17. Neutron Inelastic Scattering Study on Superconducting and Parent Phases of the Ba(Fe,Co)$_2$As$_2$ System

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We will report recent results of single-crystal growth and inelastic neutron scattering measurements on superconducting Ba(Fe,Co)$_2$As$_2$ and its parent compound BaFe$_2$As$_2$. For both the systems, large single crystals of the typical size 10x4x2mm$^3$ were obtained using the vertical Bridgman technique [1]. In the parent compound, inelastic neutron scattering using single-crystals reveals a spin-wave-like excitation mode centered at the antiferromagnetic Bragg points with the gap energy being 9.8 meV at the base temperature [2]. The spin-wave-like mode has a steep in-plane dispersion with a velocity 280 meV Å, whereas relatively weak dispersion was seen along the $c$-axis. In addition, a two-dimensional excitation continuum appears at higher energies $\hbar \omega > 20$ meV, suggesting electron-hole excitations in this energy range. As the temperature is elevated, the excitation gap closes, and above the Neel temperature, gapless spin fluctuations of much two-dimensional nature dominate the excitation spectrum. The inelastic response in the superconducting phase will be also presented.

References
Inelastic Neutron Scattering Measurements on Single Crystal BaFe$_2$As$_2$

Kittiwit Matan

International Workshop on Iron Related High-T$_c$ Superconductors
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Research Team

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Outline

- Magnetism in FeAs compounds
- Inelastic neutron scattering on single-crystal BaFe$_2$As$_2$
- Spin fluctuations above $T_N$
- Preliminary results on superconducting sample
- Summary

Superconductivity in F-doped LaFeAsO

Kamihara et al., J. Am. Chem. Soc. 130, 3296 (January 2008)

- Parent compounds are poor metals.
- Electron-doped LaFeAsO$_{1-x}$F$_x$ with $T_c$ of $\sim$26 K.
- Hole-doped La$_{1-x}$Sr$_x$FeAsO with $T_c$ of $\sim$25 K.
- Changing of La to rare earth ions results in $T_c$ $\sim$ 52 K.

What is the anomaly around 150K?
Structural and magnetic transitions in LaFeAsO

de la Cruz et al., Nature 453, 899 (June 2008)

Structural transition at 155 K

Magnetic transition at \(~138\) K

The discovery of LaFeAsO led to discoveries of many other Fe-based superconductors.

Structural and magnetic transitions in BaFe$_2$As$_2$


- Similar structure, and electronic-magnetic properties.
- Antiferromagnetic and structural transitions at $T_N \sim 135$ K.
- Superconductivity in K, Co, Cs, Ni doped AFe$_2$As$_2$, A=Ba, Sr, Ca, and Eu with the highest $T_c$ of 38 K.
Magnetism and superconductivity in BaFe$_2$As$_2$

- Powder neutron diffraction reveals antiferromagnetic spin structure in FeAs layers with an ordered moment of $0.87(3) \mu_B$.
  (Huang et al., Phys. Rev. Lett. 101, 257003)

- Magnetic order is a result of SDW instability due to Fermi surface nesting.
  (Mazin et al., Phys. Rev. Lett. 101, 057003)

- Magnetic ordered state is suppressed by doping or pressure.

- The suppression of magnetic ordered state is accompanied by the presence of superconductivity.

**Itinerant magnetism**

Magnetic excitations in parent compounds

La$_2$CuO$_4$

- Localized spins

BaFe$_2$As$_2$

- Itinerant spins

- Low energy spin wave excitations.

- Electron-hole excitations at high energy (the Stoner continuum).

Goals

I. To study anisotropic magnetic interactions; excitations and spin fluctuations.

II. Investigate itinerant magnetism, signature of the Stoner continuum.

Magnetic excitation studies using inelastic neutron scattering measurements on a single crystal sample.

Single crystal growth


Single-crystal sample
- The sample was grown in our ISSP lab.
- Bridgman method using FeAs flux.
- Size ~10mm x 5mm x 2mm.

Neutron scattering measurements
- Two co-aligned single crystals M=0.4 g
- Mosaic < 1°
- HER and GP-TAS (ISSP, U. of Tokyo)
- Aligned in h0l zone a* = 1.124(3) Å⁻¹ and c* = 0.485 Å⁻¹.

Large enough single crystals to perform inelastic neutron scattering.
Low energy spin-wave-like excitations

\[ \Delta = 9.8(4) \text{ meV} \]
\[ \nu_{ab} = 280(150) \text{ meV} \]
\[ \nu_c = 57(7) \text{ meV} \]
\[ \nu_c/\nu_{ab} \sim 0.2 \]

Origin of the gap?

