Emergent XY electronic nematicity in iron-based superconductors

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Electronic nematicity, a correlated state that spontaneously breaks rotational symmetry, is observed in several layered quantum materials. In contrast to their liquid-crystal counterparts, the nematic director cannot usually point in an arbitrary direction (XY nematics), but is locked by the crystal to discrete directions (Ising nematics), resulting in strongly anisotropic fluctuations above the transition. Here, we report on the observation of isotropic XY-nematic fluctuations, via elastoresistance measurements, in hole-doped Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ iron-based superconductors. While for $x = 0$ the nematic director points along the in-plane diagonals of the tetragonal lattice, for $x = 1$ it points along the horizontal and vertical axes. Remarkably, for intermediate doping, the susceptibilities of these two symmetry-irreducible nematic channels display comparable Curie-Weiss behavior, thus revealing a nearly XY-nematic state. This opens a new route to assess this elusive electronic quantum liquid-crystalline state, which is a candidate to host unique phenomena not present in the Ising-nematic case.

Liquid crystals are composed of molecules with anisotropic shapes, which possess a degree of orientational order. As a result, they can form nematic phases, in which translational invariance is preserved, but rotational symmetry is spontaneously broken by the selection of a director along which the molecules align. Strongly correlated electron systems often show exotic states of matter analogous to liquid-crystalline states, originating from nontrivial quantum many-body interactions. In particular, electronic nematic phases have been found in a number of quantum materials and have generated a lot of attention. After its original experimental identification in quantum Hall systems, electronic nematicity has increasingly been recognized as a ubiquitous feature of unconventional superconductors. In iron-based superconductors, electronic nematic order and fluctuations span a wide region of the phase diagram, and likely impact superconductivity. Electronically-driven rotational symmetry breaking has also been reported inside the mysterious pseudogap phase of high-$T_c$ cuprates as well as in the elusive hidden-order phase of the heavy-fermion material URu$_2$Si$_2$.

A crucial difference between electronic and liquid-crystalline nematic orders is that the former develops in the presence of a crystal, which by itself does break the rotational symmetry of the system—for instance, by restricting the possible paths along which the electrons can hop. As a result, while in liquid crystals the nematic director can point anywhere in space (i.e., it has a continuous symmetry), in electronic systems it is generally restricted to a few high-symmetry directions of the crystal (i.e., it has a discrete symmetry). While such a discrete electronic nematic state still displays interesting properties, a hypothetical continuous electronic nematic state would host several unique quantum many-body phenomena. For instance, the transverse and longitudinal fluctuations in the disordered phase have completely different dynamics, which may lead to multiscale critical behavior. Moreover, the ordered phase has a Goldstone mode associated with the breaking of the continuous symmetry by the director. Remarkably, unlike other Goldstone modes such as phonons or magnons, the nematic mode couples directly to the electronic density rather than to gradients of the density. This can lead to strange metallic behavior and strongly impact superconductivity.

At first sight, the inevitable presence of the crystal may be taken as an insurmountable obstacle to realize a continuous electronic nematic state in actual materials. However, as we argue now, and demonstrate below experimentally in the hole-doped iron pnictide Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$, a nearly-continuous nematic phase can be observed under certain conditions. To make the discussion concrete, we consider layered crystals with tetragonal symmetry, i.e., the symmetry of a square. Indeed, many of the materials where nematicity has been observed, do possess this symmetry. We start our discussion by first assuming that there was no underlying crystal. Then the electronic nematic director could point anywhere in the layer plane. In this case, in analogy to a two-dimensional nematic liquid crystal, the nematic order parameter is described in terms of a traceless symmetric 2 × 2 matrix given by: \( \mathbf{Q} = \begin{pmatrix} N_1 & N_2 \\ N_2 & -N_1 \end{pmatrix} \).

