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Thermomagnetic properties of the strongly correlated semimetal CeNiSn

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Acknowledgements:

Measurements:

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P. Sun, MPI CPfS, Dresden, Germany
S. Paschen, Vienna University of Technology, Austria
F. Steglich, MPI CPfS, Dresden, Germany

Samples:

T. Takabatake, Hiroshima University, Japan

Outline

Introduction

- Thermoel. and thermomagn. effects
- Exp. setup
- Correlated semimetal CeNiSn

Results

- Resistivity and Hall effect
- Thermopower
- Nernst effect and Righi-Leduc effect

Discussion

- Field-dependent thermopower
- Nernst effect

Summary

Introduction

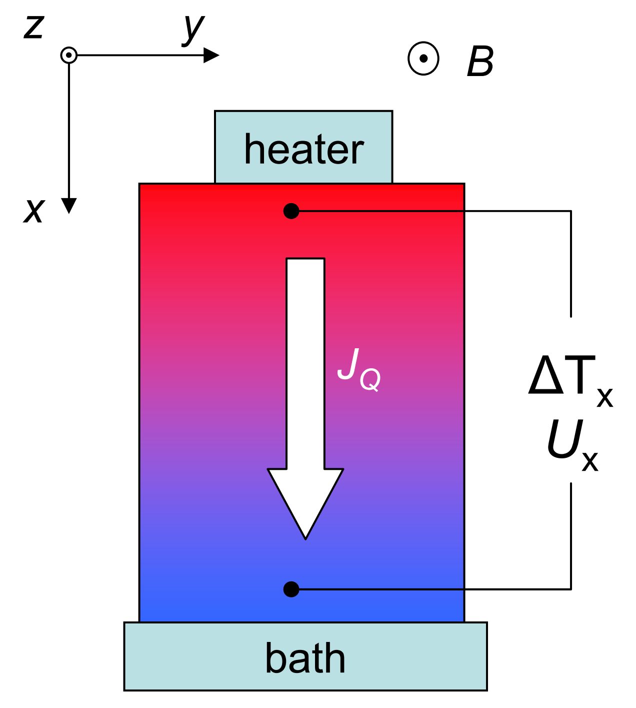
Thermoel. and thermomagn. Effects

Charge transport: $J = \sigma E - \sigma S \Delta T$

Heat transport: $J_Q = \sigma S T E - \kappa \Delta T$

Thermal conductivity: $\kappa = J_Q / \Delta T_x$

Thermopower: $S = -U_x / \Delta T_x$



Introduction

Thermoel. and thermomagn. Effects

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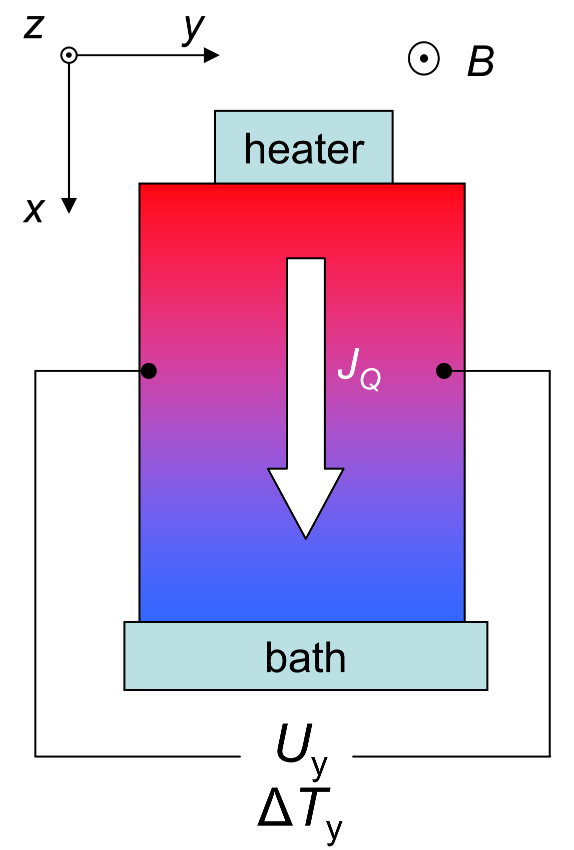
Heat transport: $J_Q = \sigma S T E - \kappa \Delta T$

Thermal conductivity: $\kappa = J_Q / \Delta T_x$

Thermopower: $S = -U_x / \Delta T_x$

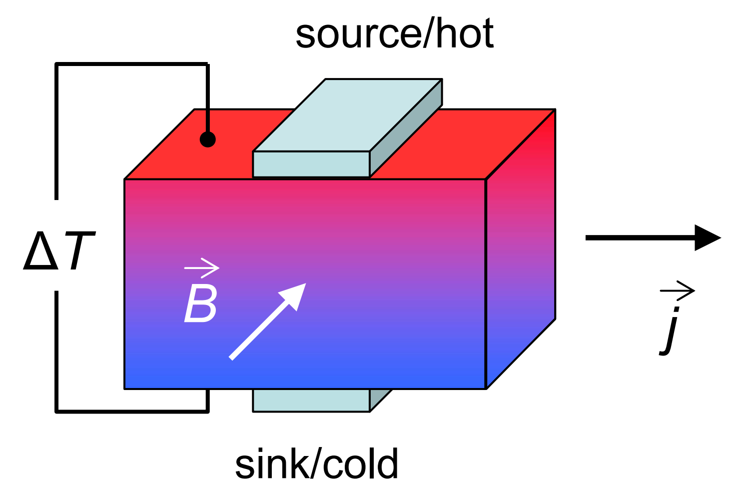
Nernst effect: $\nu = -U_y / \Delta T_x B$

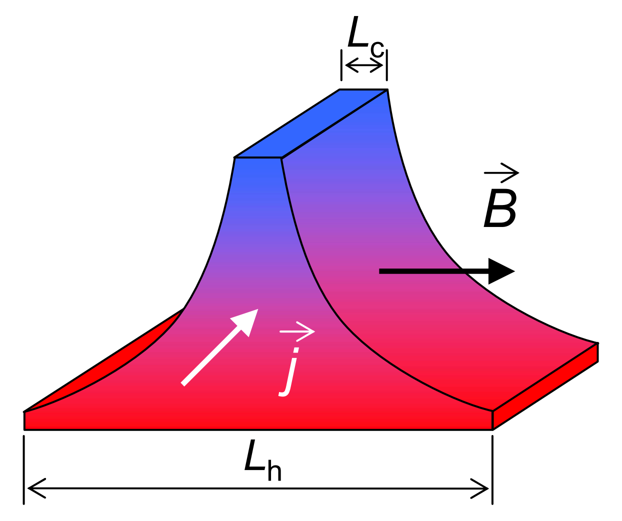
Righi-Leduc effect: $L = -\kappa_y / B \; \Delta T_y / \Delta T_x$



Introduction

Thermomagn. Effects: Ettingshausen cooling





Thermomagn. figure of merit Z_{mag}T

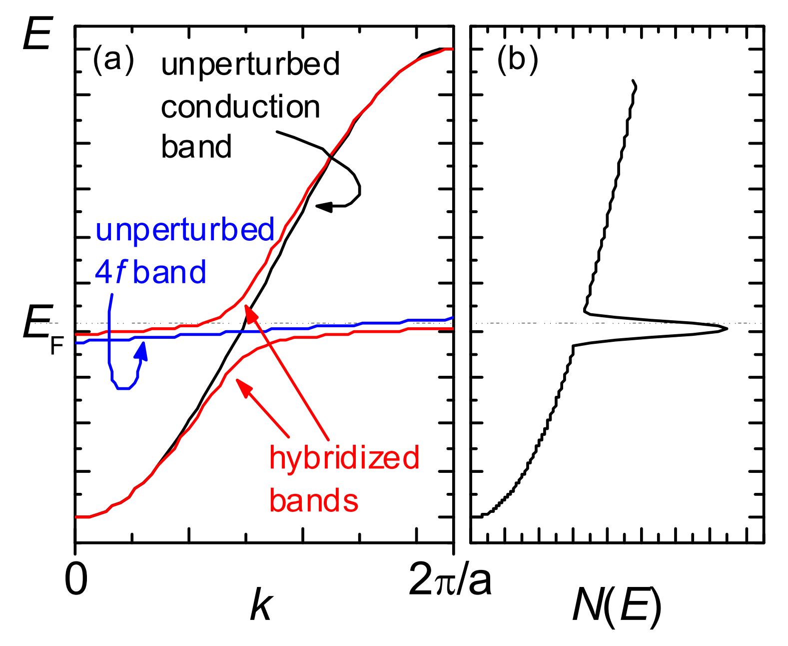
infinite stage Ettingshausen device

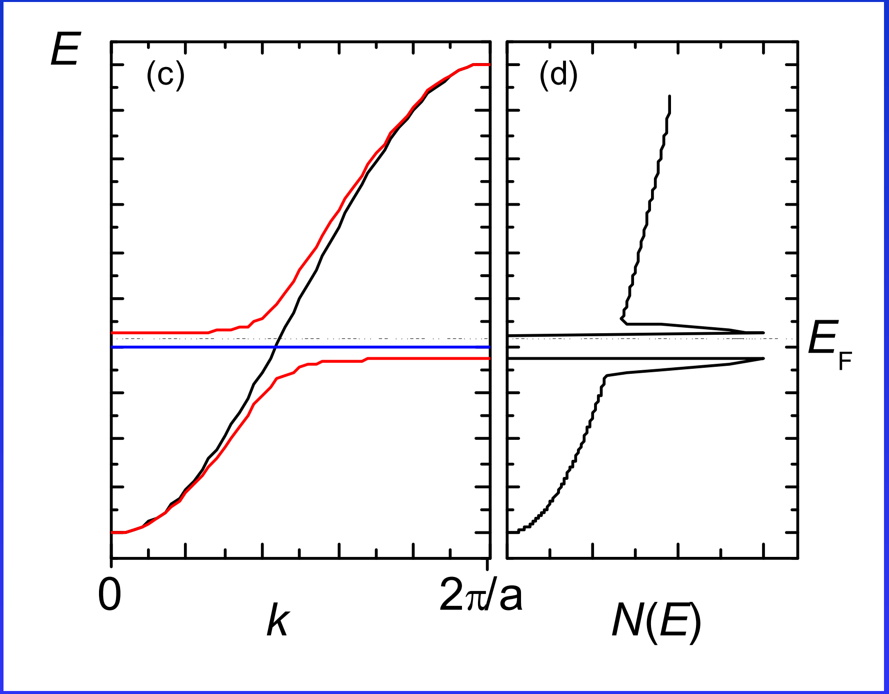
$$\Delta T_{\max} = \frac{Z_{\mathrm{mag}} T_{\mathrm{cold}}^2}{2}$$

$$Z_{\mathrm{mag}} T = \frac{\sigma(\upsilon B)^2 T}{\kappa}$$

$$\Delta T_{\max} = T_{\mathrm{hot}} \left(1 - \frac{L_{\mathrm{c}}}{L_{\mathrm{h}}}\right)^{\alpha}$$

Kondo Insulator





Heavy fermion metals

- $\rho \sim -\ln T$ at $T \approx T_K$
- enhanced DOS at E_F below $\sim T_K$

→ metal-like behavior at low T

Kondo insulator

- $\rho \sim -\ln T$ at $T \approx T_K$
- gap below $\sim T_g$

→ insulating behavior at low T

Introduction

Experimental Setup:

