the central linewidth is not determined by the hyperfine interaction, but mainly by the EFG. Whereas the linewidth decreases for \( H || [110]_o \), that the width for \( H || [100]_o \) is anomalously large and that it grows with decreasing T can only be explained if there are two unresolved sites for \( H || [100]_o \) having identical EFG tensor com-

---

**Fig. 1.** (Color online) (a) FePn layers and applied field directions. Left panel: the central As site without P dopant among its NN is named As\(_{0}\). Middle and right panels: the central As sites having one P dopant among their NN in the [100] and [010] directions are named As\(_{1}^{[100]}_1 \) and As\(_{1}^{[010]}_1 \), respectively. 75 As-NMR central line (b) and satellites (c) at 200 K for different field orientations. Continuous lines are fits to As\(_{0}\) (blue) and As\(_{1}\) (red) sites. Expected resonance positions are shown as dashed lines.

**Fig. 2.** (Color online) (a) \( T \) dependence of the quadrupole frequency \( |v| \). (b) \( T \) dependence of the distribution \( \Delta v/|v| \) where \( \Delta v \) is the full-width at half-maximum of a satellite line. Fitting error bars are within the symbols. 75 As satellites at 250 (c) and 130 K (d) for \( H || [100]_o \) and [110]o, respectively. Broken blue and red lines represent As\(_{0}\) and As\(_{1}\) sites, respectively, obtained from Gaussian fits to the lineshape (their sum is shown as a solid green line). The two sites are identical for \( H || [110]_o \), while they split for \( H || [100]_o \).
Fig. 3. (Color online) T dependence of the $^{75}$As-NMR arising from the central transition obtained for $H \parallel [110]_0$ (a) and $[100]_0$ (b). (c) $T$ dependence of the full-width at half-maximum of the centerline from the $\text{As}_0$ site in $H \parallel [110]_0$ and $[110]_0$. $\delta f_{\text{center}}$ for $H \parallel [100]_0$ starts to increase below 160 K, as observed in the linewidth of the satellite peak shown in Fig. 2(b).

Fig. 4. (Color online) (a) $T$ dependence of in-plane EFG anisotropy parameter $\eta$ for $x = 0.04$ (this work) and $x = 0$ (from Ref. 45). For $x = 0.04$, $\eta$ is derived from the angular dependence of the satellite linewidth with respect to the field. For $x = 0$, however, it is deduced from the satellite splitting owing to twinned orthorhombic domains. $^{45}$ If domains are present above $T_S$, this method does not allow the detection of $\eta \neq 0$ locally. (b) $T$ dependence of $\nu_{a,b}$ for $x = 0.04$ together with the $x = 0$ data from Ref. 45. $\nu_{a,b}^{\text{band}}$ is the quadrupole frequency estimated from band-structure calculations. $\nu_{a,b}^{\text{lat}}$ is the value calculated using a point charge model and the lattice parameters from Refs. 50 and 51. (1 $\nu_{a,b}^{\text{band}}$ vs. $x$ is derived from the $\nu$ vs. $K^{\text{spin}}$ plot (see Supplemental Material).$^{48}$

We examine the relative weights of these two contributions. We performed band-structure calculations for $x = 0$ within the local density approximation (LDA) for non-spin-polarized BaFe$_2$As$_2$ and using the lattice parameters reported previously.$^{51}$ Since the obtained $\nu_{a,b}^{\text{band}} = +1.95$ MHz at 300 K is similar to the experimental value $\nu_{a,b}^{\text{lat}} = 1.5$ MHz,$^{45}$ it is found that the on-site contribution is dominant, and the sign of $\nu_{a,b}$ is chosen to be positive in Fig. 4(b) for both $x = 0$ and 0.04 in the tetragonal phase. On the basis of theoretical$^{52}$ and experimental$^{53}$ grounds, we estimate the $T$-independent lattice contribution $(1 - \gamma_{\infty})\nu_{a,b}^{\text{lat}} = 0.45$ MHz from the extrapolation of the linear relationship between $\nu$ and the spin part of the Knight shift $K^{\text{spin}}$ (with $T$ as an implicit parameter) to $K^{\text{spin}} \rightarrow 0$ for the parent compound $x = 0$ (see Supplemental Material).$^{48}$ This contribution thus accounts for less
extrapolate to zero at a significantly lower temperature than could be overestimated at high temperatures and thus it would distortion reported in Ref. 22. Taking these results into account, estimated from the point-charge model using the lattice dis-

