MIP-2026

Superconducting and magnetic properties of $CeRu_2$ investigated by μSR

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Outline

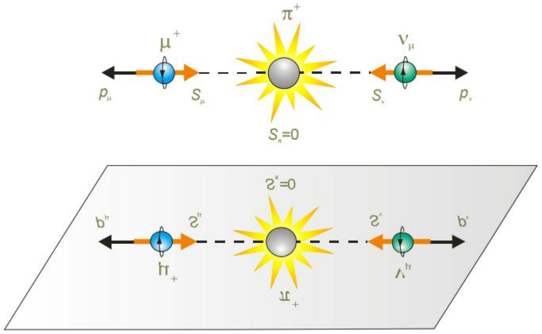
Production of muons

- μSR utilize surface muons & decay muons

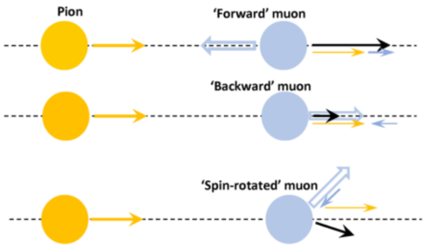
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

Energy

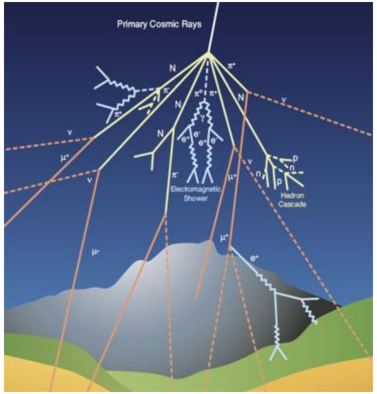
Polarization



Parity violation



Accelerator based



Surface muon 4.119 MeV
~100% polarized

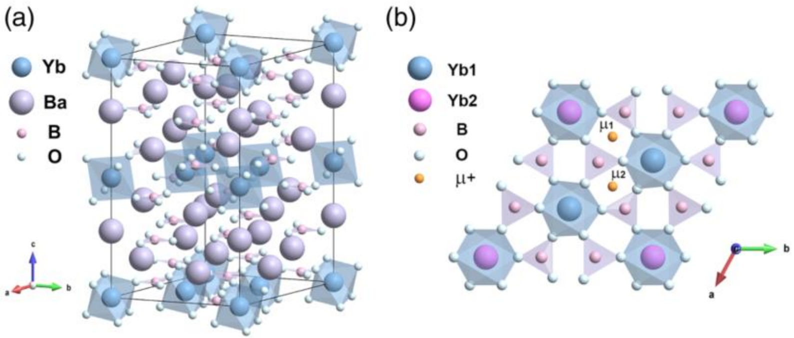
Decay muon ~ 40 MeV

Cosmic ray muon ~TeV

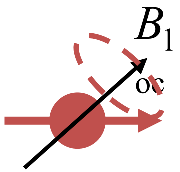
https://musr.ca/intro/musr/muSRBrochure.pdf R. Khasanov, J. Appl. Phys., 2022 https://cms.cern/content/muon-tomography

Detection of muons

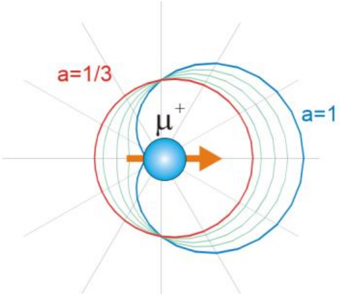
- e^+ angular distribution ⟶ μ^+ polarization $P_\mu(t)$



Slowing down……
Stopping at certain sites



Rotation / Relaxation $P_\mu(t)$



positrons

Decay with half period:
2.2 μs

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

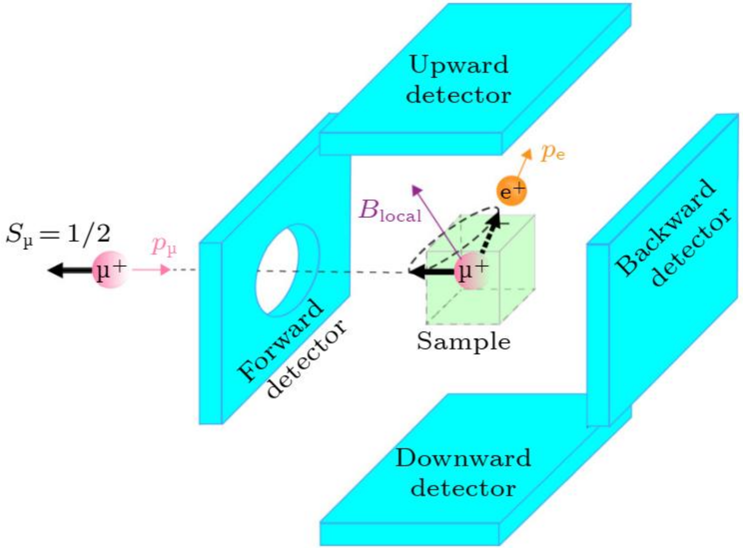
$$W(\theta) = 1 + \bar{a}\cos(\theta)$$

C. Y. Jiang *et. al.*, Phys. Rev. B, 2022

https://musr.ca/intro/musr/muSRBrochure.pdf

μSR experiment setup

- μSR experiment focus on how $P_\mu(t)$ evolutes



$$W(\theta) = 1 + \bar{a}\cos(\theta)$$

$$N_{F,B}(t) = N_0 e^{-t/\tau}(1 \pm \bar{a}P_\mu(t))$$

$$A(t) = \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = \bar{a}P_\mu(t)$$

$A(t)$ proportional to $P_\mu(t)$!

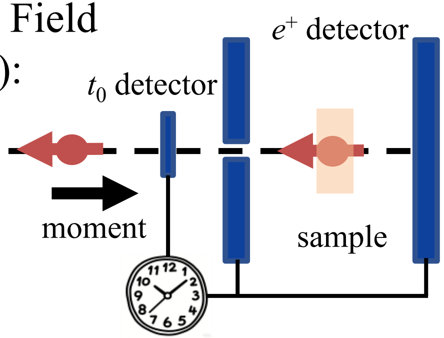
Asymmetry parameter *A*(*t*) !

Y. Wang *et al.*, Acta Phys. Sin., 2024

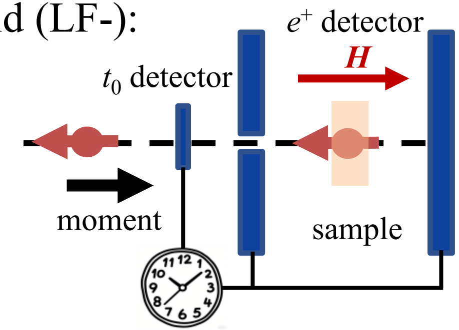
μSR experiment setup

Magnetic order / Spin dynamics

Zero Field (ZF-):

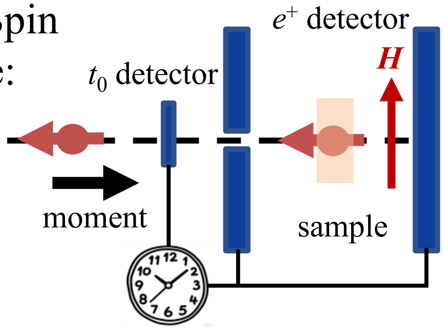


Longitudinal Field (LF-):

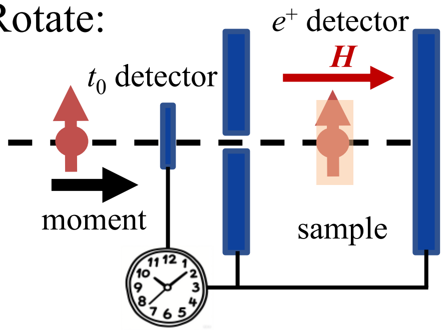


Superconducting gap symmetry

Transverse Field (TF-), Non-Spin Rotate:

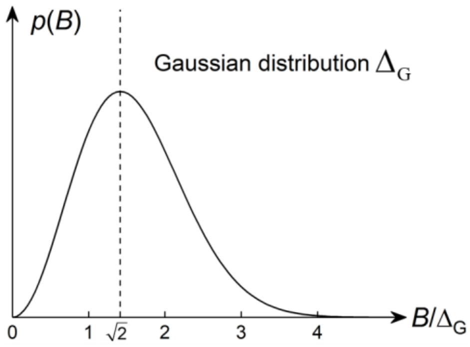


Spin Rotate:

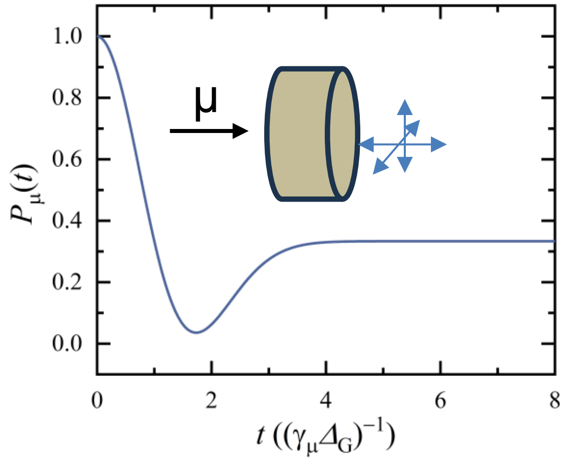


Typical relaxation function

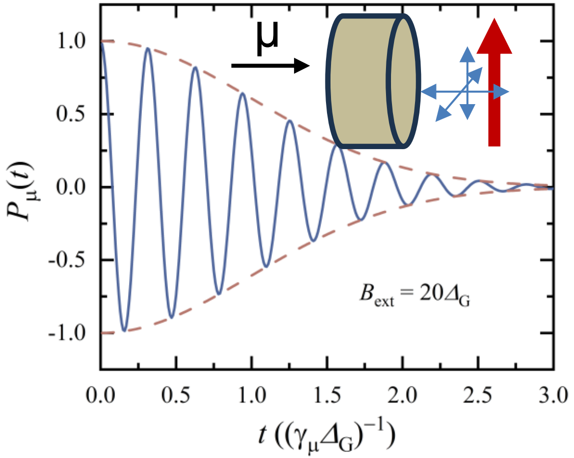
- Gaussian distribution static local fields (e.g. Nuclear dipole moment)