^{4}He cryostat

horizontal 7T magnet

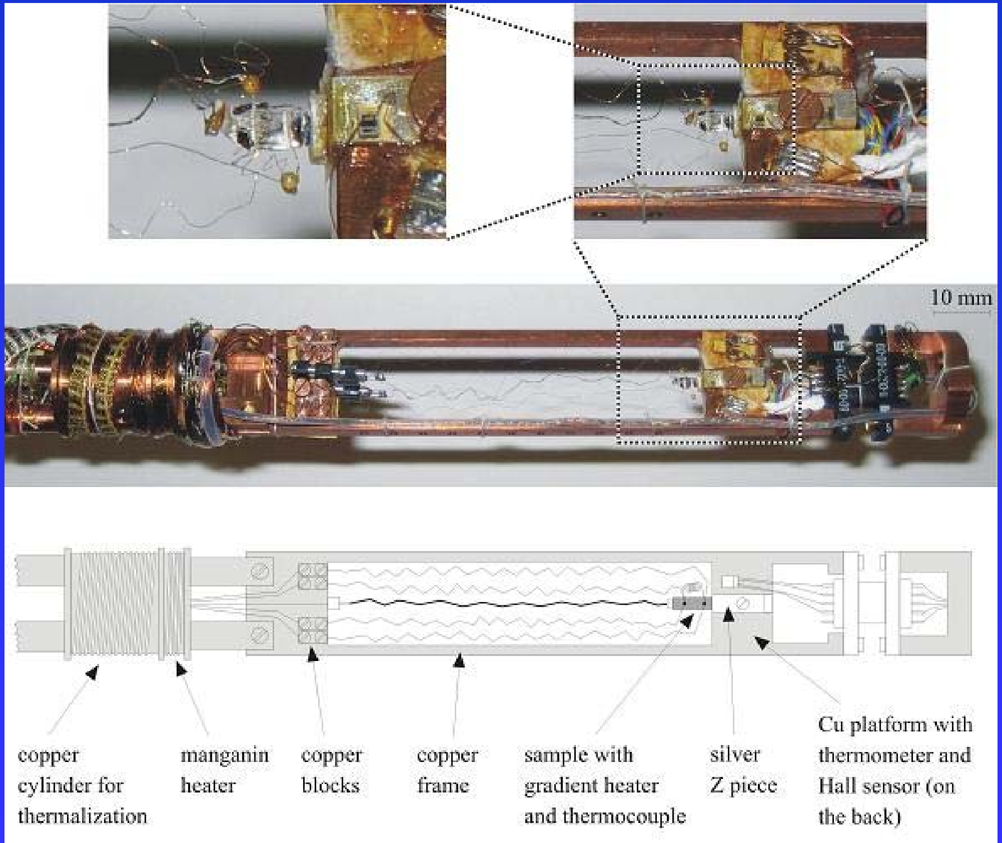
optimized for small samples with low κ

ΔT:

chromel-AuFe thermocouples

U:

copper wires, nanovoltmeter



CeNiSn

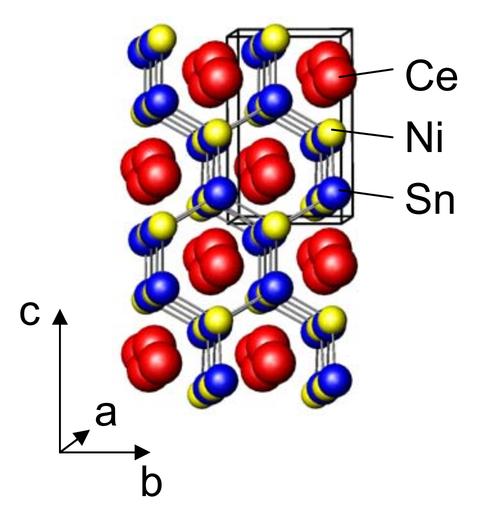
samples

orthorhombic crystal structure

chains of Cerium ions along a

easy a axis

Czochralski method annealed by SSE



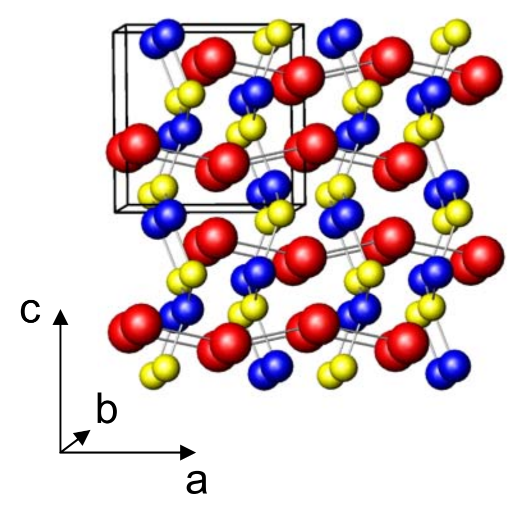
energy scales

crystal field levels: $k_B\Delta_{CEF} \approx 230K, 460K$

Kondo temp.: $T_K \approx 56$ K

pseudogap $\Delta/k_B \approx 10$ K below $T \approx 10$ K

no ordering down to 25 mK



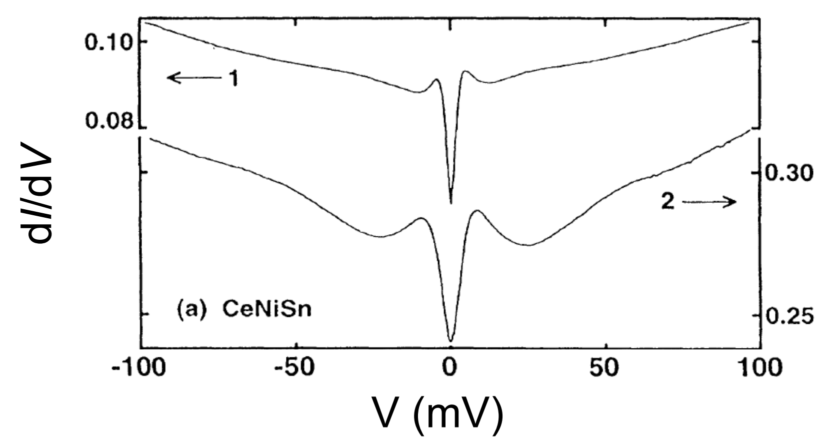
CeNiSn

gap structure

pseudogap opens around 10K

residual states at E_F

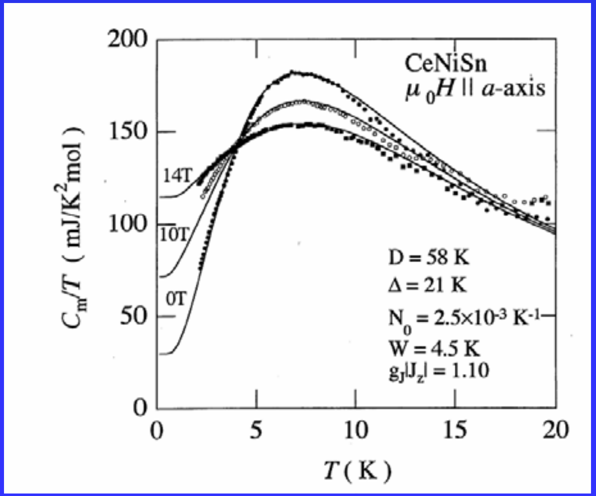
metallic ρ, large Sommerfeld coeff.



T. Ekino et al., *Phys. Rev. Lett.* **75**, 4262 (1995)

gap suppression

- magnetic fields ~10 T // a
- pressure ~ 2 GPa
- substitution (Ce/La and Ni/Cu,Co) ~ 10 %



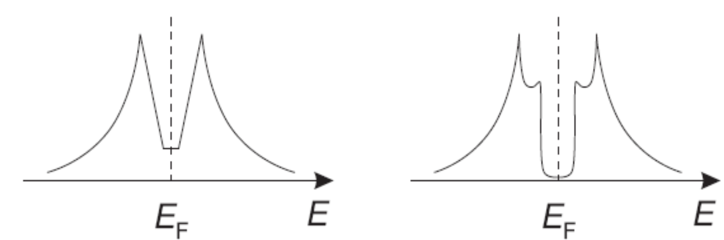
K. Izawa et al., *J. Phys. Soc. Jpn.* **65**, 3119 (1996)

CeNiSn - Kondo Insulator?

sensitive dependence on sample purity
(ρ, MR, R_H)

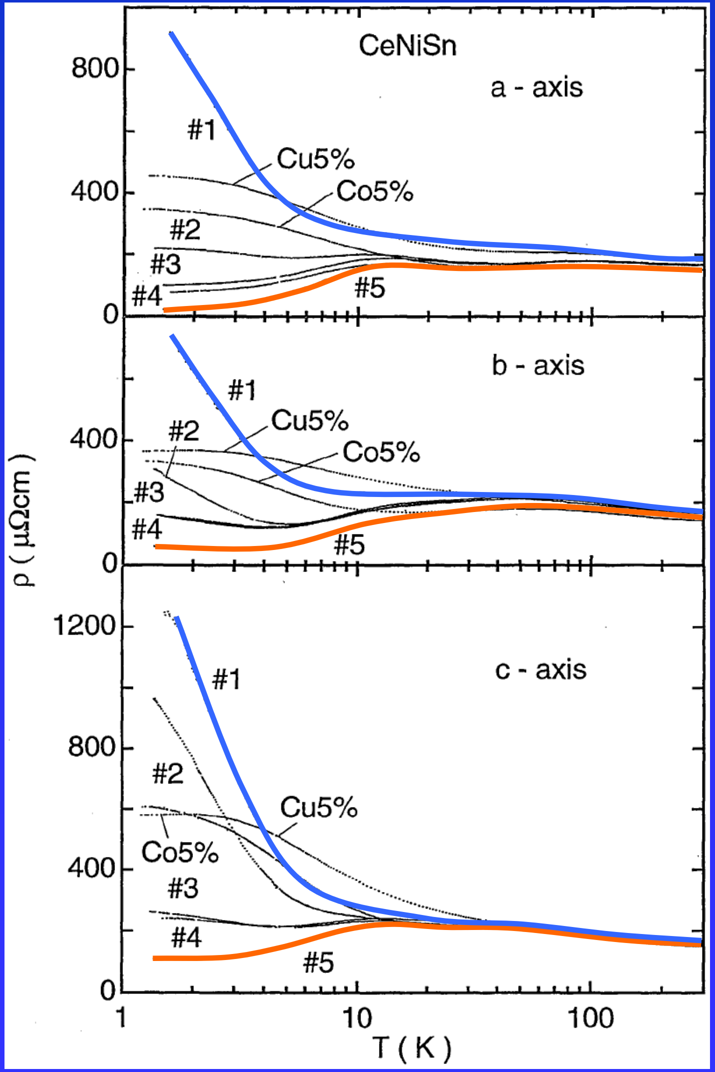
residual DOS near E_F (NMR, c_P, ρ, κ)

⇒ **CeNiSn – Kondo semimetal**



K. Izawa et al., *J. Phys. Soc. Jpn.* **65**, 3119 (1996)

H. Ikeda and K. Miyake, *J. Phys. Soc. Jpn.* **65**, 1769 (1996)

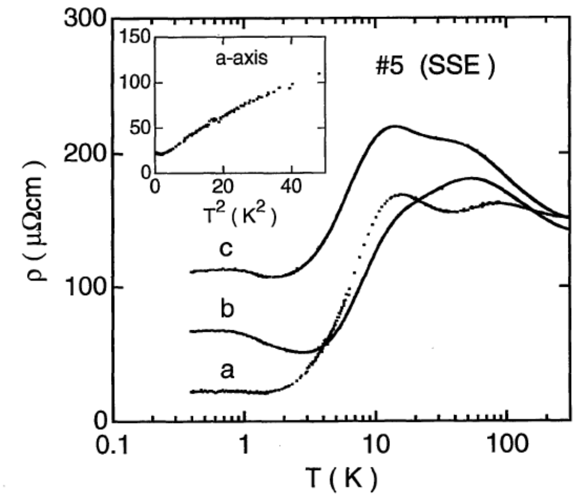


G. Nakamoto et al., *J. Phys. Soc. Jpn.* **64**(12), 4834 (1995)

Experimental

Single crystals (#5)

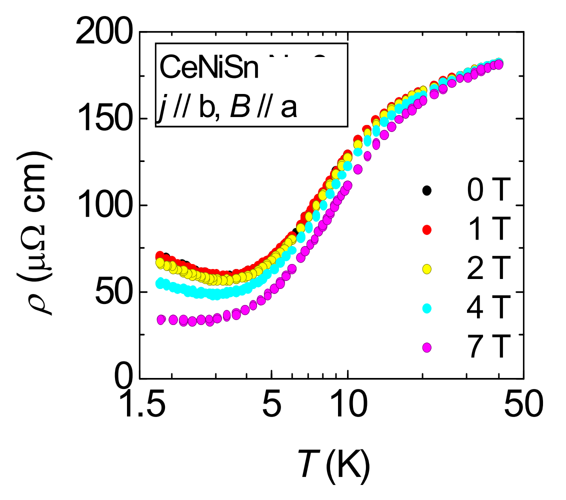
- Czochralski + SSE
- best available samples
- Orientation: Laue, χ, ρ (a/c)
- ca. 4 x 4 x 0.8 mm³
- Measurements: q // b; B // a, c



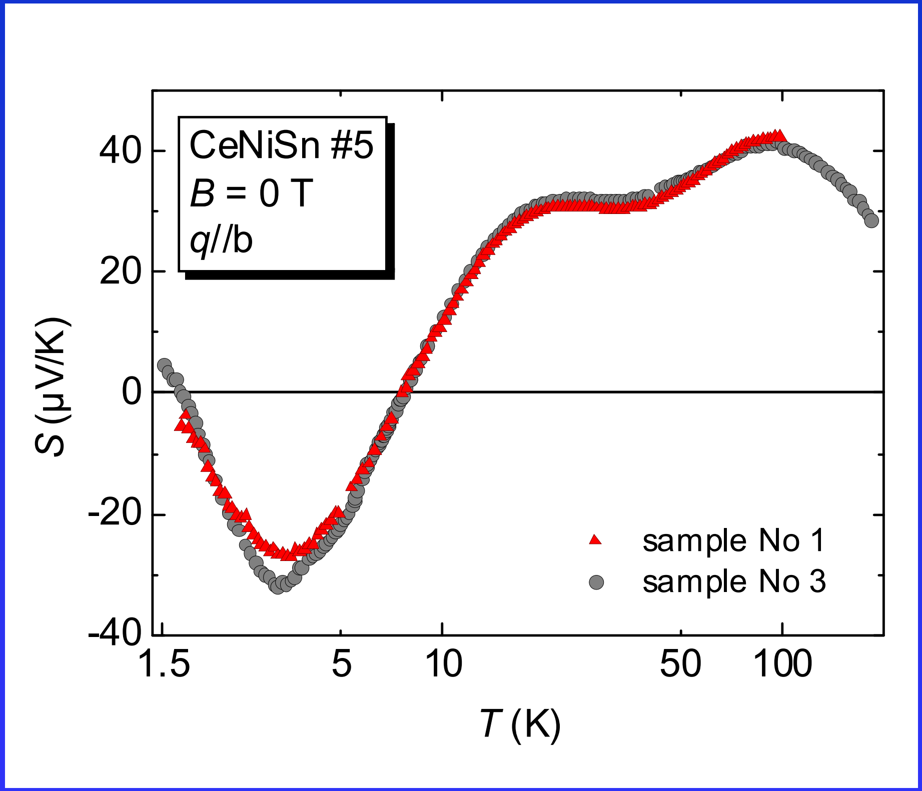
G. Nakamoto et al., *J. Phys. Soc. Jpn.* **64**(12), 4834 (1995)