Spin wave excitations in SrFe\textsubscript{2}As\textsubscript{2} and CaFe\textsubscript{2}As\textsubscript{2}

SrFe\textsubscript{2}As\textsubscript{2}

\[ \Delta \leq 6.5 \text{ meV} \]
\[ \nu_{ab} = 560 \text{ meV} \]
\[ \nu_c = 280 \text{ meV} \]

CaFe\textsubscript{2}As\textsubscript{2}

\[ \Delta = 6.9(2) \text{ meV} \]
\[ \nu_{ab} = 420(70) \text{ meV} \]
\[ \nu_c = 270(100) \text{ meV} \]

Magnetic interactions in BaFe\textsubscript{2}As\textsubscript{2} are more two-dimensional.
High energy magnetic excitations

- Normalization function obtained from acoustic phonons of copper
- Corrected for background, absorption, resolution, and magnetic form factor.
- For $\hbar \omega < 15$ meV, $S(\hbar \omega)$ shows the $1/\omega$ dependence for spin wave scattering.
- For $\hbar \omega > 15$ meV, $S(\hbar \omega)$ deviates from spin wave at 15 meV, and peaks around 20 meV.
- The integral up to 42 meV gives a fluctuating moment of 0.8(2) $\mu_B$.

What are the characters of the scattering in the gray shaded area?

Magnetic excitations at antiferromagnetic wavevectors

Excitations were observed at $(1,0,1), (1,0,3), (1,0,5), (1,0,7), (3,0,1)$.

Transverse fluctuations along b-axis:
Also spin-wave-like!
High energy magnetic excitations

- Yellow shaded areas: spin wave scattering
  \[ \Delta = 9.8 \text{ meV} \]
  \[ \nu_{ab} = 280 \text{ meV} \]
  \[ \nu_c = 80 \text{ meV} \]
- Single high point is spurious.

Gray shaded areas

- Also observed at (1,0,3), (3,0,1), and (1,0,7).
- Centered at the antiferromagnetic wavevectors co-existing with the spin waves.
- Anisotropic scattering indicate two-dimensional spin dynamics.

High energy magnetic excitations at 24 meV

(1 0 5)

(3 0 1)

Different intensity is consistent with transverse spin waves.
High energy magnetic excitations at 30 meV

(1 0 5)

\( h\omega = 30 \text{ meV} \)

(3 0 1)

\( L = 0 \)

What is this anisotropic scattering?

Magnetic excitations in metallic V\(_{2-y}\)O\(_3\)


- Spins form helical ordering along the c-axis at \( T_N = 8.5 \) K with incommensurate magnetic wave vector \( 1.7 \alpha^* \), resulting SDW instability.

Magnetic excitations

- Broad scattering that cannot be accounted for by spin waves.

- Weak coupling theory \( \Delta_s = 1.76 \alpha k_b T_N \), spin wave excitations decay into the Stoner continuum.

- \( \Delta_s = 1.4 \text{ meV} \) is very small. Only the Stoner continuum is observed.

Presence of spin waves inside the Stoner continuum and anisotropic character are NOT reported.
Magnetic excitations in BaFe$_2$As$_2$

- Low energy spin wave excitations with a spin gap.
  - Also observed in SrFe$_2$As$_2$ and CaFe$_2$As$_2$.
- Anisotropic high energy magnetic excitations.
  - Possibly the Stoner electron-hole continuum?
  - NOT observed in SrFe$_2$As$_2$ and CaFe$_2$As$_2$

Weak coupling theory

- For BaFe$_2$As$_2$, $\alpha \sim 1$, and $\Delta_s \sim 20$ meV.
- For SrFe$_2$As$_2$ ($T_N = 220$ K), $\Delta_s \sim 33$ meV.
- For CaFe$_2$As$_2$ ($T_N = 172$ K), $\Delta_s \sim 26$ meV.

Larger $\Delta_s$ might explain why the anisotropic scattering has not yet been observed in SrFe$_2$As$_2$ ($\hbar \omega_{\text{max}} \sim 16$ meV) and CaFe$_2$As$_2$ ($\hbar \omega_{\text{max}} \sim 25$ meV).

More experimental work is needed!