ZF-μSR



TF-μSR



$$D(B_{loc}^x)dB_{loc}^x = (\frac{1}{\sqrt{2\pi}\Delta_G})\exp\left[-\frac{(B_{ext}-B_{loc}^x)^2}{2\Delta_G^2}\right]dB_{loc}^x$$

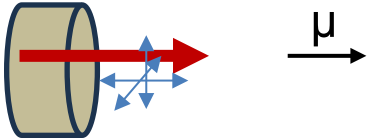
$$P_\mu(t) = \frac{1}{3} + \frac{2}{3}(1-\gamma_\mu^2\Delta_G^2 t^2)\exp(-\frac{\gamma_\mu^2\Delta_G^2 t^2}{2})$$

$$P_X(t) = \exp(-\frac{\gamma_\mu^2\Delta_G^2 t^2}{2})\cos(\gamma_\mu B_{ext} t)$$

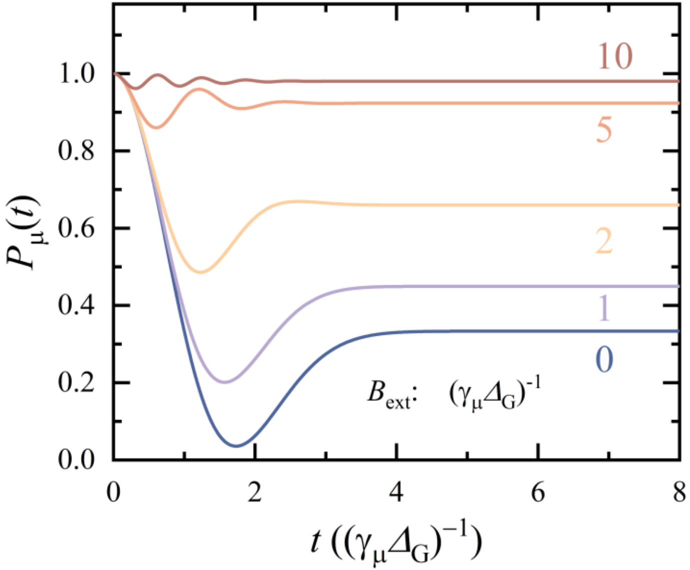
Kubo-Toyabe function

A. Yaouanc *et al.*, Muon Spin Rotation, Relaxation, and Resonance, 2011
R. Kubo *et al.*, Magnetic Resonance and Relaxation, 1967

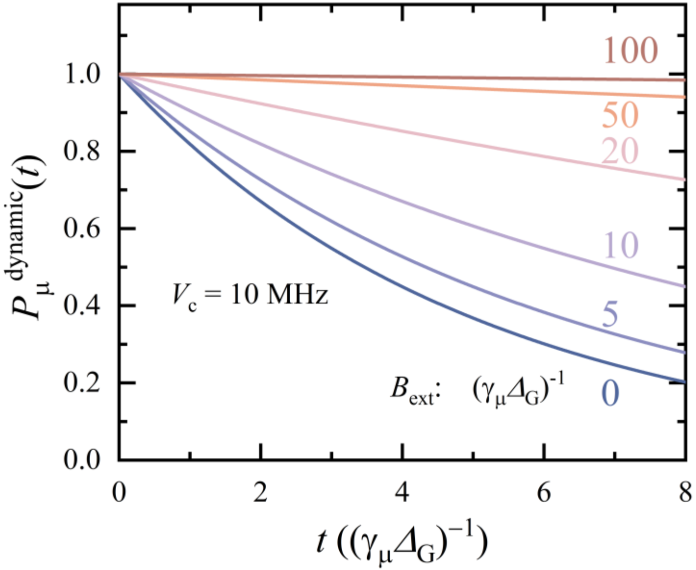
Typical polarization function



- LF-μSR — distinguish static / dynamic local fields



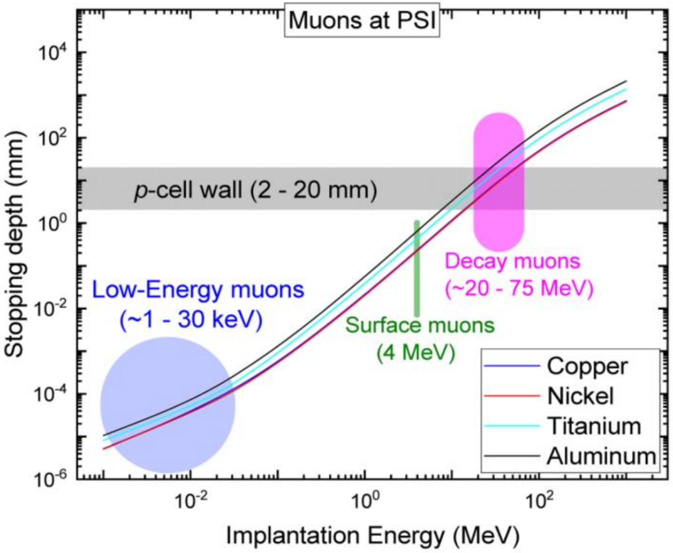
Static local fields, Decouple

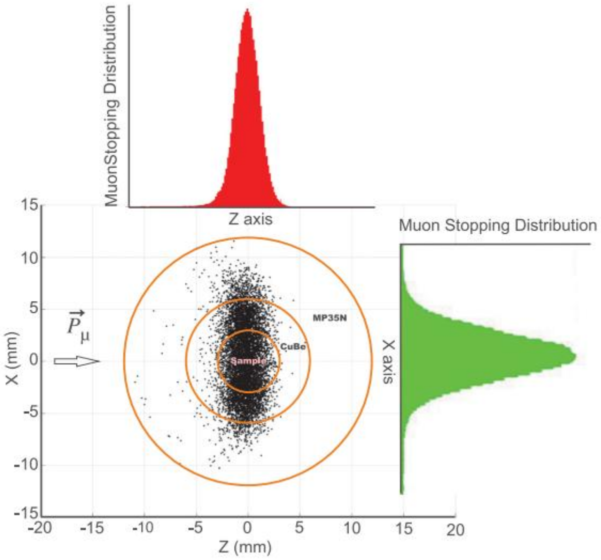


Dynamic local fields

High pressure technique

- Optimize muon momentum & beam size

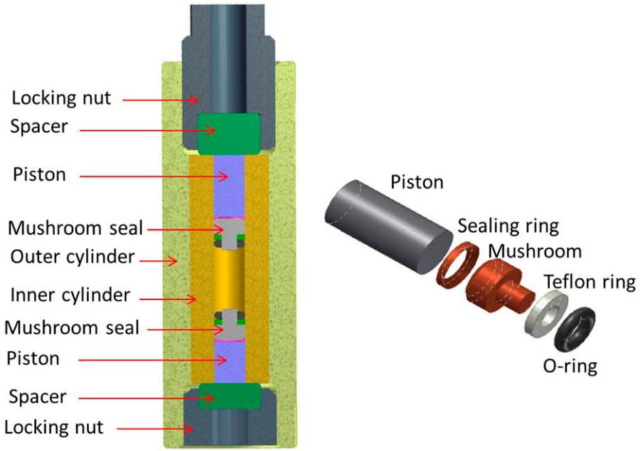




R. Khasanov, J. Appl. Phys., 2022

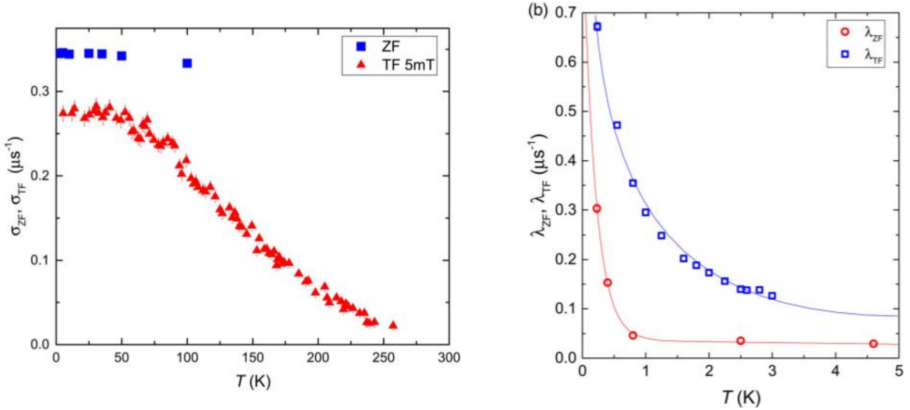
High pressure technique

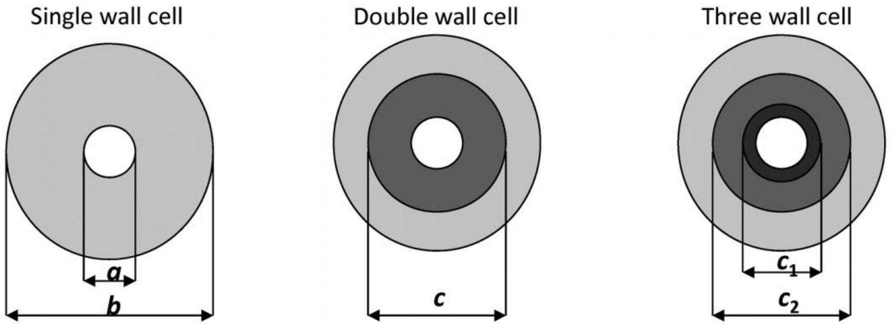
Piston pressure cells for μSR experiments @GPD PSI



BeCu (1.8 GPa)

MP35N (2.5 GPa)

