Magnetization and magnetocaloric effect measurements on spin-triplet superconductor Sr_2RuO_4

K. Tenya[1], Y. Shimura[2], T. Sakuraba[2], T. Sakakibara[2],
M. Yokoyama[3], H. Amitsuka[4], K. Deguchi[5] and Y. Maeno[6]

[1]*Faculty of Education, Shinshu University, Nagano 380-8544, Japan*

[2]*Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan*

[3]*Fucalty of Sciences, Ibaraki University, Mito 310-8512, Japan*

[4]*Department of Physics, Hokkaido University, Sapporo 060-0810, Japan*

[5]*Department of Physics, Nagoya University, Nagoya 464-8602, Japan*

[6]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

Magnetization and magnetocaloric effect measurements on spin-triplet superconductor Sr_2RuO_4

Outline

1. Introduction
   - Basic Properties in 2D Superconductor Sr_2RuO_4
   - ***d***-Vector Dynamics in Sr_2RuO_4
   - H_{c2}-Supression at Low Temperatures

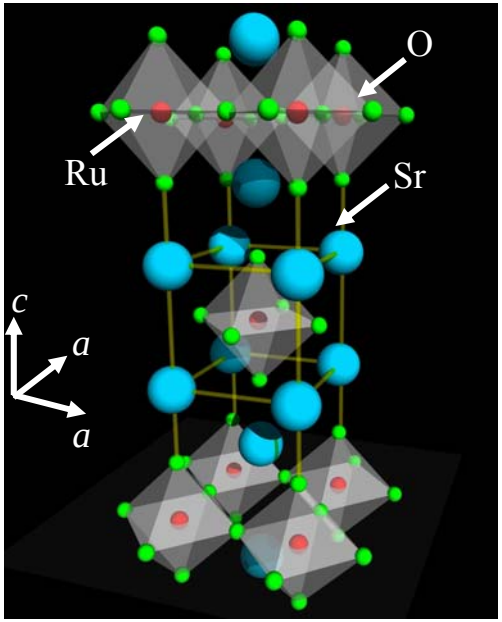
2. Experimental results for $H \,//\, c$
   - Magnetization : Anomalous Peak Effect
   - Magnetocaloric Effect

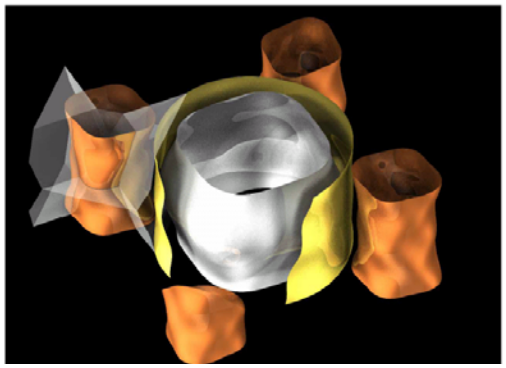
3. Discussions
   - Possible Origins of the Anomalous Features