Spin fluctuations around $T_N$

- Correlation length $\xi \sim 100$ Å $\sim 40$ times nearest neighbor distance.
- Temperature dependence shows a peak at $T_N$, coinciding with the onset of magnetic Bragg peak.
- The sharp drop on the low temperature is due to opening of the spin gap.
- The slow decrease on the high temperature side is a result of critical scattering.
- We do not observe the divergence of correlation length at $T_N$.

Spin fluctuations exist despite first-order magnetic transition reported in $^{75}$As NMR*.

Spin fluctuations above $T_N$

- In-plane correlation length of 80 Å or about 30 times nearest neighbor distance.
- L-scan shows “rod-like” scattering.
- Uncorrelated interlayer spins.
- In the paramagnetic state, two-dimensional magnetism is clearly observed.
- Similar to the cuprates, large in-plane correlation length is a result of strongly two-dimensional magnetism.

- Do spin fluctuations (enhanced by two-dimensional magnetism) remain in the superconducting state?
- Can they be responsible for superconductivity?
Magnetic excitations in superconductors

**BISCOO**
Fong et al., Nature 398, 588.

**CeColn**
Stockel et al., PRL 100, 087001.

**LBCO**
Tranquada et al., Nature 429, 536.

**YBCO**
Dai et al., Nature 406, 945.

Magnetic excitations in superconducting state of FeAs?

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**Magnetic excitations in superconducting FeAs**

\[ T = 7 \text{ K} \]

\[ T = 50 \text{ K} \]

Powdered \( \text{Ba}_{0.4}\text{K}_{0.6}\text{Fe}_2\text{As}_2 \)

- Resonant spin excitations at 14 meV in K-doped and ~10 meV in Co-doped.
- It disappears above \( T_c \).
- 2D nature is clearly observed.
- 2D spin dynamics are similar to high energy excitations in the ordered state, and spin fluctuations in the paramagnetic state.

2D magnetism \( \Leftrightarrow \) superconductivity
Magnetic excitations in superconducting FeAs

- Co concentration is ~0.25-0.30 (over-doped region)
- Sample aligned in (hk0) zone

Summary

- In the ordered state, we observe low energy spin-wave-like excitations with a spin gap (origin of the gap is not clear).
- At $T_N$, the gap closes, and we observe spin fluctuations with large in-plane correlation length.

Goal I: Anisotropic magnetic interactions

- $v_c/v_{ab} \sim 0.2$ smaller than SrFe$_2$As$_2$ and CaFe$_2$As$_2$ but much larger than cuprates.
- Above $T_N$, we observe rod-like scattering along L, attesting the two-dimensionality of this system.

Goal II: Itinerant magnetism

- At higher energy, we observe anisotropic scattering on top of spin waves (the Stoner electron-hole continuum?).
18. Spectroscopic-Imaging STM on a PrFeAsO$_{0.7}$ Single Crystal

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Recent developments of STM technology have enabled us to map conductance ($dI/dV$) images at various energies over wide field of view. One of the important applications of this spectroscopic-imaging STM (SI-STM) is that momentum-space electronic states can be explored through the Fourier analyses of the quasi-particle interference (QPI) patterns which appear in $dI/dV$ images. In superconductors, characteristic scattering vectors for QPI contain information not only on the Fermi surface but also on the superconducting gap. QPI measurements in cuprate high-$T_c$ superconductors have proven to be a powerful technique to determine the superconducting-gap dispersion in momentum space [1-3]. Recently, it has been shown that the phase of the superconducting gap can be highlighted in QPI patterns by introducing vortices as controllable quasi-particle scatters [2]. This effect is associated with the coherence factor of the vortex scattering and provides us with a new phase-sensitive approach for the superconducting gap [2]. In order to investigate the superconducting gap structure in an iron-oxipnictide superconductor, we have performed SI-STM on a PrFeAs$_{0.7}$ single crystal, especially paying attention to the possible $s_{\pm}$-symmetry [5]. Cleaved surface consists of two distinct atomic layers: FeAs and PrO planes. When measurement was done on the FeAs plane, clear atomic image was observed but the $dI/dV$ spectrum does not show clear superconducting gap. $dI/dV$ images exhibit normal-state QPI patterns which may be associated with the surface state. The PrO plane is rather unstable and individual atoms can not be identified in the topograph but the $dI/dV$ spectrum shows clear gap structure. We discuss several implications of the observations.

References
Spectroscopic-imaging STM on a PrFeAsO$_{0.7}$ single crystal

RIKEN
T. Hanaguri
S. Niito

JAEA
M. Ishikado
S. Shamoto

U. Tokyo/RIKEN
H. Takagi

AIST
H. Eisaki
A. Iyo
H. Kito

Outline

- Motivation
  - SC gap symmetry?