Measurements:

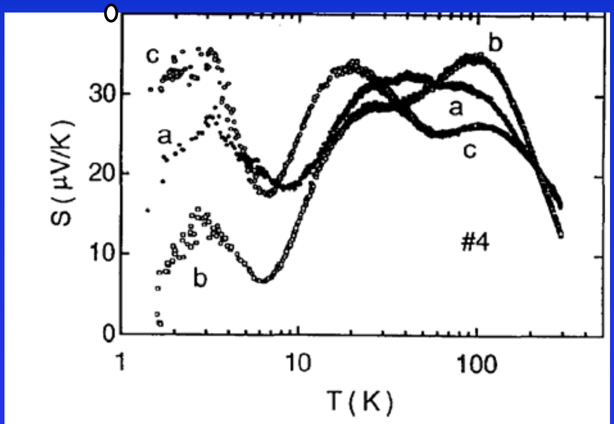
- Thermal conductivity
- Thermopower at +B and –B
- Nernst effect
- Thermal Hall effect



Results: Thermopower

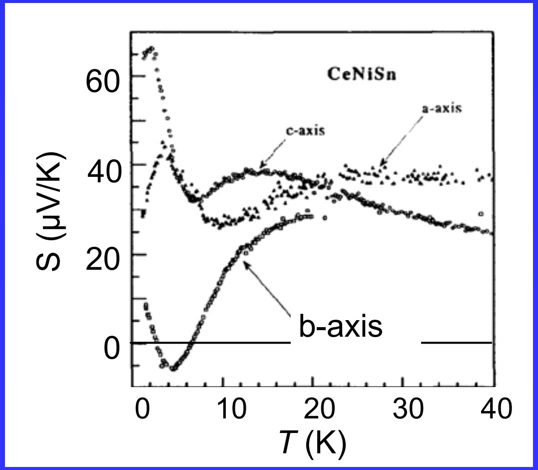


CeNiSn #4



G. Nakamoto et al., *Physica B* **306 & 307**, 840 (1995)

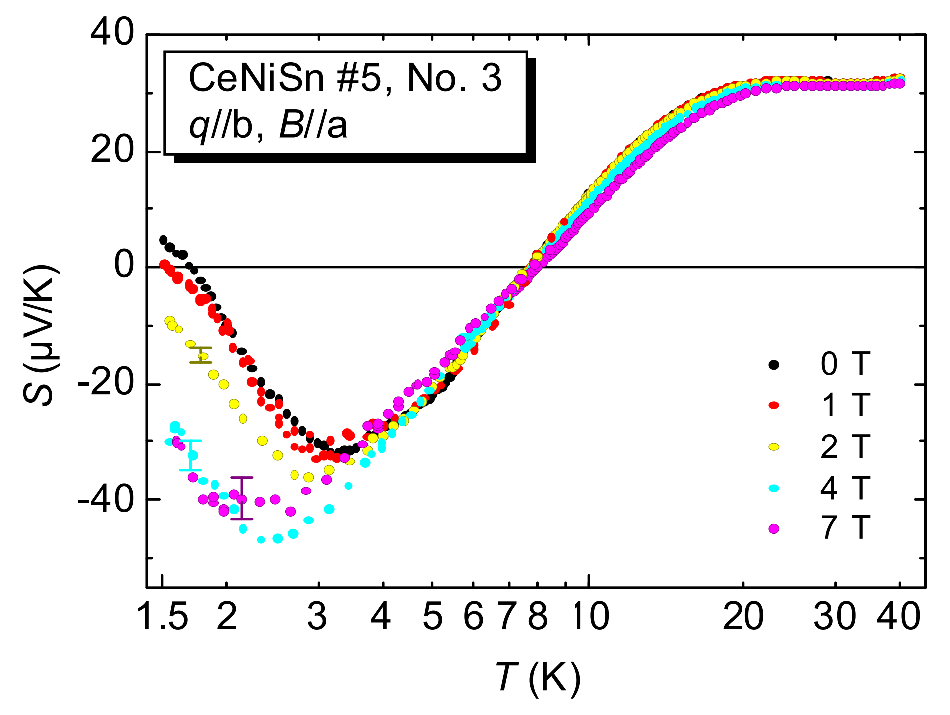
CeNiSn type unknown



J. Sakurai et al., *Physica B* **306 & 307**, 834 (1995)

- Kondo system with CEF splitting
- largest negative *S* ever observed
- very precise orientation !

Field-dep. Thermopower



literature:

- strong sample dependence at low *T*
- no comparable results in field

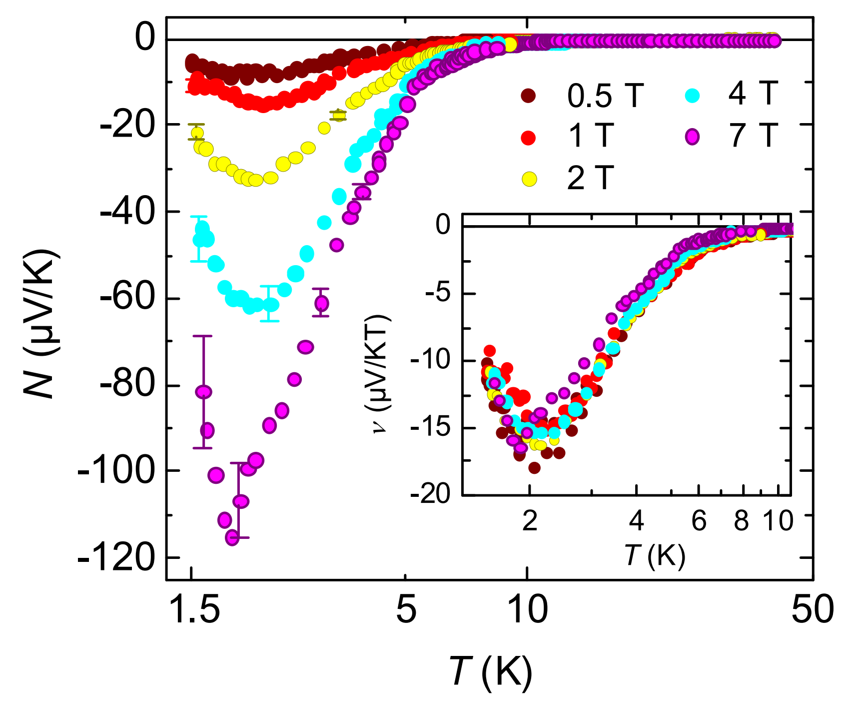
B // a: - enhanced values of |*S*|

- shift of the minimum to lower *T*

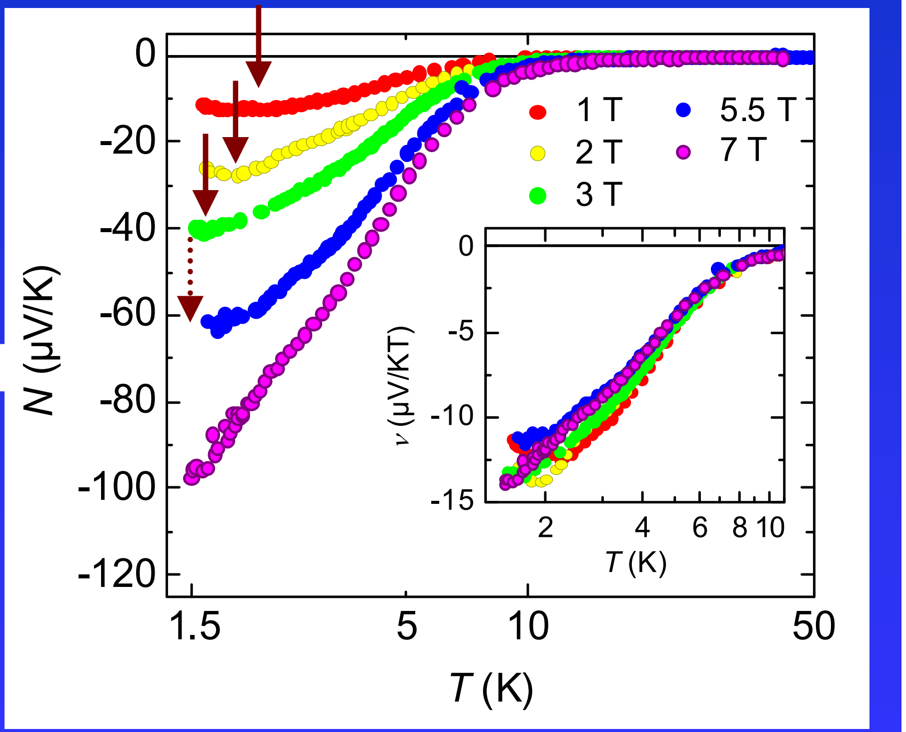
B // c: - similar, but less pronounced

Nernst effect

q // b, *B* // a



B // c



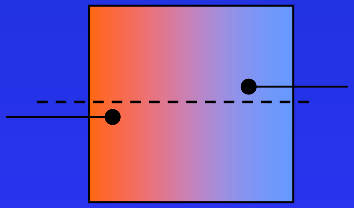
large values of *N* below 10 K (opening of the gap)

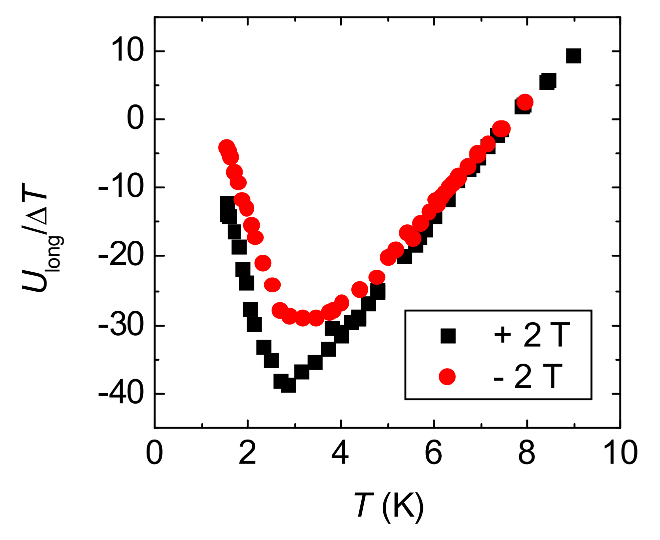
- scaling for *B* // a (easy axis!)
- shift of minimum for *B* // c

Discussion: Thermopower

variation due to

- sample dependence
- misorientation
- non-negligible Nernst contribution





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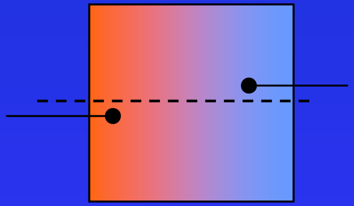

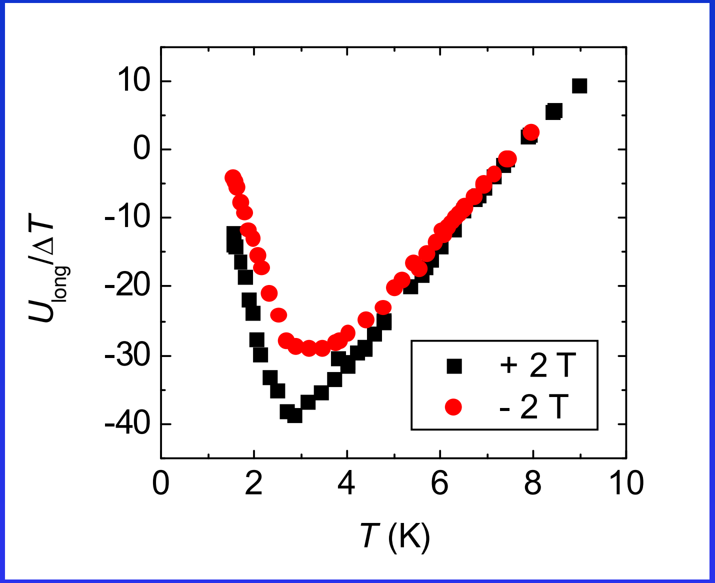

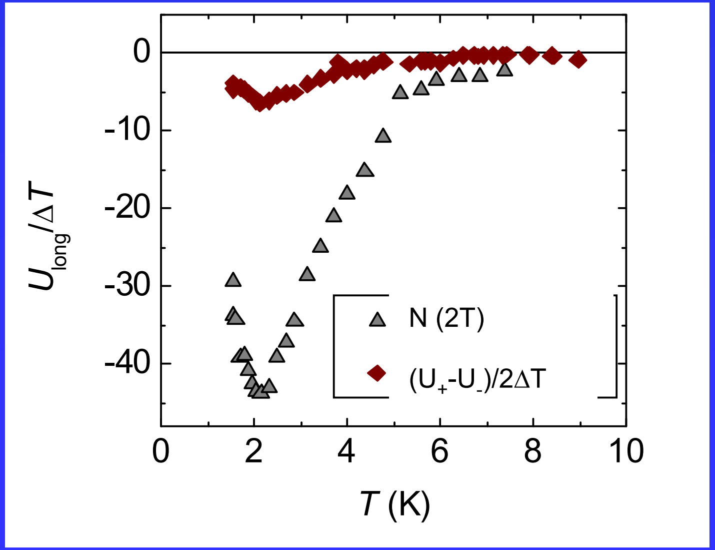

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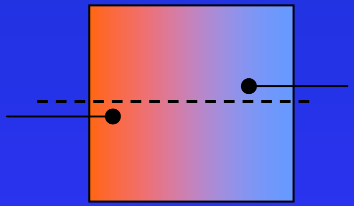