4. Summary and future works

INTRODUCTION FL properties in Sr_2RuO_4

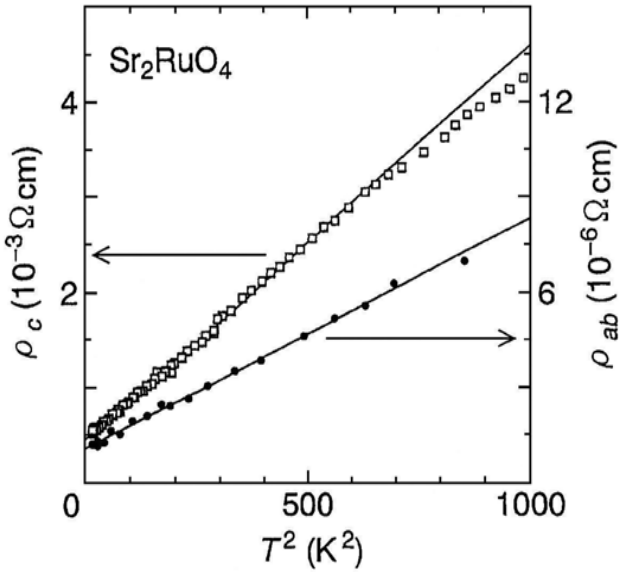
Crystal structure & Fermi surface



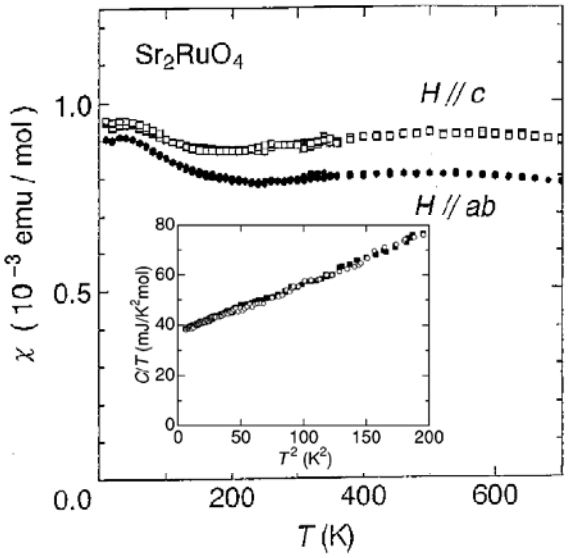


C. Bergemann *et al*. (2003)

Resistivity



Susceptibility & Specific heat



Y. Maeno *et al*. (1997)

$$\rho = \rho_0 + AT^2$$

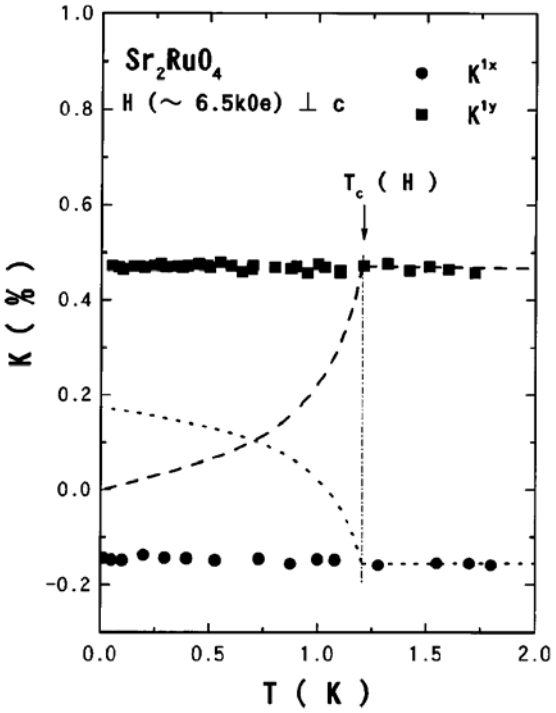
$$\chi = \text{const.}$$

$$C/T = \gamma + \beta T^2$$

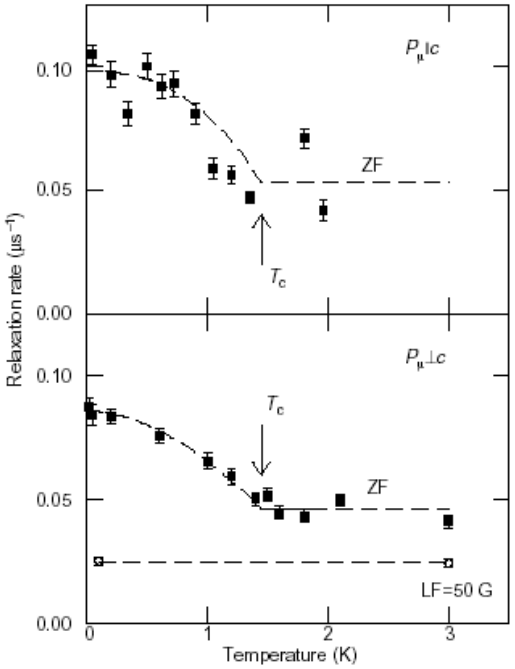
2D Fermi liquid

INTRODUCTION SC properties in Sr_2RuO_4

NMR Knight shift



μSR



Spin-triplet pairing (**STP**)

K. Ishida *et al*. (1998)

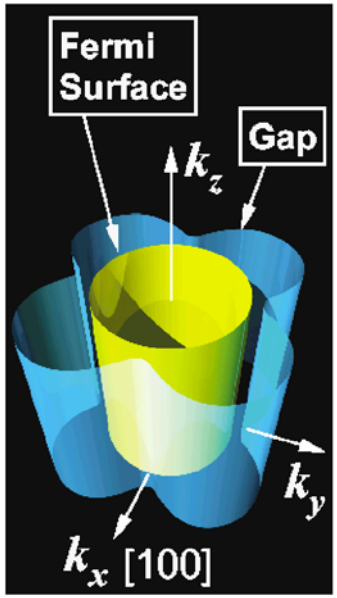
Time-reversal symmetry breaking

G.M. Luke *et al*. (1998)

Order parameter (OP)