Therefore, the value of $\nu$ for $x = 0$ and 0.04 is much smaller than in the orthorom-

bic phase of $x = 0$, but it clearly increases with decreasing $T$, especially below $\sim 160$ K. This is clearly observed in the linewidth of the central transition shown in Fig. 3. This characteristic temperature of $\sim 160$ K is consistent with the temperature at which twofold symmetry appears in the previous magnetic torque, lattice parameters, and Fe-3$d$ orbital polarization.\cite{22,24} However, more work is needed to determine whether there is a continuous change in the magnitude and length scale of the orbital polarization (our data can be fit to a Curie Weiss law) or whether there is a sharp change at $\sim 160$ K.

While quantitative evaluation of the polarization of the Fe-

3$d$ orbitals has been reported in a few experiments for the AFM ordered state,\cite{14,56,57} no such measurement has been reported for the As-4$p$ orbitals above $T_S$, to the best of our knowledge. Furthermore, the low time scale of NMR (set by the inverse linewidth of $\sim 0.5$ MHz) implies that the observed orbital ordering is static. The imbalance between 4$p_x$ and 4$p_y$ occupations most likely results from the ordering within the Fe-3$d$ orbitals, that is, the degeneracy of Fe-3$d_{xz}$ and 3$d_{yz}$ orbitals is lifted. Indeed, LDA calculations revealed that a reduction of the Fe-3$d_{xz}$ partial density of states (PDOS) is accompanied by a decrease in the As-4$p_x$ PDOS in the AFM ordered state for $x = 0$.\cite{58} This suggests that orbital ordering above $T_S$ for BaFe$_2$(As$_{0.98}$P$_{0.02}$)$_2$ produces $n_x < n_y$ for the As-

4$p$ orbitals. This in-plane orbital anisotropy must participate in lifting the degeneracy of stripe spin correlations between $\langle 100\rangle$, and $\langle 010\rangle$, directions. A similar relationship between the lattice symmetry breaking and the enhancement of spin fluctuations has been observed in LaFeAsO.\cite{59,60}

An important and unanticipated aspect of our data is that $\eta$ at the As$_0$ sites, albeit small, is nonzero even at the highest measured temperature of 250 K, that is, well above the claimed nematic transition at $T^* \sim 160$ K.\cite{22} We suspect that orbital ordering would be entirely fluctuating at high temperatures in the absence of disorder but it is made static owing to pinning by defects (most likely P dopants) and/or microstrain induced by the dopants.\cite{61} Such a phenomenon is analogous to the pinning of charge-density-wave (CDW) fluctuations above the CDW phase transition.\cite{62,63} In iron-based superconductors, there is actually theoretical\cite{64,65} and experimental evidence from scanning tunneling spectroscopy\cite{15,66-68} and transport measurements\cite{69} that defects play a role in the nematic response. We stress that intrinsic spin and/or orbital nematic correlations are not produced by defects but they can be made visible by them. We expect this to be particularly true in the absence of any aligning field, i.e., in the unstressed tetragonal phase. In a simplified picture, static, but short-range correlated, orbital order is nucleated around P sites.

To summarize, our NMR work revealed unequal populations of the As 4$p_x$ and 4$p_y$ orbitals owing to Fe-

3$d$ orbital ordering in the (unstressed) tetragonal phase of BaFe$_2$(As$_{0.98}$P$_{0.02}$)$_2$. The data reveal that these orbital-nematic correlations are involved in the appearance of a nematic state
detected below $\sim 160$ K by other probes.\textsuperscript{22,24} Furthermore, the magnitude of the orbital polarization, its static nature, and its persistence at temperatures well above 160 K place strong constraints on microscopic models of nematic order in this class of superconductors.

