Exploration of New (Fe,Ni)-Chalcogenide SCs

Fe-vacancy order, new AFM states and SC

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Online

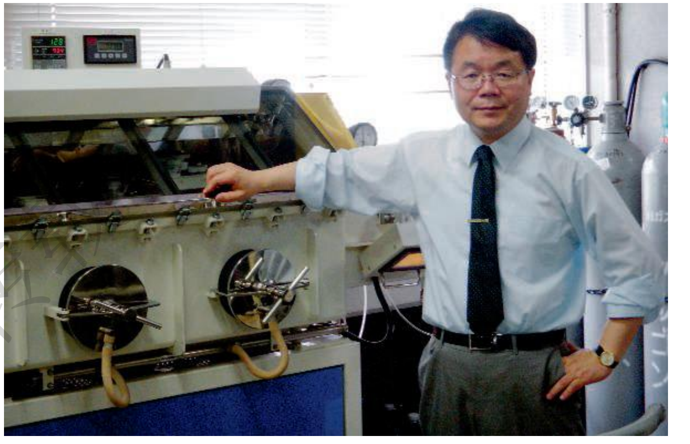
- **Review for Fe-Based Superconductors (in short).**
- **Superconductivity and Bi-collinear AFM in $FeTe_{1-x}Se_x$.**
- **Fe-vacancy super-lattice, new AFM states and SC in $(Tl, K, Rb)Fe_xSe_2$.**
- **Superconductivity and Heavy Fermion behavior in $TlNi_2Se_2$, $TlNi_2S_2$ crystals.**
- **Phase Diagram of $TlCo_{2-x}Ni_xSe_2$ System.**

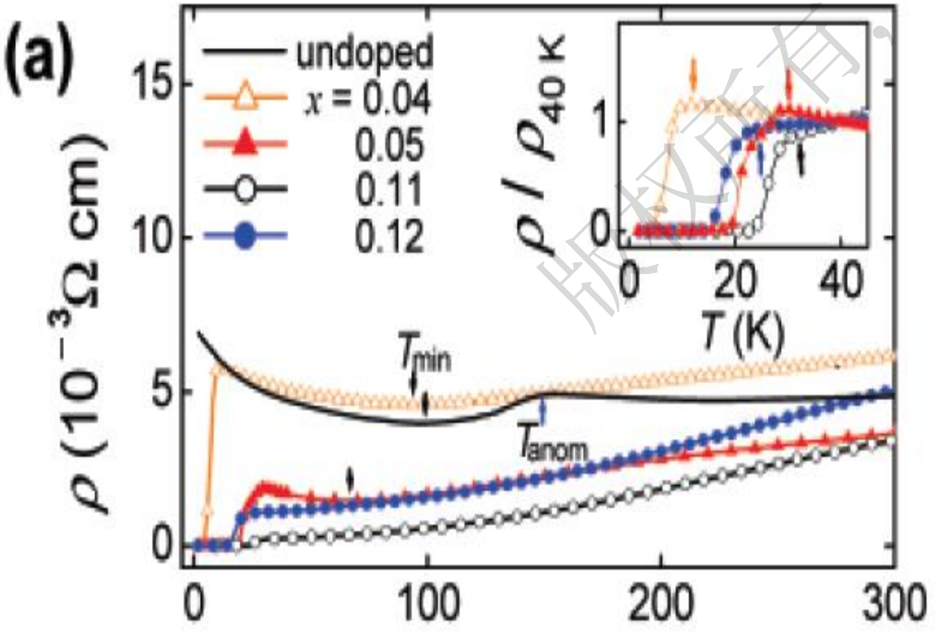
I. Review for Fe-Based Superconductors

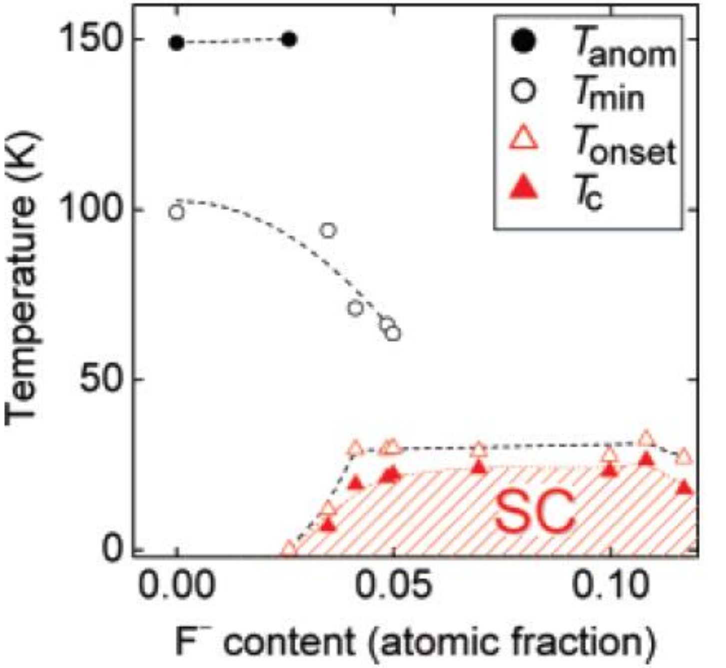
Discovery of SC in $LaO_{1-x}F_xFeAs$ in Feb. 2008

- **SC was first discovered in the F doping $LaO_{1-x}F_xFeAs$ with T_c=26K.**

Hosono's group J. Am. Chem. Soc, **130**, 3296 2008







Main Fe-based Superconductors

- **1111 Series:**

  $CeO_{1-x}F_xFeAs$: 41K $SmO_{1-x}F_xFeAs$: 55K

  $PrO_{0.89}F_{0.11}FeAs$: 52K $SmFeAsO_{1-x}$ 55K

  CaFFeAs: 36K, $La_{1-x}Sr_xOFeAs$ (Hole doping)

- **122 Series:** (both Hole and Electron Doping)

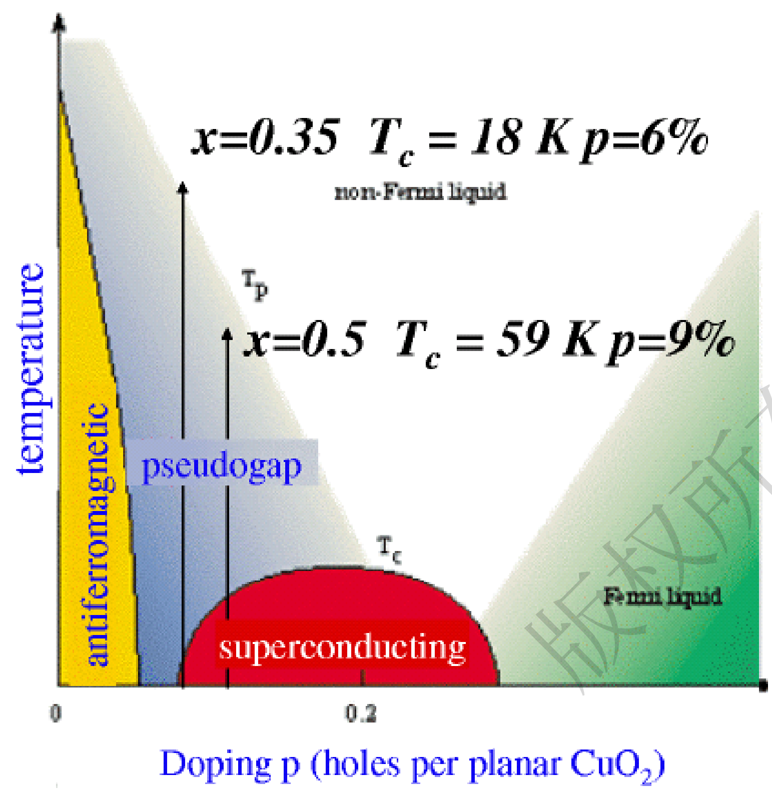
  $Ba_{1-x}K_xFe_2As_2$, $BaFe_{2-x}Co_xAs_2$ 38K

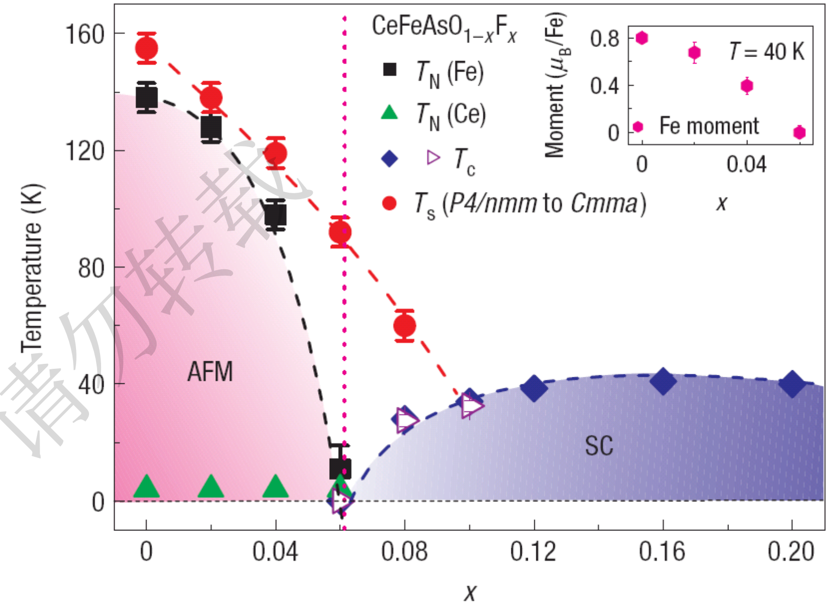
- **111 Series:** LiFeAs 16K
- **11 Series:** $Fe_{1+\delta}Se$, 8– 37K, $Fe_{1+\delta}(Te,Se)$ 14K
- **New 122 or 245 series**

  $(Tl,K,Rb,Cs)Fe_xSe_2$ (32K, 2010.11-12)

Similarity in Phase Diagram in both Fe-based compounds and Cuprates

Cuprate Phase Diagram:





Jun Zhao et al, Nature Mat. 7, 953-959 (2008).

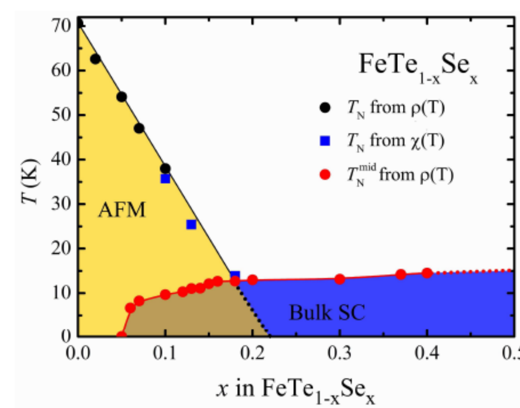
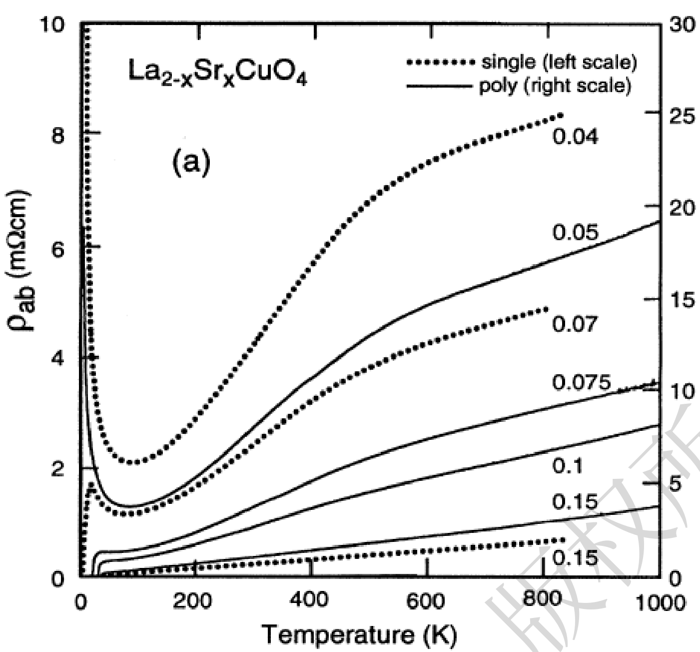


FIG. 2: (Color online)Phase diagram showing the AFM transition temperature, T_N and the superconducting temperature T_C as function of x for $FeTe_{1-x}Se_x$ system.

Chiheng Dong, Minghu Fang et al, *PRB* 84, 224506(2011)

The main difference in Parent compounds: insulator (Cuprates) to bad metal (Fe-based)



Elbio Dagotto, *Rev. Mod. Phys.66*, 763 (1994)

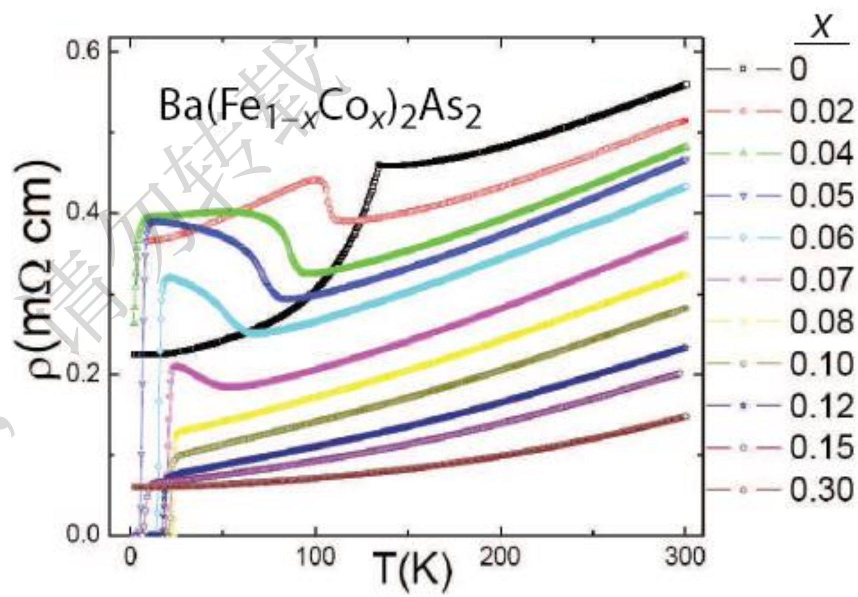


FIG. 44: (Color online) In-plane resistivity ρ versus temperature T of $Ba(Fe_{1-x}Co_x)_2As_2$ crystals for various values of x as indicated on the right edge of the figure. Reprinted with permission from Ref. 285. Copyright (2009) by the American Physical Society.

L. Fang et al. PRB 80, 140508(R) (2009)

Mott Physics: Strong correlation electron system.

Strong correlation electron system?

Motivation

- **Is there an unified picture for the Fe- and Cu-based HTSCs? How to develop a unified picture for both? (in theory).**

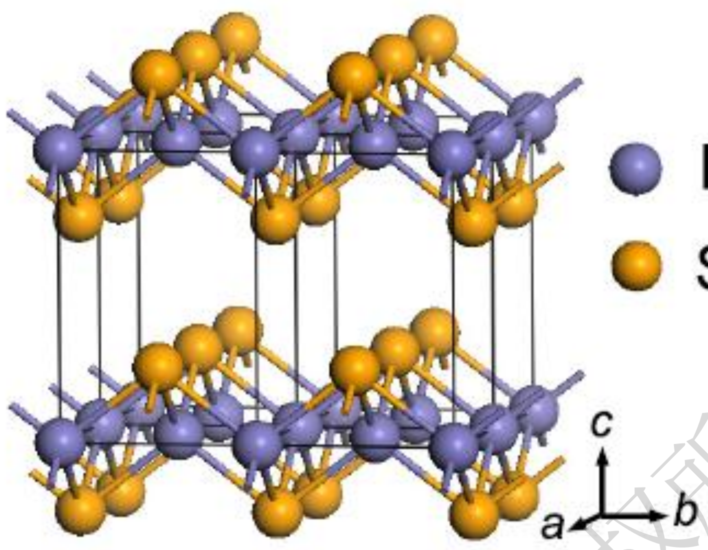
- **Are there the possibilities to tune the Fe-based compound into an insulator? (in experiment).**

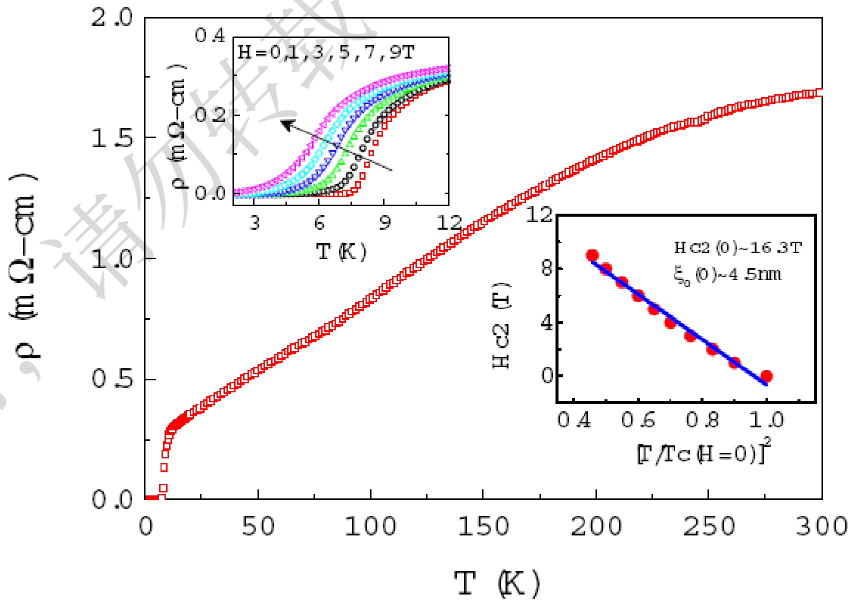
- **Are there some new magnetic long-range order states in the Fe-based compound?**

II. Superconductivity and bi-collinear AFM order in Fe(Te, Se) system

Lattice Structure of $FeSe_{1-x}$ (x=0.03-0.18)

F.C. Hsu et al PNAS,105,16262(2008), arXiv 0807-2369





- **In the July, 2008, M.K. Wu's group in Taiwan discovered superconductivity with T_c=8K in FeSe compound.**
- **Single FeSe layer, the simplest structure in Fe-based SCs.**

From 2005, our group prepared many $NiSe_2$ and $CoSe_2$ compounds in order to search for new superconductors. At that time, SC was just discovered in Na_xCoO_2+yH_2O, with a triangular lattice.

