Tuning the superconducting and magnetic properties of Fe$_2$Se$_{0.25}$Te$_{0.75}$ by varying the iron content

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The superconducting and magnetic properties of Fe$_2$Se$_{0.25}$Te$_{0.75}$ single crystals ($0.9 \leq y \leq 1.1$) were studied by means of x-ray diffraction, superconducting quantum interference device magnetometry, muon-spin rotation, and elastic neutron diffraction. The samples with $y < 1$ exhibit coexistence of bulk superconductivity and incommensurate magnetism. The magnetic order remains incommensurate for $y \geq 1$ but with increasing Fe content superconductivity is suppressed and the magnetic correlation length increases. The results show that the superconducting and the magnetic properties of the Fe$_2$Se$_{1-y}$Te$_y$ can be tuned not only by varying the Se/Te ratio but also by changing the Fe content.

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The iron chalcogenide family of superconductors Fe$_x$Ch (Ch = Se/Te) was discovered in 2008 (Ref. 1) shortly after the report of high-temperature superconductivity (HTS) in the iron pnictides. This family stands out because of its simple crystal structure relative to other Fe-based superconductors. In common with the other Fe-based HTS the parent phase, FeTe, exhibits antiferromagnetic order and superconductivity appears only upon substitution of Te with Se or S. The superconducting transition temperature $T_c$ is lower than in most of the other Fe-based superconductors, reaching a value of $\approx 14$ K in Fe$_{0.8}$Se$_{0.2}$Te$_{0.8}$ at optimal Se/Te ratio and $\approx 36$ K at high pressures. Despite its relatively low $T_c$ the binary FeCh system is attractive for fundamental investigations of the interplay between magnetism and superconductivity because of (i) its simple crystallographic structure, (ii) the relative ease with which single crystals can be grown, and (iii) the similarity of the Fermi surface topology with that of other Fe-based superconductors.

Recently, it has been reported that the superconducting and magnetic properties of Fe$_x$Se$_{1-y}$Te$_y$ do not only depend on the Se/Te ratio but also strongly on the Fe content. Here we report a systematic investigation of the magnetic and superconducting properties, and their interplay, of Fe$_{0.8}$Se$_{0.25}$Te$_{0.75}$ with different nominal Fe content in the range $0.9 \leq y \leq 1.1$. Samples with low Fe content ($y < 1$) are found to be bulk superconductors with coexistent magnetic order that sets in at a temperature below $T_c$. Stoichiometric samples ($y = 1$) show filamentary superconductivity and magnetic order. Fe-rich samples ($y > 1$) are almost purely magnetic with only traces of superconductivity. Interestingly, the magnetic order was observed to be incommensurate throughout the entire range of nominal Fe content investigated, although the correlation length increases with increasing Fe content.

The Fe$_{y}$Se$_{1-x}$Te$_{y+x}$ samples were prepared within a wide range of nominal Fe content from $y=0.9$ to 1.1 ($y=0.90, 0.95, 0.98, 1.00, 1.01, 1.02, 1.03, 1.07, 1.10$), with a fixed Se to Te ratio of $x=0.25$. The single crystals were prepared in the form of rods with masses of $m=4-5$ g by a modified Bridgman method. For a detailed description of the procedure see Ref. 22.

To establish the crystal structure and the stoichiometry, the samples were investigated by single-crystal x-ray diffraction (XRD) at room temperature. Data reduction and numerical absorption correction were performed using the Bruker AXS Inc. software package. The crystal structure was solved by direct method and refined on $F^2$, employing the programs SHELXS-97 and SHELXL-97. All crystals reveal a tetragonal lattice (space group $P4/nmm$) with the lattice parameters $a$ and $c$ presented in Table I. The refined Se/Te ratio $Se_{occ}$ is within standard deviation (±3%) close to the nominal content. The three samples with the nominal Fe content of 0.95, 0.98, and 1.03 reveal 100% (±2%) Fe occupation $Fe_{occ}$ at the 2b site ($1/4, 3/4, 1/2$) for the space group $P4/nmm$, origin choice 2]. The sample with $y=1.07$ shows an occupation of 100% Fe at the 2b position and a sharp maximum (2.7 Å from the Se/Te atom) on a difference Fourier map $F_0-F_c$ indicating that the remaining Fe (8%) para...
parts of the samples lose their polarization relatively fast because the field at the muon stopping site is a superposition of the internal field and the applied external field of 11.8 mT. The internal field distribution is examined in ZF measurements whereas LF experiments provide information whether the internal field is static or dynamic (fluctuating).

