The newly discovered iron selenide superconductors \( A_x \text{Fe}_{2-y} \text{Se}_2 \) \( (A = \text{K}, \text{Rb}, \text{Cs}) \) [1] became famous for their relatively high critical temperature, \( T_c = 32 \text{K} \), observed concurrently with a strong antiferromagnetic (AFM) order that persists far above room temperature [2, 3]. However, an ordered moment as large as \( 3.3 \mu_B/\text{Fe} \) [4] renders microscopic coexistence [5] doubtful. The superconducting (SC) phase usually appears in samples close to the 2:4:5 stoichiometry [3, 6], which is at the same time the optimal composition for the ordering of Fe vacancies into a \( \sqrt{5} \times \sqrt{5} \) superstructure, grouping the occupied iron sites in plaquettes of four ferromagnetically aligned moments. On the one hand, experiments [3, 7, 8] and band structure calculations [9, 10] suggest this superstructure to be insulating. On the other hand, angle-resolved photoelectron spectroscopy (ARPES) revealed a Fermi surface (FS) dominated by a large electron pocket at the \( M \) point [11, 12]. Recent reports reconcile these seemingly contradictory findings by the observation of several coexisting phases, seen in transmission electron microscopy (TEM) [13–16], scanning tunneling microscopy (STM) [7], x-ray diffraction [17], ARPES [18], magnetization measurements [19], muon-spin rotation (\( \mu \)SR) [20], Mössbauer [21] and optical [8] spectroscopies. While STM studies observed the SC gap on a vacancy-free surface [7], TEM measurements suggested that the second phase is an iron-vacancy disordered state [13, 14]. The phase separation scenario clearly needs more clarification in terms of the structure and stoichiometry of the SC phase for a consistent understanding of these observations.

In iron pnictides, it is established that the SC order parameter changes its sign between the hole- and electronlike sheets of the FS [22–24]. Despite the absence or strong reduction of the hole Fermi pocket in iron selenides [25], different kinds of a sign-changing gap have also been suggested [26–28]. The recent finding of a magnetic resonant mode in this compound has a quasi-two-dimensional character, similar to overdoped iron-pnictide superconductors. Moreover, it has a rich in-plane structure that is dominated by four elliptical peaks, symmetrically surrounding the Brillouin zone corner, without \( \sqrt{5} \times \sqrt{5} \) reconstruction. We also present evidence for the dispersion of the resonance peak, as its position in momentum space depends on energy. Comparison of our findings with the results of band structure calculations provides strong support for the itinerant origin of the observed signal. It can be traced back to the nesting of electronlike Fermi pockets in the doped metallic phase of the sample in the absence of iron-vacancy ordering.

Reconciled with theoretical calculations performed for the electron-doped phase with the \( A_x \text{Fe}_2 \text{Se}_2 \) stoichiometry (not matching the average chemical composition of the sample) under the assumption of a \( d \)-wave symmetry of the SC order parameter [27, 28]. Alternatively, the metallic phase could possibly be associated with (i) a vacancy-disordered structure [13, 30], which would effectively result in a rigid-band shift and broadening of the \( A_x \text{Fe}_2 \text{Se}_2 \) electronic bands [10], (ii) an electron-doped \( A_x \text{Fe}_2 \text{Se}_2 \) phase [31] with full or partial vacancy ordering, or (iii) possess a different \( \sqrt{2} \times \sqrt{2} \) superstructure that corresponds to the \( A_x \text{Fe}_{1.5} \text{Se}_2 \) composition [13, 16, 32]. However, to the best of our knowledge, first-principles calculations of the spin-excitation spectrum are not yet available for any of these alternative scenarios.

To be able to differentiate between the mentioned possibilities and thus to verify the origin of the spin-excitation spectrum, we have performed a detailed study of the reciprocal-space structure and the dispersion of the previously reported resonant mode. We show that the resonant magnetic excitations in the SC state of \( \text{Rb}_x \text{Fe}_{2-y} \text{Se}_2 \) are quasi-two-dimensional (2D) and exhibit a complex in-plane pattern, dominated by four elliptical peaks that symmetrically surround the corner of the unfolded Brillouin zone (BZ) [33]. This result is consistent with the dynamic spin susceptibility of an electron-doped \( A_x \text{Fe}_2 \text{Se}_2 \) compound, calculated in the SC state from a tight-binding model of the band structure by means of the random phase approximation (RPA) [27].