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$NiS_{2-x}Se_x$ 在 $x = 1.00$ 附近的反铁磁量子相变*

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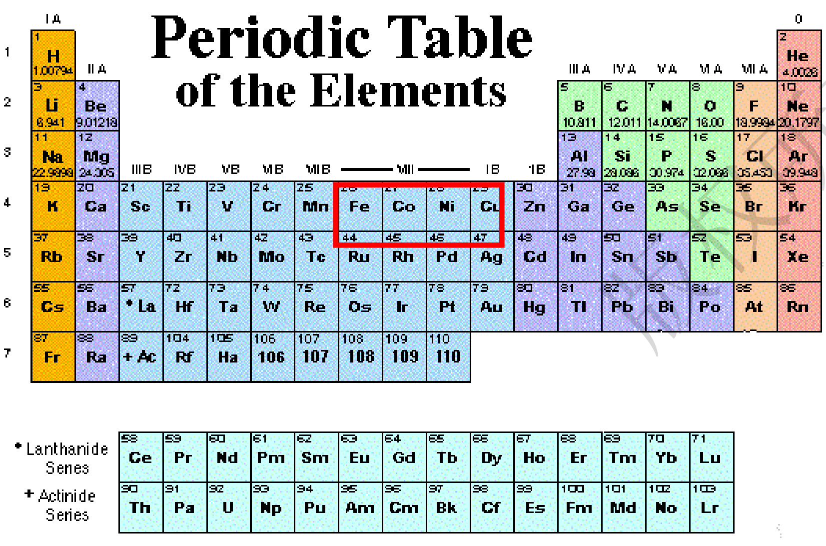
(2007 年 8 月 1 日收到；2007 年 9 月 6 日收到修改稿)



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$Co(S_{1-x}Se_x)_2$ 系统中的铁磁量子相变*

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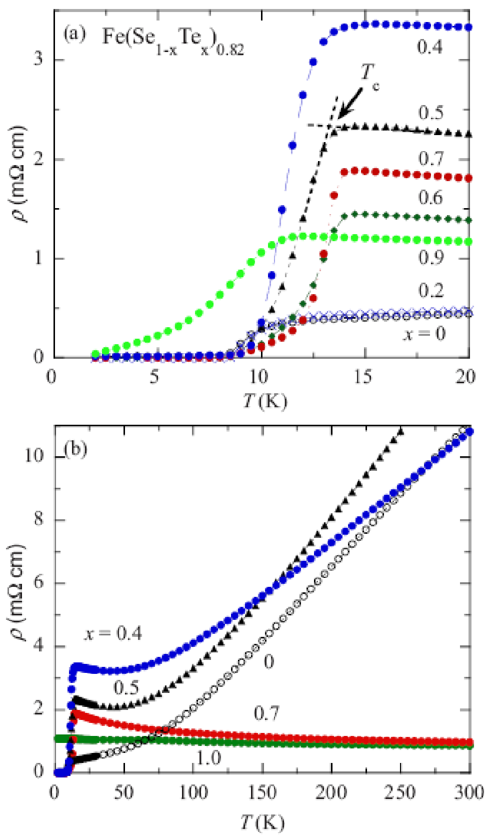
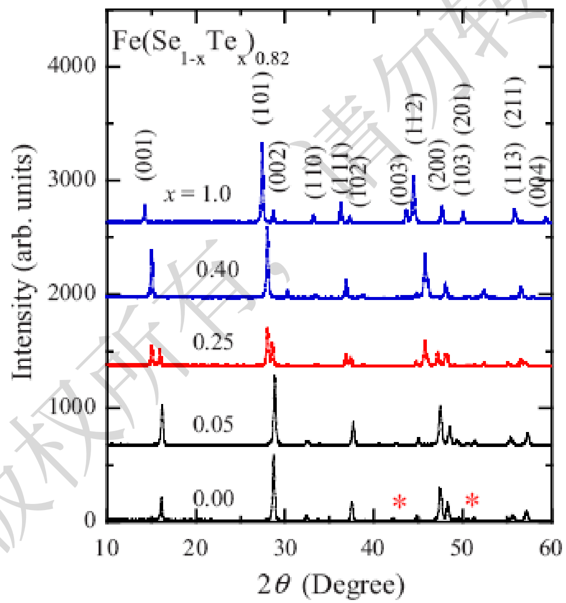
(2008 年 7 月 16 日收到；2008 年 8 月 16 日收到修改稿)

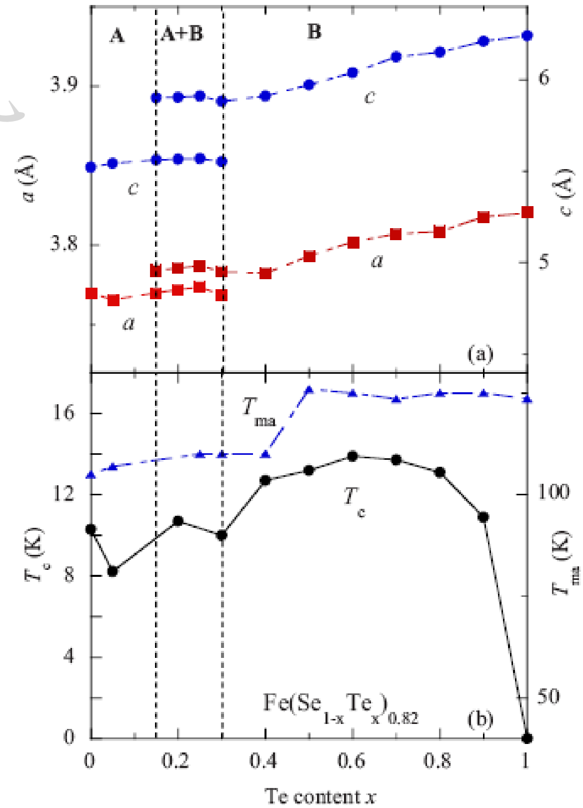
But we are not so luck, did not try to prepare FeSe.

Superconductivity in $Fe(Se_{1-x}Te_x)_{0.82}$

M.H. Fang, Z.Q. Mao et al arXiv0807.4775; *PRB*, 78, 224503(2008);
SC in FeSe, F.C. Hsu et al arXiv 0807.2369



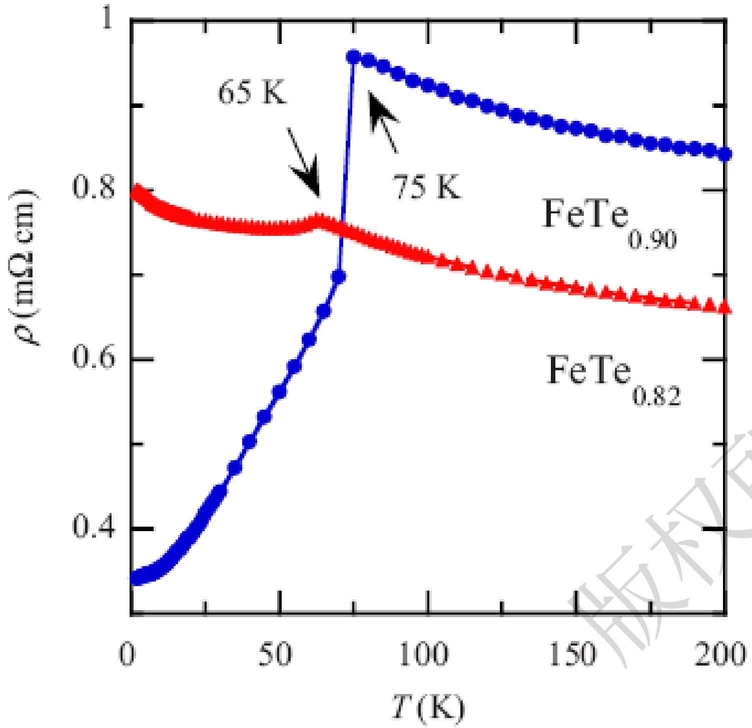


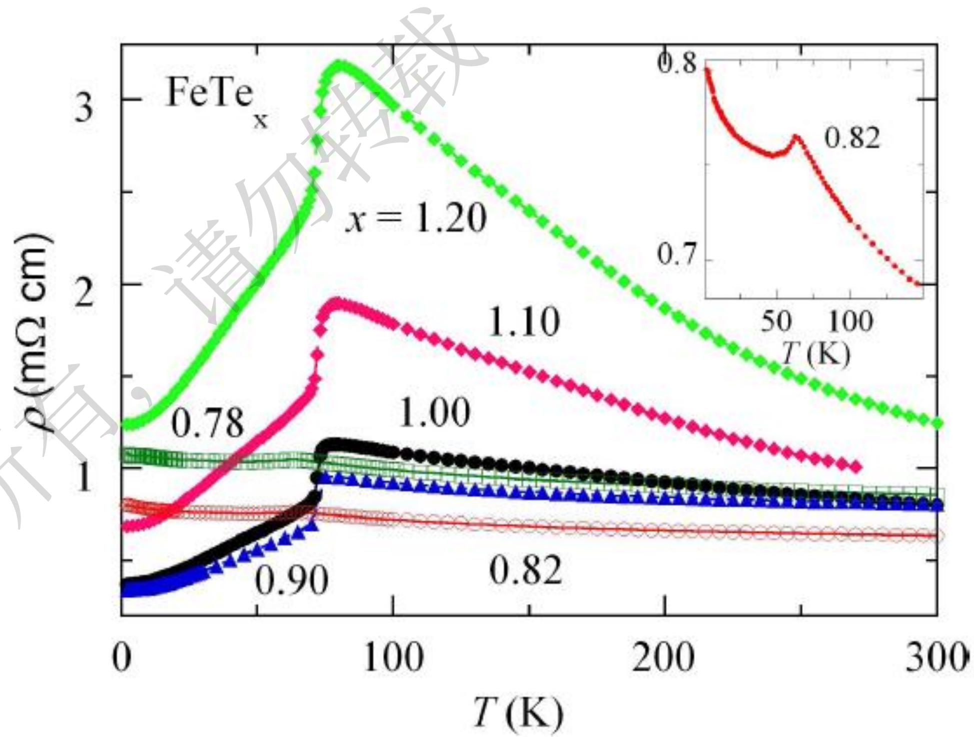


In one week after the discovery of SC in $FeSe_{1-x}$, we first reported the superconductivity with T_C^{zero}=14K in $Fe(Se_{1-x}Te_x)_{0.82}$ system.

The ρ(T) for the parent compound $FeTe_x$

M.H. Fang, ZQ Mao et al *PRB*, 78, 224503(2008), arxiv0807.4775; about 300 citations.
Wei Bao, Minghu Fang, ZQ Mao et al, arXiv0809.2058, *PRL* 102, 247001 (2009), 360 citations

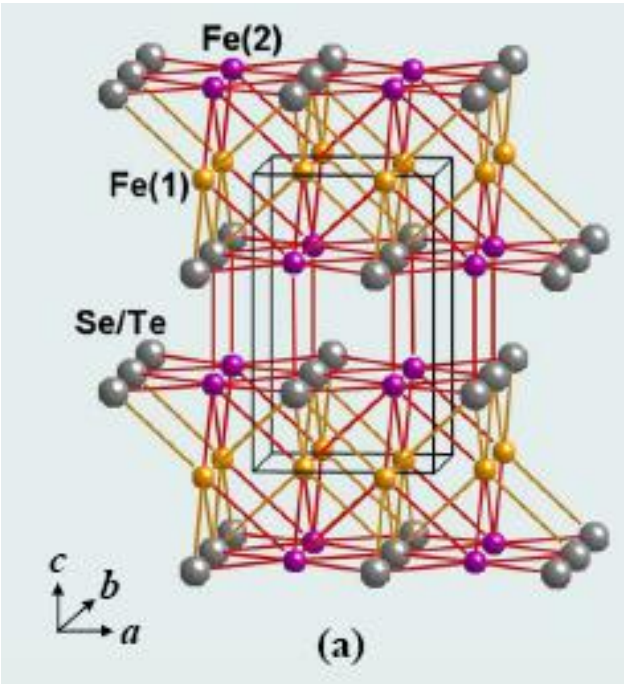


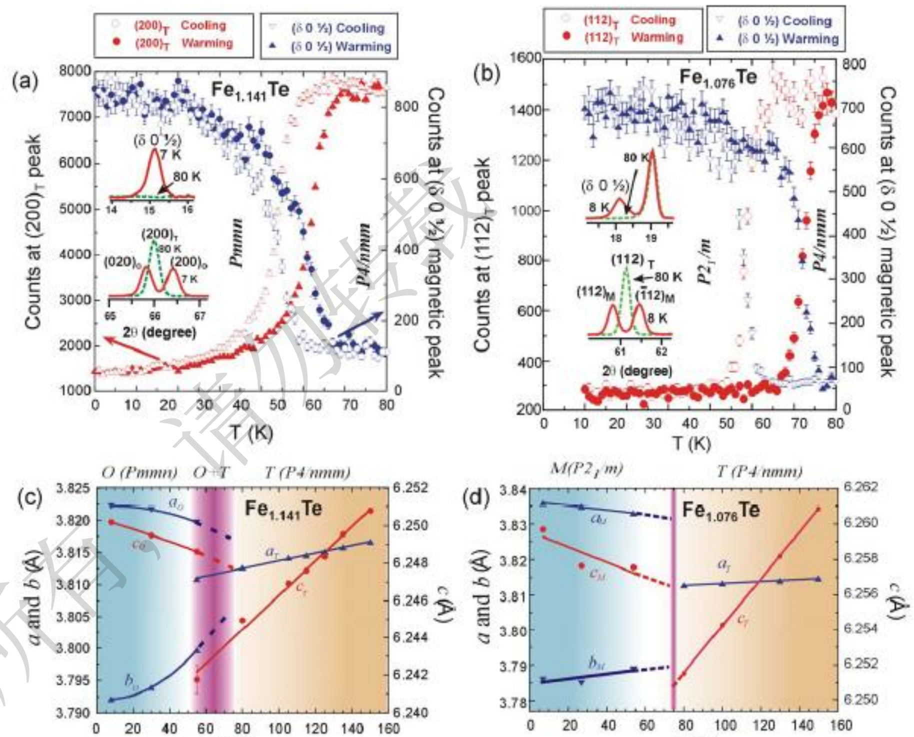


- **Above T_N, all samples with different composition of $FeTe_x$, their ρ(T) show semiconducting behavior.**
- **Below T_N, their ρ(T) depend on the excess Fe content.**

Simultaneous Magnetic and Structural transition in $Fe_{1+\delta}Te$

Wei Bao, Minghu Fang, Z.Q. Mao et al, *PRL* 102, 247001 (2009) citation 360





Nominal composition

FeTe$_{0.82}$

FeTe$_{0.90}$

Exact composition

$Fe_{1.141}Te$, *Ts*≈75K

$Fe_{1.076}Te$; Ts≈63K

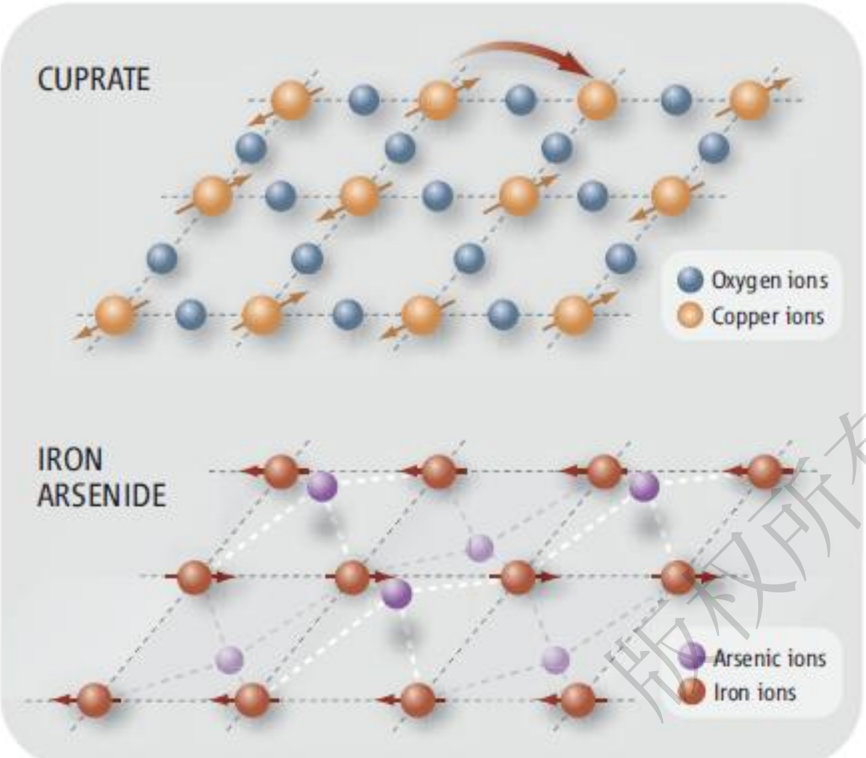
Simultaneous magnetic and structural the first-order transition

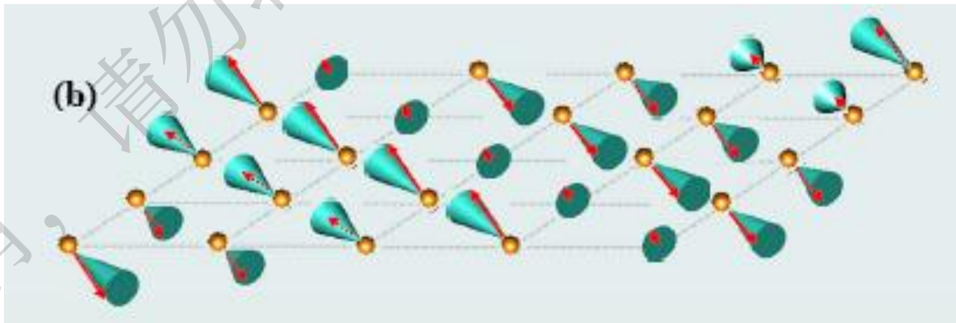
Low Tem. O(*Pmmn*) →High Tem. T(*P/4nmm*)

Low Tem. (*P2$_1$/m*) →High Tem. T(*P/4nmm*)

Bi-collinear AFM Order in the Parent Compound $Fe_{1.14}Te$

Wei Bao, Minghu Fang, Z.Q. Mao et al, *PRL* *102, 247001 (2009)*



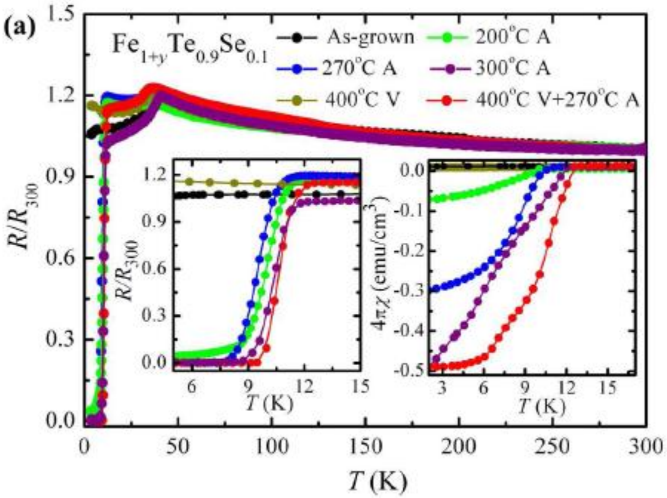


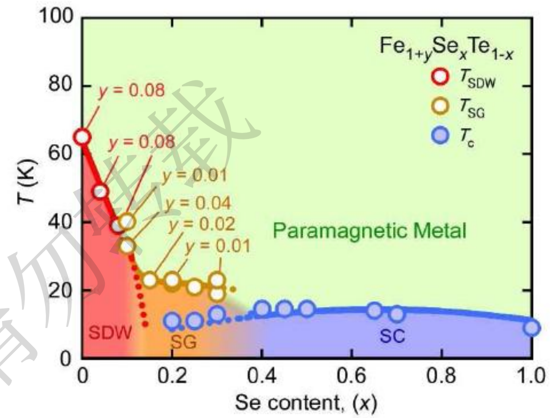
In the parent compound LaOFeAs, and $BaFe_2As_2$, collinear AFM order exists.