Here, the order parameter \( N_1 \) corresponds to a quadrupolar charge density that makes the horizontal \((x)\) and vertical \((y)\) directions inequivalent \((d_{z^2-r^2}\)-wave form fac-

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The microscopic model. The anisotropic term parameter: one of the two components of the XY nematic order logue, the axis anisotropy. Indeed, the nematic order parameter is analogous to an XY (i.e., planar) ferromagnet with an easy-energy range as long as the anisotropy coefficient be relevant to describe the system’s behavior over a wide range, that many of the properties of the XY-nematic state will over, once long-range order sets in, the collective modes like, the fluctuation spectrum is very similar to that of the XY ferromagnet, except at very low energies. More formally, the free energy expansion becomes

\[ F = \frac{\gamma}{2}(N_1^2 - N_2^2) + \frac{u}{2}(N_1^2 + N_2^2) + \frac{v}{4}(N_1^2 + N_2^2)^2. \]  

Here, \( a \) and \( u \) are Landau coefficients that depend on the microscopic model. The anisotropic term \( \gamma \) selects one of the two components of the XY nematic order parameter: \( B_{1g} \) nematic order when \( \gamma < 0 \), and \( B_{2g} \) nematic order when \( \gamma > 0 \). The situation is analogous to an XY (i.e., planar) ferromagnet with an easy-axis anisotropy. Indeed, the nematic order parameter can now be written in terms of Pauli matrices as \( \mathcal{Q} = N_1 \sigma_z + N_2 \sigma_x \), expressing the analogy between \( N_i \) and magnetic moment components. In the magnetic analogue, the \( \gamma \) term corresponds to the single-ion anisotropy that defines the magnetization easy axis. This analogy offers a fruitful insight: in ferromagnets, when the single-ion anisotropy is much smaller than the exchange coupling, although the magnetic transition is formally Ising-like, the fluctuation spectrum is very similar to that of the XY ferromagnet, except at very low energies. Moreover, over long-range order sets in, the collective modes correspond essentially to a Goldstone mode with a very small gap.

Thus, going back to the nematic case, it is expected that many of the properties of the XY-nematic state will be relevant to describe the system’s behavior over a wide energy range as long as the anisotropy coefficient \( |\gamma| \) is much smaller than the nematic energy scale, which we can set to be the nematic transition temperature \( T_{\text{nem}} \). The remaining task is to find a concrete system with \( |\gamma| \ll T_{\text{nem}} \). A promising strategy is to interpolate between two different compounds that display \( B_{1g} \) nematic order (\( \gamma < 0 \)) and \( B_{2g} \) nematic order (\( \gamma > 0 \)), forcing \( \gamma \) to cross zero. In the remainder of this paper, we show that such a situation is realized in the hole-doped iron pnictide \( \text{Ba}_{1-x}\text{Rb}_x\text{Fe}_2\text{As}_2 \).

The parent compound \( \text{BaFe}_2\text{As}_2 \) \((x = 0)\) displays an antiferromagnetic transition that is preceded by a tetragonal to orthorhombic structural transition, which makes the diagonals \([110]\) and \([110]\) of the tetragonal crystallographic unit cell inequivalent. It is well established that the structural transition is not driven by lattice degrees of freedom, but is the result of an electronic nematic instability in the \( B_{2g} \) channel. Upon increasing doping, the structural transition temperature is suppressed, approaching a putative quantum critical point near optimal doping, where the superconducting dome is peaked. The superconducting dome extends all the way up to \( x = 1 \). Interestingly, in all hole-doped systems \( \text{Ba}_{1-x}\text{A}_x\text{Fe}_2\text{As}_2 \), with alkali metal \( A = \text{K}, \text{Rb}, \text{Cs} \), the effective electronic mass is observed to be strongly enhanced near \( x = 1 \). This suggests a progressively more important role of electronic correlations in the \( 3d^{5}\) electronic configuration \((x = 1)\) as compared to the \( 3d^{6}\) configuration \((x = 0)\), which may be related to proximity to a hypothetical \( 3d^{5}\) Mott insulating state. This motivates a careful investigation of nematic tendencies in extremely hole-doped pnictides with the prospect of finding a suitable alloy series with a crossover to \( B_{1g} \) dominance, as the stronger correlations may promote a mechanism for electronic nematicity different from that of the undoped compound.