The authors thank R. Fernandes, Y. Gallais, H. Kontani, S. Onari, Y. Ohno, Y. Kobayashi, and M. Sato for valuable discussion, and O. Leynaud for X-ray measurements. This work was supported by Scientific Research grant from JSPS and by the French ANR Supratetrafer (ANR-09-BLAN-0211), Kyoto Univ. LTM center, a Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from MEXT of Japan, and Grants-in-aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS), KAKENHI (S and A) (Nos. 20224008 and 23244075). One of the authors (T.I.) is financially supported by a JSPS Research Fellowship.

**Supplemental Material for**

**“Emergent of Orbital Nematicity in the Tetragonal Phase of BaFe$_2$(As$_1-x$P$_x$)$_2$”**

Majumder et al. reported the linear relationship between $K^{\text{spin}}$ and $\nu$ with an implicit parameter $T > T_3$ in iron pnictides.\textsuperscript{53} It was indicated from theoretical point of view that the temperature dependence of $\nu$ can be influenced by the spin susceptibility in the presence of the mode-mode coupling between charge and spin density fluctuations in itinerant magnets.\textsuperscript{52} Such linear relationships are actually observed in the various itinerant magnet systems like MnSi,\textsuperscript{70} PrCoAsO,\textsuperscript{53} NaCO$_2$O$_4$,\textsuperscript{71} LiFeAs,\textsuperscript{72} and BaFe$_2$As$_2$.\textsuperscript{45} Since the existence of the mode-mode coupling between these two channels seems to be reasonable, the contribution of $(1 - \gamma_{\nu})\nu_{\text{lat}}$ for $x = 0$ can be extracted by extrapolating the linear portion of $\nu_{\text{lat}}$ versus $K^{\text{spin}}_a$ plot to $K^{\text{spin}}_a \to 0$. For the estimation, we used $\nu_{\text{lat}}$ and $K^{\text{spin}}_a$ adopted from Ref.\textsuperscript{45} to derive $(1 - \gamma_{\nu})\nu_{\text{lat}}$ (Fig. 6). Then, $(1 - \gamma_{\nu})\nu_{\text{lat}}_{a,b}$, which is the value used in Fig. 4(b), is derived by multiplying $-1/2$ to $(1 - \gamma_{\nu})\nu_{\text{lat}}$ by following the relationship $\nu_{\text{lat}}_{a,b} = -(1/2) \times \nu_{\text{lat}}$ from Laplace’s equation $\nu_{\text{lat}}^2 + \nu_{\text{lat}}^b + \nu_{\text{lat}}^c = 0$ and $\nu_{\text{lat}}^a = \nu_{\text{lat}}^b$ above $T_3$. Finally, we obtain $(1 - \gamma_{\nu})\nu_{\text{lat}}_{a,b}$ to be 0.45 MHz.