The bi-collinear AFM in $Fe_{1.14}Te$ compound is different from them.

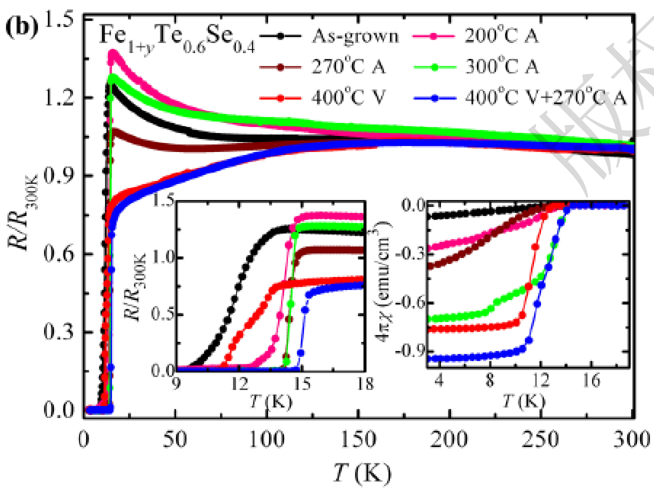
Intrinsic Phase Diagram for $FeTe_{1-x}Se_x$ system with less excess Fe atoms

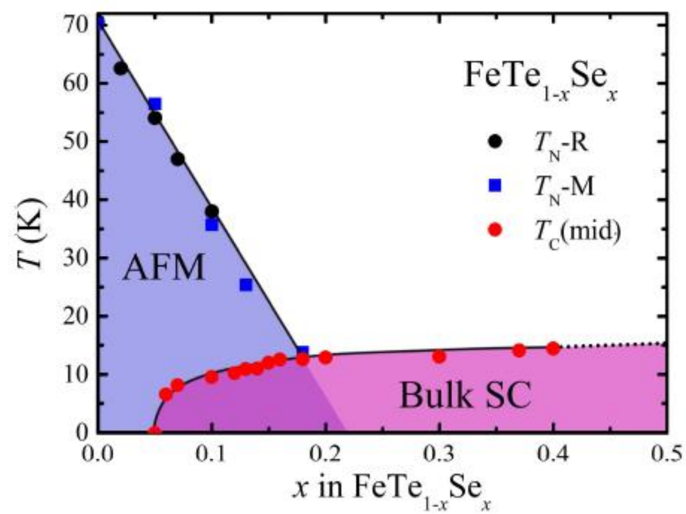
Chiheng Dong, Minghu Fang et al, *PRB* 84，224506(2011)





Natayawa et al. arXiv1003.4525, JPSJ79, 113702(2010)



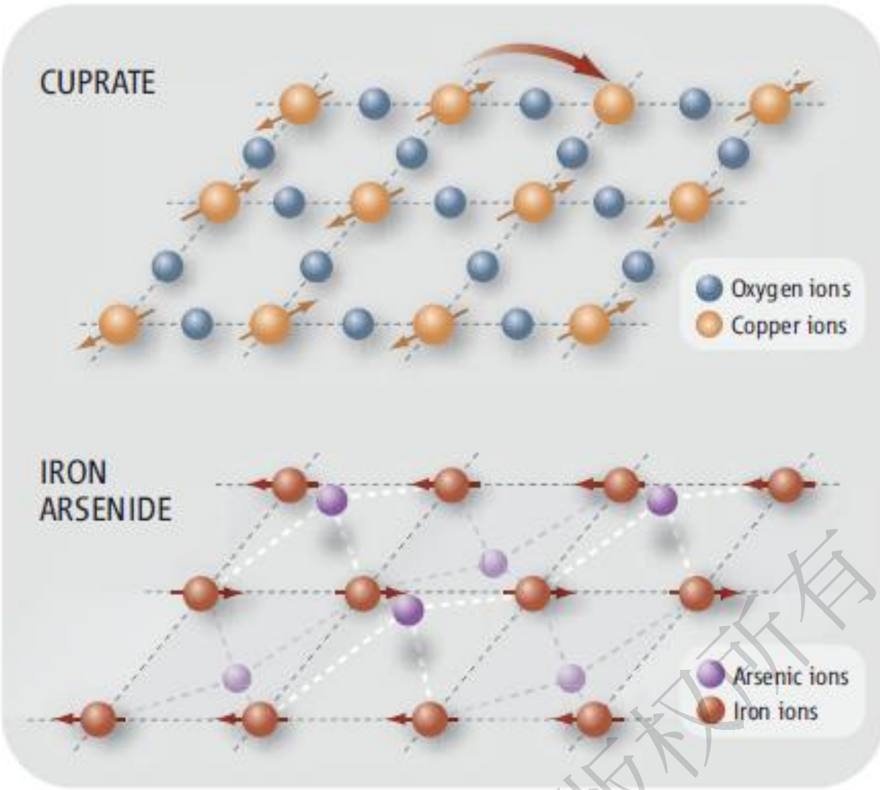


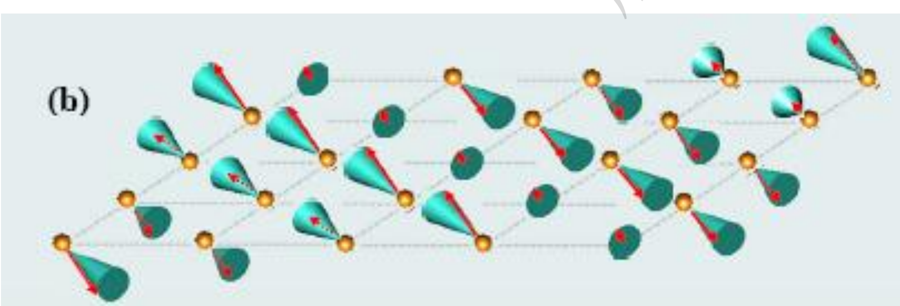
Conclusions for $FeTe_{1-x}Se_x$ system

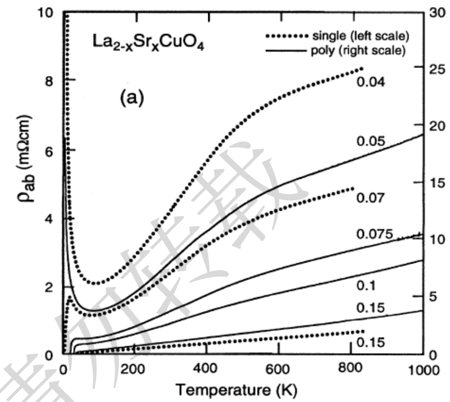
- **First report SC with 14K in 11 system.**
- **To determine the bi-collinear AFM in FeTe.**
- **It was found that the excess Fe atoms on the Se layer suppress SC.**
- **To obtain the intrinsic Phase Diagram of $FeTe_{1-x}Se_x$ with less excess Fe atoms. Coexistence of AFM and SC occurs in this system.**

III. Fe-vacancy order, new AFM state and SC in (Tl,K,Rb)Fe_xSe_2

Three types AFM ground state with HTSC







Mott Insulator:

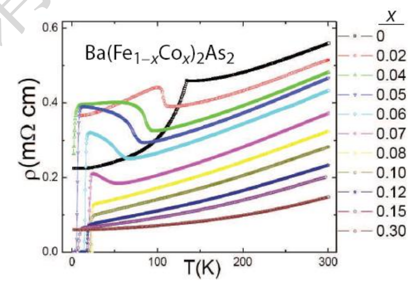
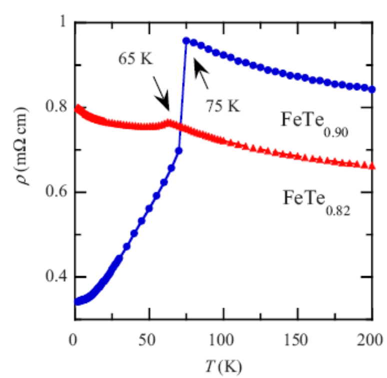


FIG. 44: (Color online) In-plane resistivity ρ versus temperature T of $Ba(Fe_{1-x}Co_x)_2As_2$ crystals for various values of x as indicated on the right edge of the figure. Reprinted with permission from Ref. 285. Copyright (2009) by the American Physical Society.

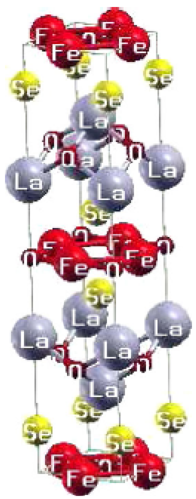
Bad metal?

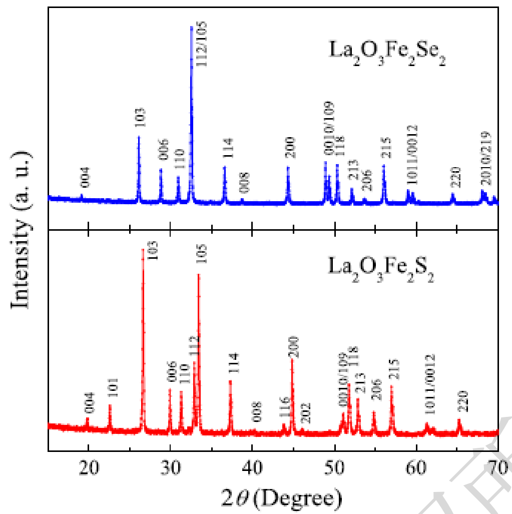


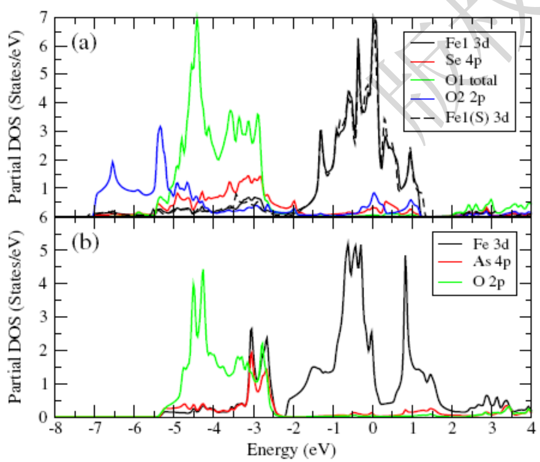
Is there a way to tune to an insulator?

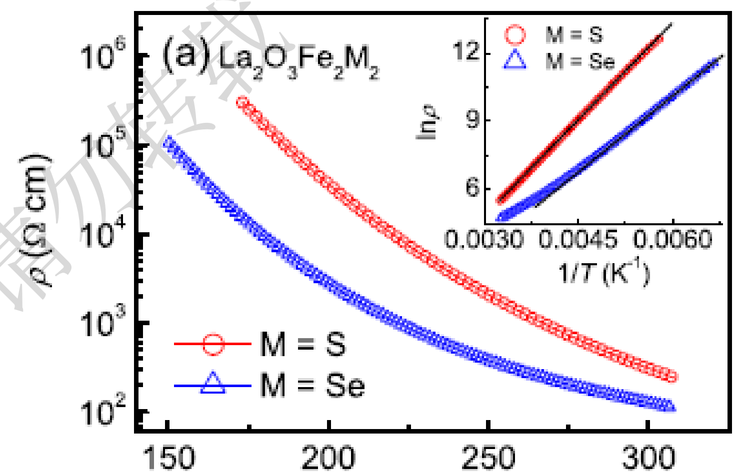
The First Effort: $La_2O_3Fe_2(Se,S)_2$
Mott Localization in Iron Oxychalcogenides

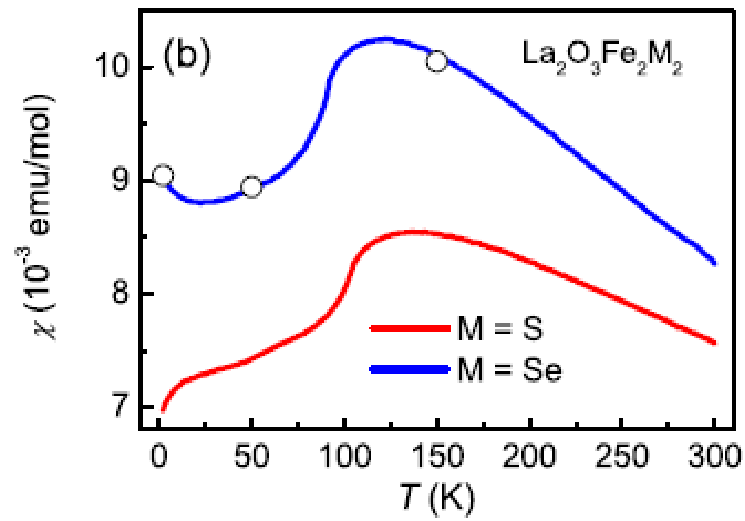
Jian-Xin Zhu, Minghu Fang, and Qimiao Si et al. *PRL* 104, 216405 (2010)











The second effort:

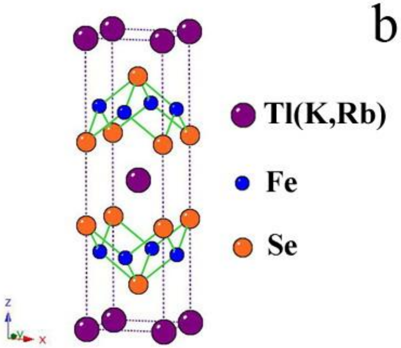
Super-lattice of Fe-vacancy in $Tl^{1+}Fe^{2+}_xSe^{2-}_2$

Minghu Fang **et al, arXiv. 1012.5236, *EPL* 94, (2011) 27009**

K. Klepp et al. ***Monatsh. Chem.***, **109** (1978)18;

M. Zabel et al, ***Rev. Chim. Miner.*** **21** (1984) 139;

a



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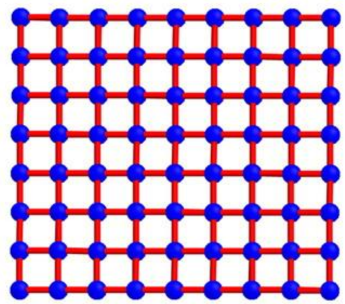
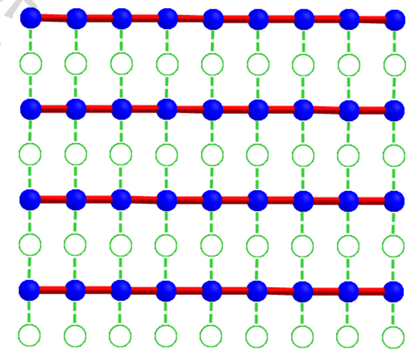


$x = 2.00$

$x = 1.00$, 112 phase



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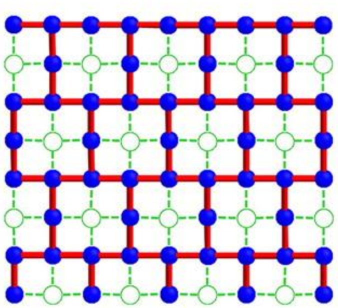
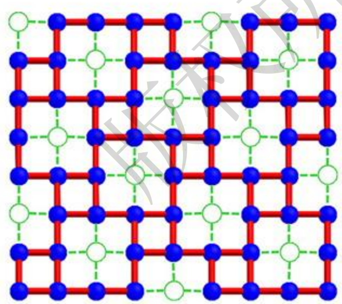


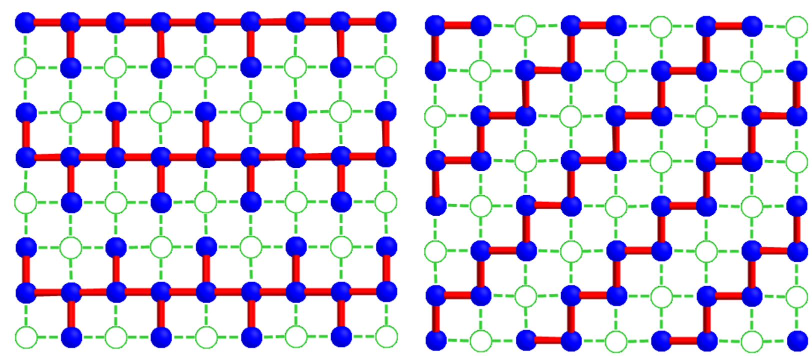
$x = 1.50,\ \sqrt{2}\times\sqrt{2}$

d



$x = 1.60,\ \sqrt{5}\times\sqrt{5}$

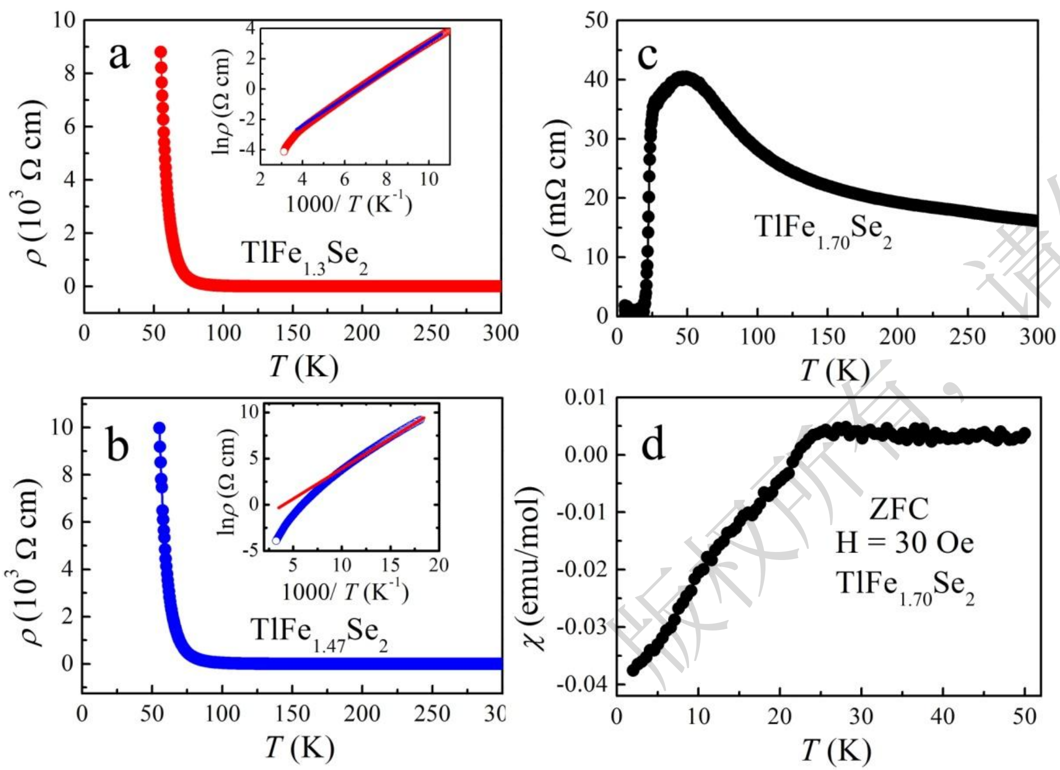
$x = 1.33$, two possibilities



They should be an AFM insulator or semiconductor.