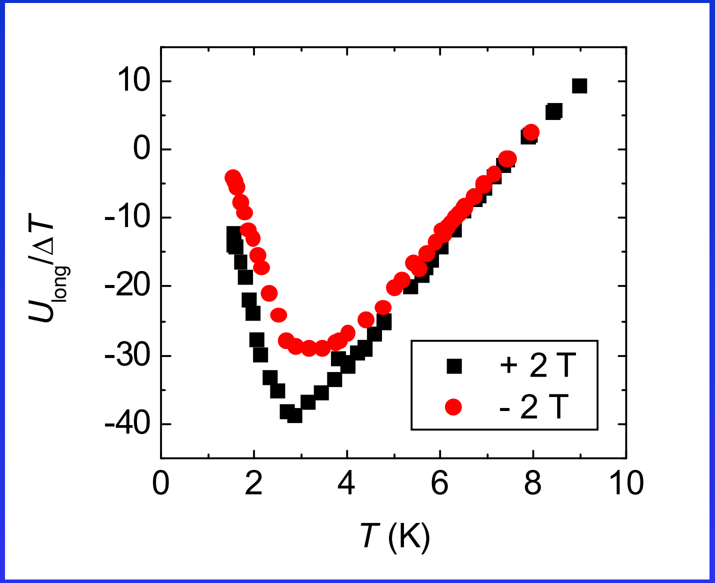

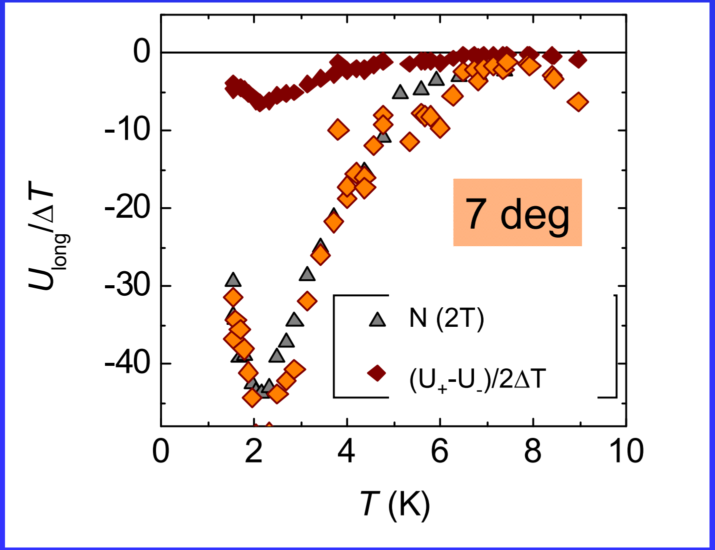

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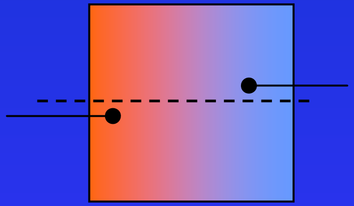
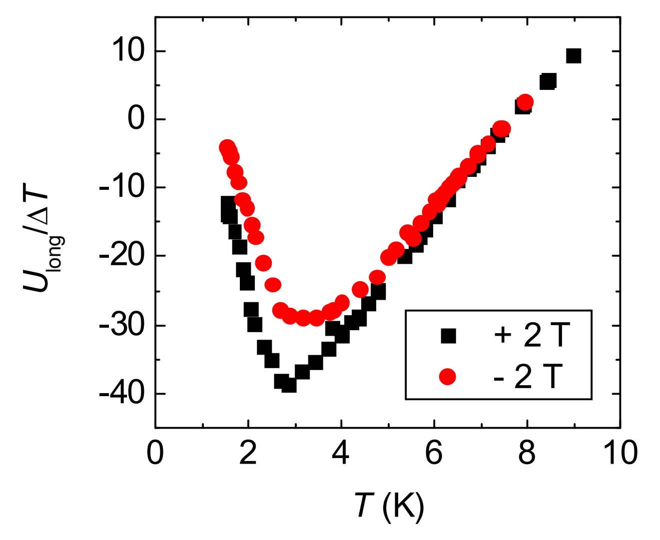
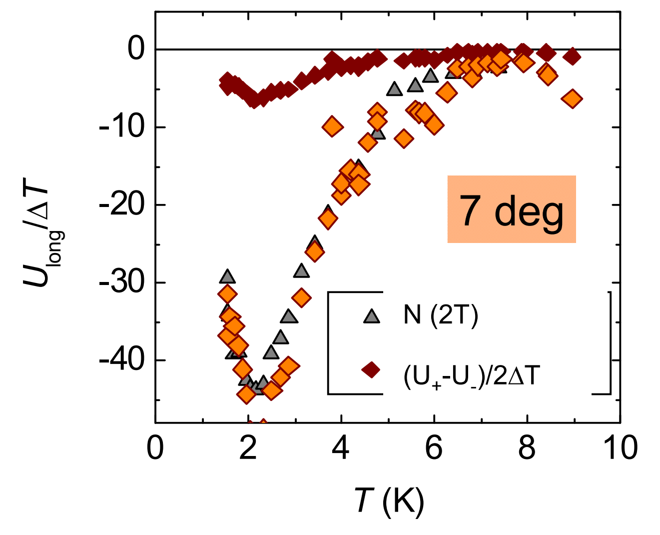


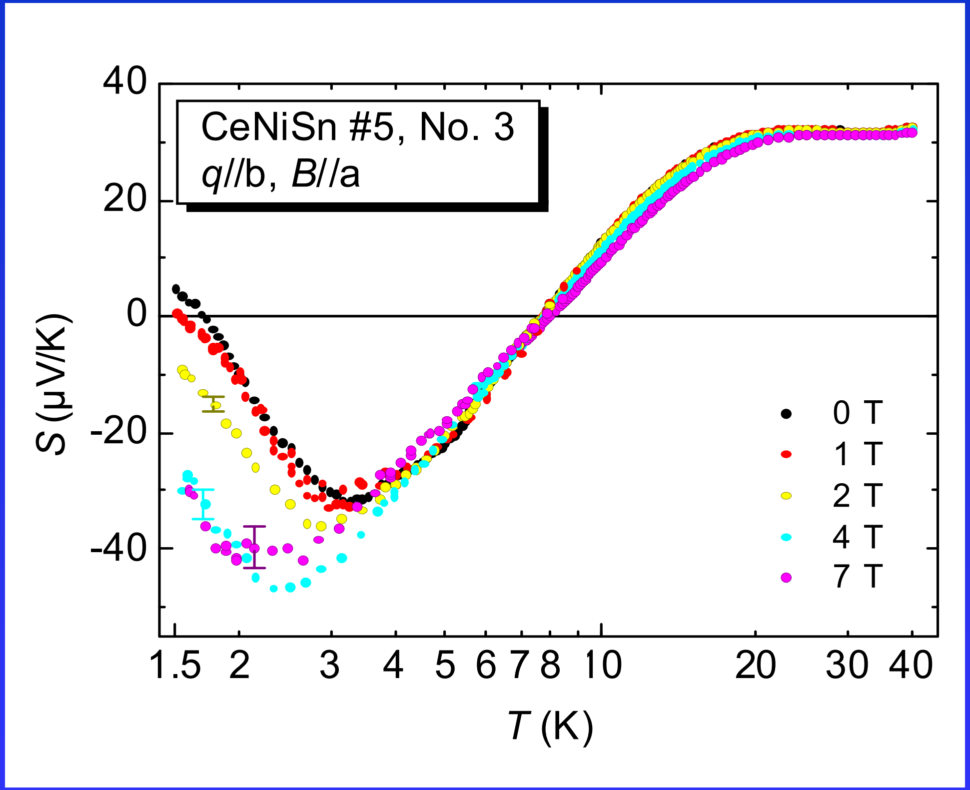


→ first systematic study of $S(T,B)$ including:

- best available samples
- precise orientation
- correction for the Nernst signal



Field-dep. Thermopower



literature:

- strong sample dependence at low *T*
- no comparable results in field

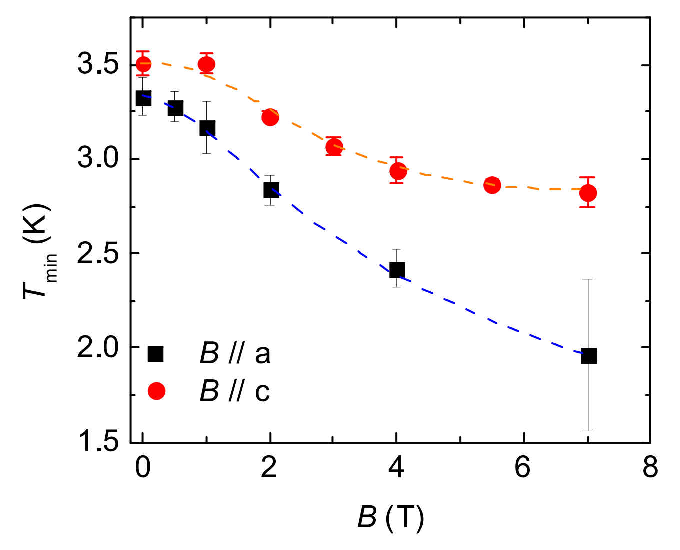
B // a: - enhanced values of |*S*|

- shift of the minimum to lower *T*

B // c: - similar, but less pronounced

Discussion: Thermopower

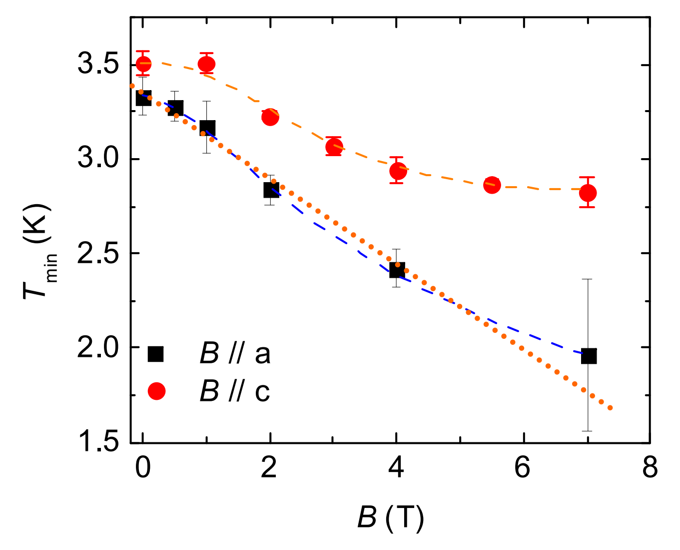
position of the minimum



- effect larger for *B // a*

Discussion: Thermopower

position of the minimum

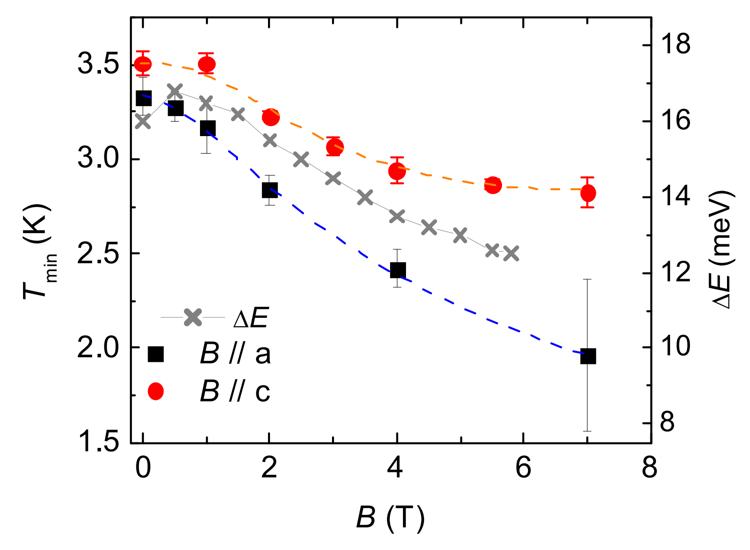


- effect larger for *B* // a
- extrapolation // a: B_c = 14 T
  (MR: 18 T)