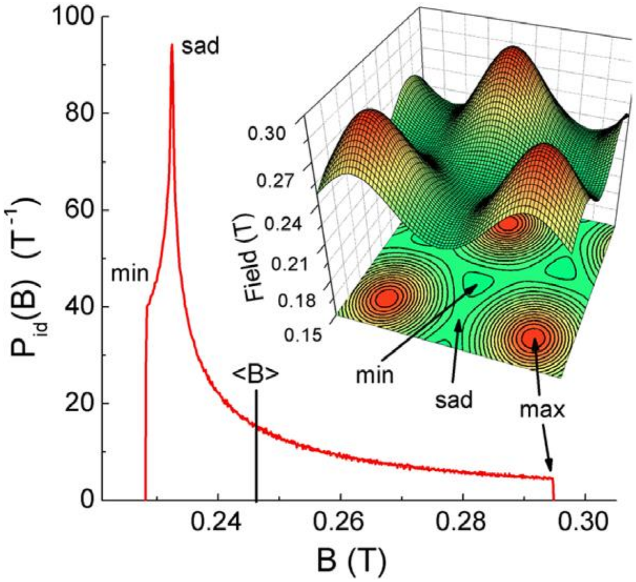




R. Khasanov *et. al.*, High Pressure Research, 2016

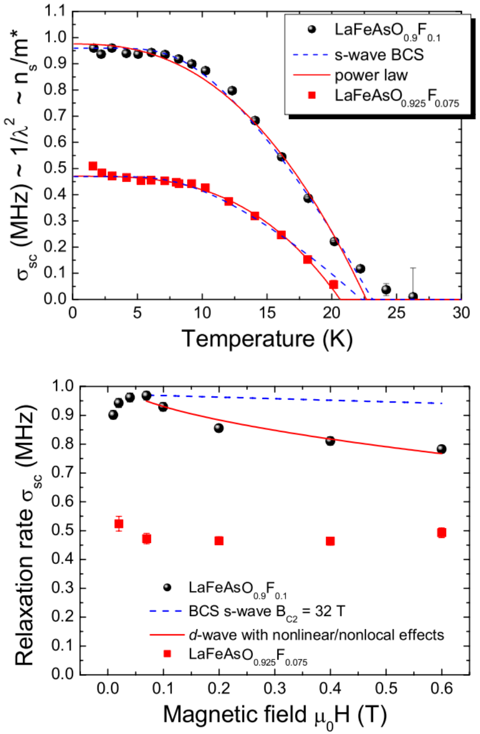
Application

➤ Unconventional gap in $LaFeAsO_{0.9}F_{0.1}$ (TF-μSR)



$$\sigma \propto \sqrt{\langle B(x,y)^2 - B^2 \rangle} \propto \frac{\Phi_0}{\lambda^2}$$

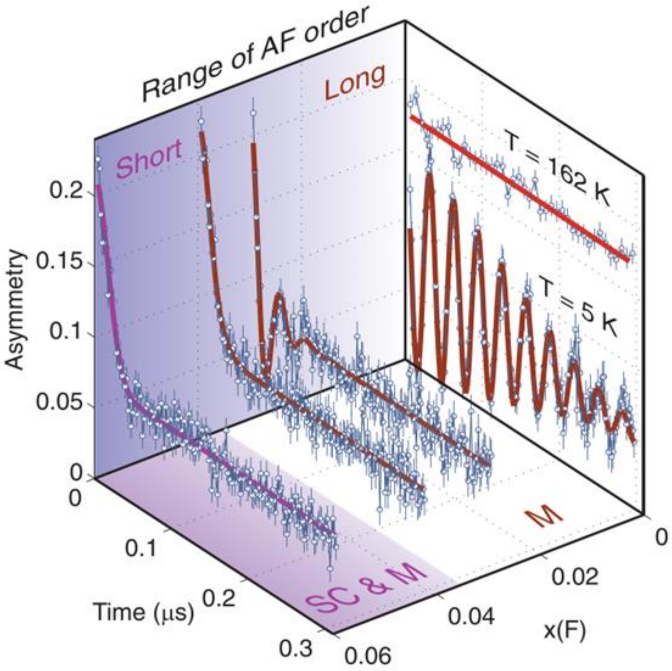
R. Khasanov *et al.*, Phys. Rev. Lett., 2007



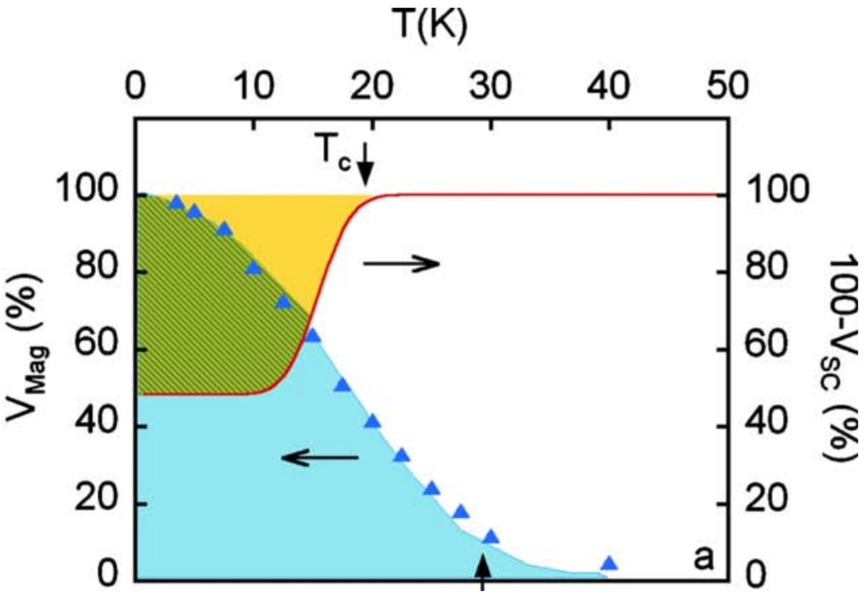
H. Luetkens *et al.*, Phys. Rev. Lett., 2008

Application

- Coexisting state of $CeFeAsO_{1-x}F_x$ (ZF-μSR)



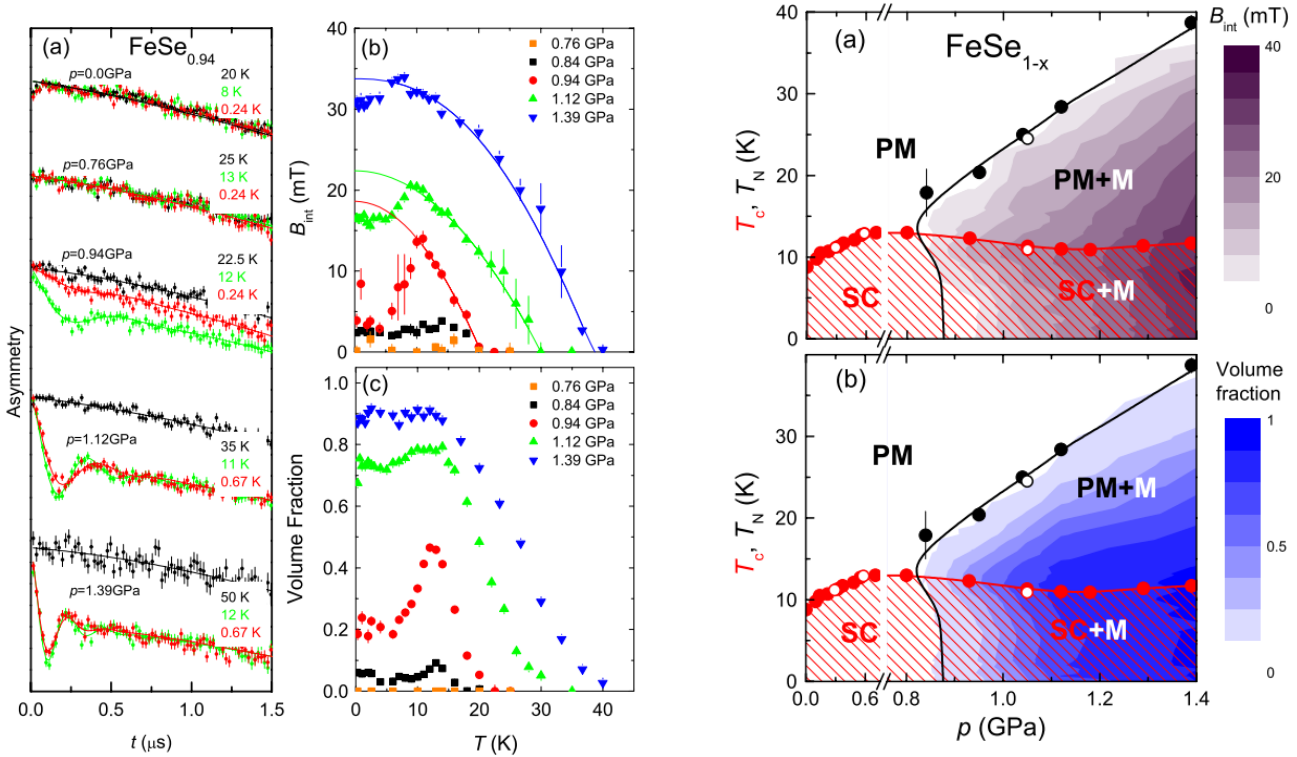
T. Shiroka *et al.*, Phys. Rev. B, 2011



S. Sanna *et al.*, Phys. Rev. B, 2010

Application

- Magnetic order in $FeSe_{1-x}$ (High pressure ZF-μSR)