Evolution from an AFM Insulating to SC in $TlFe_xSe_2$ (1.30≤x≤1.70) crystals

Minghu Fang et al arXiv. 1012.5236, *EPL*94, (2011) 27009



- **The starting materials:**
  $Tl_zFe_2Se_2$ (0.4 ≤ *z* ≤ 1.0)
  $TlFe_zSe_2$ (1.5 ≤ *z* ≤3.0)

A series of crystals obtained:
$TlFe_xSe_2$ (1.3 ≤*x* ≤1.70).

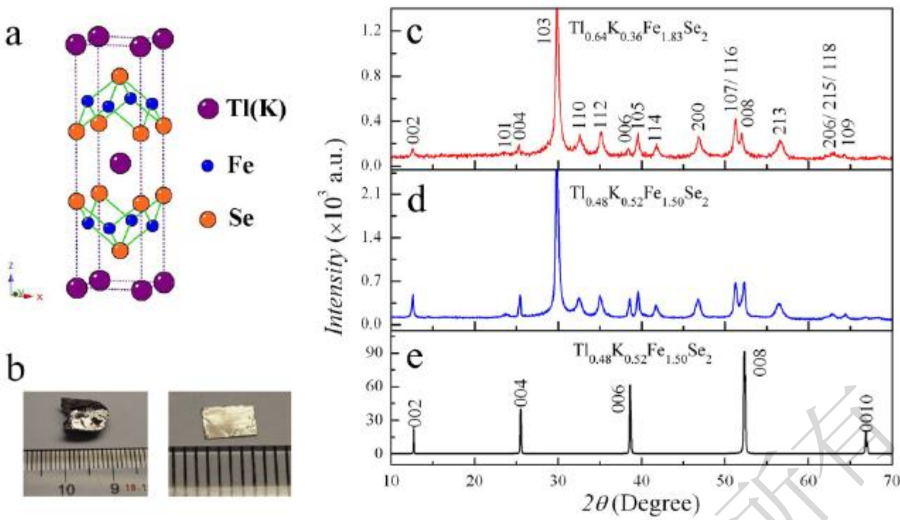
We found that:

- **It is difficult that *x*>1.70.**
- ***x*=1.30, 1.47, an insulator. The ρ(T) exhibits a thermal activated behavior. The activated energy E_a=80.2, 57.7meV.**
- ***x*=1.70 crystal, SC with T_c^{mid}=22.4K, T_c^{zero}=20K, but SC volume fraction is very small (<1%) .**

Composition determined by EDXS.

To get bulk SC, it is necessary to increase Fe content, $(Tl,K)Fe_xSe_2$ (1.50≤x≤1.88)

Minghu Fang et al arXiv. 1012.5236, *EPL* 94, (2011) 27009

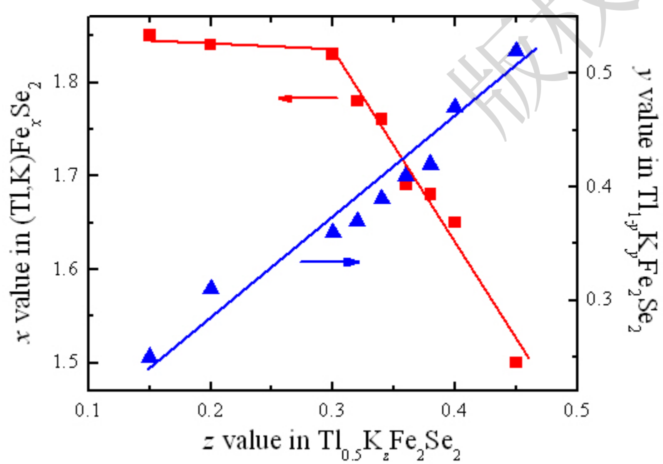


- **We add K to the starting materials.**

  $Tl_{0.5}K_zFe_2Se_2$ (0.15≤z≤ 0.45)
  $Tl_{0.4}K_zFe_2Se_2$ (0.2 ≤ z ≤ 0.5)
  $Tl_{0.8-z}K_zFe_2Se_2$ (0.1≤ z≤0.4).

- **A series of crystal obtained:**

  $(Tl,K)Fe_xSe_2$ (1.50≤x≤1.88)

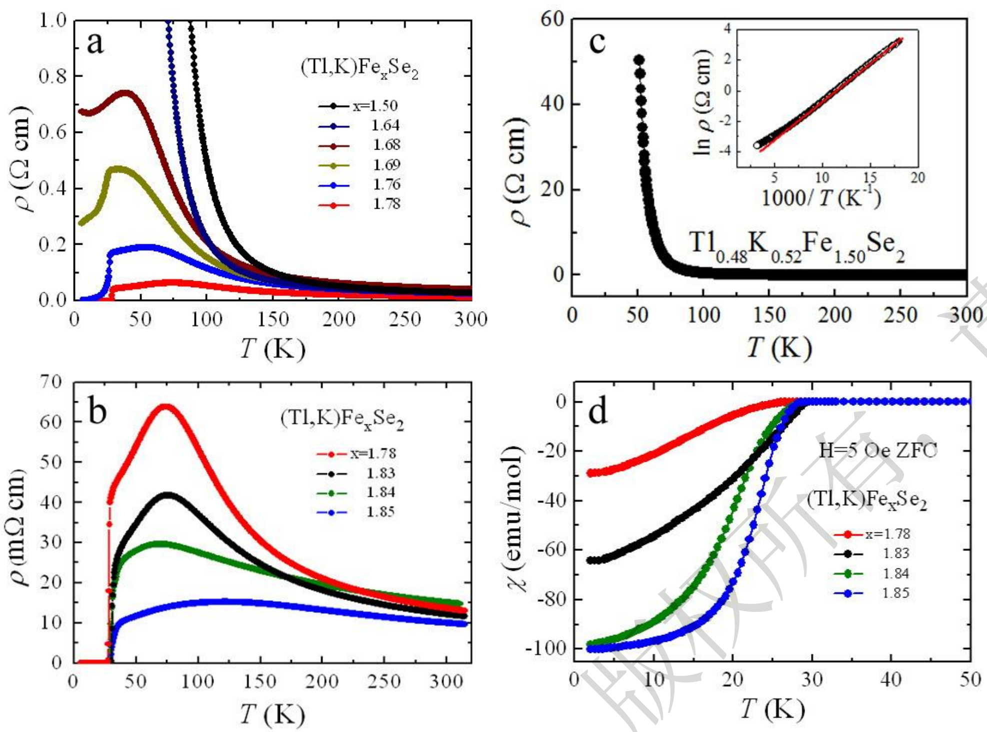


- **We found that: *x* value can reach to 1.88, after adding K in the starting materials.**

Composition determined by EDXS.

Evolution from an insulator to SC in (Tl,K)Fe_xSe_2 (1.50≤x≤1.88) crystals

Minghu Fang et al arXiv. 1012.5236, *EPL*94, (2011) 27009



Guo et al. ***PRB*** 82, 180520(2010),
$K_{0.8}Fe_2Se_2$, Tc=30K SC
Krzton-Maziopa et al. ***J. Phys. Cond. Matter*** 23, 052203(2011)
$Cs_{0.8}Fe_2Se_2$, Tc=27.4K

(1). *x*=1.50, 1.64, an insulator.
ρ(T): thermal activated behavior
E_a=36, 24meV for them, respectively.

(2). 1.64<*x*≤1.76, insulator phase and SC phase coexists, zero ρ did not observed above 2K.

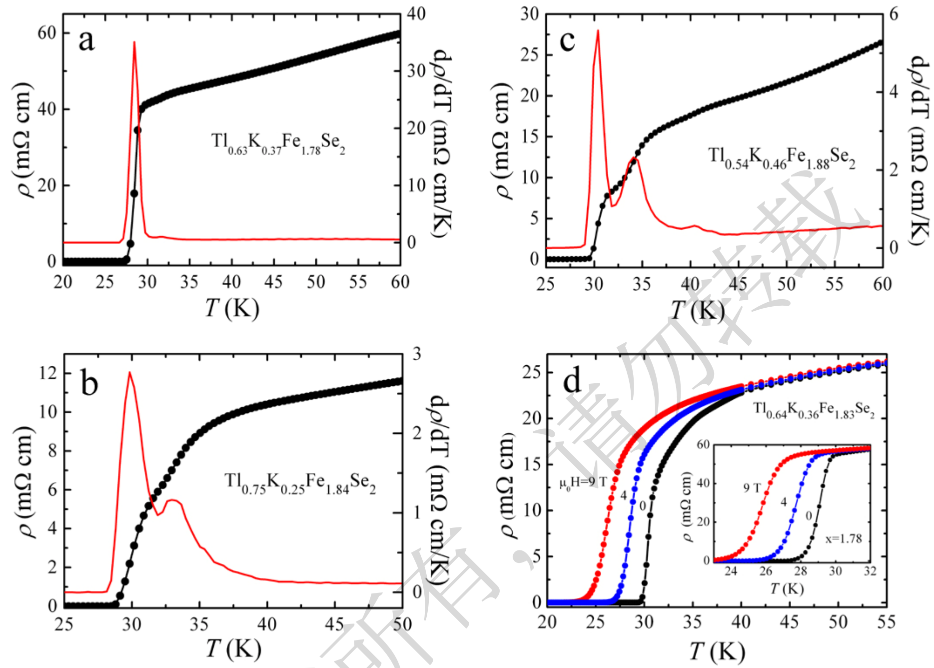
(3). *x*≥1.78, bulk SC with *T*c~30K, and SC volume fraction increases with Fe-content.

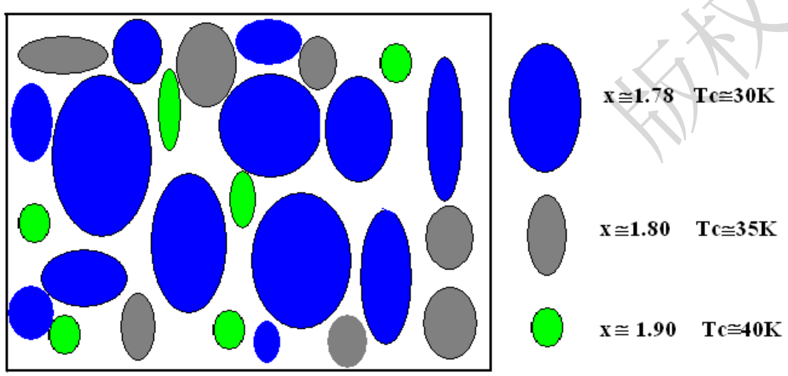
(4). There is a hump in ρ(T) at the normal state for all SC crystals.

(5). Evolution from an insulator to SC occurs in this system.

40K SC phase in (Tl,K)Fe_xSe_2 system

Minghu Fang et al arXiv. 1012.5236, *EPL*94, (2011) 27009





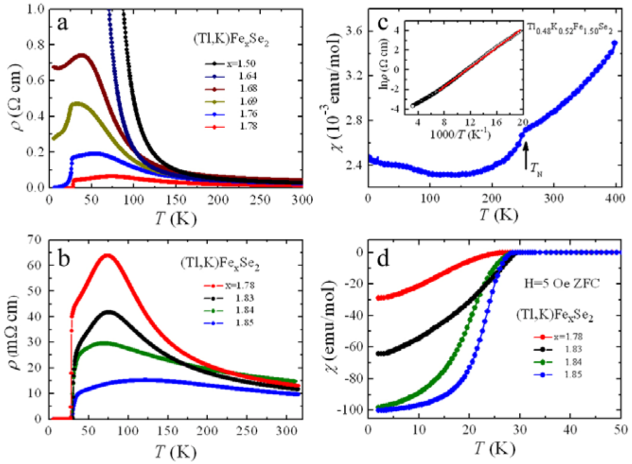
Phase separation in Fe-layers for the disorder phase.

(1). *x*=1.78, T_c=28.4K, one SC transition.

(2). *x*=1.84, *T*c=29.3K, 33K two SC transitions.

(3). *x*=1.88, *T*c=30.4K, 34.1K and 40.4K three transitions.

Hall coefficient, R_H(T), for (Tl,K)Fe_xSe_2 crystals



We choose four crystals to measure R_H(T). Two insulators, Two superconductors.

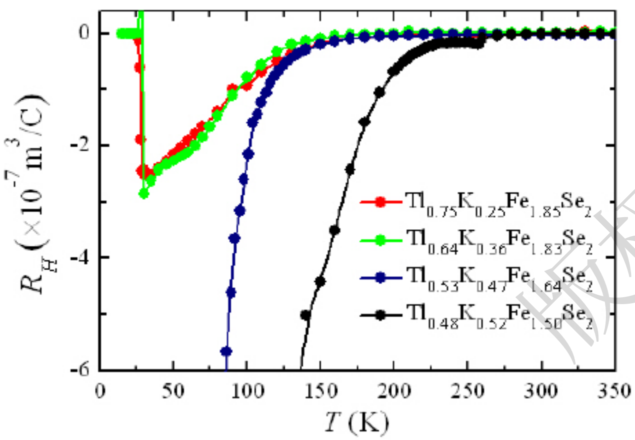


Fig. 5: (Color online) Temperature dependence of Hall coefficient for (Tl,K)Fe_xSe_2 (x = 1.50, 1.64, 1.83 and 1.85) crystals. For both x = 1.50 and 1.64 crystals, the $|R_H|$ value increases sharply at T_N = 250 and 123 K, respectively. The increase of the Fe-content results in the enhancement of the carrier concentration ($|R_H|$ value decrease). The $|R_H|$ value seems to be independent of the K content in the crystals.

(1) The negative value of R_H indicates that the carriers is dominated by electrons, which is consistent with the recent ARPES results, no hole pocket.

(2) $|R_H|$ value increases sharply at T_N=250, 123K for both insulators, indicating electron localization occurs.

(3) $|R_H|$ value decreases with increasing Fe-content, its value is almost the same for both SC crystals.

Phase diagram in (Tl,K)Fe_xSe_2 ($1.30 \le x \le 2.0$)

Minghu Fang et al arXiv. 1012.5236, *EPL* 94, (2011) 27009

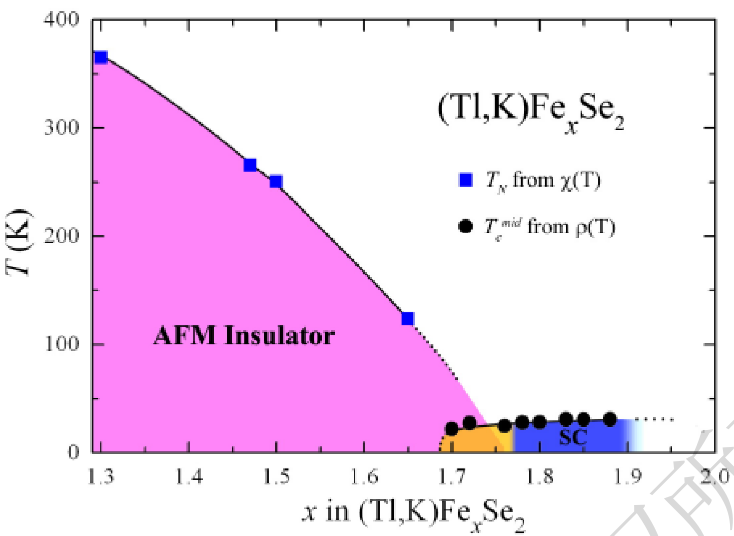


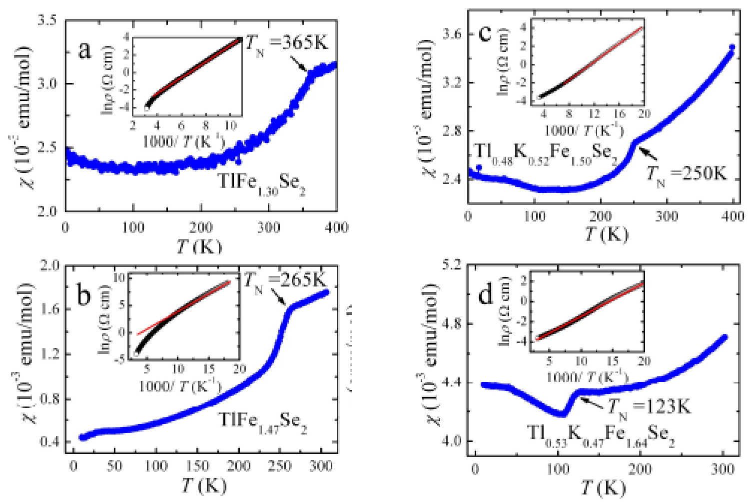
Fig. 6: (Color online) Phase diagram of the magnetism and superconductivity for (Tl,K)Fe_xSe_2 ($1.30 \le x \le 2.0$). The Néel temperature, T_N, of the AFM phase, is determined by the onset temperature of the transition in $\chi(T)$. The SC transition temperature, $T_c{}^{mid}$, is determined by the middle transition point in $\rho(T)$. Note that the crystals with $x > 1.88$ is difficult to grow in this system due to some chemical reasons.