1) K. Hashimoto, K. Cho, T. Shibauchi, S. Kasahara, Y. Mizukami, R. Katsumata, Y. Tsuruhara, H. Ikeda, M. A. Tanatar, H. Kitano, N. Salovich, R. W. Giannetta, P. Walmsley, A. Carrington, R. Prozorov, and Y. Matsuda: Science 336 (2012) 1554.
2) F. L. Ning, K. Ahilan, T. Imai, A. S. Sefat, M. A. McGuire, B. C. Sales, D. Mandrus, P. Cheng, B. Shen, and H.-H. Wen: Phys. Rev. Lett. 104 (2010) 037001.
3) M. Yoshizawa, D. Kimura, T. Chiba, S. Simayi, Y. Nakanishi, K. Kihou, C.-H. Lee, A. Iyo, H. Eisaki, M. Nakajima, and S. Uchida: J. Phys. Soc. Jpn. 81 (2012) 024604.
4) Y. Nakai, T. Iye, S. Kitagawa, K. Ishida, H. Ikeda, S. Kasahara, H. Shishido, T. Shibauchi, Y. Matsuda, and T. Terashima: Phys. Rev. Lett. 105 (2010) 107003.
5) R. M. Fernandes and J. Schmalian: Supercond. Sci. Technol. 25 (2012) 084005.
6) J.-H. Chu, J. G. Analytis, K. D. Greve, P. L. McMahon, Z. Islam, Y. Yamamoto, and I. R. Fisher: Science 320 (2010) 824.
7) J.-H. Chu, H.-H. Kuo, J. G. Analytis, and I. R. Fisher: Science 337 (2012) 710.
8) M. A. Tanatar, E. C. Blomberg, A. Kreyssig, M. G. Kim, N. Ni, A. Thaler, S. L. Bud’ko, P. C. Canfield, A. I. Goldman, I. I. Mazin, and R. Prozorov: Phys. Rev. B 81 (2010) 184508.
9) E. C. Blomberg, M. A. Tanatar, A. Kreyssig, N. Ni, A. Thaler, R. Hu, S. L. Bud’ko, P. C. Canfield, A. I. Goldman, and R. Prozorov: Phys. Rev. B 83 (2011) 134505.
10) E. C. Blomberg, M. A. Tanatar, R. M. Fernandes, I. I. Mazin, B. Shen, H.-H. Wen, M. D. Johannes, J. Schmalian, and R. Prozorov: Nat. Commun. 4 (2013) 1914.
11) A. Jesche, F. Nitsche, S. Probst, T. Doert, P. Müller, and M. Ruck: Phys. Rev. B 86 (2012) 134511.
12) A. Dusza, A. Lucarelli, F. Pfunder, J.-H. Chu, I. R. Fisher, and L. Degiorgi: Europhys. Lett. 93 (2011) 37002.
13) M. Nakajima, S. Ishida, Y. Tomioka, K. Kihou, C. H. Lee, A. Iyo, T. Ito, T. Kakeshita, H. Eisaki, and S. Uchida: Phys. Rev. Lett. 109 (2012) 217003.
14) M. Yi, D. Lu, J.-H. Chu, J. G. Analytis, A. P. Sorini, A. F. Kemper, B. Moritz, S.-K. Mo, R. G. Moore, M. Hashimoto, W.-S. Lee, Z. Husain, T. P. Devereaux, I. R. Fisher, and Z.-X. Shen: Proc. Natl. Acad. Sci. U.S.A. 108 (2011) 6678.
15) E. P. Rosenthal, E. F. Andrade, C. J. Arguello, R. M. Fernandes, L. Y. Xing, X. C. Wang, C. Q. Jin, A. J. Millis, and A. N. Pasupathy: arXiv:1307.3526.
16) Y. K. Kim, W. S. Jung, G. R. Han, K.-Y. Choi, C.-C. Chen, T. P. Devereaux, A. Chainani, J. Miyawaki, Y. Takata, Y. Tanaka, M. Oura, S. Shin, A. P. Singh, H. G. Lee, J.-Y. Kim, and C. Kim: Phys. Rev. Lett. 111 (2013) 217001.
17) L. W. Harriger, H. Q. Luo, M. S. Liu, C. Frost, J. P. Hu, M. R. Norman, and P. Dai: Phys. Rev. B 84 (2011) 054544.
18) H. Luo, M. Wang, C. Zhang, X. Lu, L.-P. Regnault, R. Zhang, S. Li, J. Hu, and P. Dai: Phys. Rev. Lett. 111 (2013) 107006.
19) S. Jiang, H. S. Jeevan, J. Dong, and P. Gegenwart: Phys. Rev. Lett. 110 (2013) 067001.

![Fig. 6](Image)

(Color online) The linear relationship between $\nu$ and $K^{\text{spin}}$ as an implicit function of $T$. A straight red line indicates the linear fitting of the data (open circles) extrapolated down to $K^{\text{spin}} \to 0$. The fitting equation with obtained parameters is also shown in the figure. The underlined value indicates the intercept, i.e., $(1 - \gamma_{\nu})\nu_{\text{lat}}$.  

$\nu_{\text{lat}} = -15.5923 \times K^{\text{spin}} - 0.89079$