- Why STM?
  - Quasi-particle interference $\rightarrow k$ space
  - Coherence factors $\rightarrow$ phase of the SC gap
  - Case study (high-$T_c$ cuprates)

- Preliminary results on PrFeAsO$_{0.7}$ and Fe(Se, Te)
  - Normal-state QPI
  - Search for SC signals

- Summary
Symmetry of the SC gap of Fe arsenides

Spin part
Knight shift

Orbital part
Role of multiple Fermi sheets?

Spin singlet pairing
How to detect $s_\pm$ symmetry?

How to determine the symmetry experimentally?

$T$ dependence of $T_1$, $g$, $\alpha$, $\lambda$, $\sigma(\omega)$...

Quasi-particle population
Full gap: $\sim \exp(-\Delta/T)$

Node: Power of $T$

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K. Nakai et al., JPSJ 77, 073701 (2008).
K. Hashimoto et al., PRL 102, 017002 (2008).
Direct gap map by ARPES

H. Ding et al., EPL 83, 47001 (2008)

Full gap likely...

But how about the phase relations among the Fermi sheets?

Note: If \( s \) symmetry, macroscopic phase-sensitive technique (e.g. \( \pi \) junction) does not work.

Coherence factor as a \( k \)-resolved probe

- Superconductivity: supported by Cooper pairs
- Individual QP scattering is prohibited.
- Strong coherence between \( k_i \to k_f \) and \(-k_f \to -k_i\)

QP scattering probability

\[
\begin{align*}
\text{Super: } \quad & w(i \to f) \propto |\langle k_i,k_f \rangle|^2 \left( \bar{u}_{k_i} u_{k_f} \mp \bar{v}_{k_i} v_{k_f} \right)^2 \\
\text{Coherence factor: } \quad & \left( uu' - vv' \right)^2 \\
\text{Ultrasonic etc.} & \\
\text{NMR etc.} &
\end{align*}
\]

- \( s \)-wave SC: \( u \) and \( v \) are isotropic.
  - Case I (time-reversal even) \( (uu' - vv')^2 \)
  - Case II (time-reversal odd) \( (uu' + vv')^2 \)

- Unconventional SC: \( u \) and \( v \) are \( k \) dependent.
Quasi-particle interference in cuprates


Dispersion relation of Bogoliubov quasi-particles (or dSC gap) can be obtained experimentally.

d-wave coherence effect and QPI ~ "extinction" rule

T. Nunner et al., PRB 73, 104511 (2006)

\[ \psi(i \rightarrow f) \propto \left( u_k u_{k_f} - v_k v_{k_f} \right) \left| V(k_i, k_f) \right|^2 J(\text{DOS}(E, k_i, k_f)) \]

coherence factors

Scalar potential \((uu'vv'v')^2\) sign-reversing scattering \((q_2, q_3, q_6, q_7)\)
Magnetic impurity \((uu'+vv')^2\) sign-preserving scattering \((q_1, q_4, q_5)\)
Inhomogeneity \((\Delta + \Delta')^2\) sign-preserving scattering \((q_1, q_4, q_5)\)
RIKEN multi-extreme STM

- Very-low and variable temp. (400 mK - 60 K)
- High field (11 T), UHV (~10^-10 Torr)
- In-situ tip/sample exchange (resonant freq. 5.5 kHz)
- Long-term stability at base temp < Å/day
- Noise levels (2 kHz BW) < 0.5 pm, 1 pA

Phase-sensitive QPI in Ca$_2$Na$_3$CuO$_2$Cl$_2$

T. Hanaguri et al., Science, in press (Express Online DOI: 10.1126/science.1166138).

$x \sim 0.14$ $V_{\text{sample}} = -0.1$ V, $I = 0.1$ nA, 45nm x 45nm

FT[Z(11T)]-FT[Z(0T)]

sign-preserving scattering $(+,-), (-,+)$: Enhanced by $B$

sign-reversing scattering $(+,-), (-,+)$: Suppressed by $B$

Hidden coherence effect has been disclosed!
How will it work in Fe arsenides?

- Sign-preserving scattering
- Sign-reversing scattering

STM is a perfect experiment.
STM/STS on PrFeAsO$_{0.7}$ by Dr. Ishikado (JAEA)

$T = 1.5$ K, $V_s = -0.2$ V, $I_s = 0.1$ nA, 10 nm $\times$ 10 nm

- Square lattice ($a \sim 4$ Å) with few % defects in between → Top-most As atoms are imaged.
- No clear SC gap... → Surface state may be important.