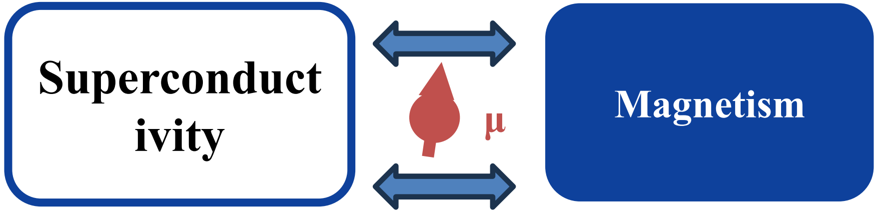


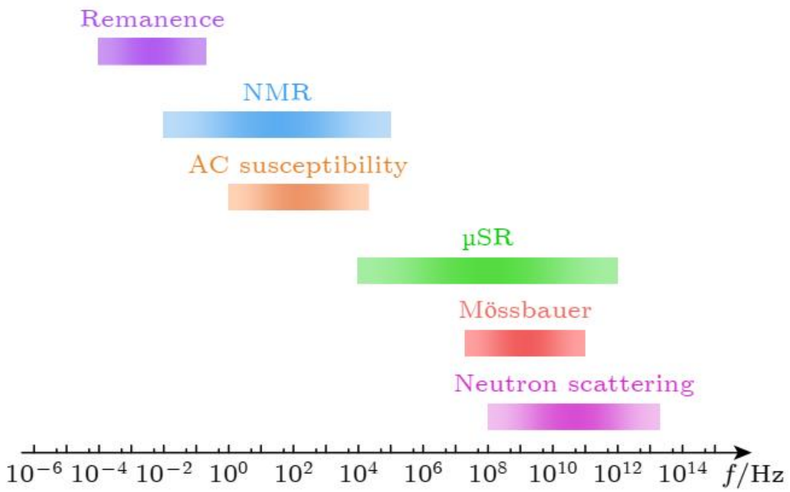
M. Bendele *et al.*, Phys. Rev. Lett., 2010

Summary

- Advantage of μSR

  - High sensitivity to magnetism (0.1 G)
  - Zero-field measurements
  - Special time window
  - Local probe (volume of magnetic phase)
  - In-situ environments: Field, Pressure…….





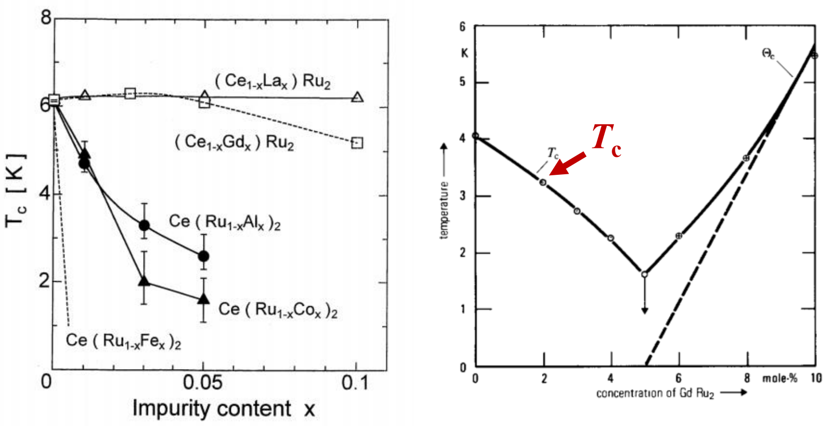
Y. Wang *et.al*, Acta Phys. Sin., 2024

Outline

$CeRu_2$ introduction

- "Conventional" superconductor with unconventional properties

Abnormal $T_c(x)$ relation: initial increase

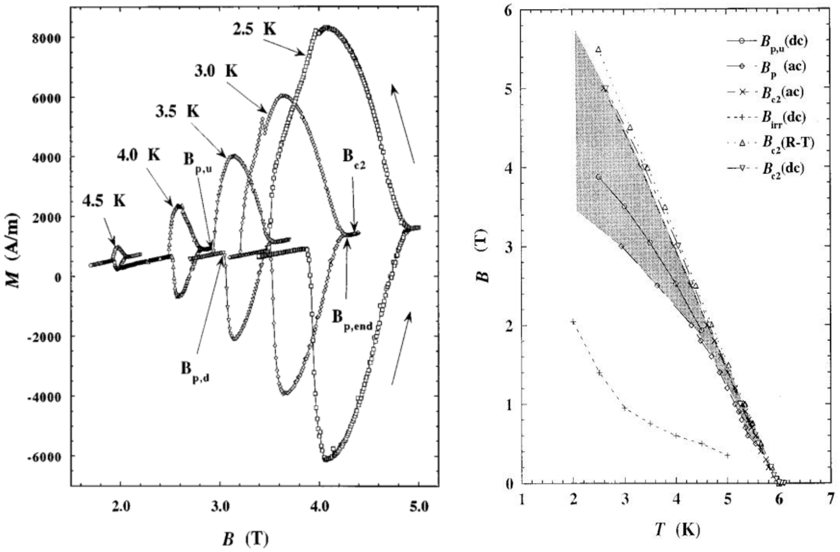


$Ce_{1-x}R_xRu_2$ (R = Gd, La)

$La_{1-x}Gd_xRu_2$

B. Hillenbrand *et al.*, Phys. Lett., 1972

Abnormal magnetization near H_{c2} —"Peak effect"



K. Kadowaki *et al.*, Phys. Rev. B, 1996

$CeRu_2$ introduction

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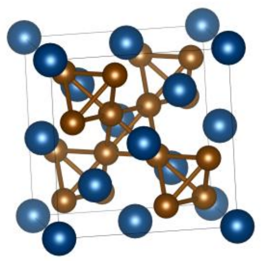
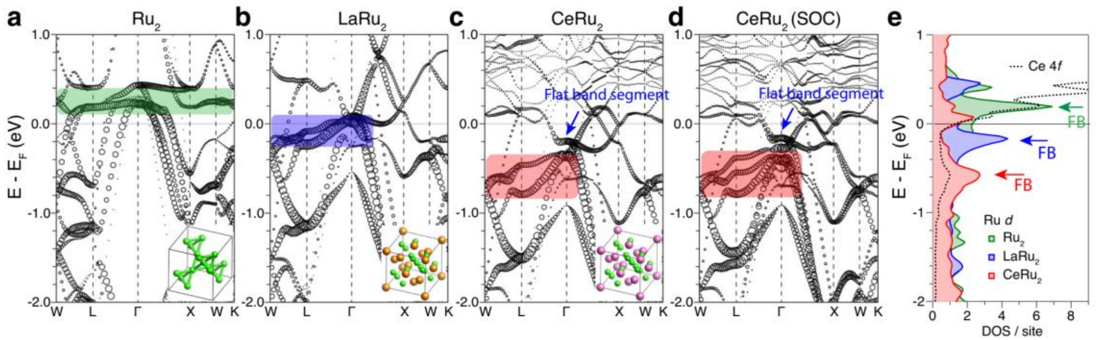
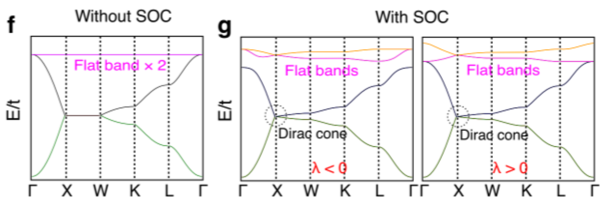
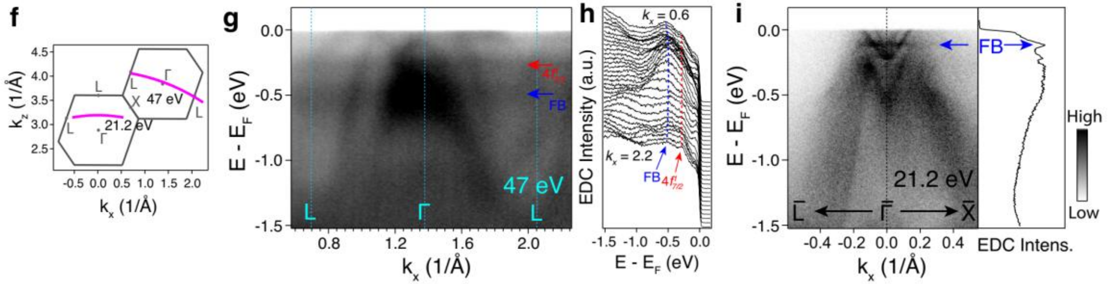
➢ 3D Pyrochlore lattice with Ce & Ru flat bands









Pyrochlore Ru Lattice (Tight-bonding model):
Flat bands, 3D Dirac points, Van Hove singularities

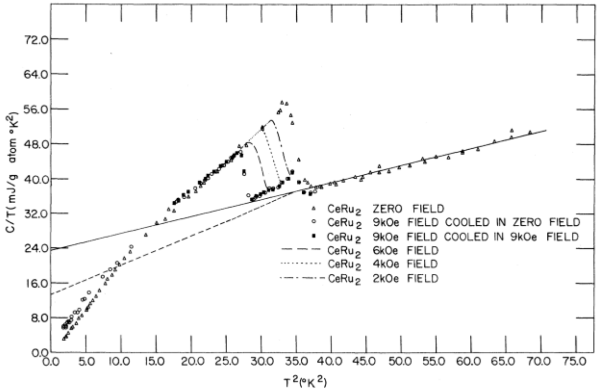
ARPES: Ce flat band (Kondo) & Ru flat band (geometry)

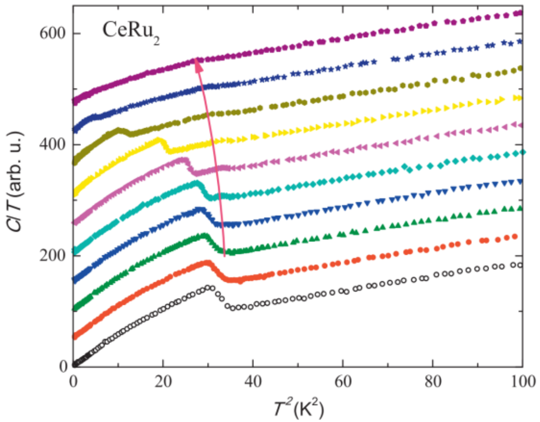
J. Huang *et al.*, npj quantum materials, 2024

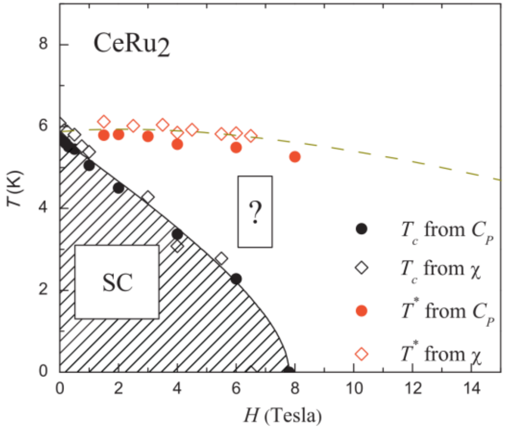
Motivation

➢ Low temperature magnetic transition near T_c ?