The ZF time spectra (not shown) of the bulk superconducting samples (y=0.90 and 0.95) show no difference between T=20 and 7 K. However, at lower temperatures an additional fast drop of the muon-spin polarization P(t) develops, and the μSR time spectra at 1.8 and 20 K do not coincide any more. This suggests that magnetic ordering observed by μSR develops in the sample at temperatures below T_c. The data were described using the function,

$$P_{ZF}(t) = P_{ZF}^{\text{fast}}(0)e^{-\lambda_{ZF}^{\text{fast}}t} + P_{ZF}^{\text{slow}}(0)e^{-\lambda_{ZF}^{\text{slow}}t}. \tag{1}$$

Here, P_{ZF}^{\text{fast(slow)}} and \lambda_{ZF}^{\text{fast(slow)}} are the initial ZF muon-spin polarization and the exponential depolarization rate of the fast (slow) relaxing component, respectively. Upon increasing the nominal Fe content to y=0.98 the change in the relaxation occurs at temperatures above T_c. At higher temperatures (T~130 K) an additional change in the ZF depolarization was observed, whose origin requires further investigation.

The magnetic ordering temperature was investigated by means of TF μSR [see Fig. 1(b)]. The TF time spectra (not shown) can be divided into a fast drop of the muon-spin polarization within the first 100 ns and a slow relaxing part below the temperature where magnetism starts to develop. Accordingly, the signal was divided into two parts,

$$P_{TF}(t) = P_{TF}^{\text{fast}}(0)\exp[-\lambda_{TF}^{\text{fast}}t]\cos(\gamma_B t + \phi) + P_{TF}^{\text{slow}}(0)\exp[-\lambda_{TF}^{\text{slow}}t]\cos(\gamma_B t + \phi), \tag{2}$$

where \(\gamma_B/2\pi=135.5\) MHz/T is the muon gyromagnetic ratio, \(\phi\) is the initial phase of the muon ensemble, and \(\lambda_{TF}^{\text{fast(slow)}}\) the exponential relaxation rate. The fast relaxing component P_{fast}, attributed to the development of magnetism, represents the magnetic volume fraction of the sample and increases with decreasing temperature [Fig. 1(b)]. In the bulk superconducting samples (y=0.90 and 0.95) it occupies at the lowest investigated temperature (T=1.6 K) more than 60% of the signal, indicating that \(\approx60\%\) of the sample is magnetically ordered. Furthermore, the relaxation of the slow relaxing part increases just below T_c indicating the formation of a vortex lattice in the superconducting state. Upon increasing the nominal Fe content to y=0.98 the samples were found to be 100% magnetic at 1.6 K as the muon-spin polarization drops to zero within the first 100 ns.

LF measurements reveal that the magnetic order is static in the bulk superconducting samples since the muon-spin polarization recovers almost 100% at B=0.64 T and the muon spins decouple from the static internal fields B_int at B_{LF} \approx 10B_{int} \tag{25}. Thus the static internal field in the superconducting samples is B_{int} \approx 0.1 T at the muon stopping site.

The ordering temperature T_N in Fig. 1(b) was determined by fitting a Fermi-type function \(f(T)=(1+\exp[(\beta(T_N-T)])^{-1}\) (\(\beta^{-1}\) is the width of transition) to the data [solid lines in Fig. 1(b)]. \tag{26} It develops with increasing nominal Fe content from
$T_N = 1.7$ K at the lowest Fe content ($y = 0.90$) to 2.7 K, 5 K, 10 K, 12.5 K, and 17 K for $y = 0.95$, 0.98, 1.00, 1.01, and 1.02, respectively. Above $y = 1.03$ it seems to saturate at $T_N = 27$ K (see Ref. 12), 28 K, and 29 K for $y = 1.03$, 1.07, and 1.10.

To investigate the change in the magnetic correlations with Fe content, we performed neutron-diffraction measurements on single crystals of Fe$_y$Se$_{0.25}$Te$_{0.75}$ for $y = 0.95$, 1.00, and 1.10 at 1.5 K. The experiments were performed on the triple-axis spectrometer TASP$^{27}$ at the SINQ spallation source (PSI).$^{28}$ The instrument was configured for a neutron wave vector of 2.66 Å$^{-1}$ with no collimation. Each sample was aligned on nuclear Bragg reflections to an accuracy of better than 0.008 r.l.u. at 1.5 K. Figure 2(a) shows elastic scans in the $(h,0,l)$ scattering plane. A background recorded around 50 K (above the magnetic ordering temperature) was subtracted in order to isolate the magnetic contribution to the scattering at 1.5 K. Diffuse incommensurate magnetic peaks centered at $q = (1/2 - \delta, 0, 1/2)$, with $\delta = 0.03$, are observed in all three samples. These results together with our previous neutron-diffraction studies show that samples in the entire range $0.95 < y < 1.10$ have incommensurate magnetic order.$^{12,21}$ We note that our results hint at a possible reduction in incommensurability $\delta$ for the $y = 1.00$ sample. However, due to the broad nature of the peak this shift may not be related to the sample. As can be seen from Fig. 2(a), the magnetic peaks along $(h,0,0.5)$ appear to become broader with reduced Fe content with correlation lengths along $a$ deduced to be 7.1(5) Å, 8.4(6) Å, and 13.8(8) Å for $y = 0.95$, 1.00, and 1.10, respectively. This would suggest that the magnetic correlations become more short ranged on lowering the Fe content.