(Normal state) QPI on PrFeAsO$_{0.7}$ surface

$T = 1.5$ K, $V_s = -50$ mV, $I_s = 0.1$ nA, 38 nm $\times$ 38 nm

- Well-defined surface (normal) quasi-particles
- Apparently heavy quasi-particle mass ($\sim 8m_0$)

Surface state may also be important for ARPES...
Search for SC signals

- No atomic resolution on a PrO layer (maybe)
- Apparent SC gap-like features in the spectra

More studies...

STM/STS on Fe(Se$_{0.5}$Te$_{0.5}$) by Dr. Niitaka (RIKEN)

Maybe SC gap but still there is an offset at $E_F$...
Summary

- Quasi-particle interference patterns under magnetic fields include information on the phase of the superconducting gap. This provides us with a new method to determine the symmetry of the superconducting gap using STM.

- The top-most FeAs surface layer of cleaved PrFeAsO$_{0.7}$ does not show superconductivity but clear interference patterns of normal quasi-particles were discovered.

- The effective mass of the surface band is anomalously heavy. ($\sim 8m_0$)

Prospects

- Search for SC signals
  - "clean" PrO layer?
  - FeSe system (with Dr. Niitaka, RIKEN)
19. Transport and High-Pressure Study Overview

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The iron-based superconductors are the second type of high-$T_c$ superconductors with their maximum $T_c$ exceeding 50 K, which is the highest besides cuprate superconductors. In order to understand the high-$T_c$ mechanism, it is important to elucidate the similarities and differences of these two types of superconductors. In this presentation, I will compare the characteristic features of the two systems in terms of the transport properties and the pressure effects. The most characteristic feature of the iron-based superconductors is the non-linearity of the Hall resistivity with the magnetic field, which likely reflects the multiband nature of the compound [1]. The temperature- and the doping- dependence of the Hall coefficient ($R_H$) in the low field limit are rather small except for that in the so-called SDW phase. This is in contrast with the behavior of the cuprate superconductors, in which $R_H$ scales with the number of doped carriers. Hydrostatic pressure dramatically affects $T_c$ in the iron-based compounds [2], while the pressure dependence strongly depends on the materials. The behavior cannot be explained based on the simple carrier doping picture, which has been applicable in the case of the cuprate superconductors. It is more likely to be correlated with the change in the local structural parameters, such as As-Fe-As bond angle of the FeAs$_4$ tetrahedron [3]. These experimental results highlight the differences rather than similarities between the two types of high-$T_c$ superconductors, suggesting the existence of another route to achieve high-$T_c$ superconductivity.

References
Transport and High-pressure Study Overview

Toshimitsu Ito
AIST & JST
Tsukuba, Japan

Collaborators

H. Eisaki, A. Iyo, H. Kito, K. Miyazawa, P. M. Shirage (sample synthesis)
Y. Tomioka, N. Takeshita (transport)
C. H. Lee, R. Kumai, H. Matsuhata, K. Kihoh (diffraction)
M. Ishikado, S. Shamoto, M. Arai (sample synthesis, transport, diffraction)
K. Yamada, M. Braden, M.T. Fernandez-Diaz (neutron scattering)
M. Nakajima, S. Ishida, S. Uchida (transport)
How to highlight the hidden coherence factors?

Introduce controllable QP scatterers which activate only one of the two scatterings.

→ Vortices

• inhomogeneity $(A+1)^2$ : sign-preserving scattering $(q_1, q_4, q_5)$
• Phase gradient $(uv + v')^2$ : sign-preserving scattering $(q_1, q_4, q_5)$

Vortices will selectively enhance sign-preserving scatterings and highlight the coherence-factor effect.

Necessary conditions for FT-QPI experiments

• $k$ range $\sim$ (pixel size)$^{-1}$
  $>$ 1st BZ

  Atomic spatial resolution

• $k$ resolution $\sim$ (scan range)$^{-1}$
  $<$ 1 % of BZ

  Wide field of view

Transition-metal compounds: Lattice const. $\sim 4$ Å

$dI/dV$ spectra must be taken on a grid with spacing less than 2 Å over a field of view more than 400 Å × 400 Å.