To study nematicity in the extremely hole-doped regime, we use elasto-resistance measurements, which have been shown to probe the static nematic susceptibility. In this technique, we measure the relative change in resistance \( \Delta R/R \) in response to an externally applied strain \( \epsilon \), which is controlled by a piezoelectric device. Because uniaxial strain couples linearly to the nematic order parameters, in the linear response regime the quantity \( \chi_{\text{nem}} \sim \frac{1}{R} \frac{\partial \Delta R}{\partial \epsilon} \) is proportional to the nematic susceptibility (see Supplementary Information). Specifically, in the iron pnictides, the nematic susceptibilities in the \( B_{1g} \) and \( B_{2g} \) symmetry channels (denoted here by \( \chi_{\text{nem}}^{(1)} \) and \( \chi_{\text{nem}}^{(2)} \), respectively, with the superscript denoting the strain direction) can be obtained by applying strain along the nearest neighbor Fe-As and Fe-Fe bond directions, corresponding to \([100]\) and \([110]\), respectively (Fig. 1a).

Figures 1b-e show representative data of \( \Delta R/R \) as a function of applied strain \( \epsilon \) along the \([100]\) and \([110]\) directions. In \( \text{BaFe}_2\text{As}_2 \), which displays the \( 3d^{6}\) electronic configuration, the elasto-resistances in the two channels show a striking anisotropy, with the response to the strain along the \([110]\) direction being much larger than that along \([100]\) (Fig. 1b,c). This is consistent with previous reports and reflects the Ising-like character of the \( B_{2g} \) nematic state, which sets in when \( \chi_{\text{nem}}^{(2)} \) peaks. In sharp contrast, in \( \text{CsFe}_2\text{As}_2 \) with \( 3d^{5}\) electronic configuration, the elasto-resistence for strain applied along \([100]\) becomes much larger than that along \([110]\), indicating that Ising-like \( B_{1g} \) nematic fluctuations are dominant. Such a difference can be clearly seen in the temperature dependence of the nematic susceptibilities ob-
strained from the slopes of $\Delta R/R$ as function of $\epsilon$, as shown in Fig. 2a,b. Although the nematic susceptibilities presented here were evaluated from longitudinal elastoresistance measurements, we confirmed that they are identical to those determined by using a modified Montgomery method, indicating negligible contaminations of $A_{1g}$-symmetry strain effect (see Supplementary Information).

In the case of BaFe$_2$As$_2$ (Fig. 2a), $\chi_{\text{nem}}^{[110]}$ is much larger and has a more pronounced temperature dependence as compared with $\chi_{\text{nem}}^{[100]}$. Moreover, as demonstrated previously [13], $\chi_{\text{nem}}^{[110]}$ has a peak at the nematic transition temperature $T_{\text{nem}}$. Above this temperature, the nematic susceptibility can be described by a Curie-Weiss expression

$$\chi_{\text{nem}} = \chi_0 + \frac{C}{T - T_0}.$$  

Here, $C$ is a constant, and $\chi_0$ is a temperature-independent term not related to the nematic fluctuations. The Curie-Weiss temperature $T_0$ represents the “bare” nematic transition temperature without nemato-lattice coupling effects. Such a $B_{2g}$ Ising-nematic order has been observed in many iron-based superconductors [22, 58]. However, in CsFe$_2$As$_2$ (Fig. 2b), we find that the dominant nematic fluctuations appear in the $B_{1g}$ channel, since $\chi_{\text{nem}}^{[100]}$ displays a considerably larger magnitude and stronger temperature dependence than $\chi_{\text{nem}}^{[110]}$. We also note that the sign of $\chi_{\text{nem}}^{[100]}$ is positive for CsFe$_2$As$_2$, in contrast to the negative sign of $\chi_{\text{nem}}^{[110]}$ in BaFe$_2$As$_2$. Such a sign reversal has also been reported for the in-plane resistivity anisotropy in Ba$_{1-x}$K$_x$Fe$_2$As$_2$, where the hole doping changes sign of $\rho_b/\rho_a - 1$ from positive to negative [23].