$$\boldsymbol{d} \propto \hat{\boldsymbol{z}}(\sin k_x \pm i \sin k_y)$$

SC-domain structure

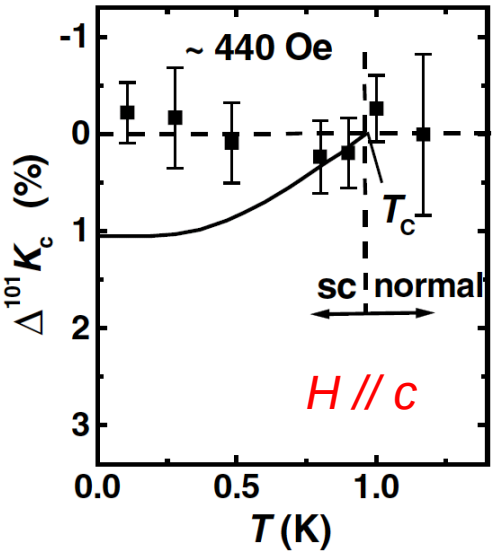


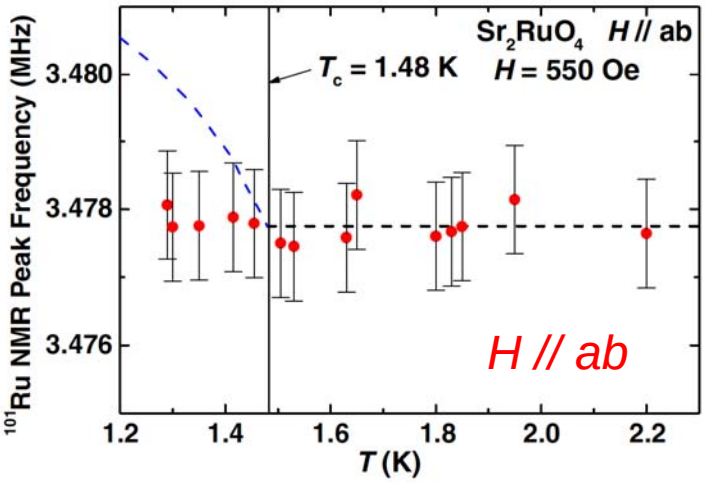
Small arrows: // spin pair ($S_z = 0$)

Large arrow: orbital moment ($L_z = 1$)

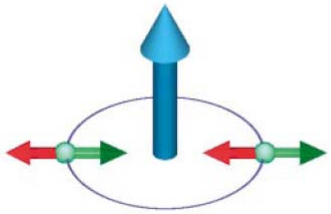
INTRODUCTION SC properties in Sr_2RuO_4

No change of Knight shift down to ~ 500 Oe

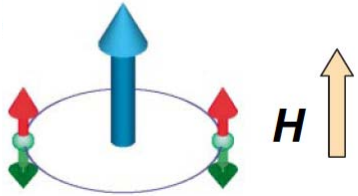




→ *H // c* : ***d***-vector should flip at smaller fields



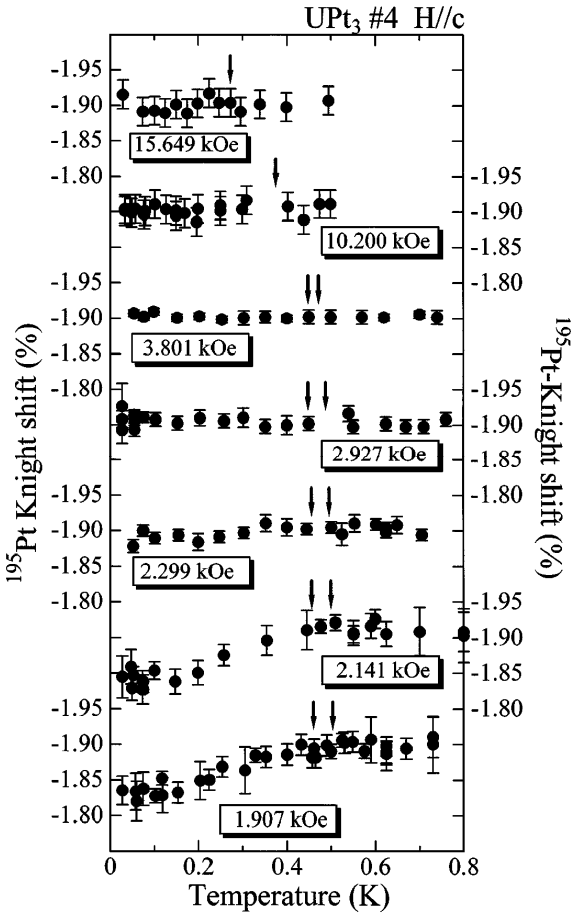
(at small fields)



(*H* > 500 Oe)

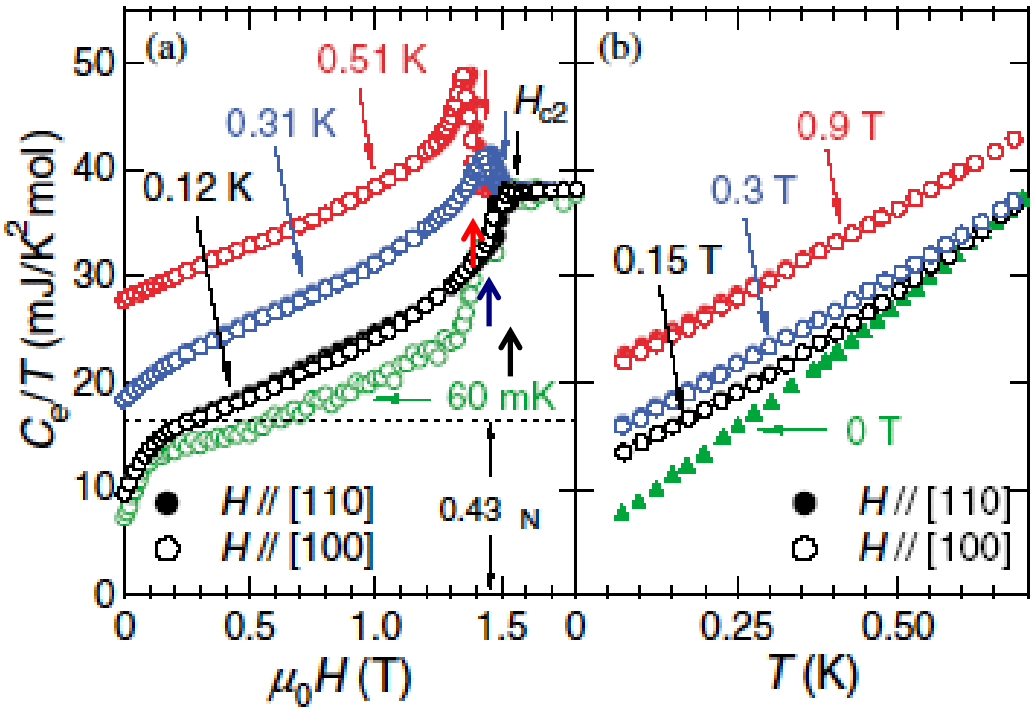
H. Murakawa *et al*. (2004, 2007)