Anomaly from β-Ce or Ce_xRu_y impurities ?





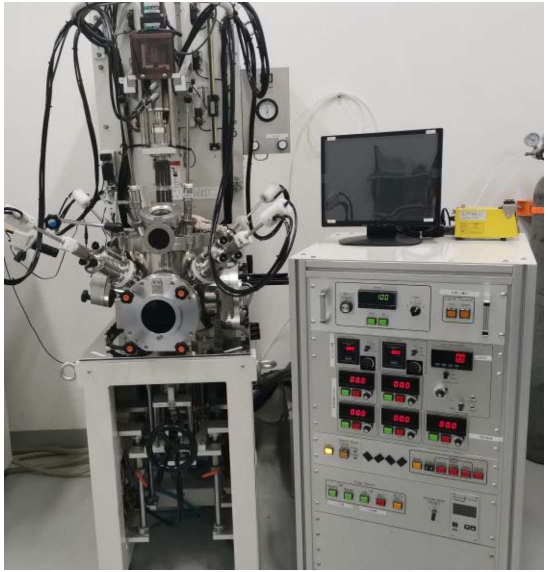


R. R. Joseph *et al.*, Phys. Rev. B, 1972

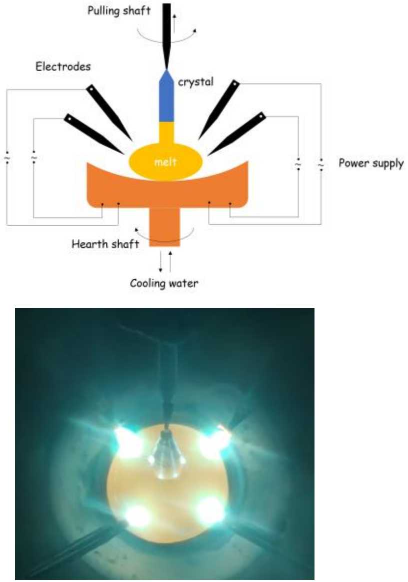
C. L. Huang *et al.*, Physica C, 2010

CeRu$_2$ sample growth

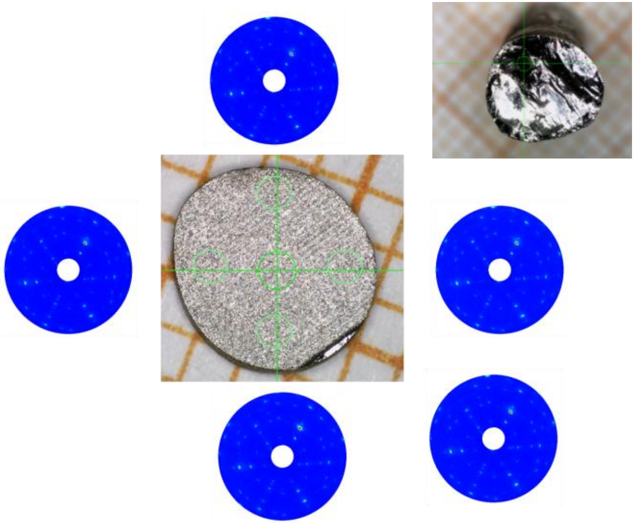
- High quality single crystals by Czochralski method



Tetra-arc furnace



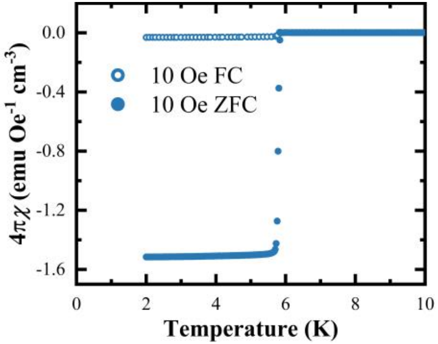
Single-crystal growing

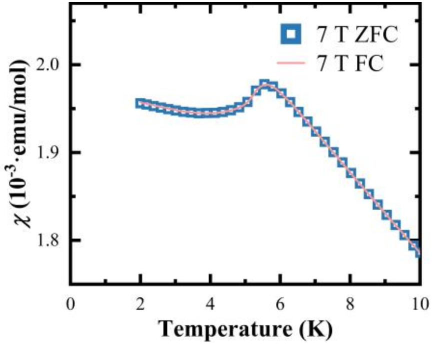


Laue pattern

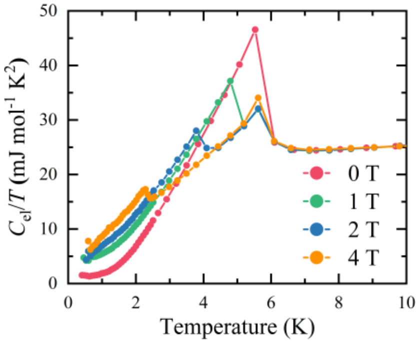
Specific heat

➢ Intrinsic magnetic order & energy gap in high-field normal states

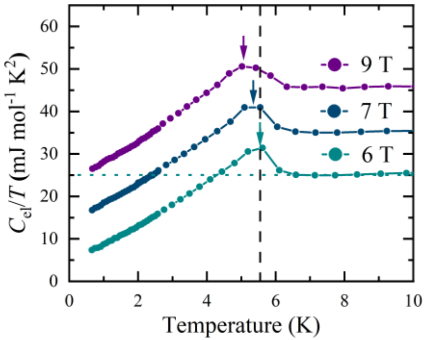




SC state: $\mu_0 H < 6$ T



normal state: $\mu_0 H \geq 6$ T



@1 mT: Superconductivity

$T_c = 6$ K

@7 T: AFM like Order

$T_m \sim 6$ K

- Superconducting state Residual:
  $\gamma_N = 25$ mJ mol^{-1} K^{-2}

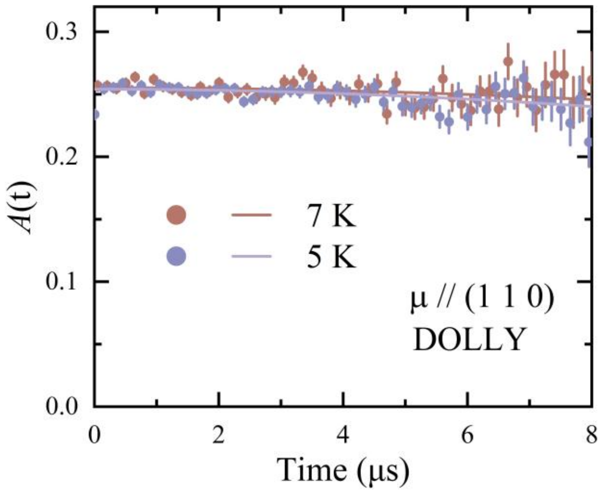
- High quality sample: sharp transition, 100% volume
- AFM like order near 6 K when SC suppressed

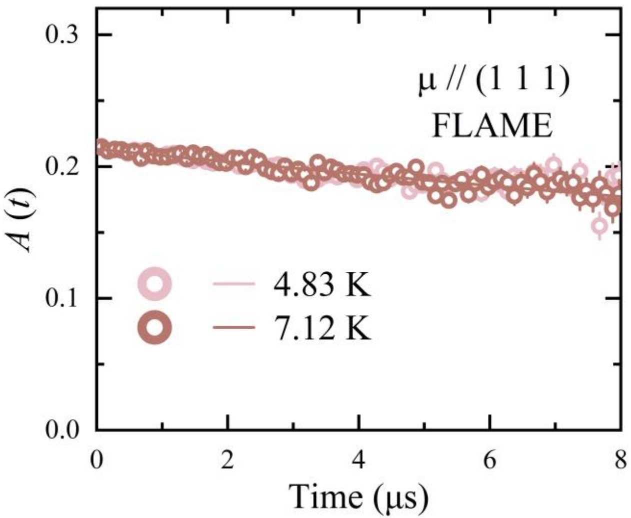
- Normal state Residual @ 0.6 K 6 T:
  $\gamma_0 = 7.4$ mJ mol^{-1} K^{-2} **$\gamma_0 / \gamma_N \sim 30\%$**

What happened across $T_m \sim 6$ K ?