The sample for this study is identical to the one used in Ref. 29. It comprises several coaligning single crystals with the chemical composition \( \text{Rb}_{0.8} \text{Fe}_{1.6} \text{Se}_2 \) and a total mass of \( \sim 1 \text{g} \). These crystals are bulk superconductors with a \( T_c \) of 32 K [29], which have been characterized by transport, magnetometry and specific heat measurements (batch BR16 in Ref. 6). The experiments were conducted at the thermal-neutron spectrometer IN8 (ILL, Grenoble), which was operated both in the triple-axis-spectrometer (TAS) and in the FlatCone multianalyzer configurations. The latter al-
we observe a substantial magnetic response, which becomes considerably enhanced below $T_c$. The center of both peaks lies at $K_0 = (0.244 \pm 0.002)$, close to the commensurate position at $K = \frac{1}{2}$. In Fig. 1 (b), the INS intensity at $Q = (\frac{1}{2}, \frac{1}{2}, 0)$ and $E = 14$ meV is plotted as a function of the out-of-plane momentum component along $\frac{1}{2} \pm L$ for both temperatures. The intensity difference between 1.5 and 35 K [Fig. 1 (c)], representing the resonant enhancement, is maximized at $L = 0$ and then monotonically decreases for larger $L$ following the Fe$^{2+}$ magnetic form factor. This closely resembles the 2D nature of the signal in overdoped BaFe$_{2-x}$Co$_x$As$_2$ [23], but is in contrast to the behavior of underdoped BaFe$_{2-x}$Ni$_x$As$_2$, where it is modulated as a function of $L$ and exhibits a maximum at $L = \frac{1}{2}$ [33].

The weak $L$-dependence of the resonant signal can also be inferred from the energy scans measured above and below $T_c$, such as those presented in Fig. 1 (d) for $k_L = 2.662 \, \AA^{-1}$ and $4.1 \, \AA^{-1}$. The intensity difference between the two temperatures is shown in panel (e) for both integer and half-integer $L$. Neither the energy nor the amplitude of the resonance peak shows any notable $L$-dependence beyond the uncertainty of the fit. This fact is consistent with ARPES measurements of the weak $k_L$-dispersion of the electron band at the $M$ point and of the SC gap [12].

Based on the quasi-2D character of the magnetic intensity, we have mapped out the resonant enhancement of spin

lowed us convenient mapping of the reciprocal space at a constant energy. In the FlatCone configuration we utilized Si(111) monochromator and analyzer with the fixed final wave vector $k_f = 3 \, \AA^{-1}$. For the TAS measurements, we used pyrolytic graphite (002) monochromator and analyzer with double focusing. The TAS measurements were done with constant $k_L = 2.662 \, \AA^{-1}$ and $4.1 \, \AA^{-1}$, and a pyrolytic graphite filter was installed between the sample and the analyzer to suppress higher-harmonic contamination. In order to measure the dispersion and the intensity distribution of the resonant mode along the $c$ axis, we mounted the sample in the $(2H H L)$ scattering plane. Subsequent investigations of in-plane excitations were done in the $(H K 0)$ plane. Here and throughout the paper our notation is given in unfolded reciprocal lattice units (r.l.u.), which refer to the iron sublattice with the lattice parameters $a = b = 2.76 \, \AA$ and $c = 7.25 \, \AA$ [29]. The existence of an Fe-vacancy-ordered AFM phase in our sample has been verified by measuring the magnetic superstructure reflections [29].

In Fig. 1 (a) we present longitudinal [as seen from $(\frac{1}{2}, \frac{1}{2}, 0)$] momentum scans at the resonance energy, $\hbar\omega_{\text{res}} = 14$ meV, along the $(\frac{1}{2} K - \frac{1}{2})$ direction in the normal state at 35 K and in the SC state at 1.5 K. Already in the normal state,
The intensity is integrated over the whole extent of the ellipse. This resulted in a doping level of $0.18 \text{ electrons/Fe}$. In order to reduce the statistical noise in the data, we have rebinned this data set on an $81 \times 81$ grid and symmetrized it with respect to both axes of the ellipse. The resulting intensity map is shown in Fig. 2 (b) as a contour plot.