The temperature at which magnetic order sets in appears also to be dependent on $y$ in Fe$_y$Se$_{0.25}$Te$_{0.75}$ as shown in Fig. 2(b). In the $y = 1.10$ sample magnetic order is found to develop below $\approx 50$ K. However, for $y = 1.00$ and $y = 0.95$ the transition temperature is reduced to around 30 K. These results are in good agreement with the change in $T_N$ with doping observed by $\mu$SR, but due to the difference in fluctuation rates sampled by neutrons and muons, the temperatures at which spin freezing occurs are not the same.

The results of the magnetization and $\mu$SR measurements of Fe$_y$Se$_{0.25}$Te$_{0.75}$ are summarized in a phase diagram in Fig. 3(a). In the region of $y < 1$ a coexistence of superconductivity and magnetism is observed. A recent nuclear-magnetic-resonance study on BaFe$_{2-x}$Co$_x$As$_2$ showed the appearance of magnetic order on all Fe sites and ruled out nanoscale segregation in this material.$^{29}$ More reasonable is a coexistence of the two order parameters on atomic scale, as was already suggested earlier$^{12,28,30}$ and in agreement with models recently proposed.$^{31,32}$

It has been predicted theoretically that the height of the chalcogenide above the Fe plane $h_{Se/Te}$ can influence the magnetic ordering in Fe$_y$Se$_{0.25}$Te$_{1-y}$. For that reason $h_{Se/Te}$ derived from XRD measurements is plotted in addition to $T_c$ and $T_N$ in Fig. 3(a). The crossover from the purely magnetic to the coexistence region occurs at $h_{Se/Te} = 1.72$ Å. This result is in good agreement with density-functional theory calculations, which predict a change from double- to single-
stripe antiferromagnetic ordering at $h_{\text{Se/Te}} \sim 1.71 - 1.72 \, \text{Å}$. However, the theoretical calculations are based on Se substitution only and do not take into account any excess Fe. Furthermore, $h_{\text{Se/Te}}$ might not be the only contribution since bulk superconductivity appears only for $y \leq 0.98$ whereas the proposed critical height $h_{\text{Se/Te}} = 1.72 \, \text{Å}$ is reached already at $y = 1.03$.

The amount of excess Fe seems to play a major role in this system as only for $y \leq 1$ does bulk superconductivity occur. Here the magnetic correlations in the system become more short ranged and lead to less well correlated magnetic order as compared with $y > 1$. Thus, only upon reducing the magnetic correlations by lowering the amount of Fe in the system does it become superconducting. Nevertheless, it seems unlikely that the excess Fe acts as isolated magnetic moments that destroy superconductivity. It might on the other hand act as a magnetic electron donor that suppresses superconductivity and induces weakly localized electronic states.19,20

The tentative three-dimensional phase diagram of the transition temperatures $T_c$ and $T_N$ of Fe$_x$Se$_{1-x}$Te$_{y}$ for $0 \leq x \leq 0.5$ and $0.9 \leq y \leq 1.1$ is shown in Fig. 3(b). Fe$_y$Te is always antiferromagnetically ordered.8,9 Upon substituting Te by Se the order becomes weaker while superconductivity is enhanced and finally the system becomes bulk superconducting. This behavior can be tuned not only by the substitution of Se but also by adjusting the Fe content. The superconductivity is suggested to be of multiband nature, where different doping channels might be involved.22

To conclude, we have found that the phase diagram of Fe$_x$Se$_{0.25}$Te$_{0.75}$ in the range $0.9 \leq y \leq 1.1$ exhibits a strong dependence of its superconducting and magnetic phases on $y$. In the low Fe content region $y \leq 1$ bulk superconductivity and incommensurate magnetism coexist. With increasing $y$ the magnetic order becomes correlated over a longer range and superconductivity vanishes. This work emphasizes that not only the Se/Te ratio but also the Fe content is important in controlling the magnetic and superconducting properties of the iron chalcogenides.

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