As shown in Fig. 2c, similar $B_{1g}$ Ising-nematic behavior as in CsFe$_2$As$_2$ is also observed in RbFe$_2$As$_2$, suggesting that nematicity along the Fe-As direction, $45^\circ$ tilted with respect to the Fe-Fe direction, is a generic feature of the $3d^{5.5}$ electronic configuration. Indeed, recent nuclear magnetic resonance and scanning tunneling microscopy studies suggested $B_{1g}$ nematicity in these compounds [24, 25], although the presence of long-range nematic order has not been settled. Here, we note that not only do the $\chi_{\text{nem}}^{[100]}(T)$ curves for both CsFe$_2$As$_2$ and RbFe$_2$As$_2$ follow Curie-Weiss behavior over a wide temperature range, but also does the nematic susceptibility of RbFe$_2$As$_2$ exhibit a distinct peak at $T_{\text{nem}} \sim 38$ K, indicative of the onset of long-range nematic order in the $B_{1g}$ channel. Recent specific-heat measurements un-
order in-plane field rotation indeed show two-fold oscillations near $T_g$, supporting the $B_{1g}$ nematic order in RbFe$_2$As$_2$ [26]. This is consistent with a positive Curie-Weiss temperature $T_0 \approx 25$ K obtained for RbFe$_2$As$_2$ by fitting Eq. (2) to $\chi_{\text{nem}}^{[100]}(T)$. In contrast, we have found $T_0 \approx -4$ K for CsFe$_2$As$_2$, from which we conclude that CsFe$_2$As$_2$ is close to a possible $B_{1g}$ nematic quantum critical point (QCP), which would correspond to $T_0 = 0$. The largely enhanced magnitude of $\chi_{\text{nem}}^{[100]}$ is also consistent with quantum-critical fluctuations of $B_{1g}$ nematicity [22]. We note in passing that, at low temperatures, $\chi_{\text{nem}}^{[100]}$ in CsFe$_2$As$_2$ shows a noticeable deviation from the Curie-Weiss behavior. Similar deviations have been seen in several iron-based materials in the vicinity of their putative $B_{2g}$ nematic QCP, when the Curie-Weiss temperature extrapolates to zero [22, S3]. Although disorder effects have been discussed as a possible origin of this behavior, the observation of a similar deviation in the very clean CsFe$_2$As$_2$ compound, where sharp quantum oscillations are clearly observed [16], suggests that mechanisms other than disorder may be important for the behavior close to a nematic QCP.

Our elastoresistance measurements thus establish two parent iron-pnictide compounds, the $3d^6$ BaFe$_2$As$_2$ and the $3d^{5.5}$ RbFe$_2$As$_2$, that display Ising-nematic orders in two orthogonal channels, namely, $B_{2g}$ (corresponding to $\gamma > 0$ in Eq. (11)) and $B_{1g}$ (corresponding to $\gamma < 0$ in Eq. (11)), respectively. Following the strategy outlined above, it is thus straightforward to search for signatures of XY nematicity in the doped compound Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$.

The doping evolution of the elastoresistance is depicted in Fig. 3. For Rb concentrations up to $x = 0.65$, $\chi_{\text{nem}}^{[110]}$ remains considerably larger than $\chi_{\text{nem}}^{[100]}$. For $x = 0.65$, the temperature dependence of $\chi_{\text{nem}}^{[110]}$ continues to follow a Curie-Weiss behavior with a negative $T_0$, indicating the dominance of $B_{2g}$ nematic fluctuations, but there is no evidence for long-range nematic order (Fig. 3a). As the Rb concentration further increases ($x = 0.75, 0.80$, and $0.86$), the magnitude of $\chi_{\text{nem}}^{[100]}$ gradually grows at the expense of $\chi_{\text{nem}}^{[110]}$, as shown in Fig. 3b-d, reflecting the development of a $B_{1g}$ nematic instability near $x = 1$. Remarkably, for $x = 0.80$ and $0.86$, the nematic susceptibilities in the two channels have comparable magnitudes and similar temperature dependencies at high temperatures. In this doping range, the system displays long-range $B_{1g}$ nematic order, as signaled by the positive $T_0$ and, more importantly, by the peak in $\chi_{\text{nem}}^{[100]}(T)$, which defines $T_{\text{nem}}$. Interestingly, despite the onset of long-range order in the $B_{1g}$ channel, $\chi_{\text{nem}}^{[110]}$ continues to increase even below $T_{\text{nem}}$, indicating the importance of both nematic modes for all temperatures. In the $x$ range between $B_{1g}$ and $B_{2g}$ nematic orders, i.e., for $x = 0.75$, the absence of peaks in the nematic susceptibilities indicates the absence of long-range nematic order. In addition, the two nematic susceptibilities show almost identical temperature dependencies, with very similar Curie-Weiss temperatures. This is direct evidence that this compound is very close to an XY-nematic state.