UPt_3 (STP)



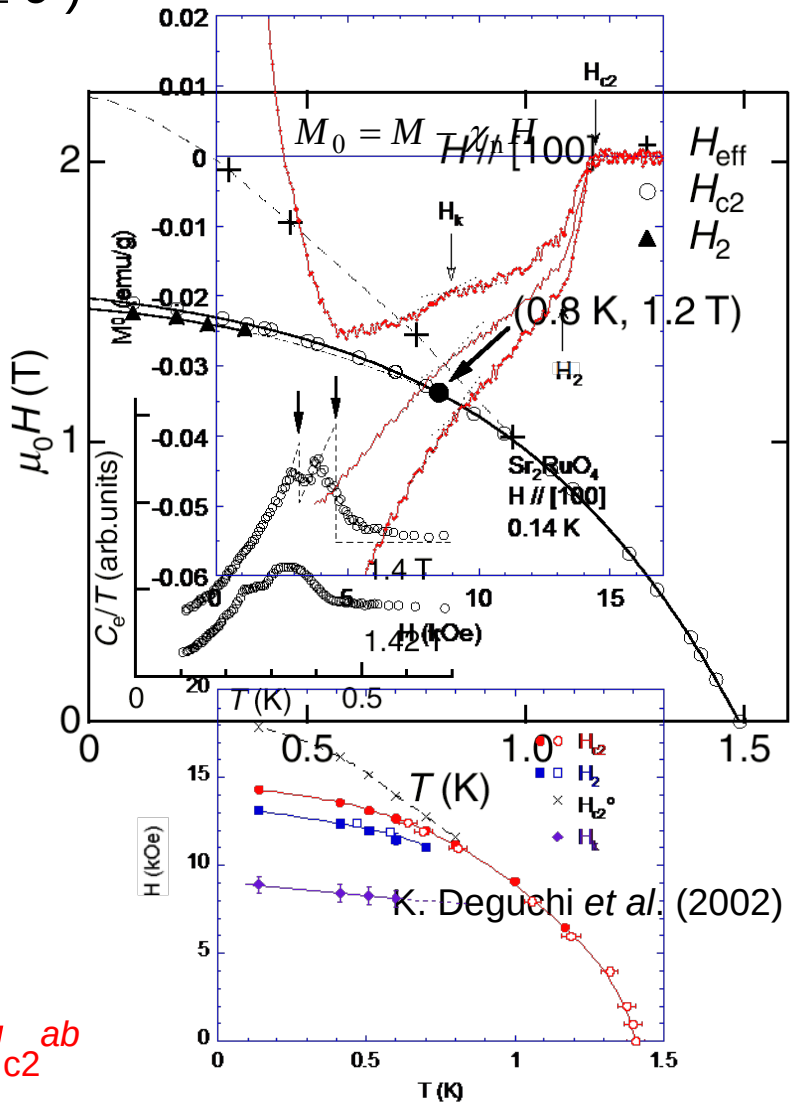
INTRODUCTION SC properties in Sr_2RuO_4

Specific heat under magnetic field ($H \perp c$)



K. Deguchi *et al*. (2004)

Magnetization



K. Deguchi *et al*. (2002)

Anomalous behaviors just below H_{c2}^{ab}

EXPERIMENTAL

Magnetization measurements of Sr_2RuO_4 for $H \,//\, c$ (Hokkaido Univ.)

Sample : Single crystals prepared by a floating-zone method in infrared image furnace (Kyoto Univ.)