There are three composition regions:

(1) 1.30≤x<1.70, the compound is an insulator.

(2) 1.70≤x<1.78, SC+Insulator, SC volume fraction is less than 1%.

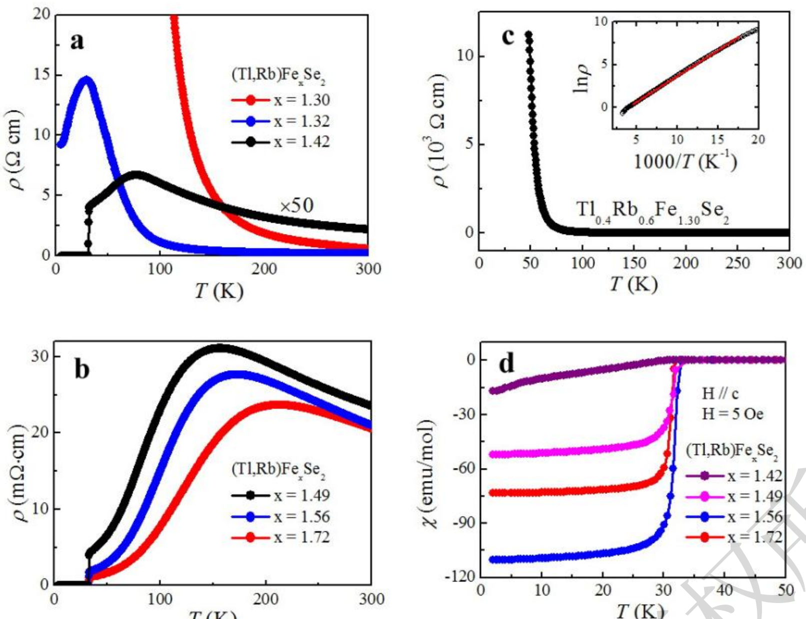
(3) 1.78≤x≤1.88, bulk SC with *T*c=31K emerges.

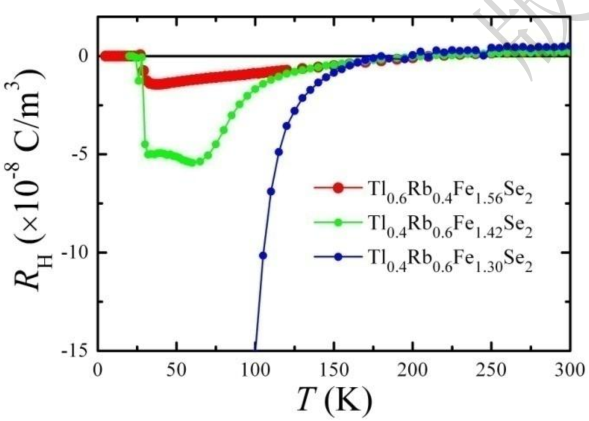


SC with 31K in (Tl,K)Fe_xSe_2 system is at the verge of an AFM insulator.

Evolution from an insulator to SC in (Tl,Rb)Fe_xSe_2 (1.30≤x≤1.75) crystals

Hangdong Wang, Minghu Fang et al. *EPL*93, 47004(2011)





For the superconductors:

(1) With Fe-content increase, crystals become SC.

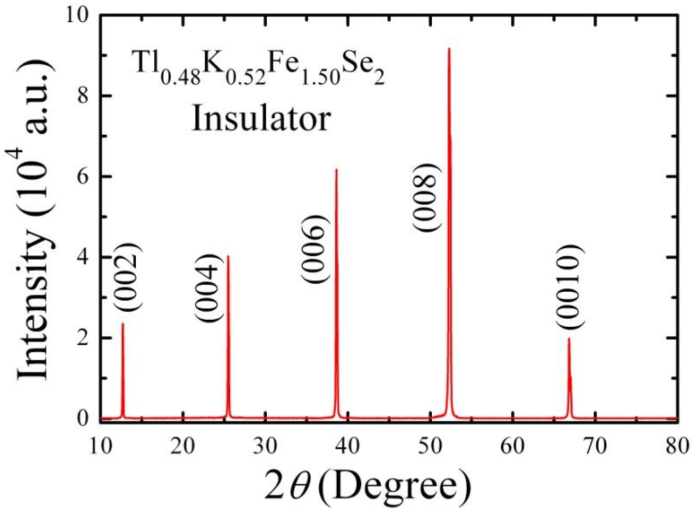
(2) The SC volume fraction increases with Fe-content.

(3) Carrier concentration increases with Fe-content.

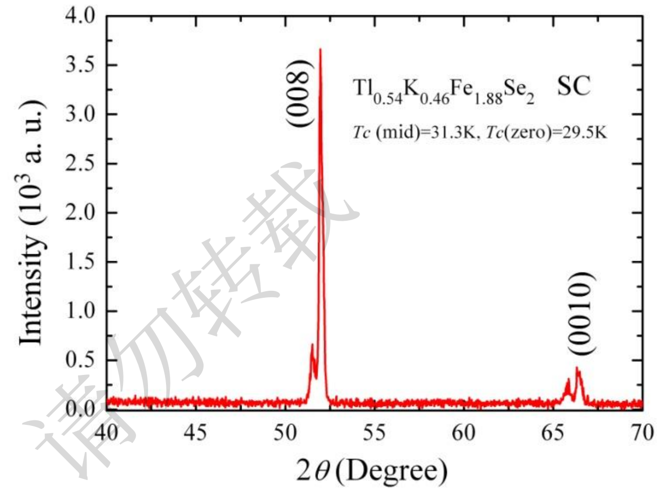
(4) Neutron diffraction: T_N=500K, Block AFM coexists with SC phase.

How to understand the coexistence of Block AFM and SC. Phase separation?

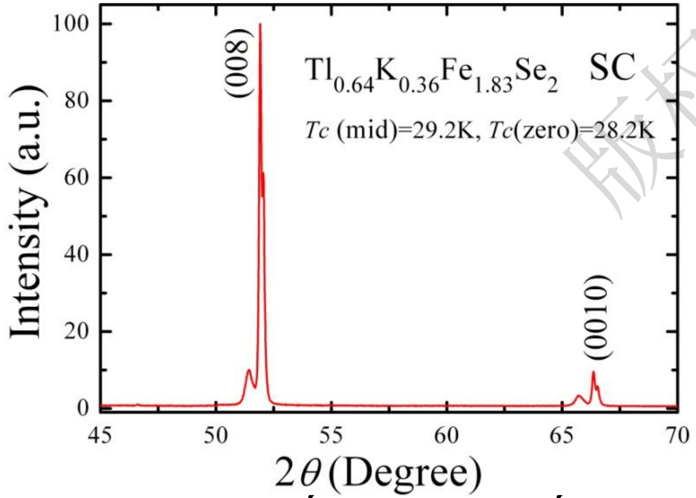
Evidence 1 -Super-lattice in *c* axis in SC $(Tl,K)Fe_xSe_2$



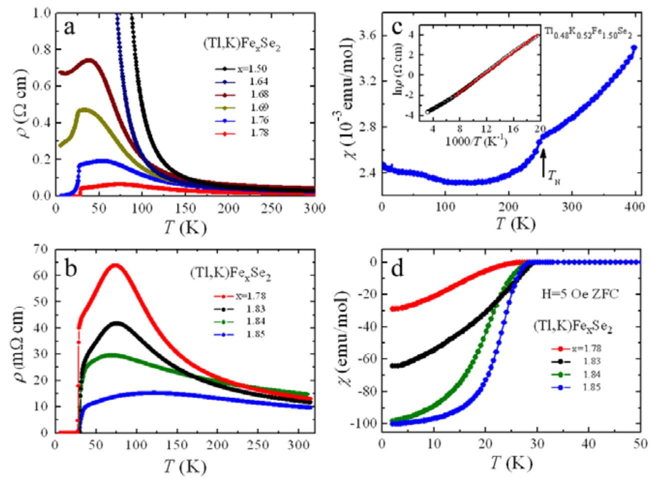
c = 13.99 Å



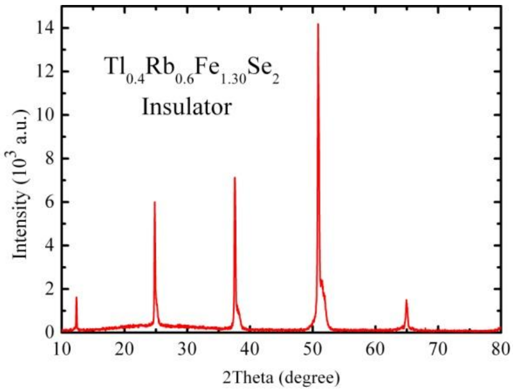
c_1 =14.07Å, c_2 =14.20Å

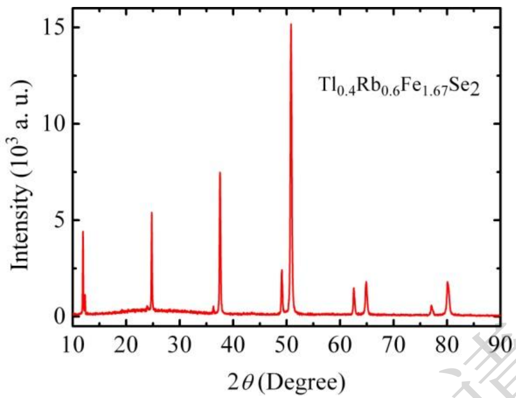


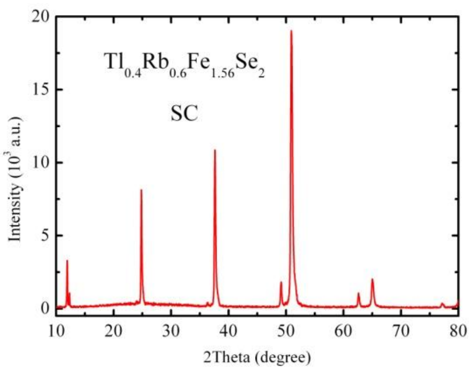
c_1 =14.08Å, c_2 =14.20Å

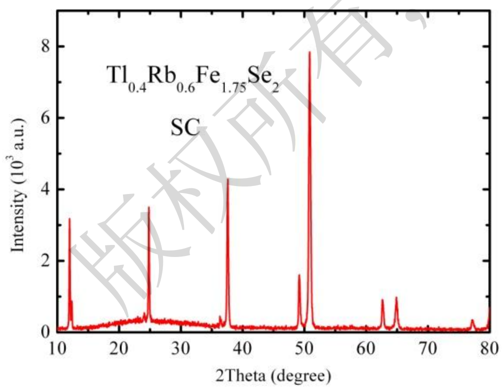


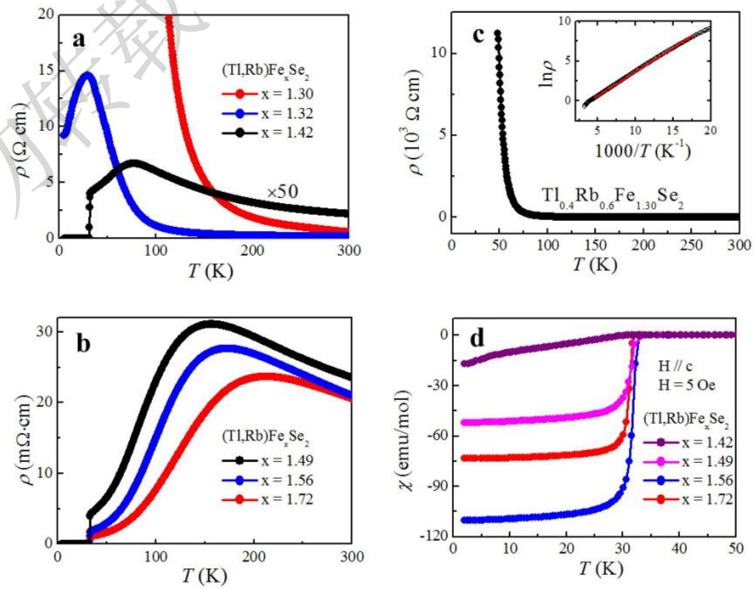
Super-lattice in c axis in SC $(Tl,Rb)Fe_xSe_2$











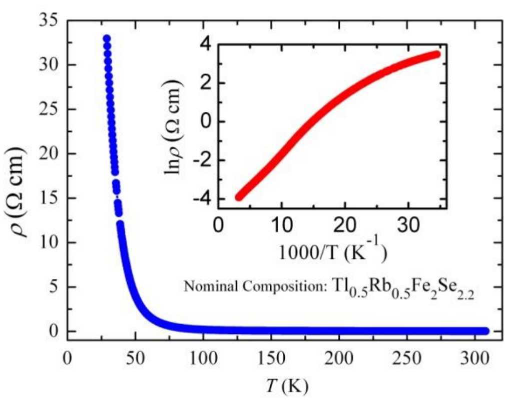
$Tl_{0.58}Rb_{0.42}Fe_{1.72}Se_2$

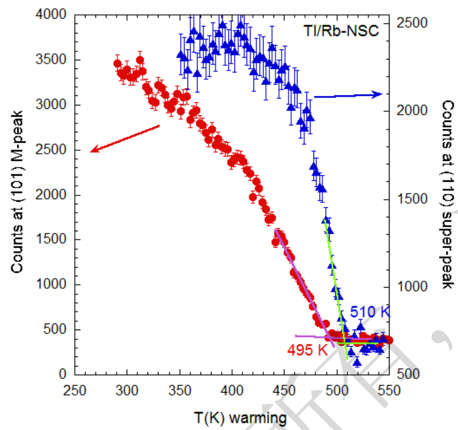
$c_1 = 14.30$Å, $c_2 = 14.81$Å

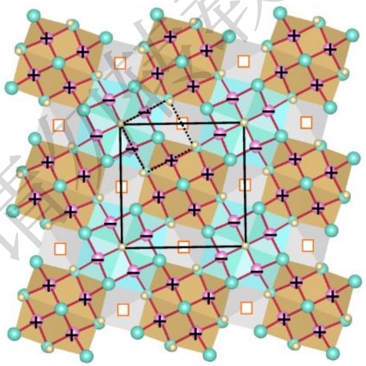
Direct evidence 2 for phase separation:
Neutron Diffraction for (Tl,Rb)Fe_xSe_2

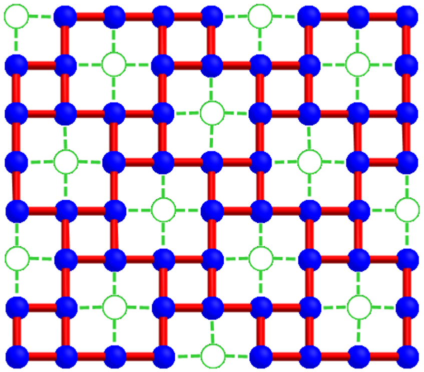
Q.Z. Huang (Private Comm., unpublished)

- **For Non-SC, AFM insulator (or semiconductor)**









Δ=400-500K

The Results of ND.