Our main findings are summarized in the Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ phase diagram shown in Fig. 4. The electronic nematic director rotates by $45^\circ$ with increasing Rb doping, changing from $B_{2g}$ Ising-nematic order near $x = 0$ (blue region) to $B_{1g}$ Ising-nematic order at $x = 1$ (red region). In an intermediate doping range, the nematic susceptibilities in the two channels become very similar, thus revealing an emergent nearly-XY nematic fluctuating regime (purple region). The Curie-Weiss temperature extracted from the $B_{1g}$ nematic susceptibility shows an abrupt change near the $x = 0.80$ composition, below which long-range $B_{1g}$ nematic order is no longer detected. It is noteworthy that in the related compound Ba$_{1-x}$K$_x$Fe$_2$As$_2$, the Fermi pockets near the Brillouin zone corner change from electron-like to hole-like near a similar doping composition [27]. Whether this Lifshitz transition is related to the loss of long-range $B_{1g}$ nematic order remains to be established. Although the microscopic origin of this novel nematic state is not clear at present, the opposite trends of the $B_{2g}$ and $B_{1g}$ nematic transition temperatures with doping indicate that the two nematic states likely have different origins. Unlike BaFe$_2$As$_2$, neither a structural distortion nor long-range magnetic order have been reported so far for RbFe$_2$As$_2$. Recent studies of possible charge order in RbFe$_2$As$_2$ [28] and in KFe$_2$As$_2$ under high pressure [29] suggest that charge degrees of freedom could be important. The resemblance of this region of the phase diagram to that of the underdoped high-$T_c$ cuprates may offer new insights to elucidate the origin of the observed nematicity.

The present observation of electronic XY-nematic fluc-
FIG. 4. Phase diagram of Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$. Temperature ($T$) versus Rb concentration ($x$) phase diagram obtained in this study. The structural transition temperature $T_{nem}$ (purple triangles) and the superconducting transition temperature $T_c$ (open squares) refer to previous results on polycrystalline samples [30]. $T_c$ of the single crystals synthesized in this work are denoted by closed squares. The onset temperature $T_{nem}$ (red closed triangles) of the new B$_{1g}$ nematic state is defined by the peak in $\chi_{\langle 100 \rangle}$ [100]. The Curie-Weiss temperatures $T_0$ are extracted from the Curie-Weiss fittings of $\chi_{\langle 100 \rangle}$ (red inverted triangles) and $\chi_{\langle 110 \rangle}$ (blue inverted triangles). The Curie-Weiss temperatures of the B$_{2g}$ nematic susceptibilities in underdoped Ba$_{1-x}$K$_x$Fe$_2$As$_2$, obtained by shear modulus measurements [31], are also shown for comparison. The lines are guides to the eyes. The blue, red, and purple shaded regions highlight the three different types of nematic fluctuations observed above the ordering temperatures.

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**METHODS**

**Single crystals**

Single crystals of \( RbFe_2As_2 \) and \( CsFe_2As_2 \) were grown from arsenic-rich flux as described in Ref. [16]. The crystals grown by this method have been characterized by several measurements including X-ray, thermal expansion, ac susceptibility, and specific heat [16-18], and quantum oscillations have been observed in the magnetotransport [16] indicating the cleanness of these samples. Single crystals of \( Ba_{1-x}Rb_xFe_2As_2 \) with various \( Rb \) concentrations \( x \) were grown by the FeAs self-flux method. \( x \) was determined by energy dispersive X-ray spectrometry and also checked from the \( c \)-axis lattice constant measured by X-ray diffraction.

**Elastoresistance measurements**

Elastoresistance measurements were conducted as described elsewhere [13, 22]. The sample was directly glued onto the top surface of the piezolectric device, and the strain induced to the sample was controlled by applying a voltage to the piezo-stack. The amount of the strain was measured by a strain gauge attached to the back side of the device.