$CeRu_2$ ZF-μSR

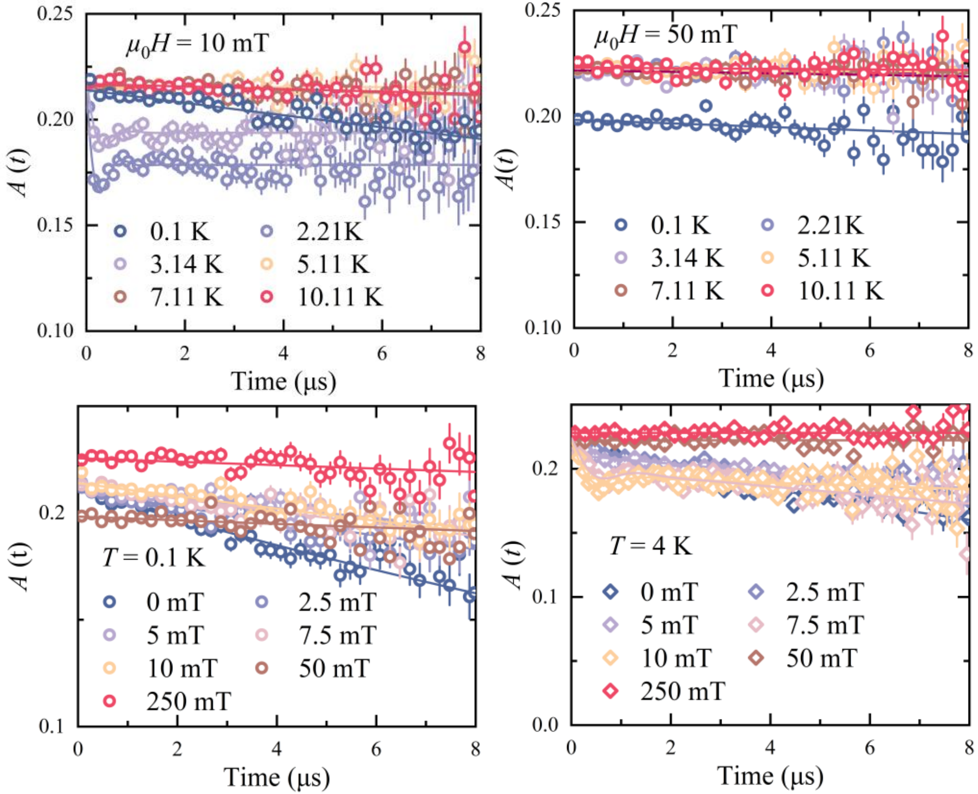
- No transition across 6 K

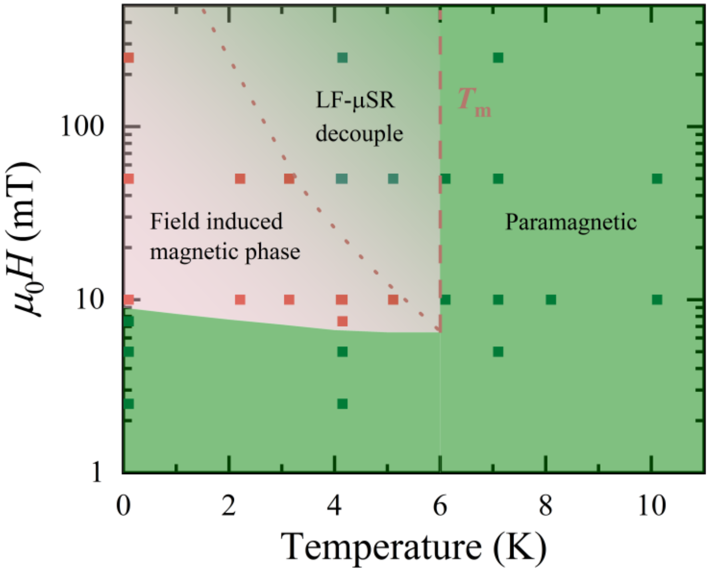




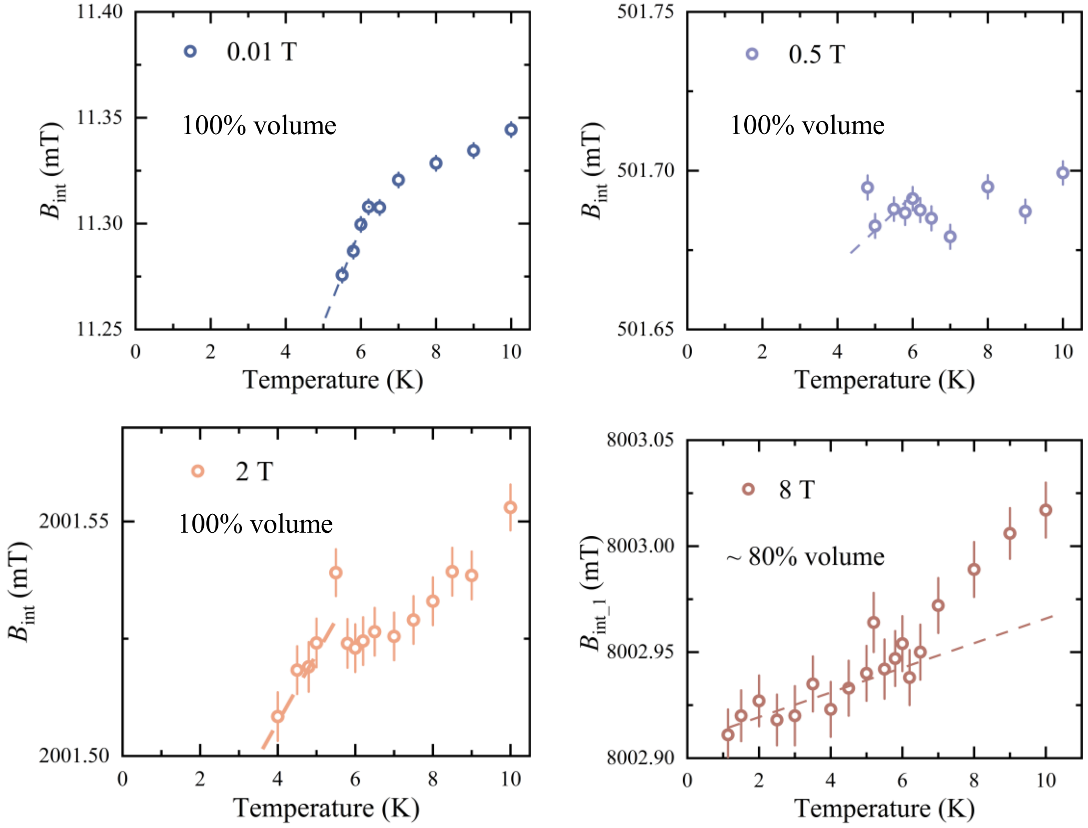
$CeRu_2$ LF-μSR

- Field induced anomaly near 10 mT





$CeRu_2$ TF-μSR



- $B_{int}(T)$ slop change near 6 K
- Bulk magnetism ≥80 % volume

$CeRu_2$ intrinsic order

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- Impurity magnetism or intrinsic ?

Pros

- Small residual $C(T)/T$: **$\gamma_0/\gamma_N = 30.8\%$**
- High field TF-μSR: Slop change in $B_{int}(T)$

Cons

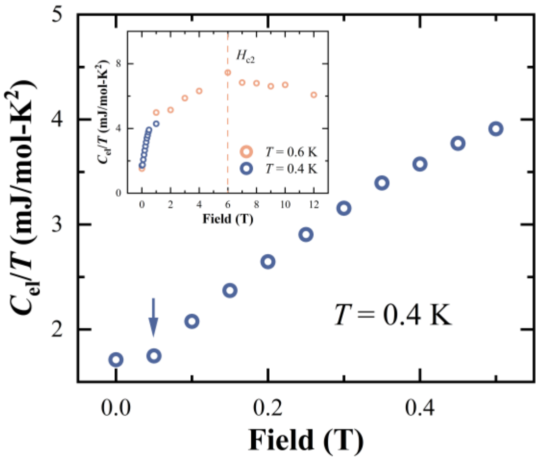
- Sample dependence

  (May be explained by Ru site defect)

- Field induced or exists @ 0 T?

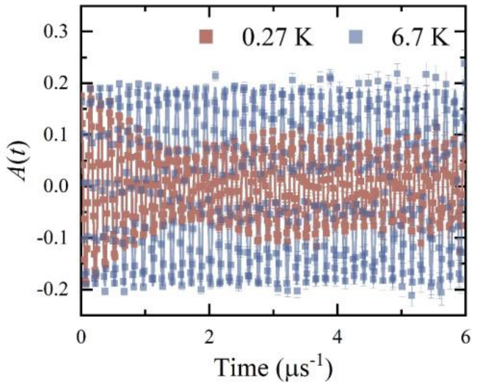
Pros (Field induced):

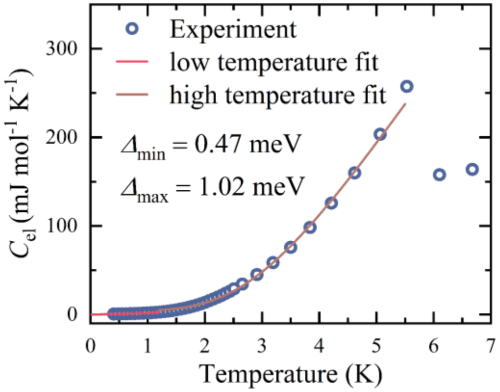
- LF-μSR: anomaly at for $\mu_0 H > 10$ mT
- ZF-μSR: absent magnetism below 6 K
- Transition in $C(H)/T$

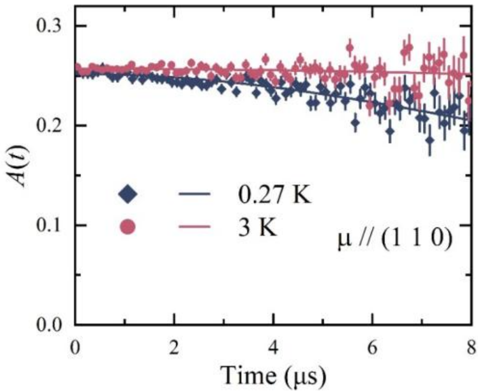


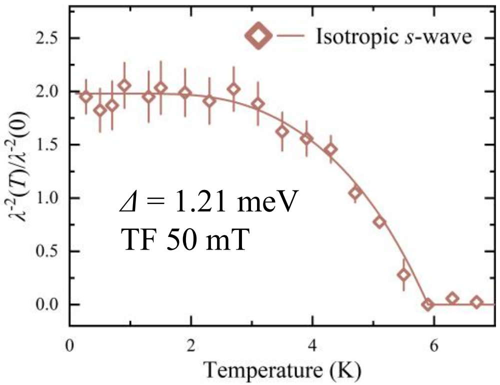
Outline

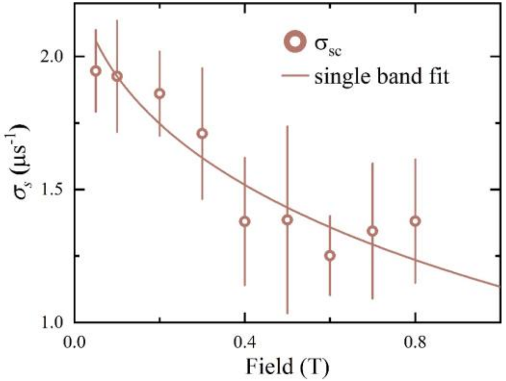
TF-μSR vs Specific heat











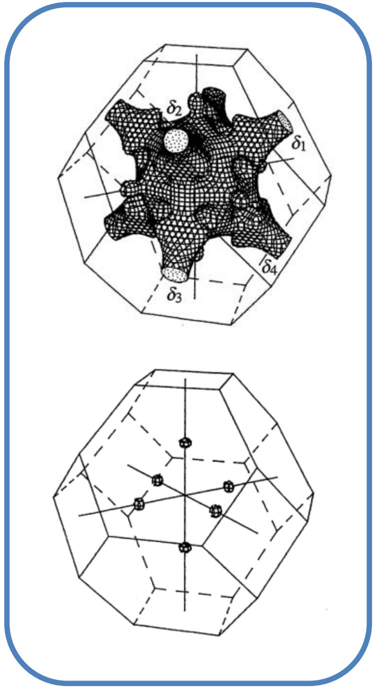
- $\sigma_{sc}(T)$: isotropic *s*-wave
- $\sigma_{sc}(T)$: single band