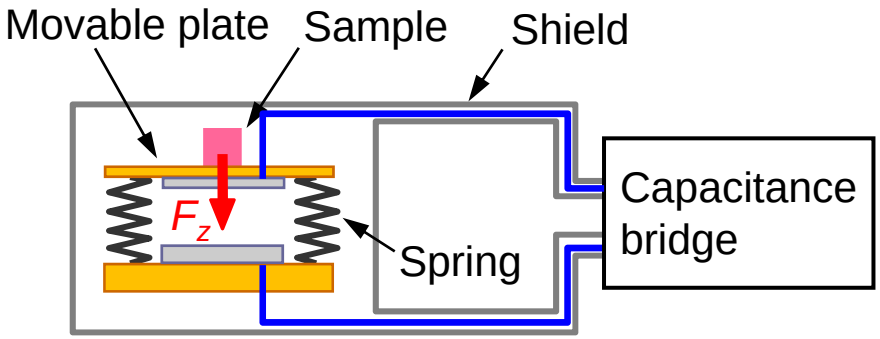
Sample #1 T_c = 1.43 K
Sample #2 T_c = 1.49 K
Sample #3 T_c = 1.49 K

Magnetocaloric effect measurements of Sr_2RuO_4 for $H \,//\, c$ (ISSP)

Thermodynamic relation

$$\Delta\left(\frac{\delta T}{\delta H}\right)_H = -\frac{T}{C}\Delta\left(\frac{\partial M}{\partial T}\right)_T \approx -\frac{T}{C}\Delta\left(\frac{\partial M}{\partial H}\right)_H\left(\frac{\mathrm{d}H}{\mathrm{d}T}\right)_T$$

- Operation principle



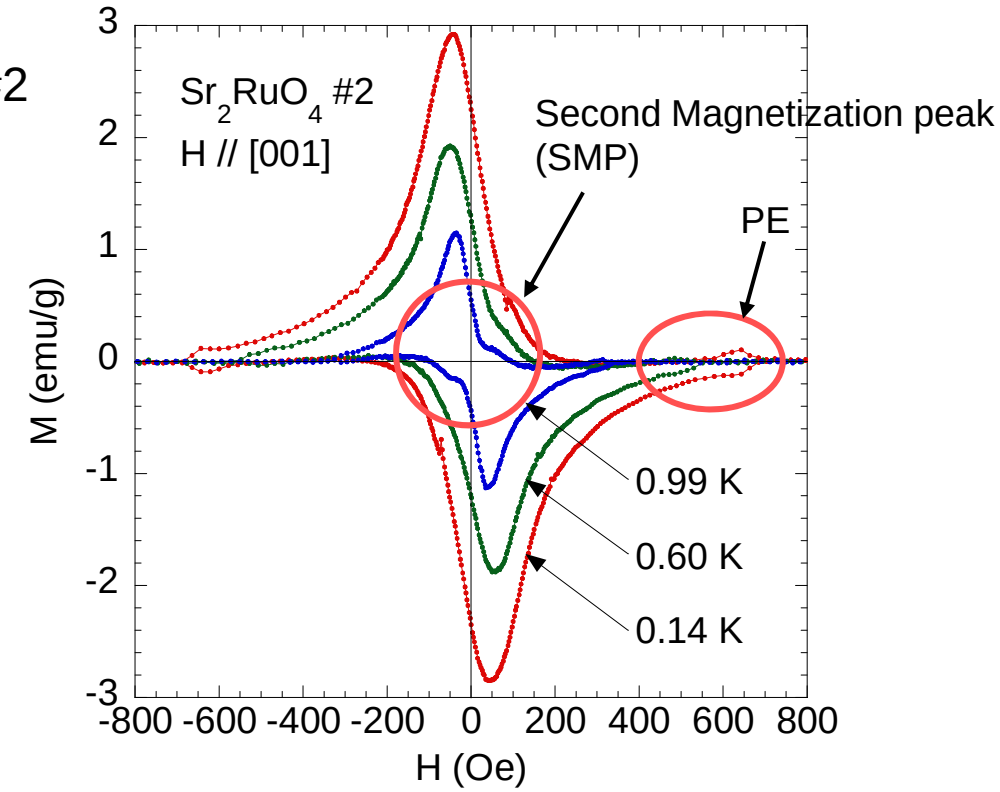
$$F_z = M_z \frac{\mathrm{d}H_z}{\mathrm{d}z} = k\Delta d \qquad \Delta d = \varepsilon_0 S\left(\frac{1}{C(H)} - \frac{1}{C_0(H)}\right)$$