→ shift ~ closing of the gap

Discussion: Thermopower

position of the minimum



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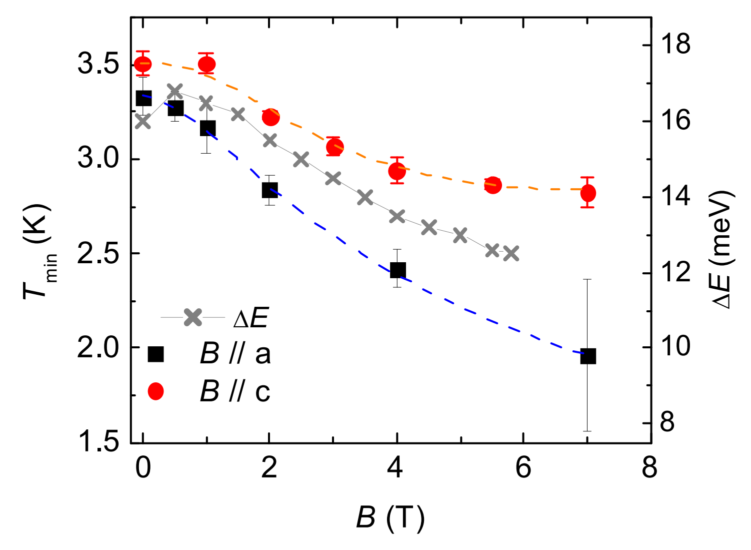
→ shift ~ closing of the gap
(ΔE from tunneling spectroscopy)

T. Ekino et al., *Physica B* **230-232**, 635 (1997)

Discussion: Thermopower

position of the minimum



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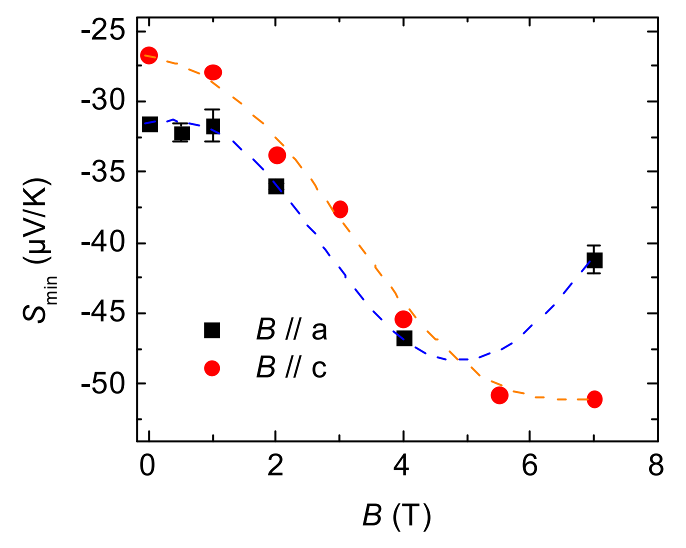
T. Ekino et al., *Physica B* **230-232**, 635 (1997)

value at the minimum



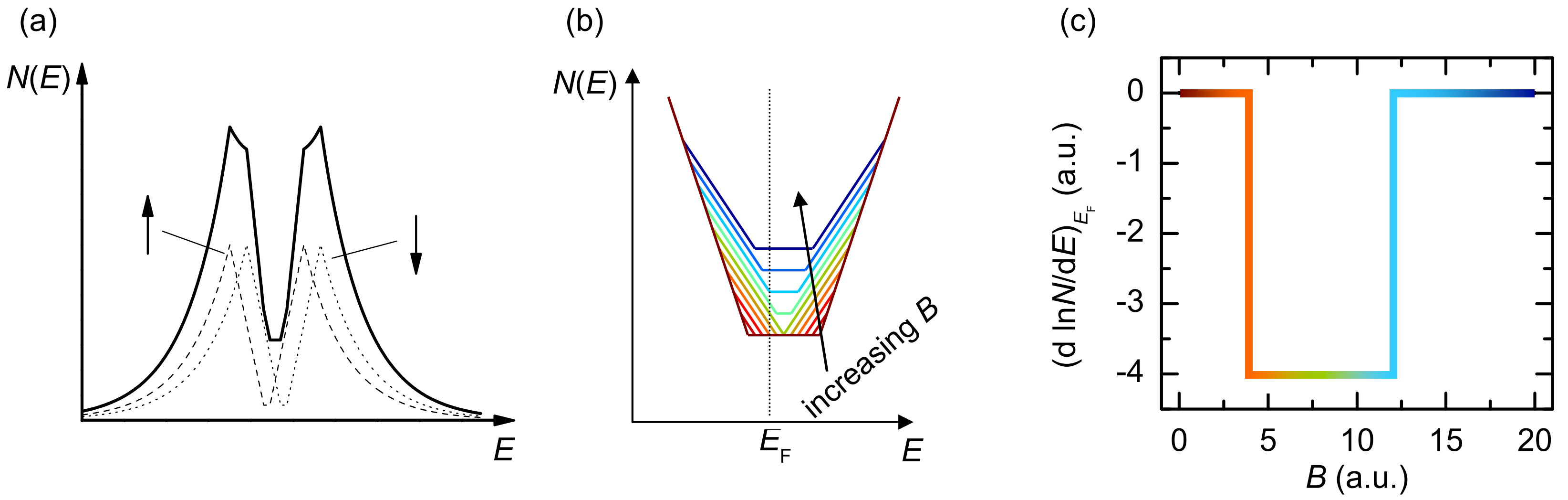
- effect larger for *B* // a
- change of the DOS near E_F due to Zeeman splitting (c_P)
- similar results for *S*(*T*) at low *T*

K. Izawa et al., *J. Phys. Soc. Jpn.* **65**, 3119 (1996)

S. Paschen et al., *Phys. Rev. B* **62**, 14912 (2000)

Discussion: Thermopower

V-shaped DOS in field



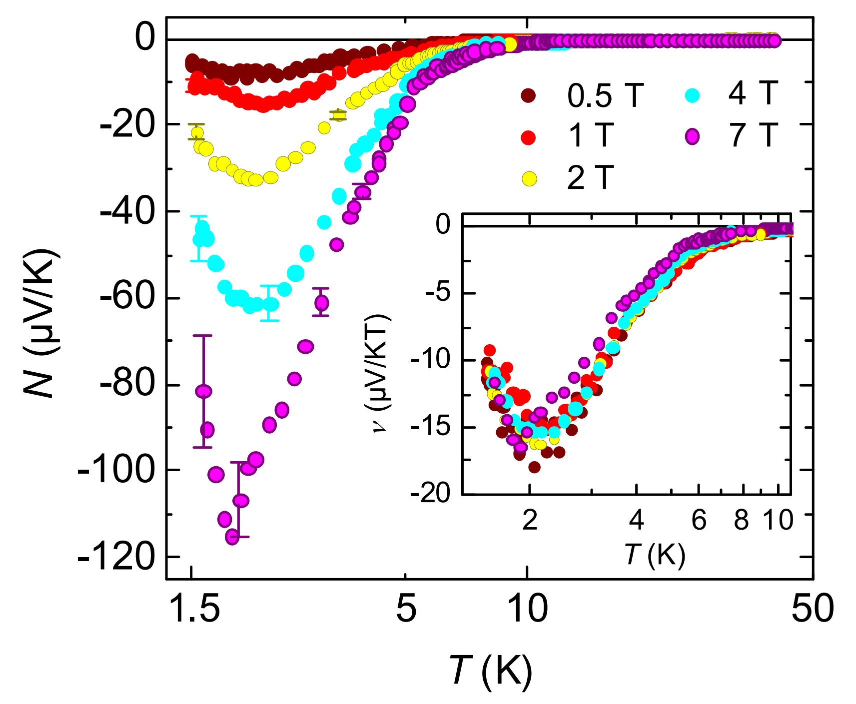
$$S \propto \left.\frac{\partial \ln N}{\partial \varepsilon}\right|_{E_F}$$

similar analysis for $C_P(T,B)$
(enhanced γ value in field)

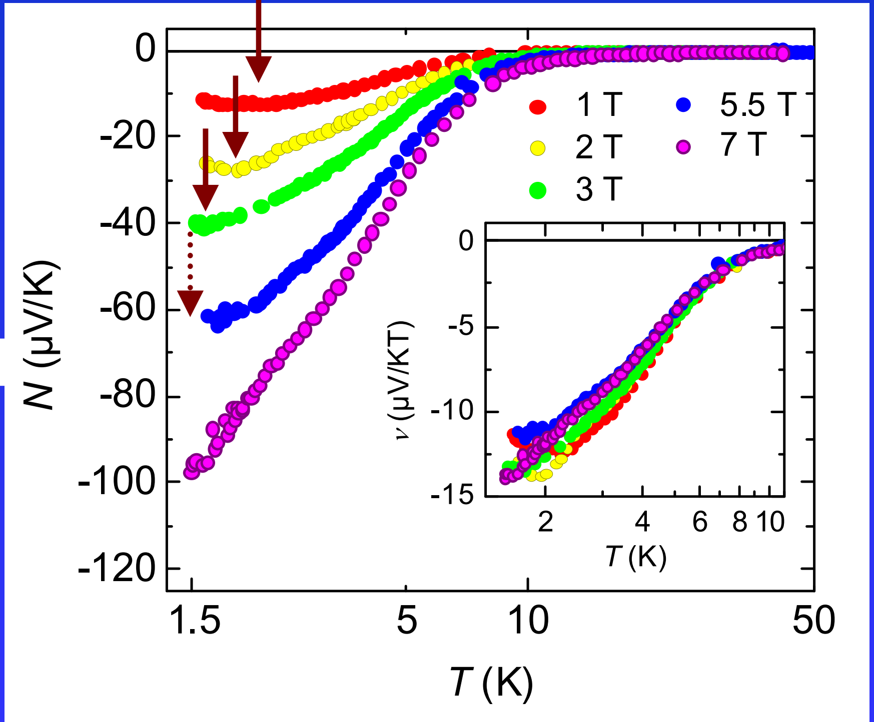
K. Izawa et al., *J. Phys. Soc. Jpn.* **65**, 3119 (1996)

Results: Nernst effect

q // b, *B* // a



B // c



large values of *N* below 10 K (opening of the gap)

- scaling for *B* // a (easy axis!)
- shift of minimum for *B* // c

→ open question: weak sensitivity to magnetic fields // a

Discussion: Nernst effect

Nernst effect:

$\nu^a = \nu^n - \varepsilon_{yy}/\kappa_{yy} L_{xy}$

ν^n: normal Nernst coeff.

ν^a: adiabatic Nernst coeff.

due to transverse temp. gradient

For CeNiSn, $\Delta T_y \approx 0$, $L_{xy} \approx 0$

(below resolution limit)

→ $\nu^a = \nu^n$

Boltzmann approximation:

$$\nu^n = \frac{\pi^2}{3}\frac{k_B^2 T}{m^*}\left.\frac{\partial \tau}{\partial \varepsilon}\right|_{E_F}$$

with Hall angle $\tan\Theta_H = \frac{\sigma_{yx}}{\sigma_{xx}}$

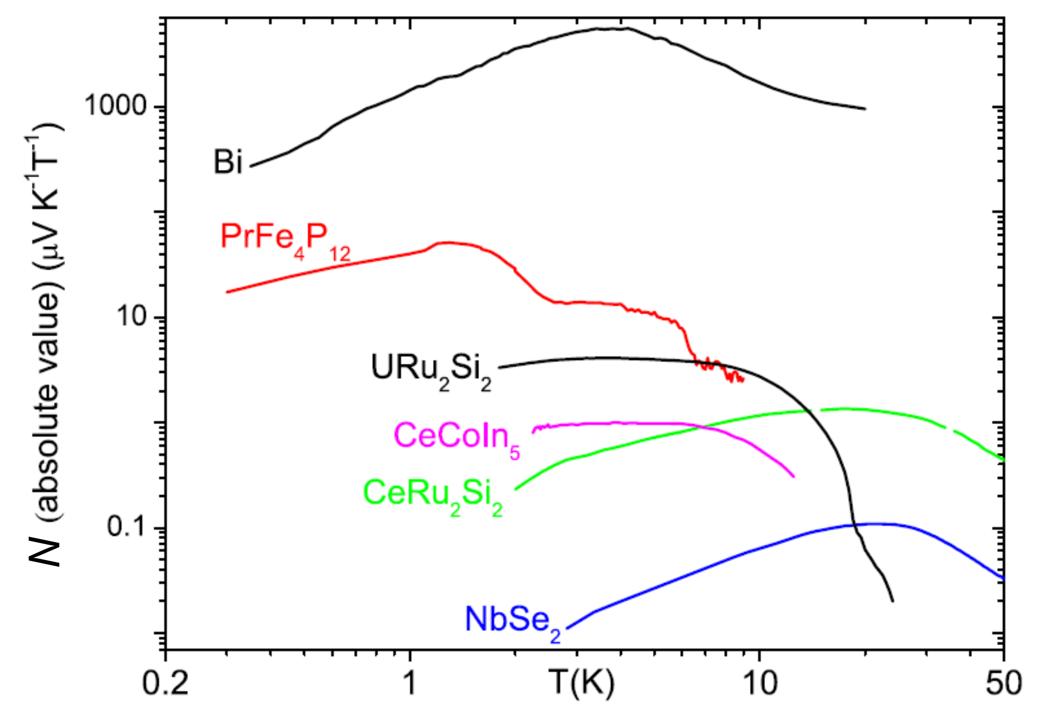
$$\nu^n \approx \frac{\pi^2}{3}\frac{k_B^2 T}{Be}\frac{\tan\Theta_H}{E_F}$$

Large Nernst coefficient:

- Low charge carrier concentration
- Small Fermi energy

Discussion: Nernst effect

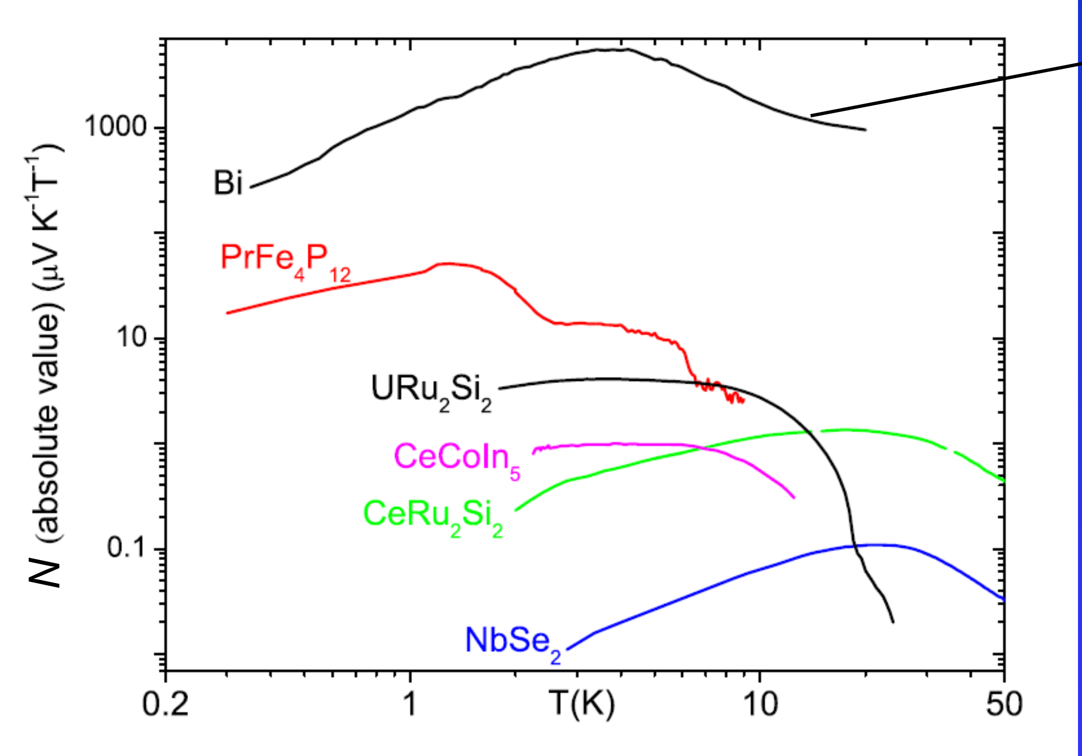
How to obtain large Nernst coefficients?



Behnia et al., *Phys. Rev. Lett.* **98**, 076603 (2007)

Discussion: Nernst effect

How to obtain large Nernst coefficients?

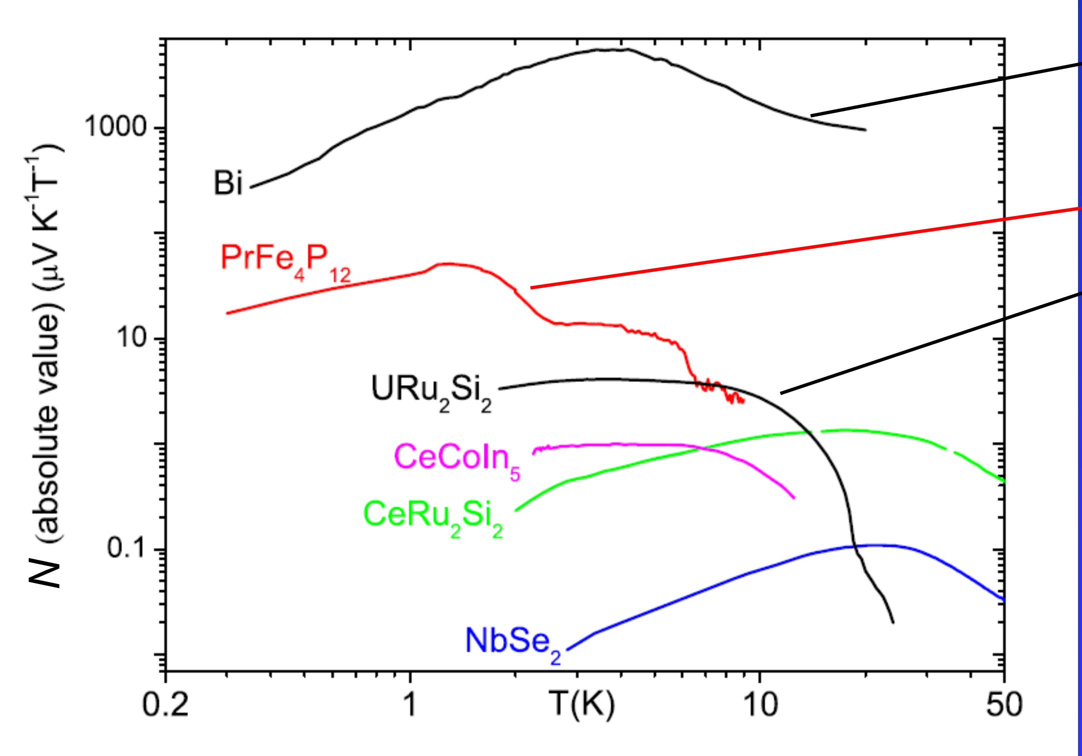


Bi normal semimetal

Behnia et al., *Phys. Rev. Lett.* **98**, 076603 (2007)

Discussion: Nernst effect

How to obtain large Nernst coefficients?



Bi normal semimetal

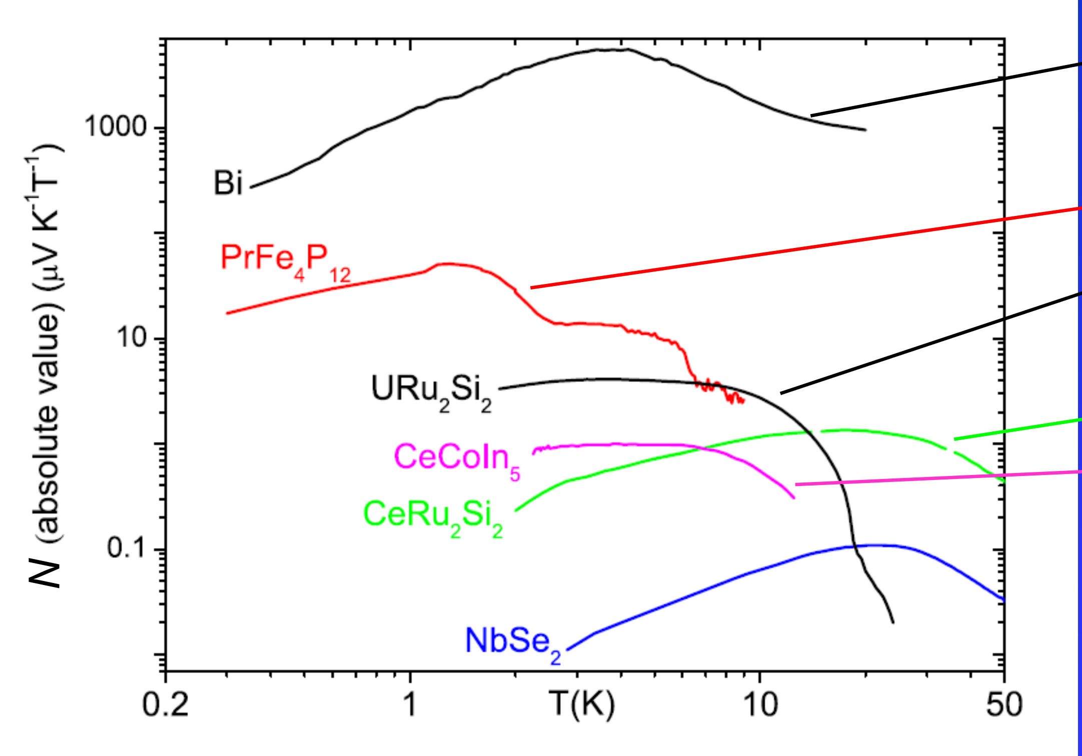
$PrFe_4P_{12}$
URu_2Si_2

correlations,
unconventional
order

Behnia et al., *Phys. Rev. Lett.* **98**, 076603 (2007)

Discussion: Nernst effect

How to obtain large Nernst coefficients?



Bi normal semimetal

$PrFe_4P_{12}$
URu_2Si_2
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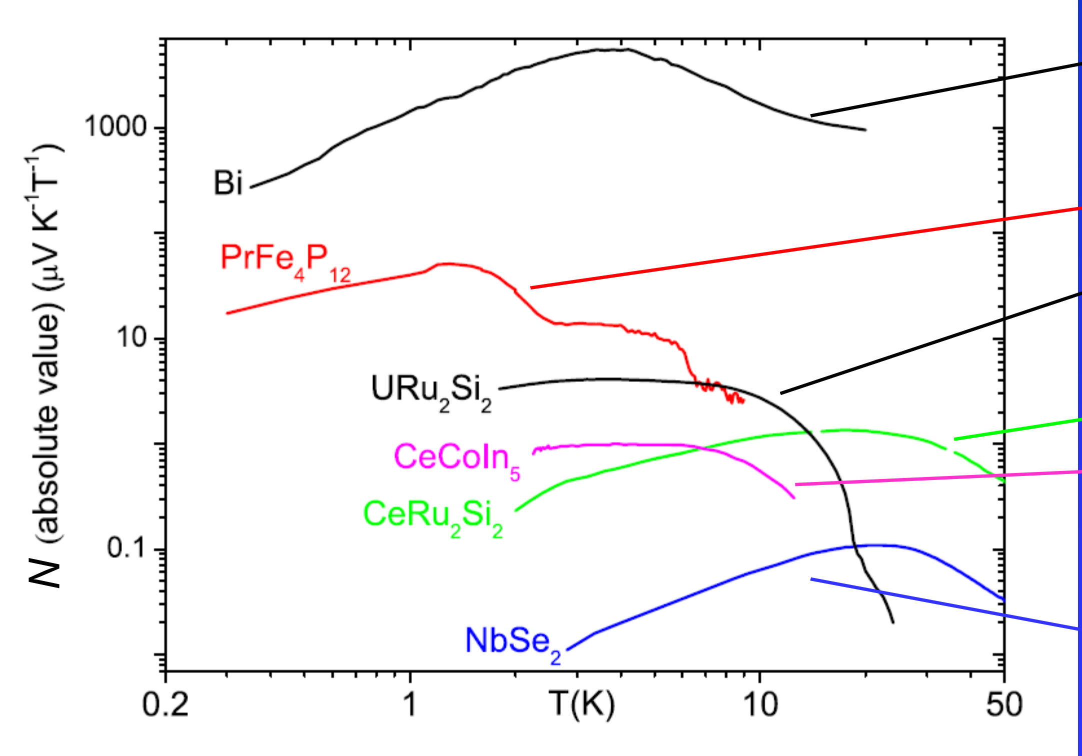
$CeRu_2Si_2$
$CeCoIn_5$
enhanced mass

Behnia et al., *Phys. Rev. Lett.* **98**, 076603 (2007)

Discussion: Nernst effect

How to obtain large Nernst coefficients?



Bi normal semimetal

$PrFe_4P_{12}$
URu_2Si_2
correlations, unconventional order

$CeRu_2Si_2$
$CeCoIn_5$
enhanced mass

$NbSe_2$ bipolar Nernst effect

Behnia et al., *Phys. Rev. Lett.* **98**, 076603 (2007)

Discussion: Nernst effect

Boltzmann approximation:

$$N^{\mathrm{n}} = \frac{\pi^2}{3}\,\frac{k_{\mathrm{B}}^2 T}{m^*}\,\frac{\partial \tau}{\partial \varepsilon}\bigg|_{E_{\mathrm{F}}}$$

with Hall angle $\tan\Theta_{\mathrm{H}} = \dfrac{\sigma_{yx}}{\sigma_{xx}}$

$$N^{\mathrm{n}} \approx \frac{\pi^2}{3}\,\frac{k_{\mathrm{B}}^2 T}{Be}\,\frac{\tan\Theta_{\mathrm{H}}}{E_{\mathrm{F}}}$$

BUT: CeNiSn with two types of charge carriers

Discussion: Nernst effect

Boltzmann approximation:

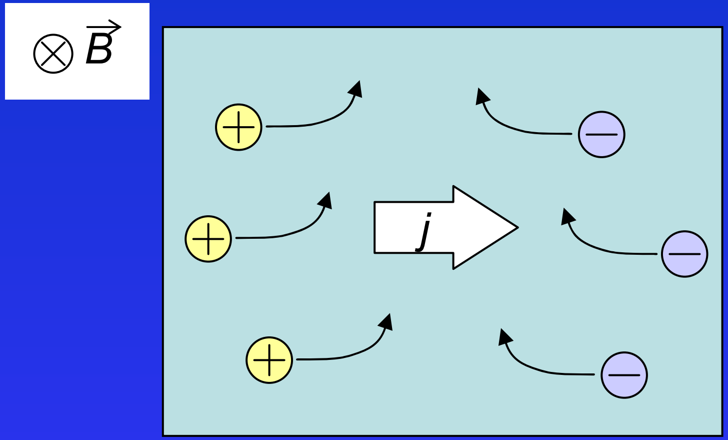
$$N^{\mathrm{n}} = \frac{\pi^2}{3} \frac{k_{\mathrm{B}}^2 T}{m^*} \left.\frac{\partial \tau}{\partial \varepsilon}\right|_{E_{\mathrm{F}}}$$

with Hall angle $\tan \Theta_{\mathrm{H}} = \frac{\sigma_{yx}}{\sigma_{xx}}$

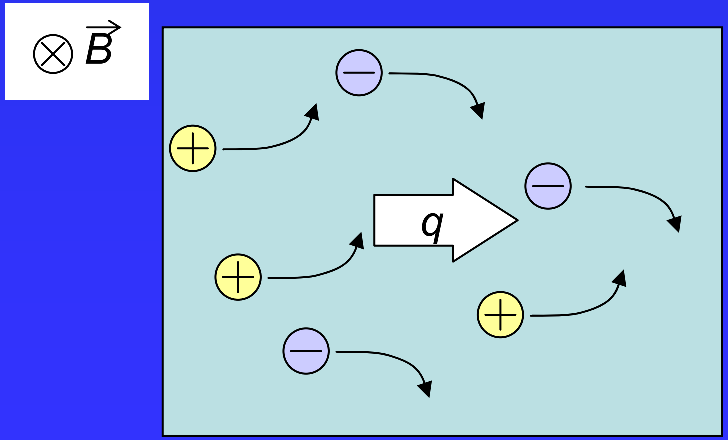
$$N^{\mathrm{n}} \approx \frac{\pi^2}{3} \frac{k_{\mathrm{B}}^2 T}{Be} \frac{\tan \Theta_{\mathrm{H}}}{E_{\mathrm{F}}}$$

BUT: CeNiSn with two types of charge carriers

Hall effect



Nernst effect



V. Oganesyan and I. Ussishkin, *Phys. Rev. B* **70**, 054503 (2004)

A. Pourret et al., *Phys. Rev. Lett.* **96**, 176402 (2006)

Discussion: Nernst effect

Boltzmann approximation:

$$N^{\mathrm{n}} = \frac{\pi^2}{3} \frac{k_{\mathrm{B}}^2 T}{m^*} \left. \frac{\partial \tau}{\partial \varepsilon} \right|_{E_{\mathrm{F}}}$$

with Hall angle $\tan \Theta_{\mathrm{H}} = \frac{\sigma_{yx}}{\sigma_{xx}}$

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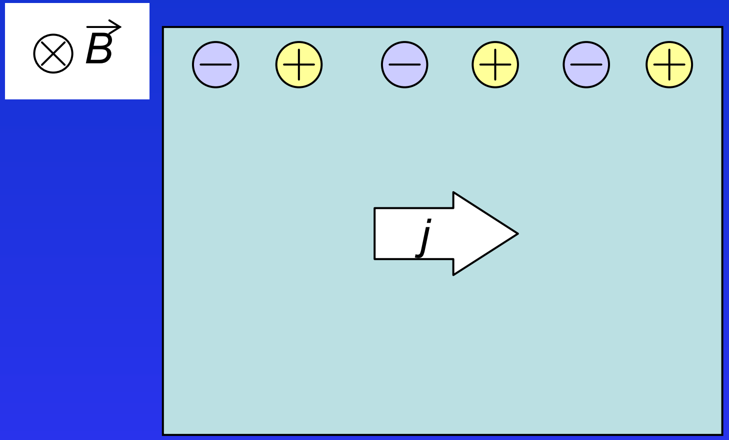

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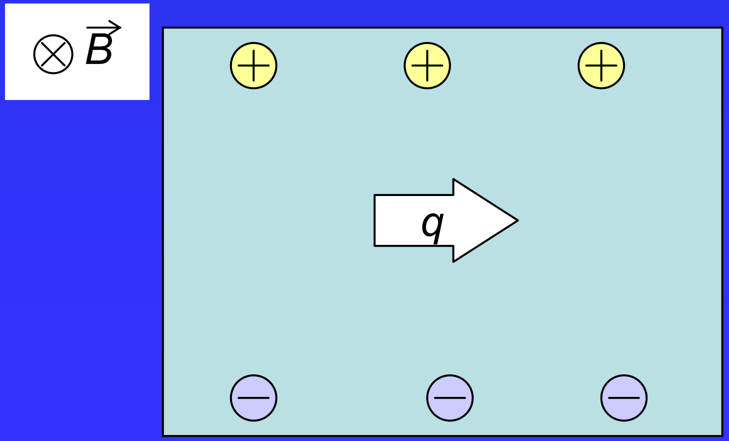
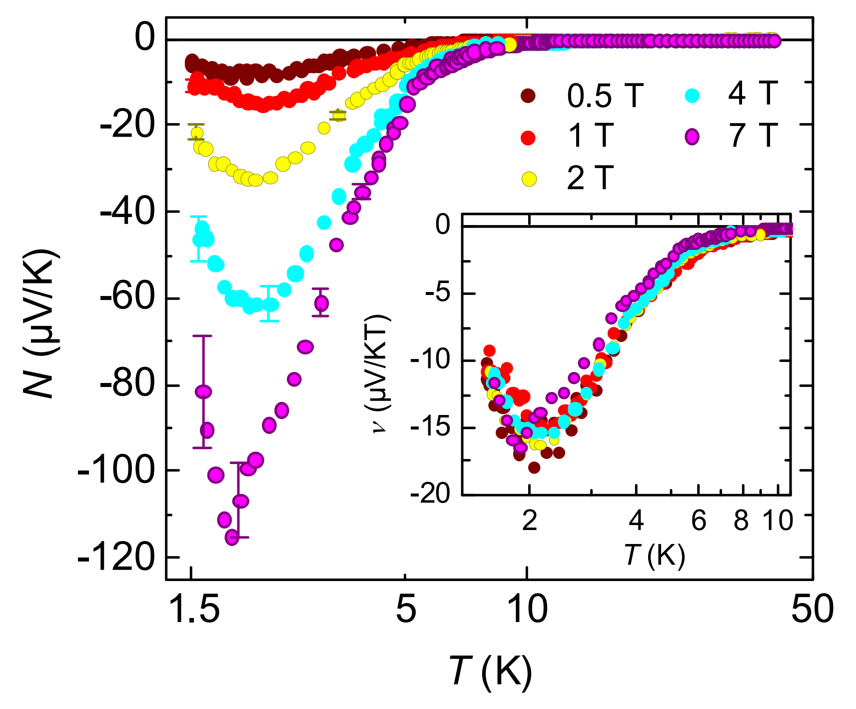
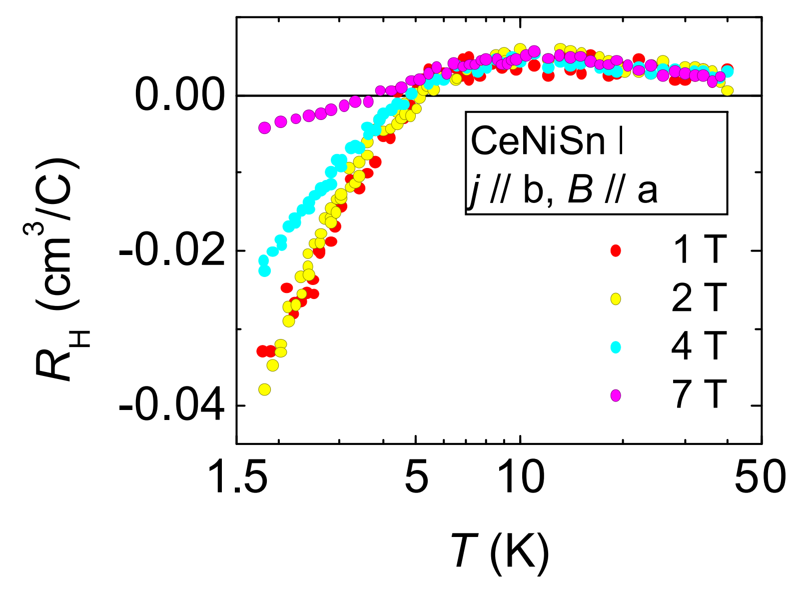


Discussion: Nernst effect

q // b, *B* // a





sign change in R_H
but not in *N*

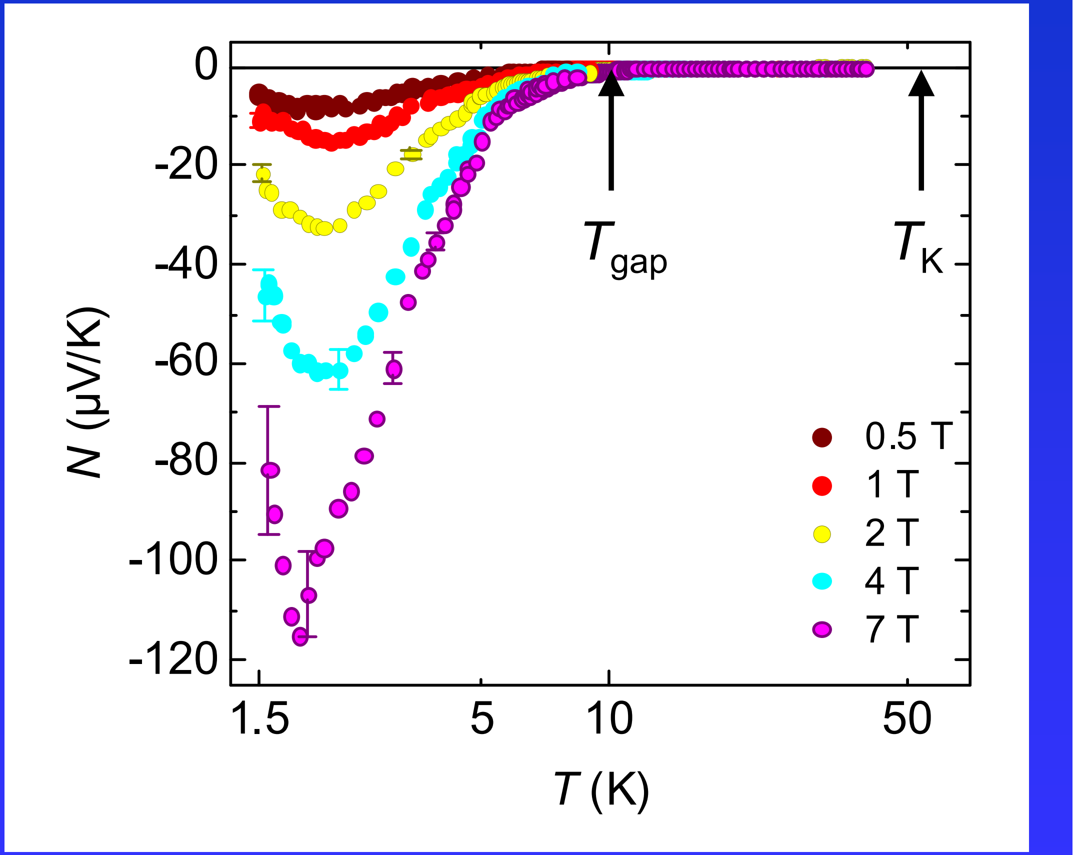
Discussion: Nernst effect

relevant mechanism:

opening of the gap ↔ enhanced values of N

low Fermi energy T_K

q // b, B // a

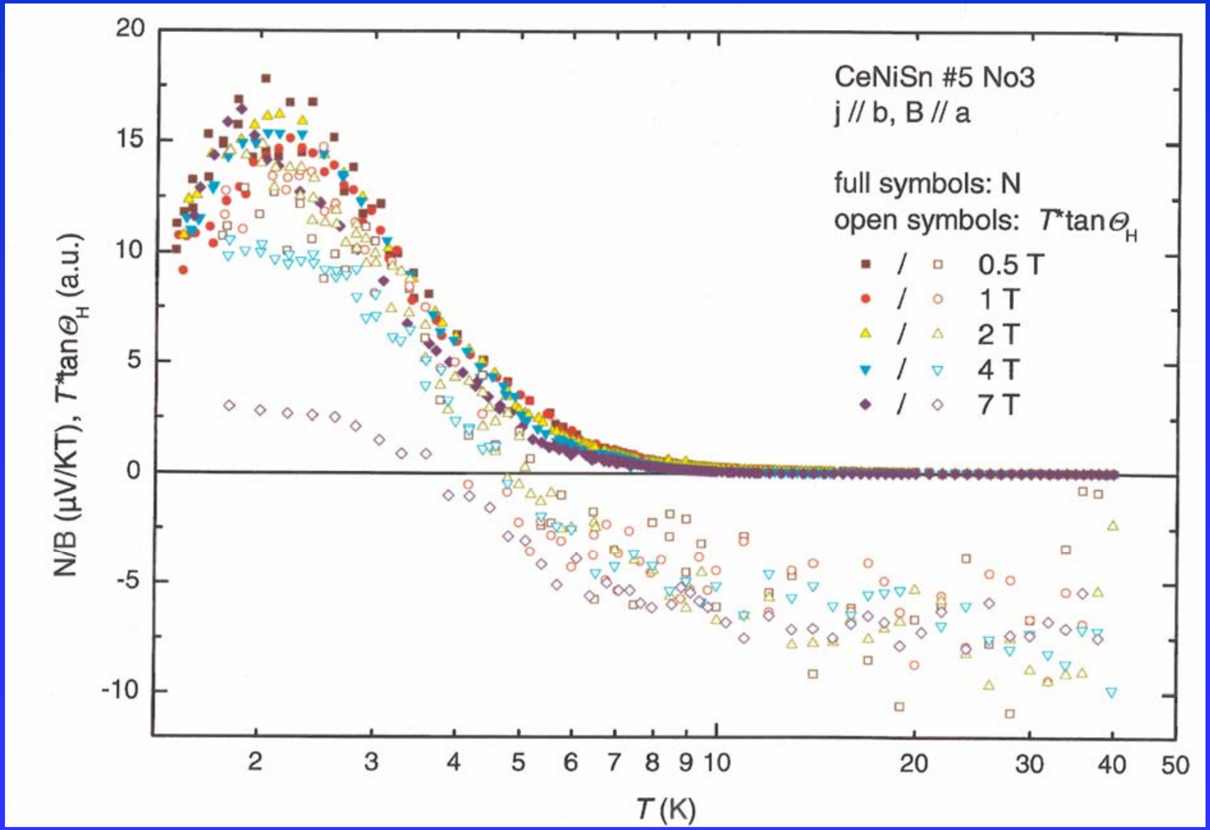


Discussion: Nernst effect

$$\nu^{n} \approx \frac{\pi^{2}}{3}\frac{k_{B}^{2}T}{Be}\frac{\tan\Theta_{H}}{E_{F}}$$