$$\delta_B = 0.172\frac{\Phi_0}{\lambda^2}\frac{(1-b)}{2\pi}\left[1+1.21(1-\sqrt{b})^3\right]$$

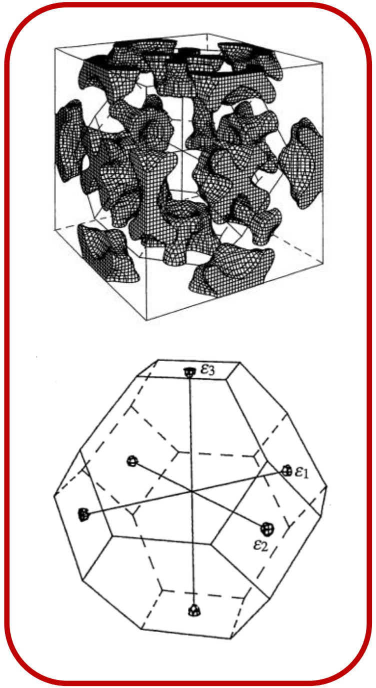
- Specific heat: Multigap/Anisotropic *s*-wave superconductivity?

$CeRu_2$ Fermi surface

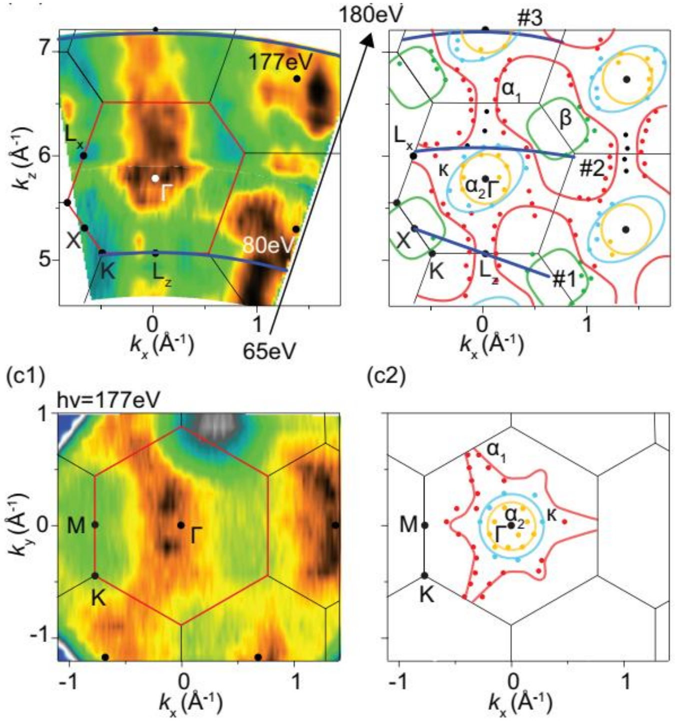
Hole (DFT)：



Electron (DFT)：



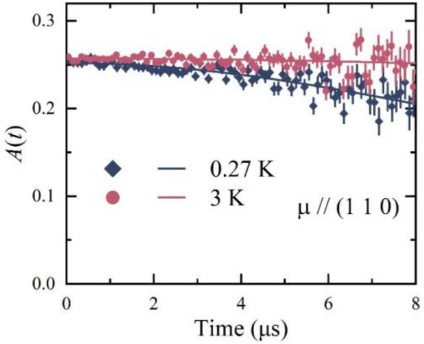
ARPES：

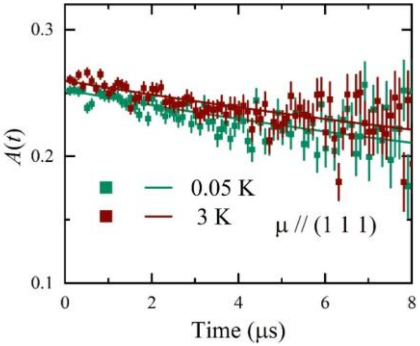


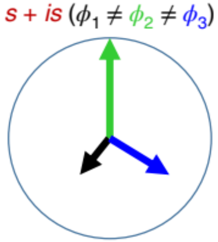
M. Hedo, J. Phys. Soc. Jpn., 1995

S. Sangphet, PRB, 2026.

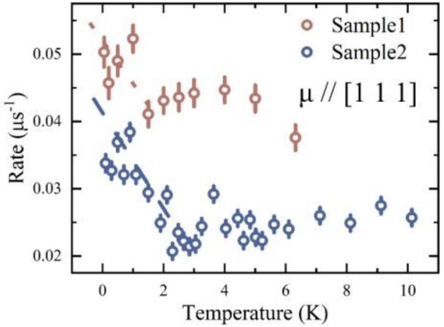
Inter-band correlation



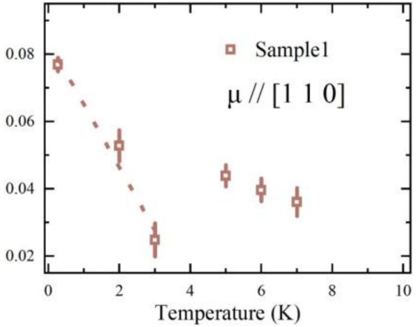




V. Grinenko, Nat. Phys. 2021



Rate for μ//[1 1 1]

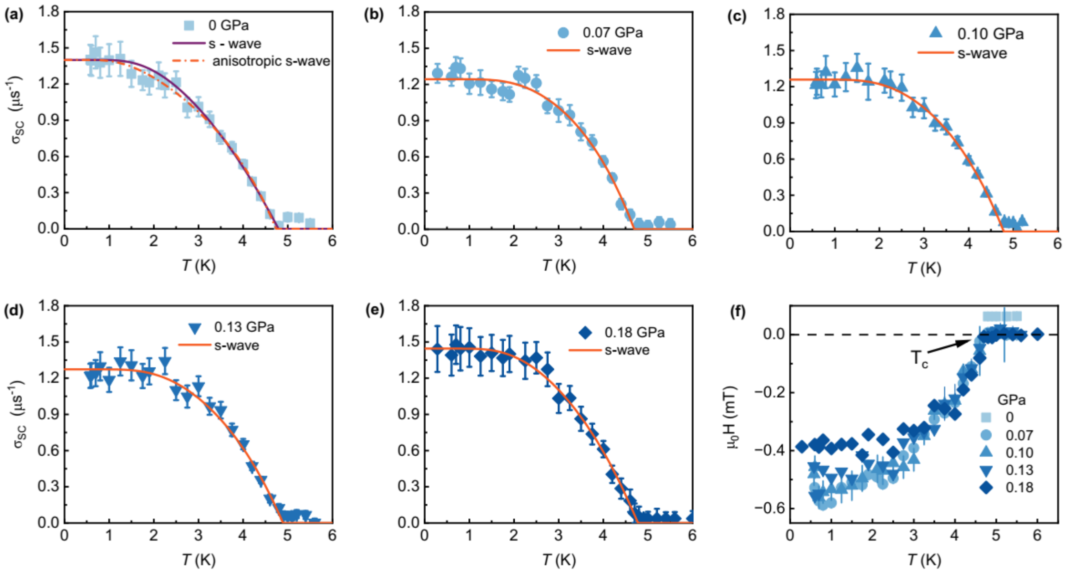


Rate for μ//[1 1 0]

- Superconductivity gap on Active/Passive band
- Magnetic Field suppress small gap (isotropic @ 0.05 T TF-μSR)
- Field induced magnetism

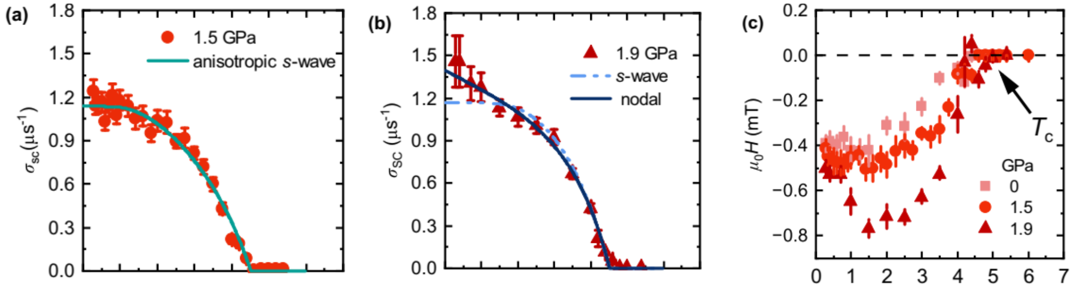
CeRu$_2$ latest research

Uniaxial Pressure:



Tunable ground States !