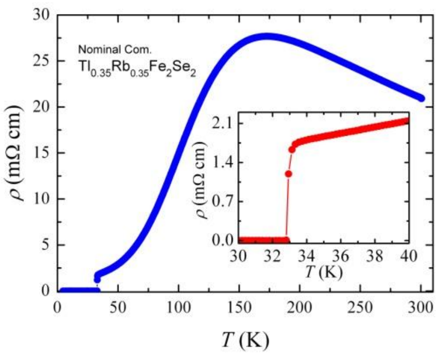
Wei Bao et al.
arXiv. 1102.3674,
***CPL*28, 086104(2011),**

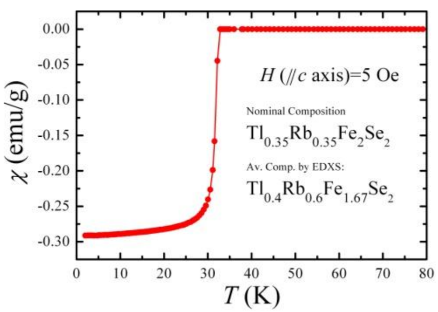
Minghu Fang et al.
arXiv. 1012.5236,
***EPL*94, (2011)27009**

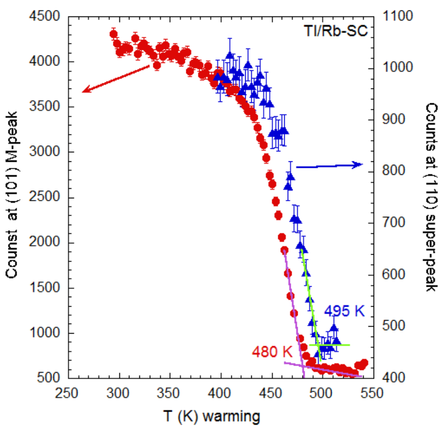
- **Nom. Comp.:** $Tl_{0.50}Rb_{0.50}Fe_2Se_{2.2}$
- **Aver. Comp. by EDS:** $Tl_{0.46}Rb_{0.54}Fe_{1.33}Se_2$
- **Fitting Comp. by ND at 550K:** $Tl_{0.452}Rb_{0.452}Fe_{1.578}Se_2$

- **HT (>510K), pure 122 structure,** ***I4/mmm*****,** $(Tl,Rb)_{0.904}Fe_{1.578}Se_2$
- **LT (<500K), pure 245 block phase.** ***I4/m*****,** $(Tl,Rb)_{0.904}Fe_{1.578}Se_2$

For SC $Tl_{0.5}Rb_{0.5}Fe_{1.67}Se_2$ crystals







- **Nom. Comp.:** $Tl_{0.35}Rb_{0.35}Fe_2Se_2$
- **Aver. Comp. by EDS:** $Tl_{0.4}Rb_{0.6}Fe_{1.67}Se_2$
- **Fitting Comp. by ND at 550K:** $Tl_{0.374}Rb_{0.374}Fe_{1.764}Se_2$

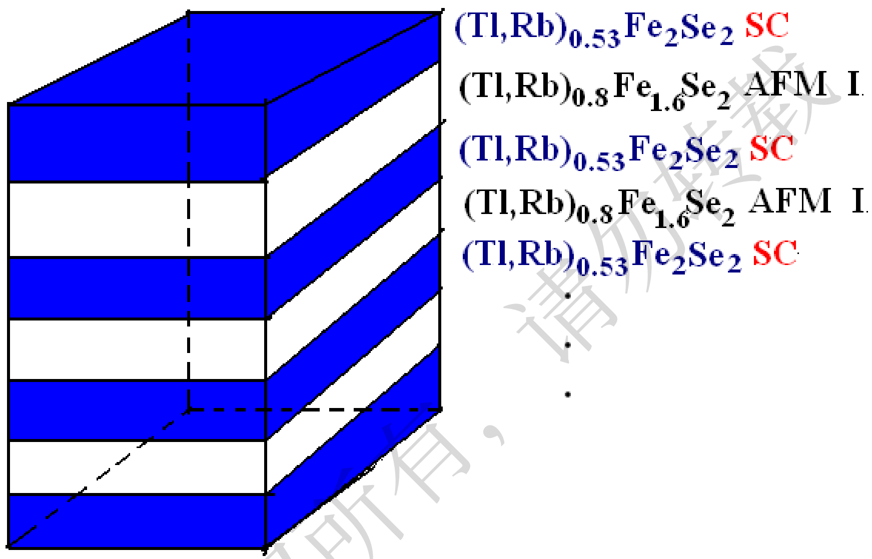
- **Only 122 phase above 510K.**
- **Two phase exist below 495K.**

RT: $(Tl,Rb)_{0.826}Fe_{1.563}Se_2$ (I4/m, AFM 70.9%)
+$(Tl,Rb)_{0.532}Fe_2Se_2$ (I4/mmm, Non-mag 21.5%)

	30K	RT	400K
I4/m- 245 phase (AFM)	**70.8%** a=8.668Å, c=14.235Å	**70.9%** a=8.707Å, c=14.335Å	**70.0%** a=8.730Å, c=14.355Å
I4/mmm-122 phase (Non-mag.)	**20.8%** a=3.826Å, c=14.589Å	**21.5%** a=3.842Å, c=14.820Å	**21.8%** a=3.855Å, c=14.894Å

Different Fe-content in various Fe-layer:

Phase separation along *c* axis

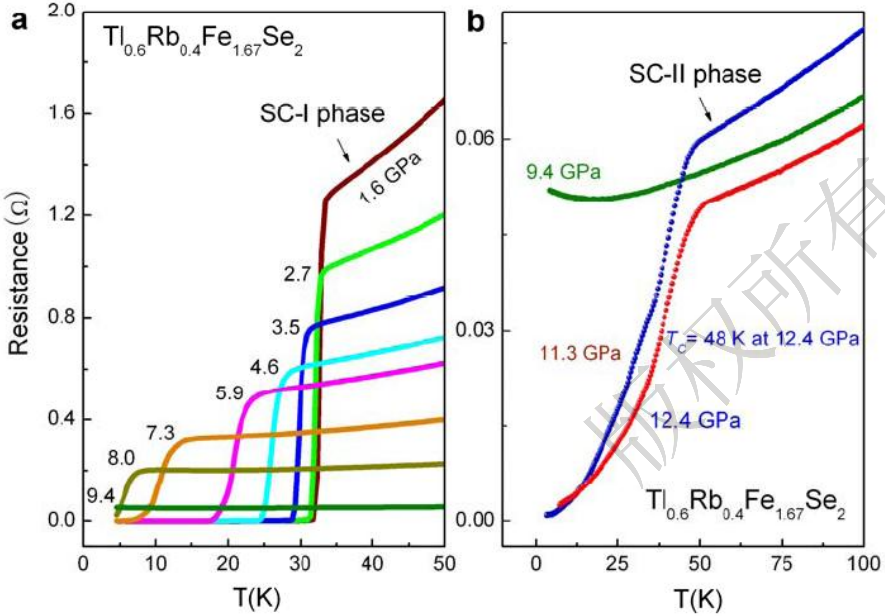


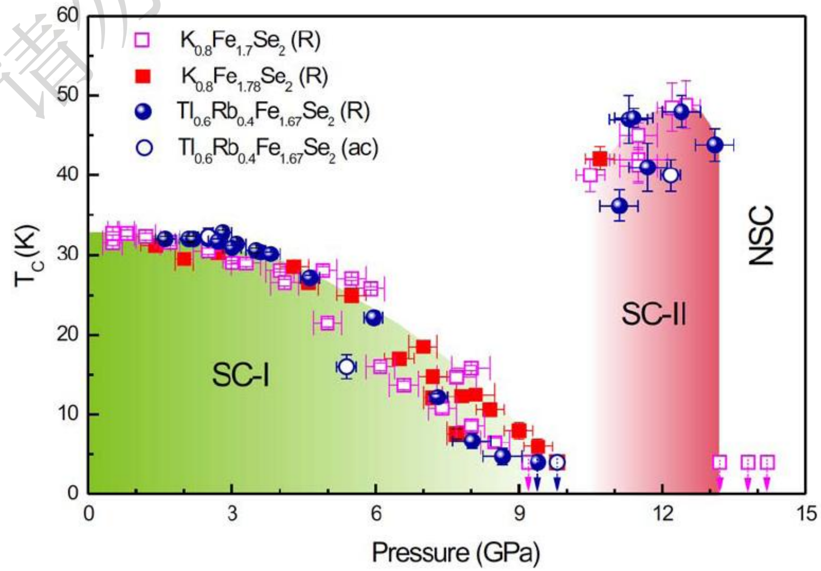
Phase separation in c axis

Fei Han, H.H. Wen et al ***Phil. Mag.*** 92(2012), 2553-2562 (Disorder)
Z. Wang, J.Q. Li et al. ***PRB*** 83, 140505(2011); ***EPL*** 95, 37007(2011) (TEM)
Ricci et al. ***PRB*** 84, 060511(2011); V. Ksenofontov et al. ***PRB*** 84, 180508(2011)
R.H. Yuan, N.L. Wang et al. ***Sci. Rep.*** 2, 221(2012);
W. Li, X. Chen et al. ***Nature Phys.*** 2155(2011); A. Charnukha et al. ***PRL*** 109, 017003(2012)

48K SC under high pressure

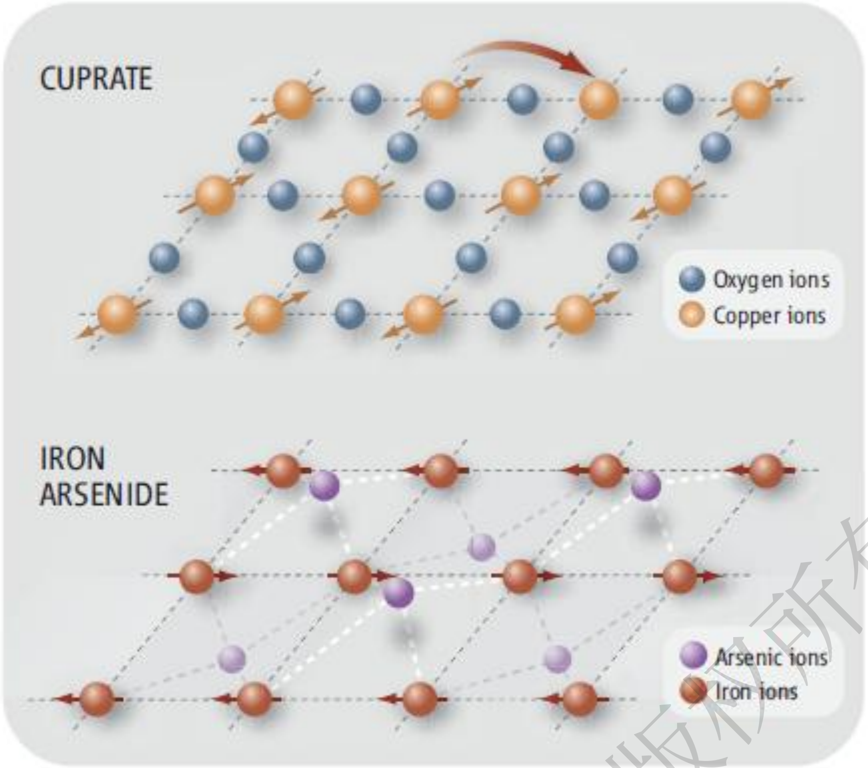
Liling Sun, ***Minghu Fang***, Zhongxian Zhao *et al*. ***Nature*** 483, 67(2012)





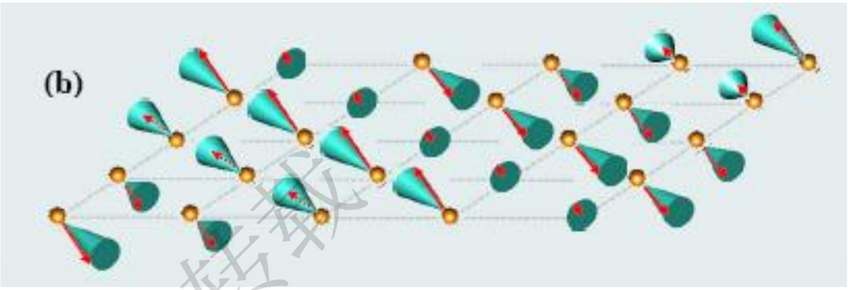
IV. AFM orders in (Tl,K,Rb)Fe_xSe_2

Three types AFM Order in the Fe-based Compounds



In LaOFeAs, and $BaFe_2As_2$,
Collinear AFM order.

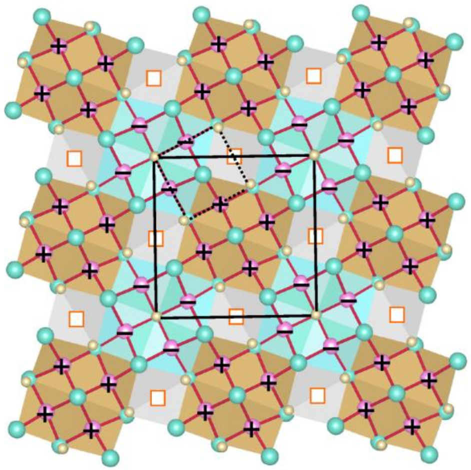
C. de la Cruz, Pengcheng Dai et al,
Nature 453, 899 (2008)



In FeTe, Bi-collinear AFM order.

W. Bao, Minghu Fang, Z.Q. Mao et al, *PRL*102, 247001(2009)

M.H. Fang, Z. Q. Mao et al. *PRB*, 78, 224503(2008)



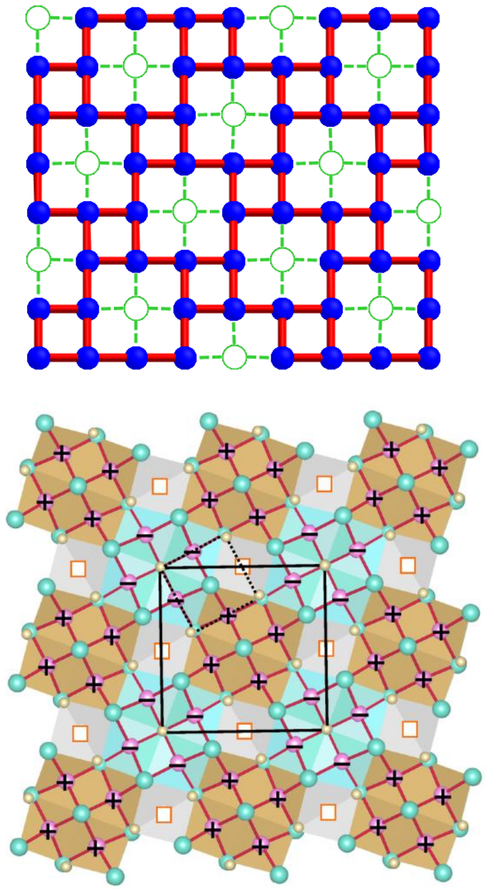
In (Tl,K,Rb,Cs)Fe_xSe_2, Block AFM order.

W. Bao et al *CPL*28, 086104(2011),

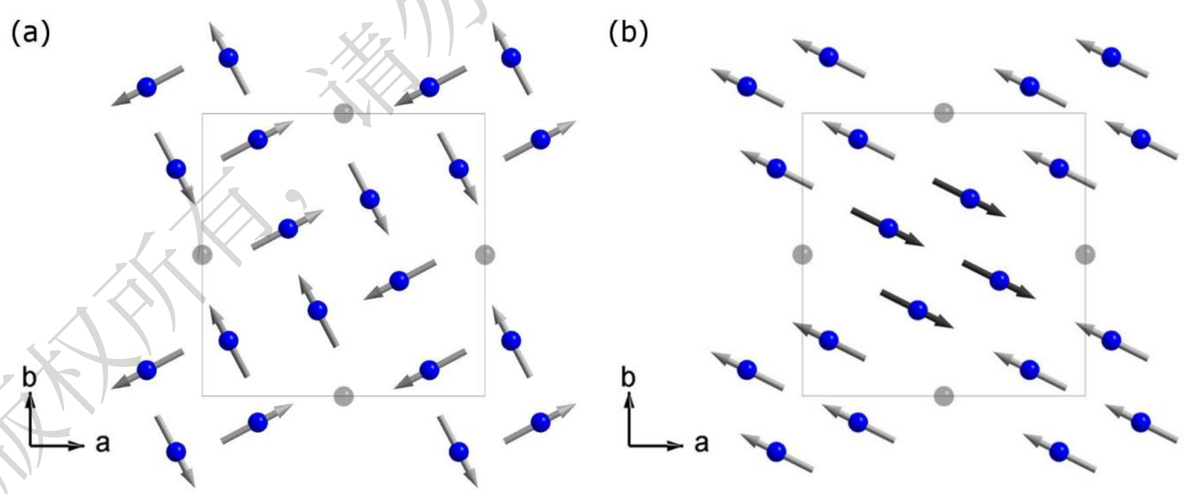
W. Bao, X.H. Chen, Minghu Fang et al. arXiv1102.2882, *PRL*. 107, 137003 (2011)

ND Experiment:
Spin reorientation in $TlFe_{1.6}Se_2$

A. F. May *et al.* arXiv. 1207.1318, *PRL* 109, 077003(2012)



No change in Fe-vacancy super-lattice



Along c axis Block-AFM, Above 100K

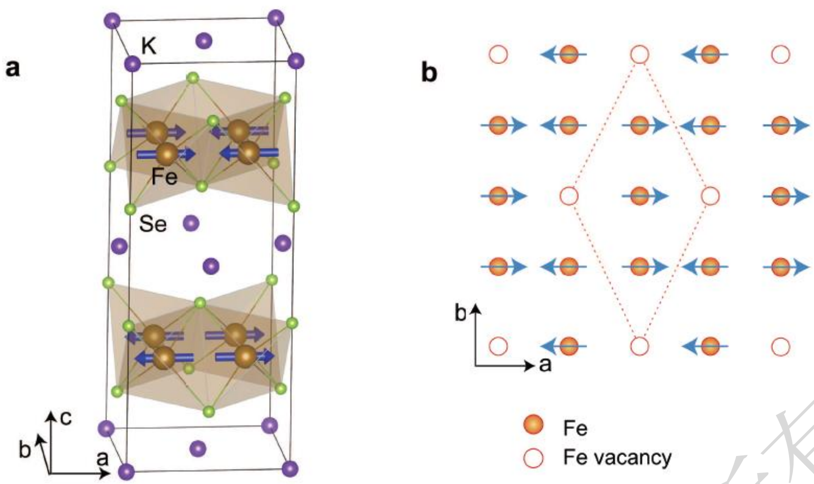
New AFM order, Below 100K

Non-collinear,

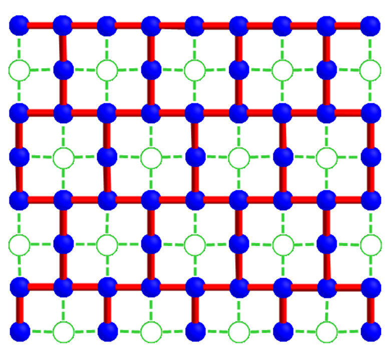
In-plane Block-checker AFM

ND Experiment: In addition to the Block-AFM, there is another AFM order in $K_xFe_{2-y}Se_2$

Jun Zhao et al. arXiv. 1205.5992; *PRL*109, 267003(2012)

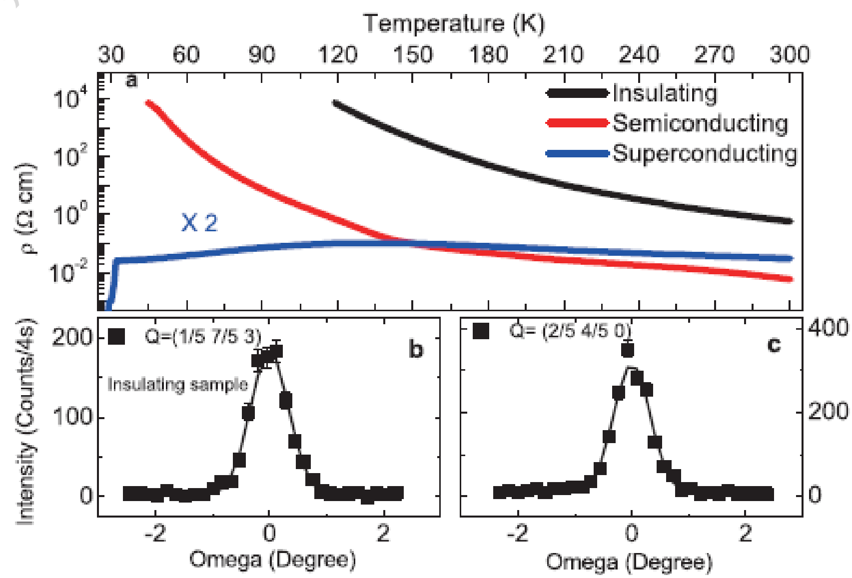


In the semiconducting crystals, there is another AFM order. Which is the same as that in pnictides.