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**AUTHOR CONTRIBUTIONS**

T.S. conceived and supervised the project. K.I., M.T., S.I., A.I., H.E. grew the \( Ba_{1-x}Rb_xFe_2As_2 \) single crystals and T.W., K.G., H.v.L. provided \( RbFe_2As_2 \) and \( CsFe_2As_2 \) single crystals. K.I., M.T., S.H., Y.M. designed and carried out the elastoresistance measurements. K.I., M.T., T.S. analyzed the data. R.M.F. contributed to the theoretical interpretation of the data in terms of XY electronic nematicity. K.I., R.M.F., T.S. wrote the manuscript with help from H.v.L. All authors reviewed and commented on the manuscript.
Supplementary Information

1. Resistivity measurements

The temperature dependence of the in-plane resistivity is measured by the standard four-probe method, and the results of Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ single crystals are shown in Fig. S1. The superconducting transition temperature $T_c$ of the crystals was determined by the onset of superconducting transition (black arrows). The characteristic S-shaped temperature dependence as well as overall doping dependence of $T_c$ are similar to that reported in Ba$_{1-x}$K$_x$Fe$_2$As$_2$ single crystals [S1].

![Fig. S1. Temperature dependence of the resistivity for the Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ single crystals.](image)

We have systematically evaluated the $B_{1g}$ and $B_{2g}$ nematic susceptibility in AFe$_2$As$_2$ ($A =$ Ba, Cs and Rb) and Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ (Figs. 2 and 3) from longitudinal elastoresistance measurements, where the current direction is parallel to the applied strain $\epsilon_{xx}$. At present, we have not obtained reliable data for KFe$_2$As$_2$, whose crystals are more sensitive to air.

For the longitudinal measurements we use rectangular crystals with typical dimensions of $\sim 1.0 \times 0.4 \times 0.02 \text{ mm}^3$. The resistance of the sample ($R_{xx}$) was measured by the conventional four-probe method (Fig. S2a). For the $B_{1g}$ and $B_{2g}$ nematic susceptibility measurements, the edges of the samples are aligned along the tetragonal [100] and [110] directions, respectively.

It should be noted that, strictly speaking, the strain transmitted to the sample via the orthorhombic deformation of the piezoelectric stack has not uniaxial but highly anisotropic biaxial character, which can be decomposed into in-plane $A_{1g}$-symmetry strain ($\frac{1}{2} (\epsilon_{xx} + \epsilon_{yy})$) and $B_{1g}$/2g-symmetry strain ($\frac{1}{2} (\epsilon_{xx} - \epsilon_{yy})$). However, since $\epsilon_{xx}$ and $\epsilon_{yy}$ have opposite signs, and their ratio is characterized by the in-plane Poisson’s ratio $\nu_p$ of the piezoelectric device ($\epsilon_{yy} = -\nu_p \epsilon_{xx}$), the $A_{1g}$-symmetry strain is small compared to the $B_{1g}$/2g-symmetry strain $S2$. To see the effect of $A_{1g}$-symmetry strain on the elastoresistance, we also conducted additional elastoresistance measurements using a modified Montgomery method $S3$. For this type of measurement, samples with square shape were used ($\sim 0.6 \times 0.6 \times 0.03 \text{ mm}^3$), and the resistances along both $x$ and $y$ directions ($R_{xx}$ and $R_{yy}$) are measured by switching the current and voltage configurations (Fig. S2a). In this method, the nematic susceptibility $\chi_{\text{nem}}$ is given by $\chi_{\text{nem}} \sim 1/2((\Delta R/R)_{xx} - (\Delta R/R)_{yy})/\epsilon_{xx}$, in which $A_{1g}$-symmetry strain effect can be removed.

As shown in Fig. S2b, the data of [110] $\chi_{\text{nem}}(T)$ in Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ with $x = 0.65$ determined by two methods are almost identical, revealing that the $A_{1g}$-symmetry strain effect is negligibly small in the present measurements, and the longitudinal elastoresistance measurements can be used to extract nematic susceptibility in our study.

2. Nematic susceptibility

As shown in Fig. S2b, the data of [110] $\chi_{\text{nem}}(T)$ in Ba$_{1-x}$Rb$_x$Fe$_2$As$_2$ with $x = 0.65$ determined by two methods are almost identical, revealing that the $A_{1g}$-symmetry strain effect is negligibly small in the present measurements, and the longitudinal elastoresistance measurements can be used to extract nematic susceptibility in our study.

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