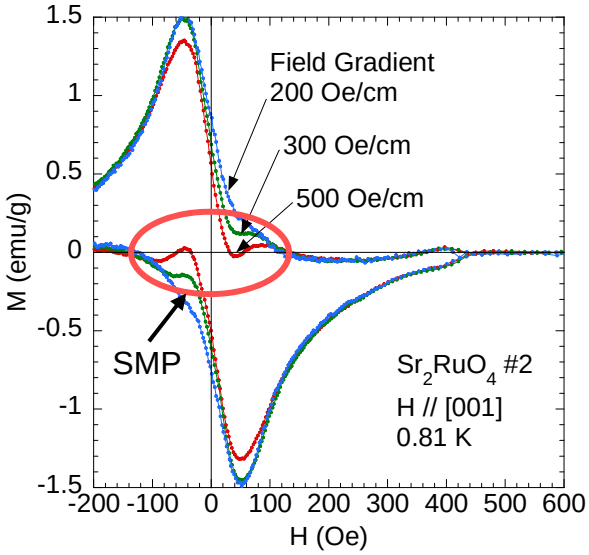
without field gradient

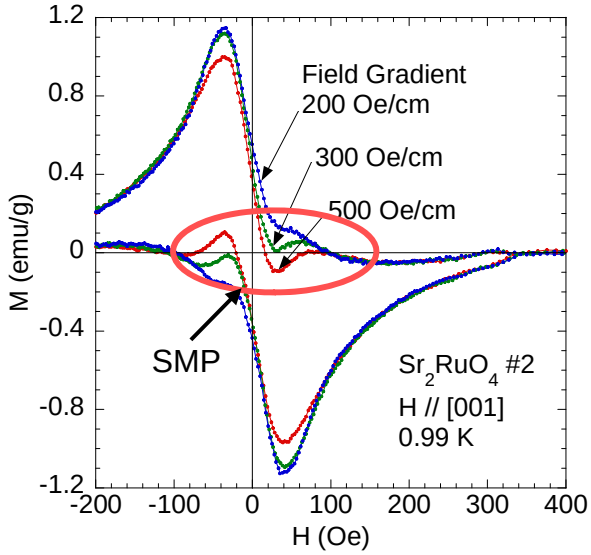
RESULTS Field-gradient-dependent Magnetization

Second magnetization peak (SMP)

Sample #2



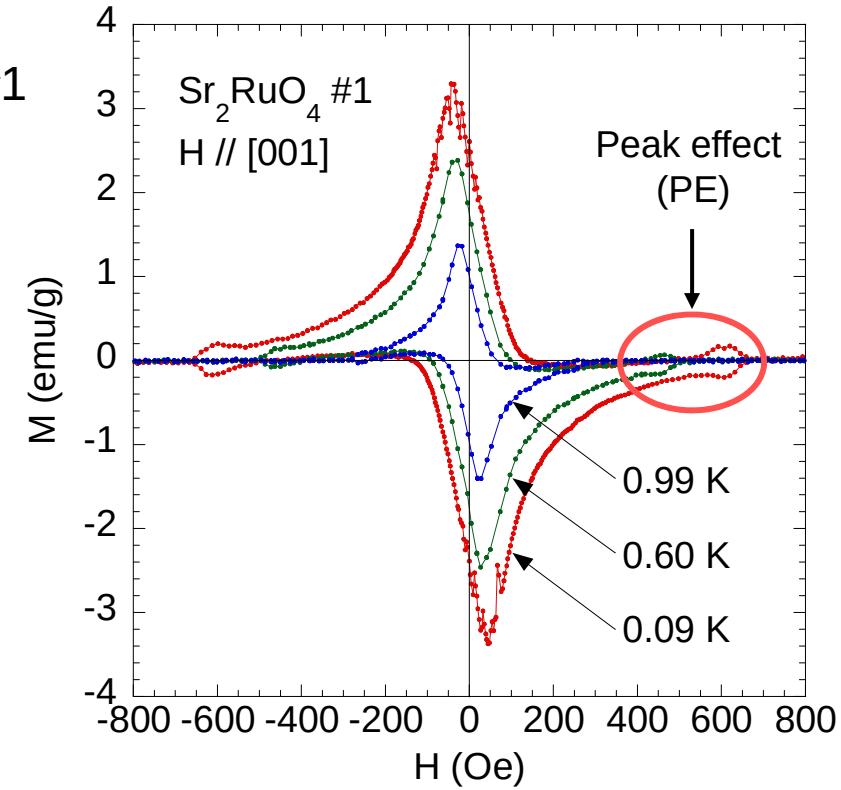


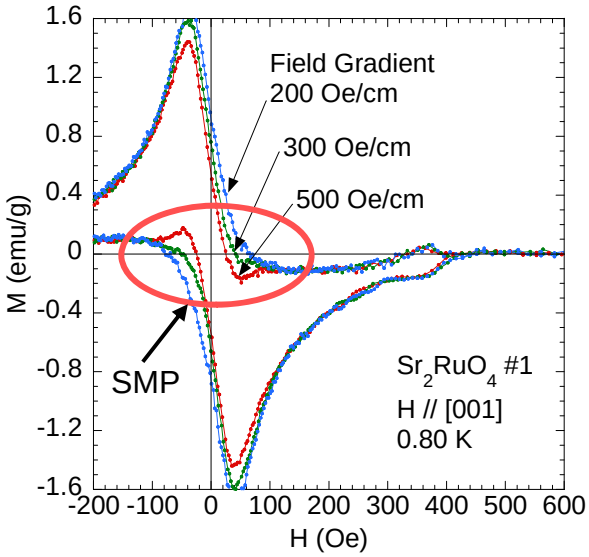


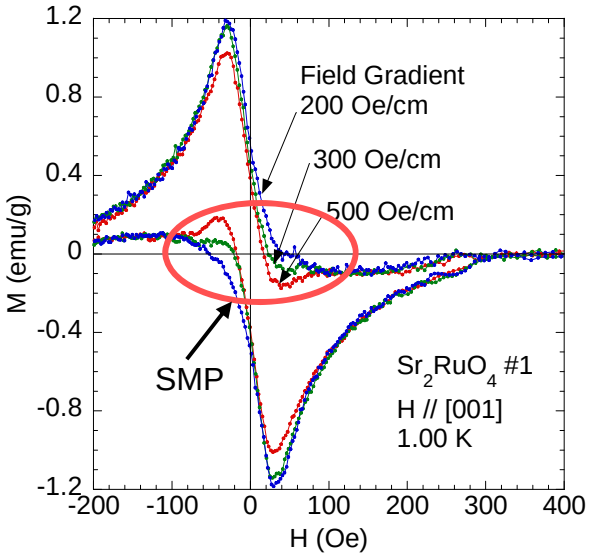
RESULTS Field-gradient-dependent Magnetization