256 × 256 points, 20 energies, 0.1 sec/energy

⇒ 36 hours
Outline

1. Pressure effect
   Q) What determines $T_c$ of iron arsenide superconductors?
      - correlation between crystal structure and $T_c$
      - through artificial modification of crystal structure

2. Transport properties
   Q) What is the difference between iron arsenide and cuprate superconductors?
      - nonlinear transport
      - comparison of their transport properties

Pressure effect
Close correlation between $T_c$ and geometrical factor of structure

![Graph showing correlation between $T_c$ and geometrical factor of structure](image)

Material dependence
C. Lee et al., JPSJ 77 (2008) 083704.

Artificial modification of crystal structure by pressure

![Diagram showing artificial modification of crystal structure](image)

Change in crystal structure (lattice constant & local structure)

High pressure transport (cubic anvil apparatus)

- Synchrotron radiated x-ray
- Diamond anvil cell

Homogeneous hydrostatic pressure

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Correlation from theoretical calculations

\[ \delta z_{As} = 0.04 \quad (0.035 \text{Å}) \]

\[ E(V) \]

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**Physical Review Letters**

**Density Functional Study of LaFeAsO$_1$F$_x$: A Low Carrier Density Superconductor Near Itinerant Magnetism**

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Transport Properties
Anisotropic resistivity of BaNi$_2$P$_2$

3D intermetallic superconductor

$T$-dependence of resistivity of BaNi$_2$P$_2$

Corssover from $T^5$ to $T$

Bloch–Gruneisen

Electron–phonon scattering
Electron–phonon superconductivity in LaNiPO

- Low density of states of carriers
- Relatively strong electron–phonon coupling
- $T_c$ is expected $\sim 2.6K$

PHYSICAL REVIEW B 78, 060506(R) (2008)

Electron-phonon superconductivity in LaNiPO

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We report first-principles calculations of the electronic structure, phonon dispersions, and electron-phonon coupling of LaNiPO. These calculations show that this material can be explained as a conventional electron-phonon superconductor in contrast to the FeAs-based high-temperature superconductors.

Hall resistivity of BaNi$_2$P$_2$

$R_H = d\rho_{xy}/dH = -1/(ne)$
$\sim -2 \times 10^{-4} \text{ [cm}^3/\text{C}]$
$(n \sim 10^{22} \text{ /cm}^3)$

Hall resistivity, $\rho_{xy}$ linear on $H$ for high $T$
non-linear at $T < 50 \text{ K}$

Multi-band
Hall resistivity in two carrier model

"Sign reversal in the field dependence of the Hall effect in YZn..."

\[
\rho_{xy} = \frac{B \left[ \sigma_e^2 R_e + \sigma_h^2 R_h + \sigma_e^2 \sigma_h^2 R_e R_h \left( R_e + R_h \right) B^2 \right]}{\left[ (\sigma_e + \sigma_h)^2 + \sigma_e^2 \sigma_h^2 \left( R_e + R_h \right) B^2 \right]}
\]

(\sigma_e and R_e (\sigma_h and R_h); conductivities and Hall coefficients for electrons (holes))

\[
\rho_{xy} = \frac{B \left( 1/e \right) \left[ n_h \mu_h^2 - n_e \mu_e^2 + \left( n_h - n_e \right) \mu_h \mu_e \mu^2 B^2 \right]}{\left[ (n_h \mu_h + n_e \mu_e)^2 + \left( n_h - n_e \right) \mu_h \mu_e \mu^2 B^2 \right]}
\]

(n_e and \mu_e (n_h and \mu_h); carrier numbers and mobility of electrons (holes))

\[
(a = n_h/n_e, b = \mu_h/\mu_e)
\]

Hall resistivity of BaNi_2P_2

Fitting (dotted line)
\[ R_e = 1/(n_e e) \]
\[ = -4.1 \times 10^{-4} \text{[cm}^3/\text{C]} \]
\[ \mu_e = 96 \text{[cm}^2/\text{Vs]} \]
\[ a = n_h/n_e \sim 0.0043 \]
\[ b = \mu_h/\mu_e \sim 12.50 \]

Small hole FS
with high mobility

Consistent with dHvA
T. Terashima and H. Harima

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**dHvA of BaNi$_2$P$_2$**

Small hole pocket

**Fermi surface in BaNi$_2$P$_2$**

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**Hall coefficient of cuprate superconductors**

$H$-linear $p_{xy}$ (single band)
Doping dependence of $R_H$ is large.
$T$ dependence of $R_H$ is large.
Summary

- Possible correlation between geometrical factors in tetrahedron like bond angle and superconductivity

- Nonlinear transport due to multiband nature

- Small doping- and T-dependence of Hall coefficient in contrast to the behavior of the cuprates