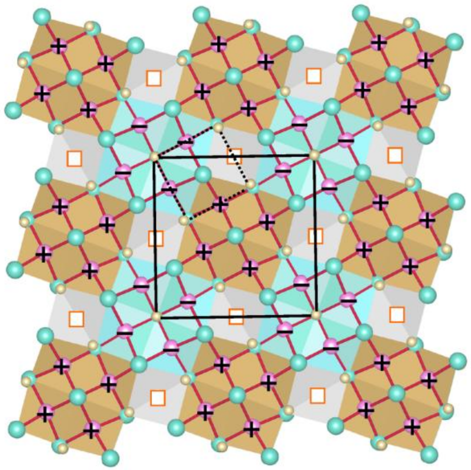


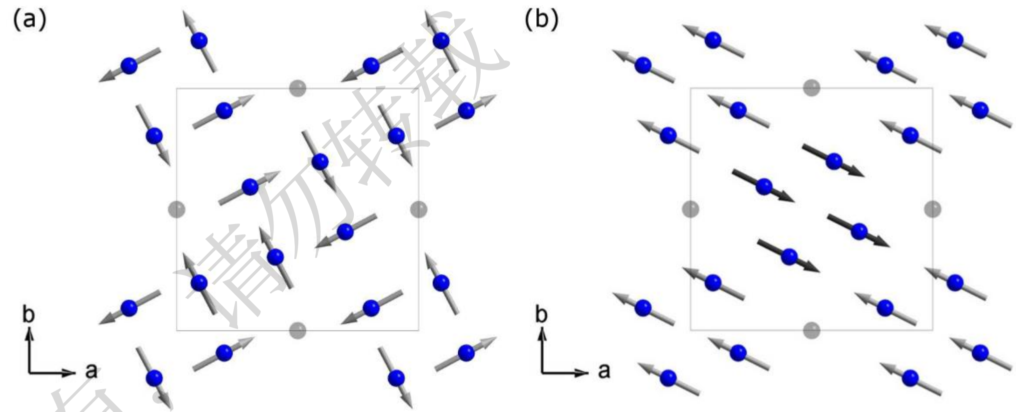
$$x = 1.50,\ \sqrt{2}\times\sqrt{2}$$

Minghu Fang et al. *EPL* 93, 47004



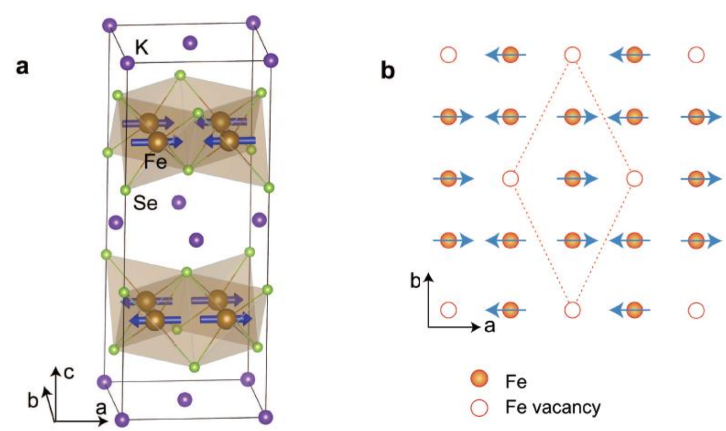
Which is the parent AFM order of $(Tl,K,Rb)Fe_xSe_2$?





A. F. May *et al.* arXiv. 1207.1318

W. Bao et al *CPL*28, 086104(2011),
W. Bao, et al. *PRL* 107, 137003 (2011)



Jun Zhao et al. arXiv. 1205.5992

Conclusions for (Tl,K,Rb)Fe_xSe_2 system

- **To suggest the existence of Fe-vacancy super-lattice in Fe-based SC.**

- **To discover the evolution from an insulator to SC in (Tl,K,Rb)Fe_xSe_2 system with increasing Fe content.**

- **Phase separation occurs in the new 122 compound.**

- **Which is a "parent AFM" of (Tl,K,Rb)Fe_xSe_2 system?**

WEB OF KNOWLEDGE

RESEARCH FRONTS 2013

100 Top-Ranked Specialties in the Sciences and Social Sciences

Christopher King
David A. Pendlebury

April 2013

THOMSON REUTERS™

PHYSICS

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Alkali-doped iron selenide superconductors	49	2,000	2011.2
2	Spin-orbit coupled Bose-Einstein condensates	48	1,752	2011.1
3	Dark matter direct detection experiments	48	3,285	2010.6
4	Evidence of majorana fermions	44	2,887	2010.6
5	Top quark forward-backward asymmetry	48	2,213	2010.6
6	Quantum simulations with trapped ions	36	2,017	2010.5
7	Nodal gap structure in iron-based superconductors	36	1,863	2010.4
8	Holographic Fermi surfaces and entanglement entropy	37	2,643	2010.1
9	Interpreting quantum discord	41	3,650	2010.0
10	Topological insulators	45	8,957	2009.9

Source: Thomson Reuters Essential Science Indicators

CHINESE SCIENTISTS AT THE FOREFRONT

Thomson Reuters analysts are frequently asked: "When will China have its first home-grown Nobel laureate in the sciences?" It is a question impossible to answer because no one knows what remarkable discoveries will be made in the future or how the Nobel committees decide on their specific honorees for research published in the past. Nonetheless, the rise of China in the internationally influential journal literature indexed by Thomson Reuters—in terms of share of world output—is the most significant event in the structure of scientific research in the past 30 years. In 1983, China produced just .6 percent of articles surveyed by Thomson Reuters in the Science Citation Index (Web of Science). Now, China produces some 13 percent of the literature, second only to the United States at 29 percent. Output, or world share, does not necessarily alig with research impact as measured by citations, but there is typically some correspondence between capacity and quality, eventually.

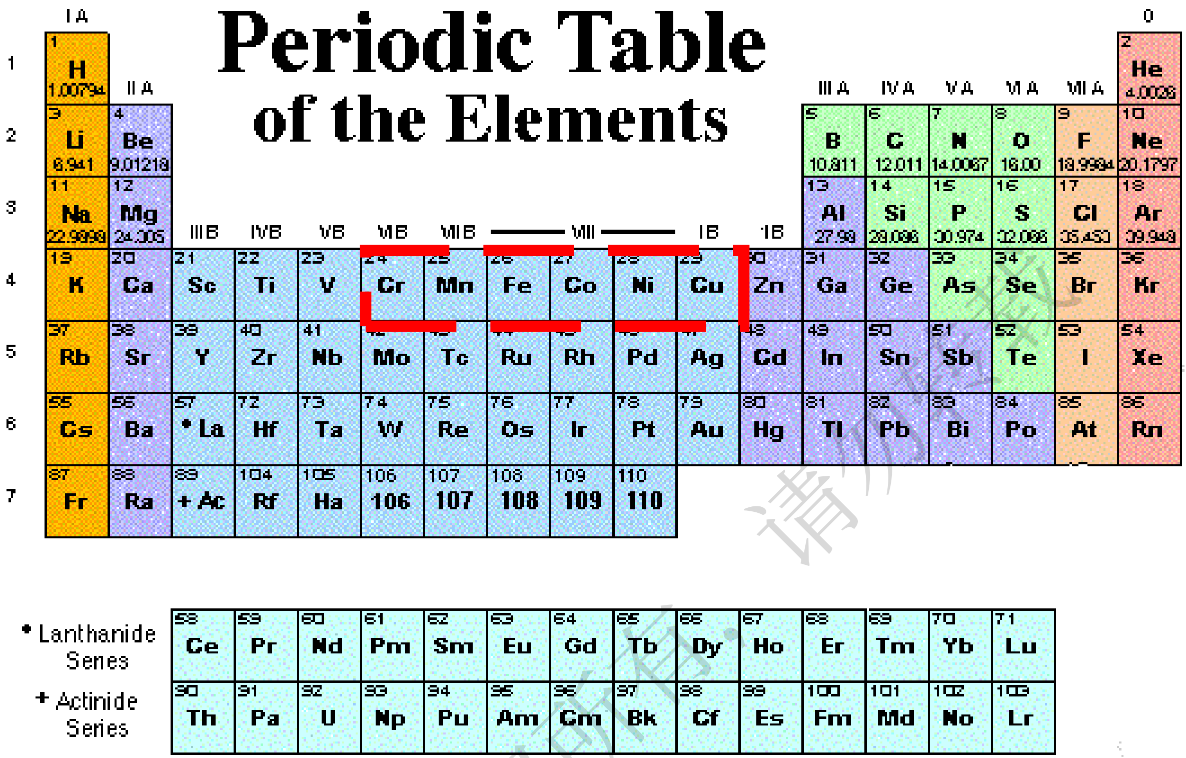
The research front ranked first in the table on page 18 focuses on a new class of superconducting materials. The analysis below of the national and institutional affiliations of the authors on the front's 49 highly cited core papers reveals China's dominant position in this cutting-edge area of condensed matter physics. Also listed are the researchers with the greatest number of core papers in the front – and all are affiliated with Chinese institutions.

RANK	NATION	%	INSTITUTIONS	%	SCIENTISTS	%
1	China (30)	61.2	Chinese Academy of Sciences (15)	30.6	Gen-Fu Chen, Renmin University (9)	18.4
2	USA (15)	30.6	Renmin University of China (13)	26.5	Xian-Hui Chen, USTC (8)	16.3
3	Germany (7)	14.3	University of Science and Technology of China (8)	16.3	Jun-Bao He, Renmin Univ (7); Du-Ming Wang, Renmin Univ (7); Jian-Jun Ying, USTC (7)	14.3
4	Japan (5) Moldova (5) Switzerland (5)	10.2	Zhejiang University (7)	14.3	Xiang-Feng Wang, USTC (6)	12.2
5	France (4)	8.2	University of Augsberg (6)	12.2	Chi-Heng Dong, Zhejiang Univ (5); Ming-Hu Fang, Zhejiang Univ (5); Jiang-Ping Hu, CAS (5); Ai-Feng Wang, USTC (5); Hang-Dong Wang, Zhejiang Univ (5); Meng Zhang, USTC (5)	10.2

Source: Thomson Reuters Essential Science Indicators

http://sciencewatch.com/sites/sw/files/sw-article/media/research-fronts-2013.pdf

V. Superconductivity in $TlNi_2Se_2$ and $TlNi_2S_2$



Nowadays, SC emerging in some Cr, Mn, Cu, Fe, Co compounds with *3d* electrons is close to some AFM or FM order, such as Cuprates, Fe-based compounds, $NaCoO_2$+yH_2O, especial for the recently discovery CrAs, $K_2Cr_3As_3$ and MnP.

Only in Ni-based compounds, SC is not close to any magnetic order, seems to be a conventional SC?

Ni-Based Superconductors

Ni-pnictides:

LaONiAs (2.75 K), *Z. Li et al* ***PRB*** 78, 060504(2008), (γ_N =7.3 mJ/molK^2)
$BaNi_2As_2$ (0.7 K), N. Kurita et al ***PRL*** 102, 147004(2009), (γ_N =12.3 mJ/molK^2)
$SrNi_2P_2$ (1.4 K), *F. Ronning et al.* ***PRB*** 79, 134507(2009), (γ_N=15mJ/mol K^2)
$BaNi_2P_2$ (2.4K), *Y. Tomioka et al.* ***PRB*** 79, 132506(2009), (γ_N=14mJ/mol K^2)

Low T_C, Paramagnetism, Structure Transition, a conventional SC？

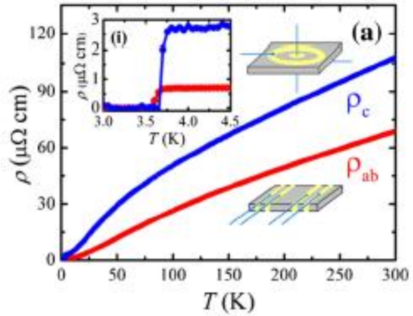
Ni-Chalcogenides:

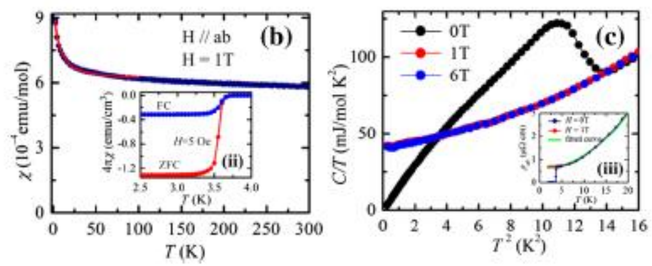
KNi_2Se_2 (0.8 K), J. R. Neilson *et al* ***PRB*** 86, 054512(2012), (γ_N =44 mJ/mol K^2)
KNi_2S_2 (0.47K), J. R. Neilson *et al* ***PRB*** 87, 045124(2013), (γ_N =40 mJ/mol K^2)
The authors suggested that SC is close to a dynamical CDW order in both systems.
Our group discovered:
$TlNi_2Se_2$ (3.7 K), M.H. Fang *et al.* ***PRL***111, 207001(2013) (γ_N =40 mJ/mol K^2)
$TlNi_2S_2$ (2.3K), M.H. Fang *et al* arXiv:1305.1033, appearing in *JOP* (γ_N =31 mJ/mol K^2)
$CsNi_2Se_2$(2.7K), M.H. Fang *et al* arXiv:1508.05167, (γ_N =77.9 mJ/mol K^2)

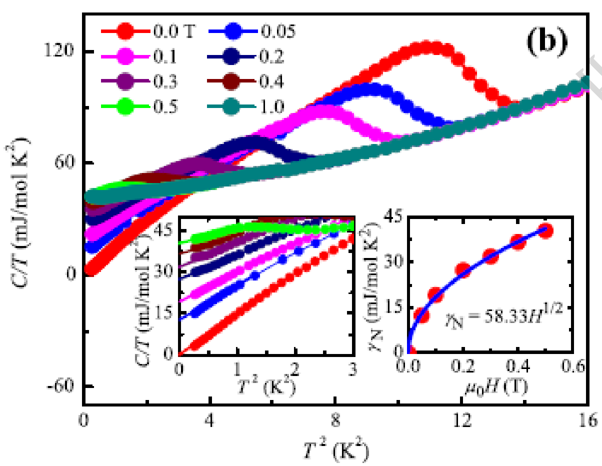
Although low T_C, I shall tell you that their SC is also close to a AFM.
an Unconventional SC?

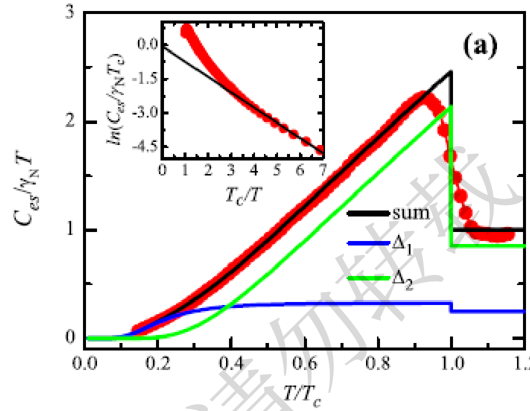
Multi-gap SC in $TlNi_2Se_2$

Hangdong Wang, *Minghu Fang* et al, *PRL*111, 207001 (2013)









Two gaps fitting

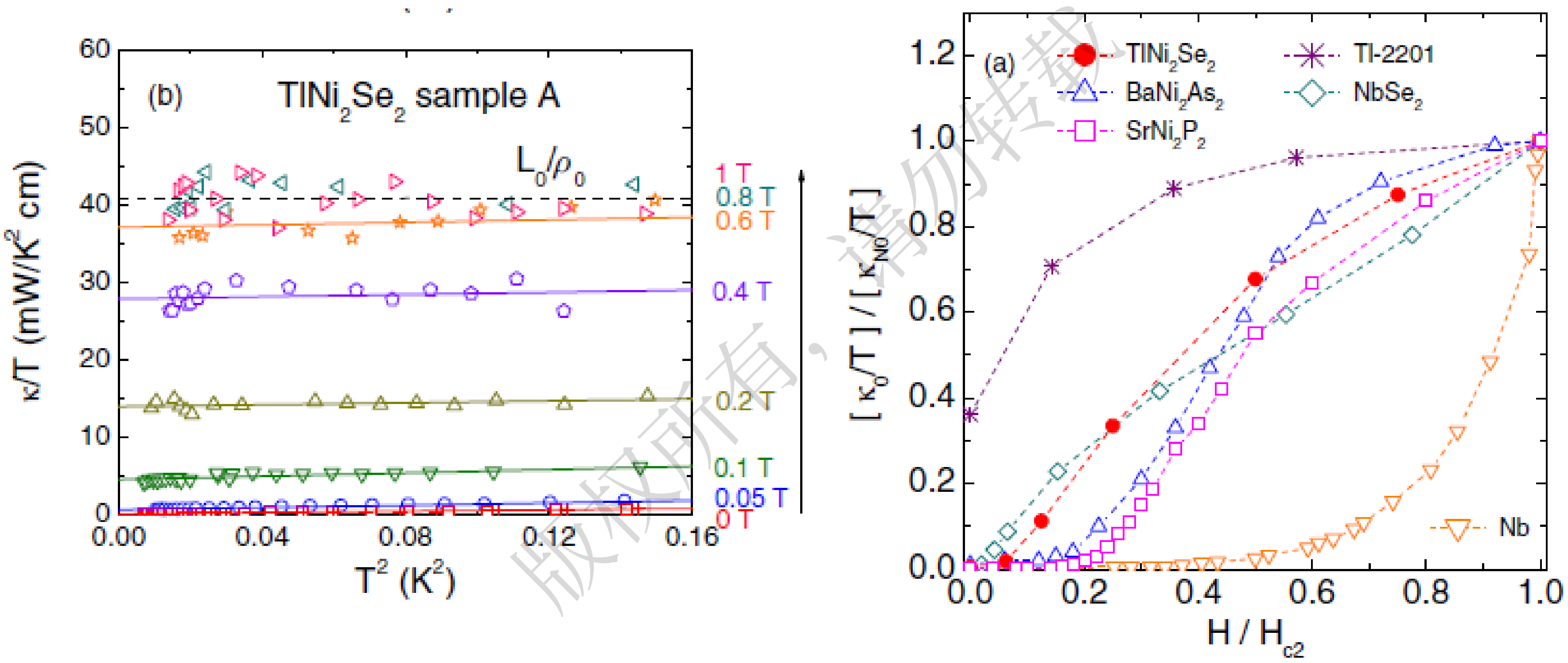
$\Delta_1 = 0.84 k_B T_C$, 25%

$\Delta_2 = 2.01 k_B T_C$, 75%

1. SC with T_C=3.7K
2. In the normal state:
   $RRR = \rho(300K)/\rho(2K) = 103$, high quality crystals.
3. Small anisotropic.
   $\rho_c(300K) / \rho_{ab}(300K) = 1.57$, even a layer structure
4. Feimi liquid behavior at LT
   $\rho_{ab}(T) = \rho_0 + AT^2$, $A = 4.94\times10^{-3}$ μΩ cm
   Kadowaki-Woods ratio: $A/\gamma^2 = 0.308\times10^{-5}$
   similar to Conventional HF
5. Wilson Ratio, R_w=1.24
6. γ_0=40 mJ/mol·K^2, m^*/m_b=14, middle correlation?
7. $\gamma_0(H) \sim H^{0.5}$, a common feature of *d*-wave SC.