Second magnetization peak (SMP)

Sample #1



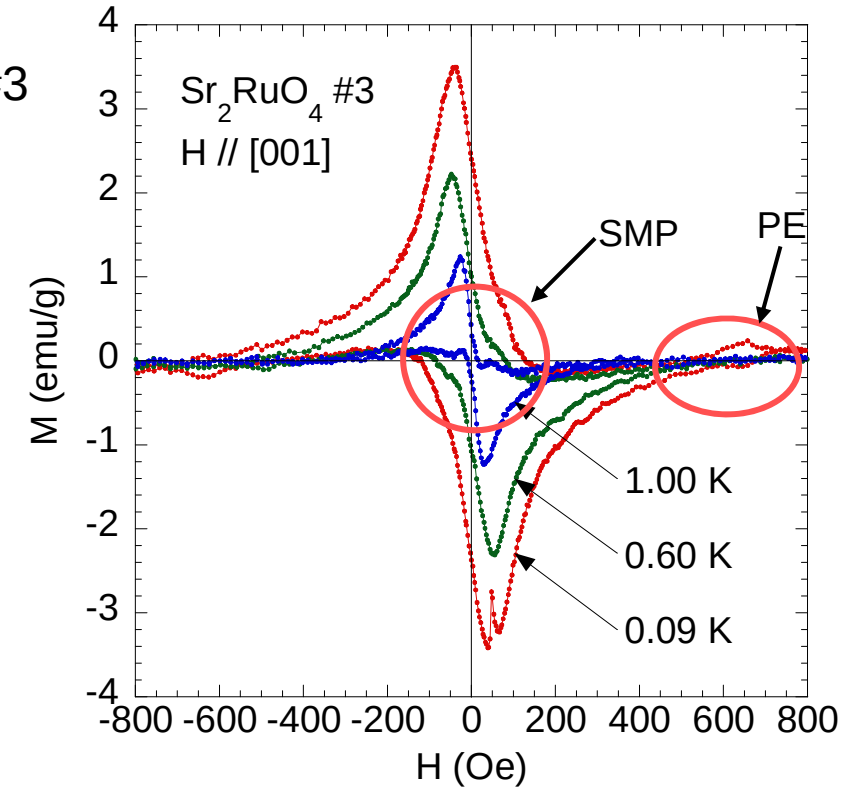


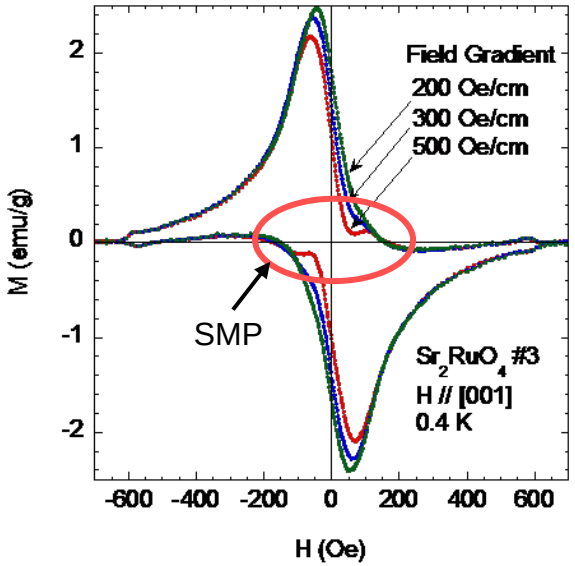


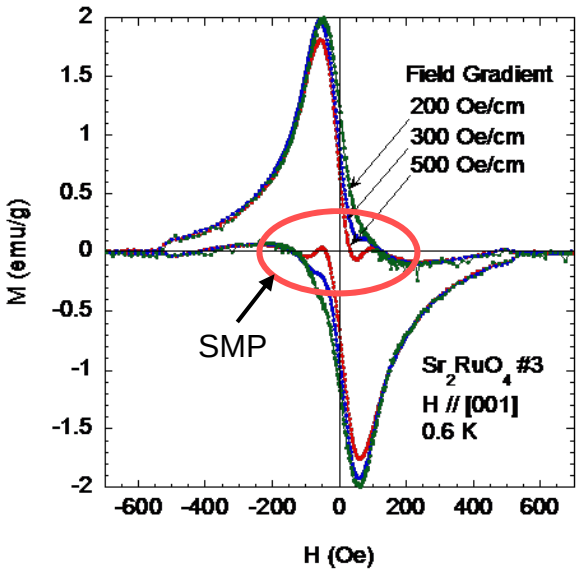
RESULTS Field-gradient-dependent Magnetization

Second magnetization peak (SMP)