$$\tan\Theta_{H} = \frac{\sigma_{yx}}{\sigma_{xx}}$$

$\nu \sim T/B \tan\Theta_H$



Increase below T_g

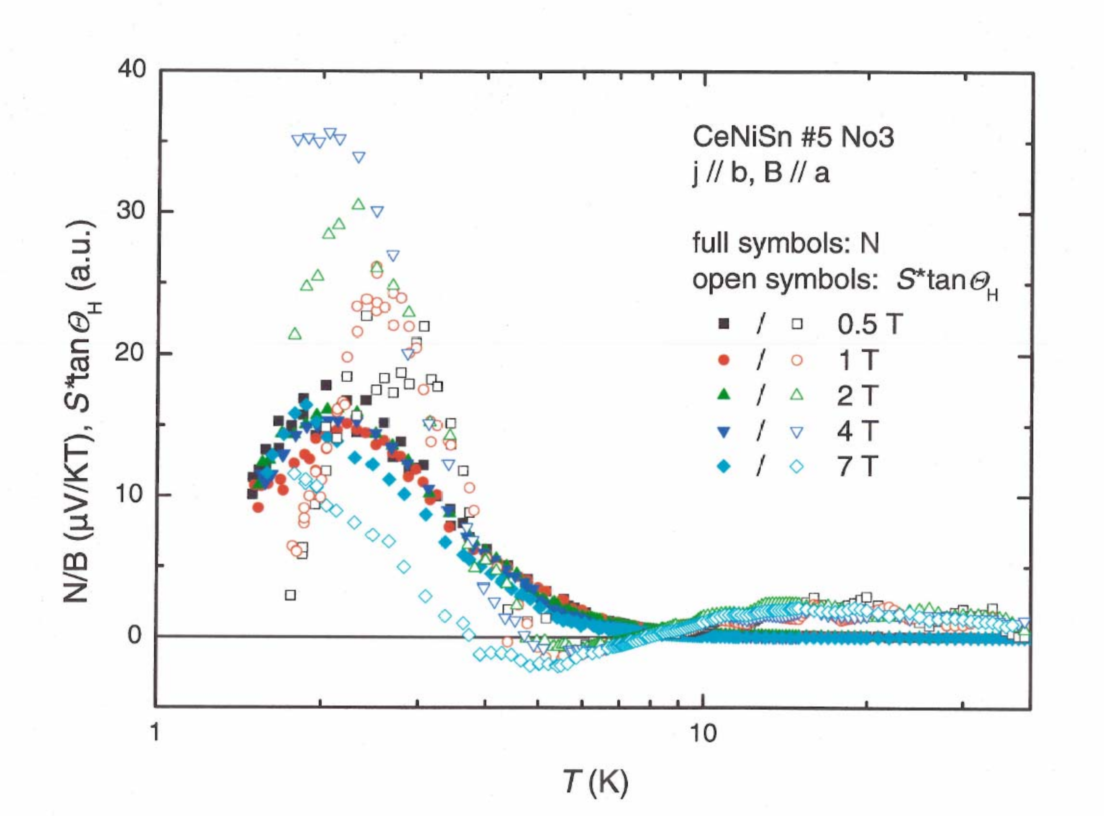
No scaling

Hall coefficient stronger suppressed in field

Discussion: Nernst effect

$$\nu^{\mathrm{n}} \approx \frac{\pi^2}{3}\frac{k_{\mathrm{B}}^2 T}{Be}\frac{\tan\Theta_{\mathrm{H}}}{E_{\mathrm{F}}}$$

$\nu \sim S/B \tan \Theta_H$



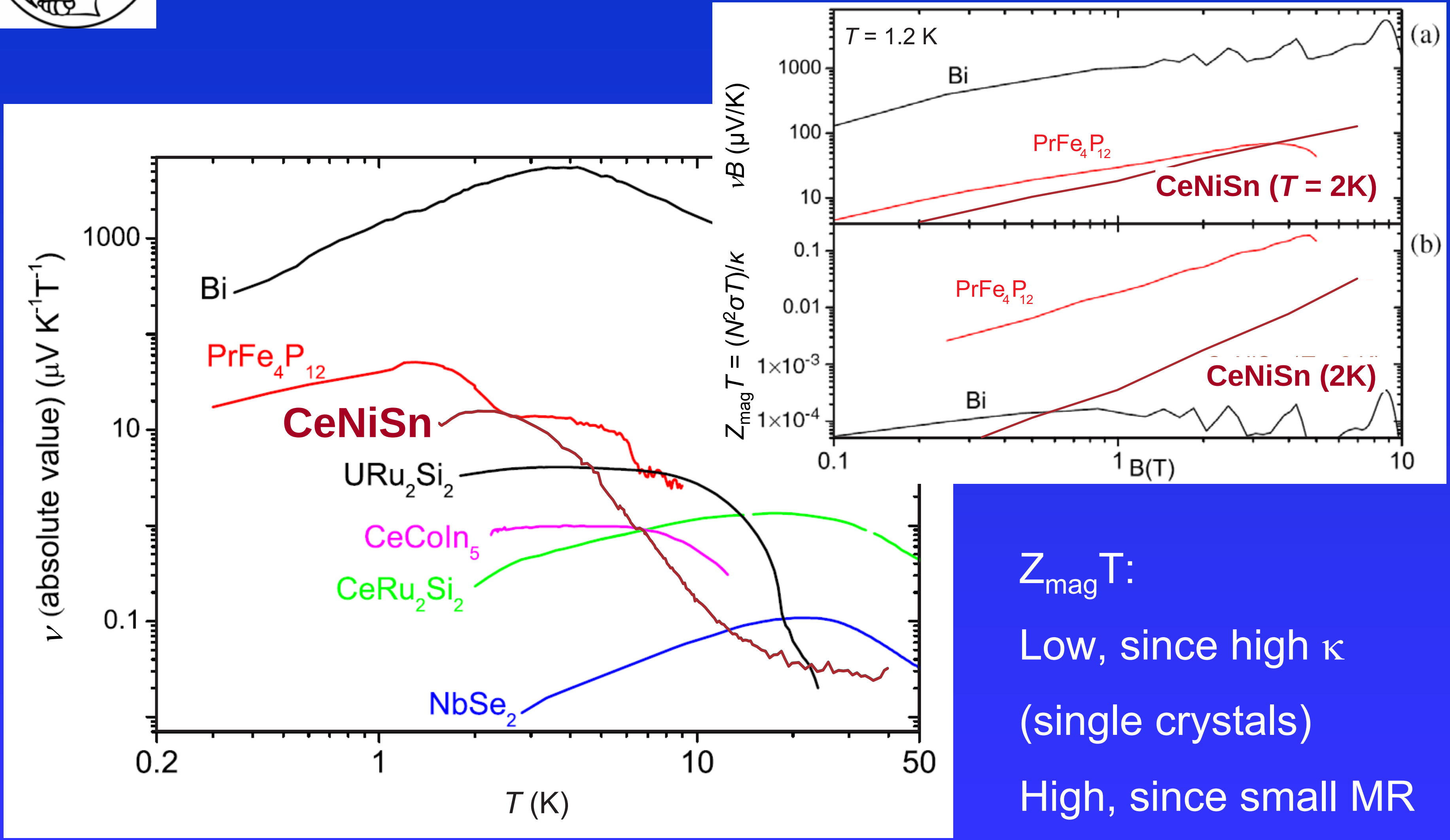
Increase below T_g

No scaling

Maximum in S tan Θ_H shifts in contrast to N/B

→ Multiband effects must be included

Discussion: Nernst effect



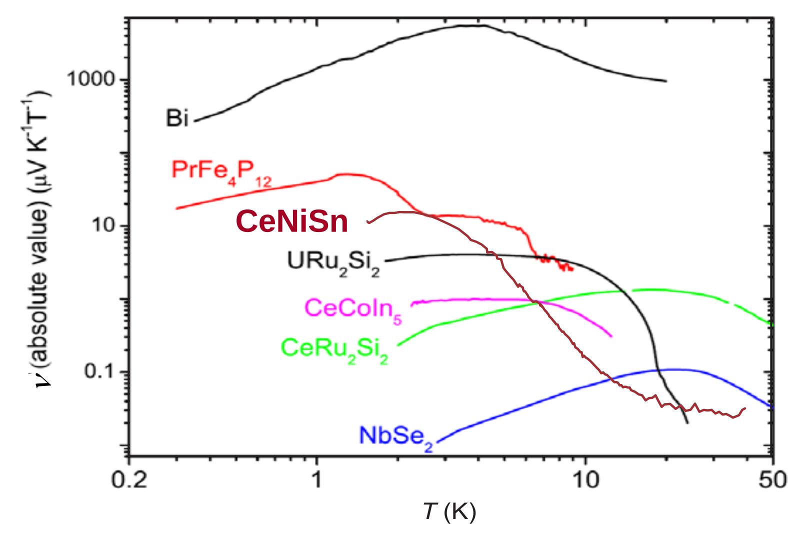
$Z_{mag}T$:

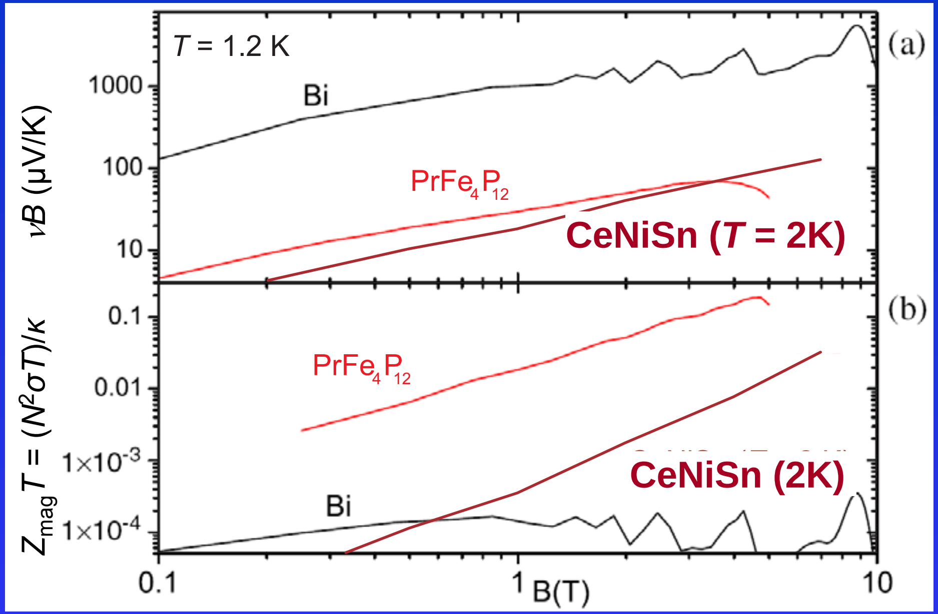
Low, since high κ

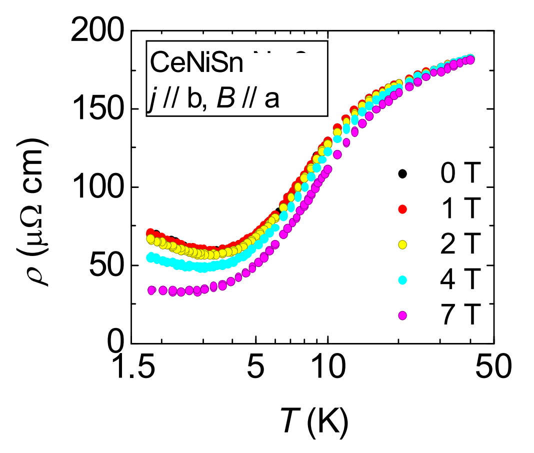
(single crystals)

High, since small MR

Discussion: Nernst effect







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Summary

thermopower:

- first systematic study of $S(T,B)$ taking into account the Nernst signal
- reported sample dependence partly due to misorientation/ Nernst signal
- low-T thermopower governed by the pseudogap opening
- Unusal field dependence due to gap closing and Zeeman splitting

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- first systematic study of *S*(*T*,*B*) taking into account the Nernst signal
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- low-*T* thermopower governed by the pseudogap opening
- Unusal field dependence due to gap closing and Zeeman splitting

Nernst coefficient:

- large signal below gap opening
- scaling for B//a
- high relevance of the pseudogap
- potential of correlated semiconductors for Ettingshausen cooling (low $\rho(B)$)