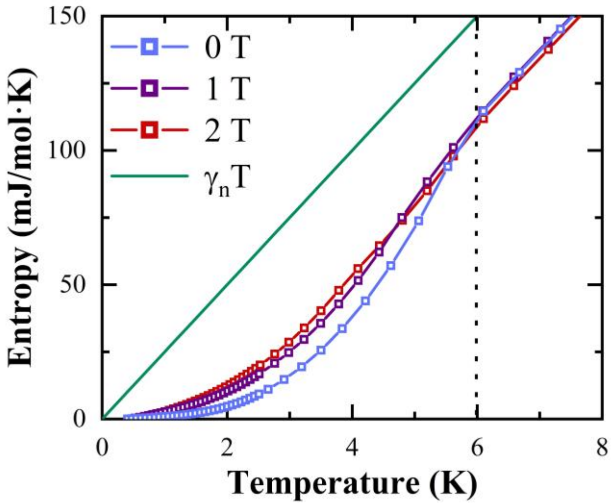
Hydrostatic Pressure:



O. Gerguri, Commun. Phys. 2026

Entropy

➢ Redistribution of electron entropy between superconductivity and intrinsic order



- Invariant entropy between pure SC and SC + magnetism state
- Redistribution of electron entropy turned by magnetic fields

Outline

Summary & Outlook

- μSR is a powerful technique for investigation of SC & magnetism

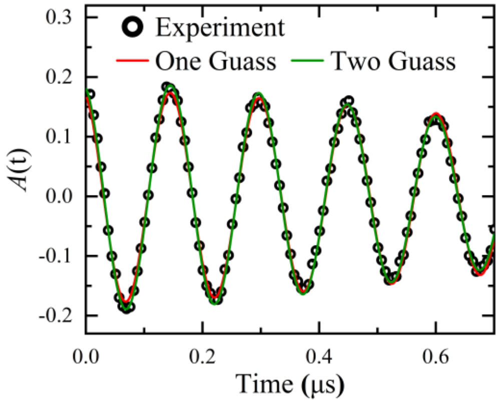
Specific heat → ZF/LF-μSR → TF-μSR

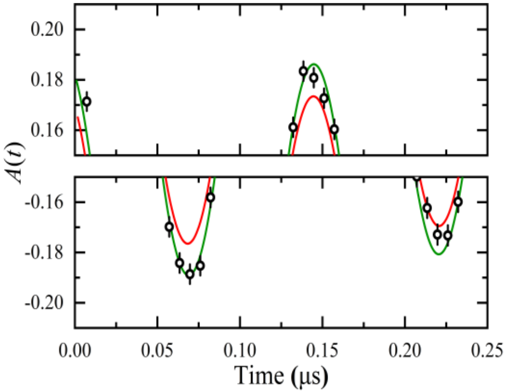
- Intrinsic order induced by external fields
- Possible multigap SC from distinct active/passive bands
- SC & intrinsic order competing a total electron entropy

Looking forward to muon spectrometer @ HIAF & CiADS & CSNS

Thank for attention !

$CeRu_2$ TF-μSR



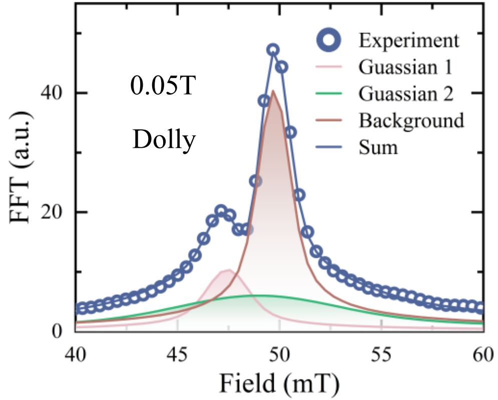


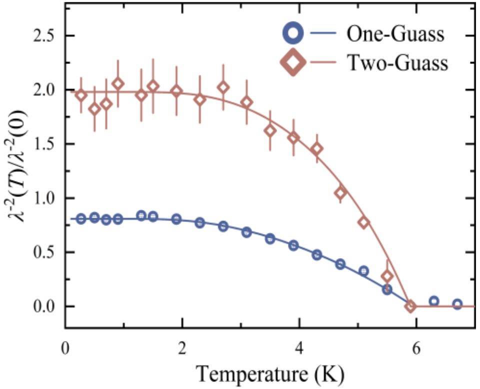
Fit function：

$$A(t) = \sum_{i=1}^{2} e^{-\frac{\sigma_i^2 t^2}{2}} \cos(\omega_i t + \phi_i) + e^{-\frac{\sigma_{bg}^2 t^2}{2}} \cos(\omega_{bg} t + \phi_{bg})$$

$$\sigma^2 = \sum_{i=1}^{2} \frac{A_i}{A_1 + A_2}\left[\sigma_i^2 + \gamma_\mu^2 (B_i - \langle B \rangle)^2\right]$$

A. Maisuradze *et al.*, J. Phys.: Condens. Matter, 2009

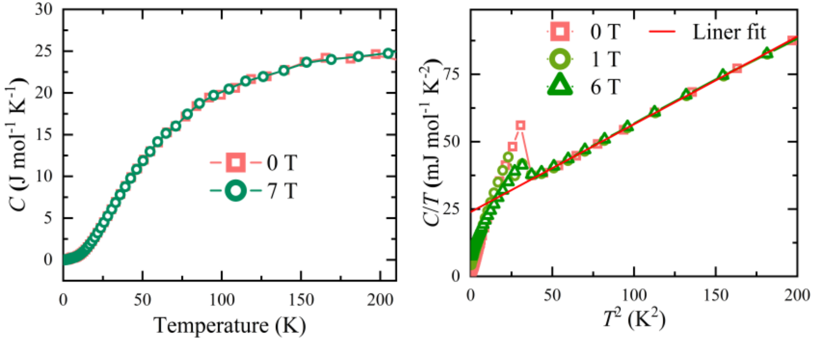


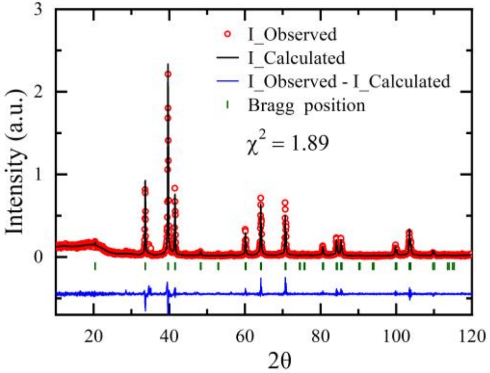


- Two gauss, better fitting
- Low nuclear dipole relaxation rates in $CeRu_2$
- $\lambda_{one}(0) = 3300$ Å, $\lambda_{two}(0) = 2150$ Å

  ($\lambda(0) \sim 2000$ Å from H_{c1}, H_{c2})

Phonon substruction





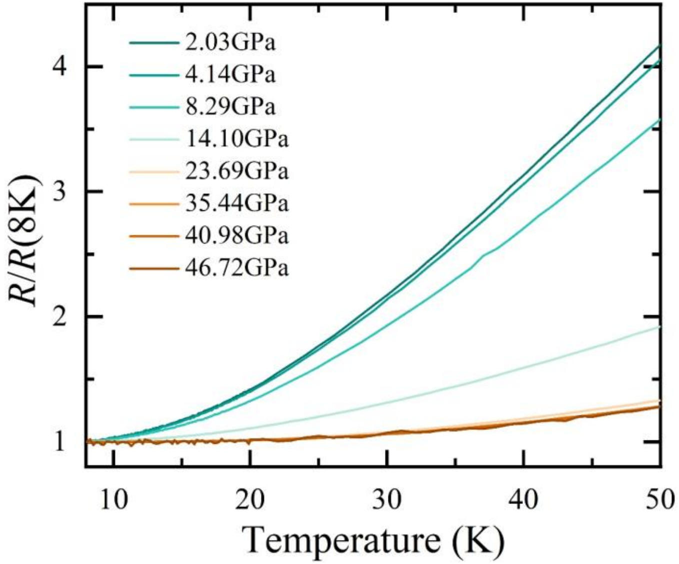
Phonon contribution： $C(T)/T = \gamma_N + \beta T^2$

$\gamma_N = 23.9(2)$ mJ mol^{-1} K^{-2}

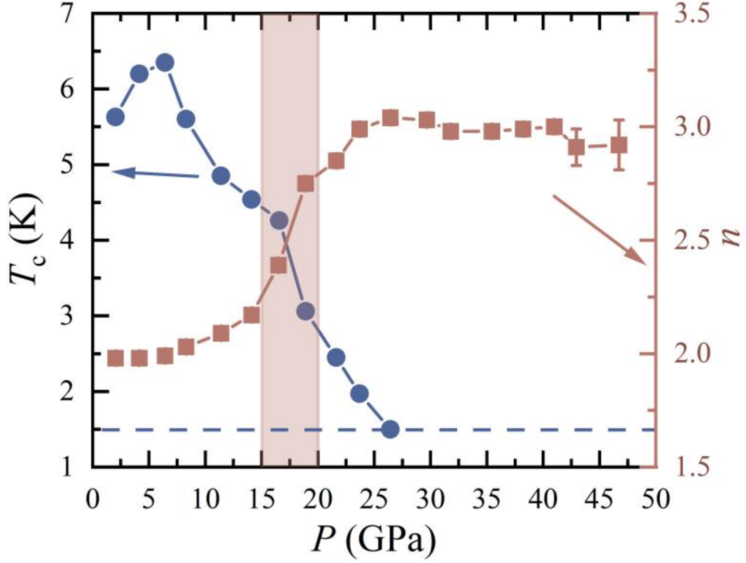
$\beta = 0.326(2)$ mJ mol^{-1} K^{-4}

Inter-band scattering

- 15-20 GPa n and T_c change simultaneously（$R = R_0 + AT^n$）
- Superconductivity in $CeRu_2$ affected by interband scattering



Normal state（8-50K）R-T



T_c（left）and n（right）vs P

LF-μSR

☐ LF−muSR – 10 mT

LF-muSR Asymmetry