Thermal Conductivity of $TlNi_2Se_2$

X. C. Hong, Minghu Fang S. Y. Li *et al.* *PRB*90, 060504(R) (2014)

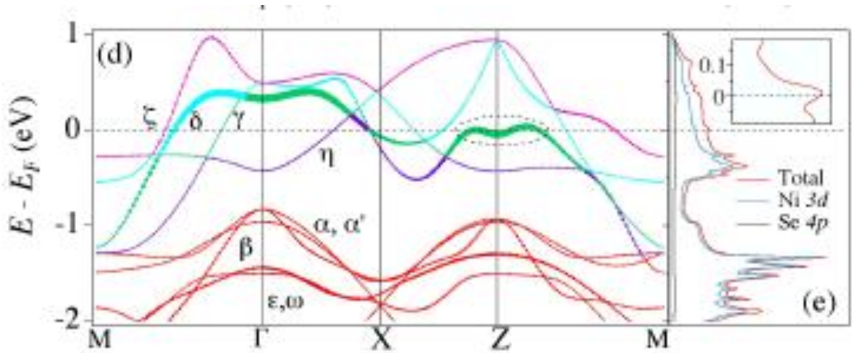


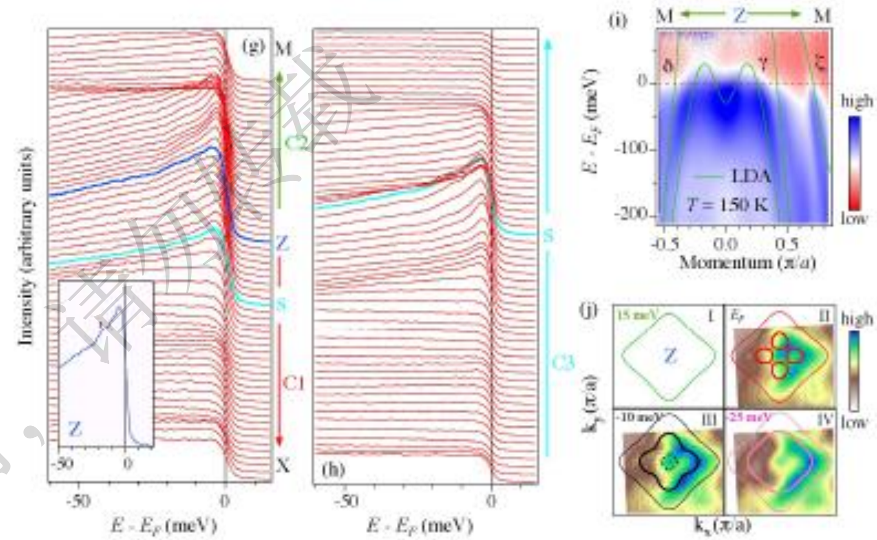
Multi-gap superconductivity, but nodeless!

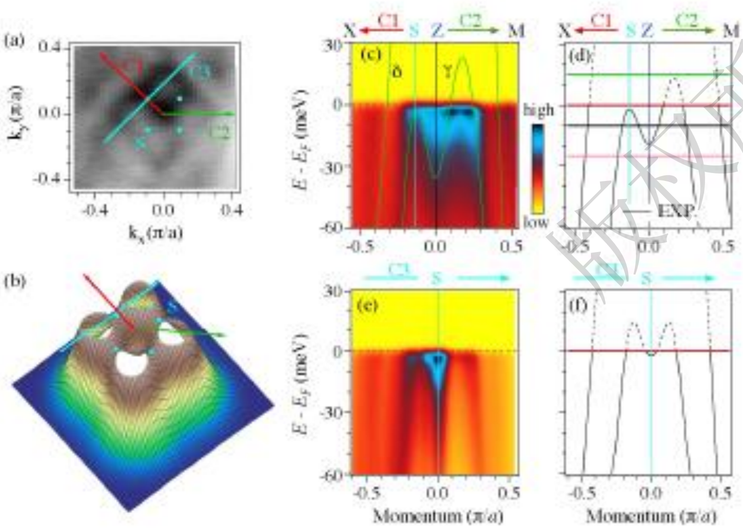
Conventional *s*-wave SC?

Electronic Structure of $TlNi_2Se_2$

N. Xu, Minghu Fang, H. Ding, and M. Shi *et al*. arXiv. 1412.7016, ***PRB*** 92, 081116(R) (2015)





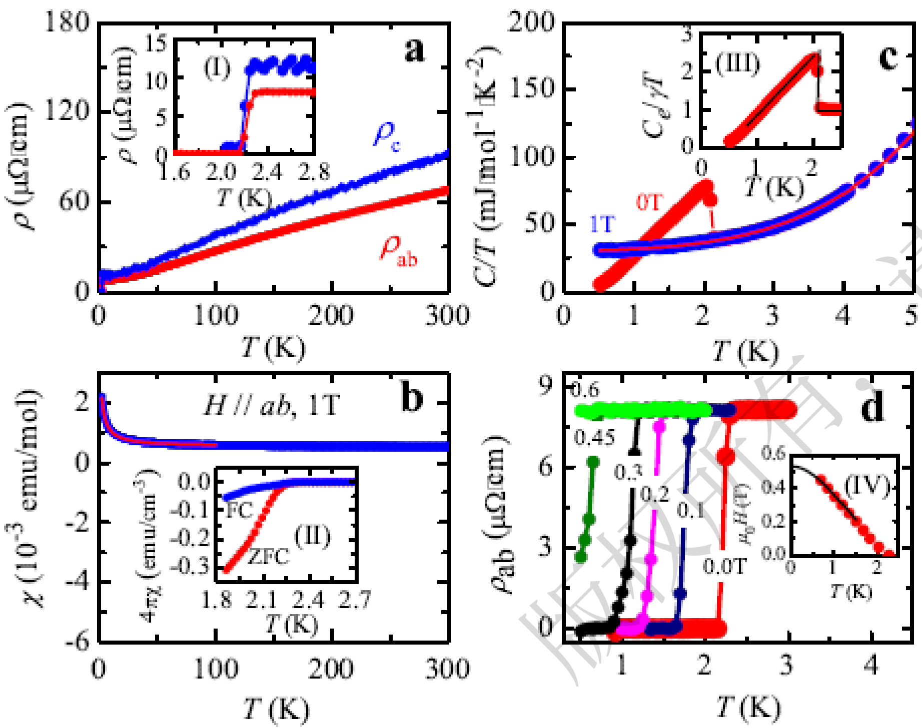


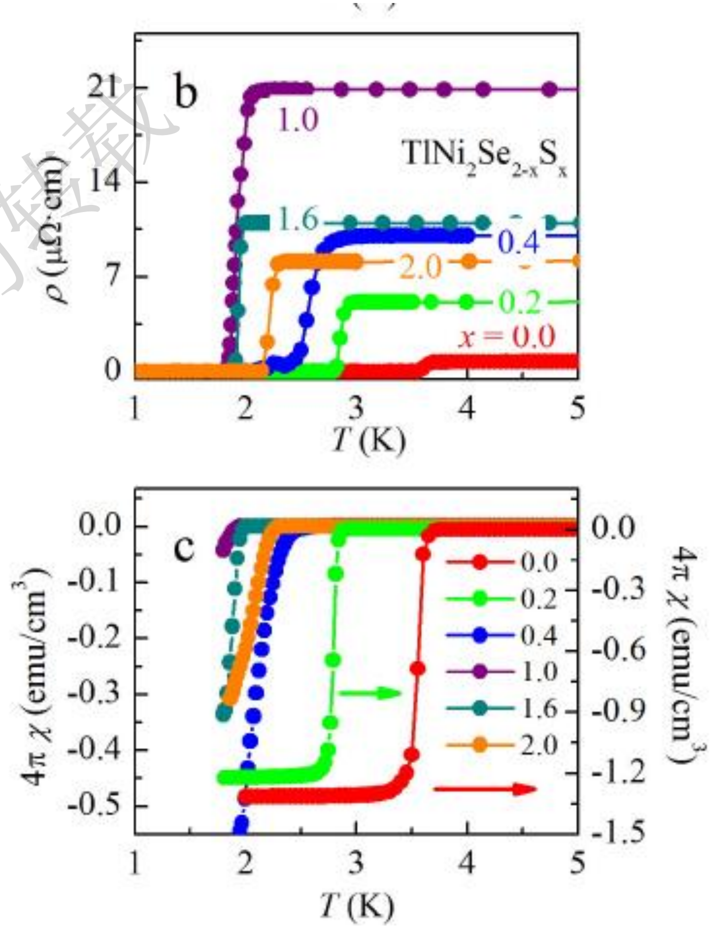
1. Near E_F , Ni 3*d* - Multiband.
2. Weak electronic correlations, bandwidth renormalization 1.4.
3. Camelback-shaped band lies in the mediate vicinity of Fermi level. A pronounced van Hove singularity results in Heavy band mass.

SC in $TlNi_2Se_{2-x}S_x$ (0≤x≤2.0)

Hangdong Wang, Minghu Fang *et al.* arXiv. 1305.1033, *JOP* in press

$TlNi_2S_2$





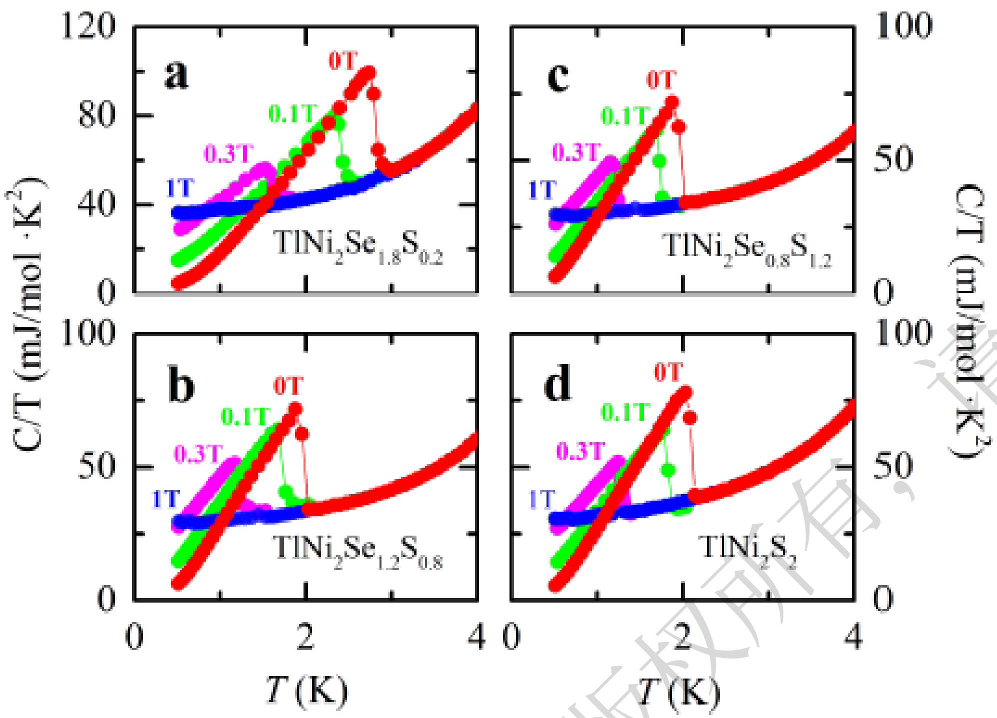
All the $TlNi_2Se_{2-x}S_x$ (0≤x≤2.0) crystals are SC.

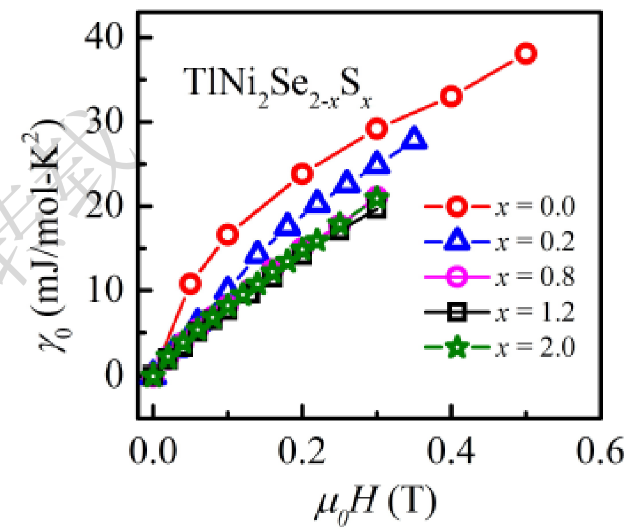
Identical-valance substitution of S for Se may induce:

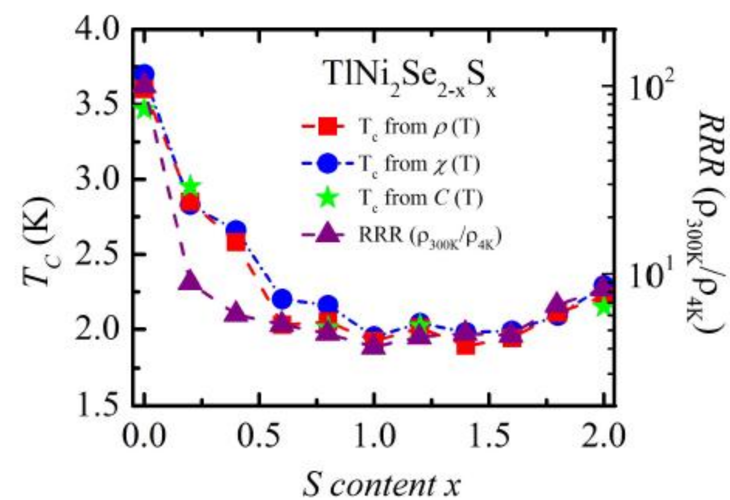
Chemical Pressure and Disorder, but no charge carriers.

SC in $TlNi_2Se_{2-x}S_x$- continued

Hangdong Wang, Minghu Fang *et al.* arXiv. 1305.1033, *JOP* in press







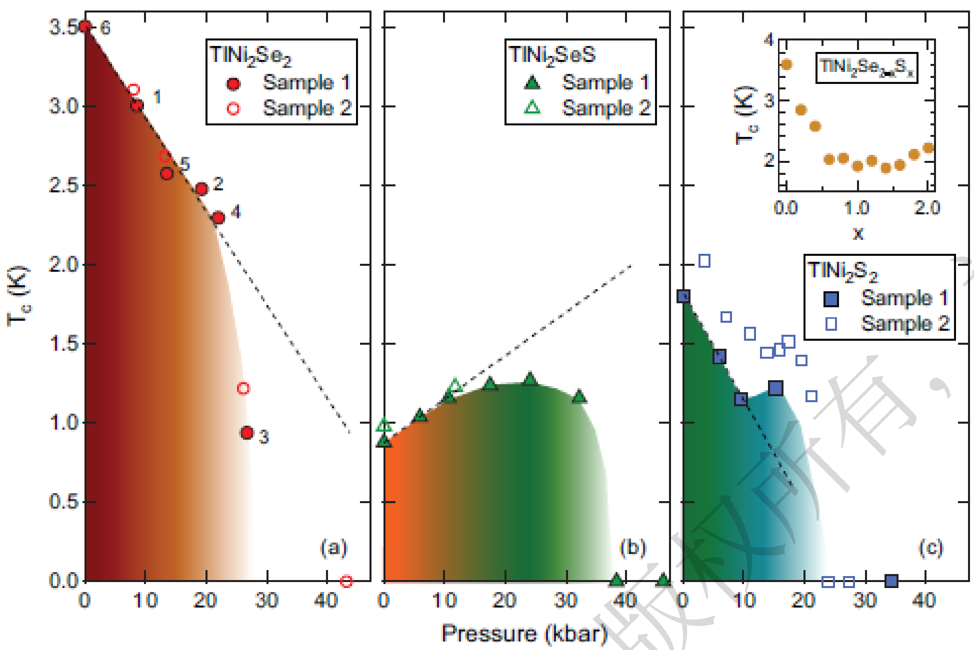
The substitution of S for Se:

1. γ_0 **decreases.**
2. $\gamma_0(H)$, **From $H^{0.5}$ to a linear H^1 with S content**
3. **The relationship between T_C and disorder.**

Provides a platform to study the effect of disorder on the multi-band SC.

The Pressure Dependence of SC for $TlNi_2Se_2$, $TlNi_2SeS$ and $TlNi_2S_2$

Swee K. Goh, Hangdong Wang, Minghu Fang *et al.* *PRB*90, 201105(R) (2014)



(a) At a moderate pressure for all three compositions, SC disappears.

(b) A dome-shaped pressure dependence of T_C for $TlNi_2SeS$.

(c) Double dome-shaped pressure dependence of T_C for $TlNi_2S_2$.

The multi-dome emerges in $TlNi_2Se_{2-x}S_2$ system. Similar to FeSe: K. Miyoshi *et al*. *JPSJ* 78, 093703(2009),
M. Bendele *et al.* *PRL* 104, 087003 (2010).
$LaFeAsO_{1-x}H_x$, S. Iimura *et al*. *Nat. Commun* 3, 943(2012),
M. Hiraishi *et al*. *Nat. Phys.* 10, 300(2014)

Summary for SC in $TlNi_2Se_{2-x}S_x$

- T_C is low, which may relate to a weak correlation.
- A large γ_N may origin from the van Hove singularity.
- Multi-gap nodeless SC, two gaps exist in the SC state.
- $\gamma_N(H) \sim H^{0.5}$ or H, dependent on S content.
- Dome shape in the pressure dependence of SC.
- T_C relates to the disorder.

Some behaviors is similar to Fe-based SC, whether SC in this system is also close to magnetic order?

We choose Co($3d^7 4s^2$) to replace Ni($3d^8 4s^2$), what happens?

Thank you for your attention!