One sees that the in-plane shape of the resonant intensity takes an elliptical form, elongated transversely with respect to the vector connecting it to $(\frac{1}{4} 0 0)$. We emphasize this by presenting cuts through all ellipses in the map of Fig. 2 (a) in the longitudinal [Fig. 2 (c)] and transverse [Fig. 2 (d)] directions. The intensity is integrated over the whole extent of the ellipse perpendicular to the cut, as indicated by the black bars in (a), in order to capture the whole resonant intensity. We observe an agreement between equivalent cuts through the ellipse in the SC and normal states. Again, strongly anisotropic widths of the transverse and longitudinal profiles are observed in the intensity difference. The peak in the longitudinal direction for both resonances near $(\frac{1}{2} \frac{1}{2} 0)$ and $(\frac{1}{2} 0 0)$. The intensity is integrated over the whole extent of the ellipse. This resulted in a doping level of $0.18 \text{ electrons/Fe}$. In order to reduce the statistical noise in the data, we have rebinned this data set on an $81 \times 81$ grid and symmetrized it with respect to both axes of the ellipse. The resulting intensity map is shown in Fig. 2 (b) as a contour plot.

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Next, we present momentum scans measured by TAS in longitudinal [Fig. 3 (a)] and transverse [Fig. 3 (b)] directions through the ellipse in the SC and normal states. Again, strongly anisotropic widths of the transverse and longitudinal profiles are observed in the intensity difference. The peak in the longitudinal direction for both resonances near $(\frac{1}{2} \frac{1}{2} 0)$ and $(\frac{1}{2} 0 0)$. The intensity is integrated over the whole extent of the ellipse. This resulted in a doping level of $0.18 \text{ electrons/Fe}$. In order to reduce the statistical noise in the data, we have rebinned this data set on an $81 \times 81$ grid and symmetrized it with respect to both axes of the ellipse. The resulting intensity map is shown in Fig. 2 (b) as a contour plot.
Fig. 4 (color online). (a) The difference of the calculated imaginary parts of the dynamic spin susceptibility for the SC and normal states, taken at the resonance energy, $\chi_{\text{sc}}^{\text{Im}}(Q, \omega_{\text{res}}) - \chi_{\text{n}}^{\text{Im}}(Q, \omega_{\text{res}})$. The calculation was done within RPA from the tight-binding band model of $A_2\text{Fe}_5\text{S}_{12}$ [27], which was rigidly shifted to match the experimental peak positions. An isotropic Gaussian broadening with a standard deviation of 0.02 r.l.u. has been applied to mimic the experimental resolution. (b) The resulting FS in the $(H K 0)$ plane corresponds to the doping level of 0.18 electrons/Fe. The black arrows are the in-plane nesting vectors responsible for the resonance peaks observed in our present study.

reveals good agreement between the two $Q$-space patterns, as both the orientation and the aspect ratio of the elliptical peaks is well captured by the calculation. The origin of these peaks can be traced back to the nesting of electronlike Fermi pockets, as indicated in Fig. 4 (b) by black arrows.

To conclude, the fact that the complicated pattern of resonant intensity in $Q$-space can be successfully reproduced by our calculation strongly supports the itinerant origin of the observed magnetic response. The signal shows no signatures of the $\sqrt{5} \times \sqrt{5}$ reconstruction, indicating that it originates in the metallic phase of the sample without iron-vacancy ordering, as suggested recently [13, 14, 36]. This distinguishes the newly observed signal from the previously reported spin-wave excitations in this class of compounds [37] that stem from the magnetic superstructure Bragg positions in the insulating vacancy-ordered phase and are insensitive to the SC transition. The incommensurability of the resonance peak, as well as its variation with the out-of-plane momentum component and with energy, further indicates that it is not pinned to a particular position in $Q$-space, but is arbitrarily determined by the level of electron doping, in line with the assumptions of Ref. 27.

Furthermore, we note that iron-pnictide compounds generally exhibit a tendency towards a 2D behavior of spin fluctuations with an increase of the doping level or $T_c$ [33, 38]. For example, optimally doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$, which has the highest known critical temperature among all 122-compounds, shows almost no dispersion of the resonant energy, $\hbar \omega_{\text{res}}$, along the $c$ direction [34]. Our data on $\text{Rb}_x\text{Fe}_2\text{Se}_2$ with a comparable transition temperature are fully consistent with this trend.

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