Sample #3







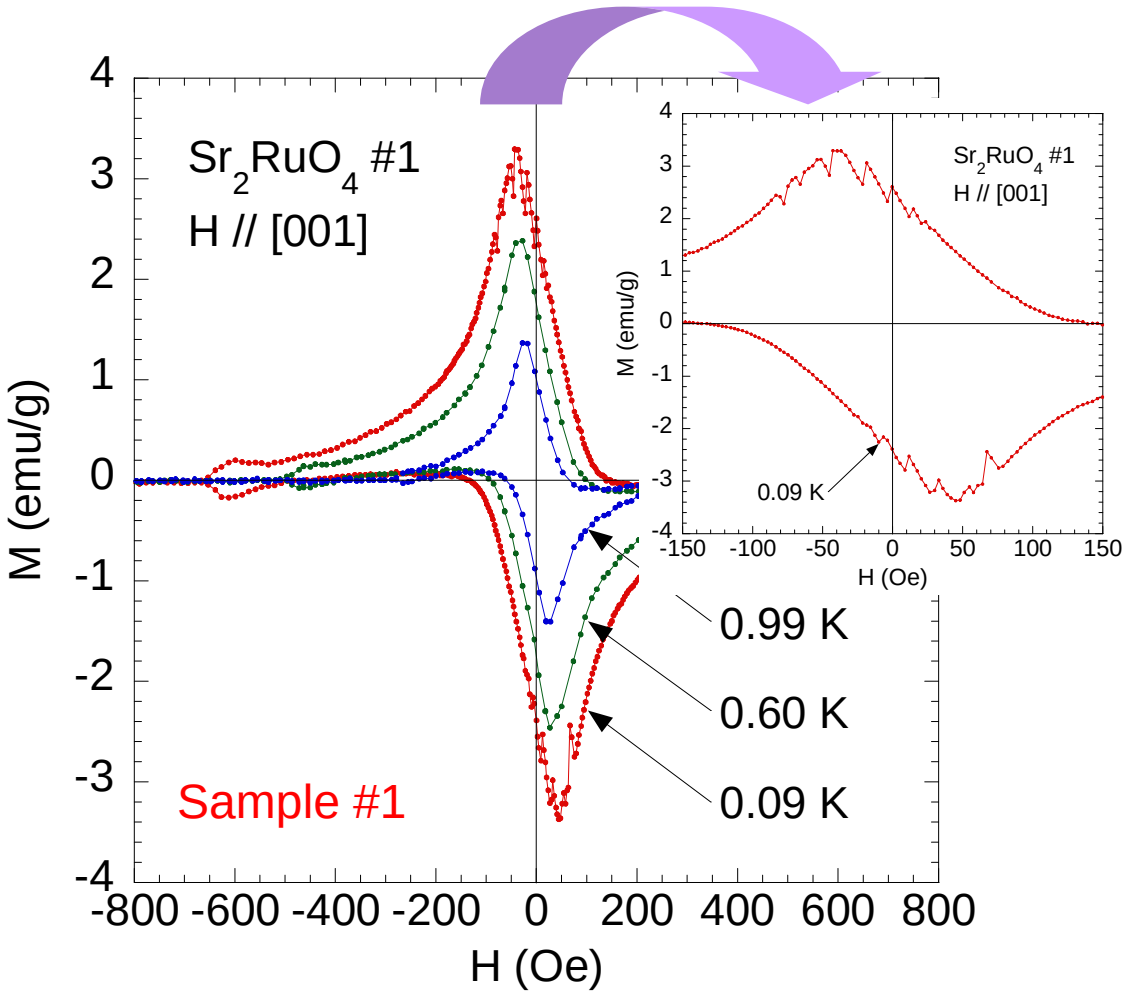
Second magnetization peak (SMP) appears below 100 Oe.

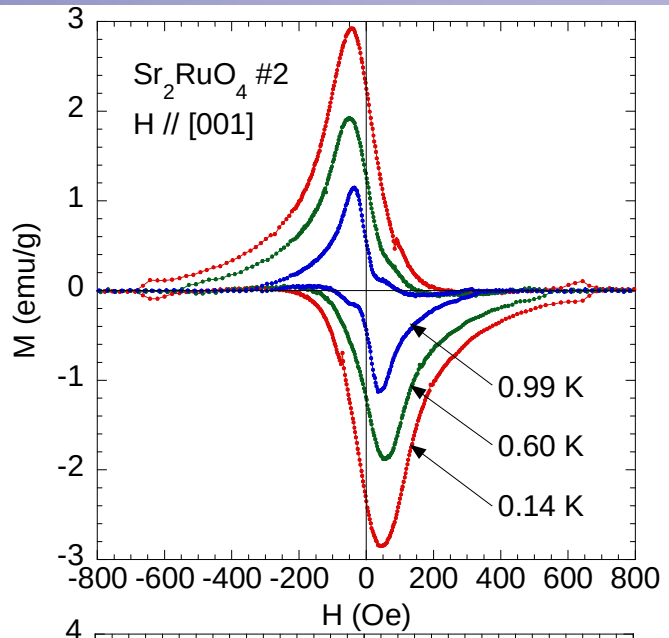
(Clearer SMP in the cleaner sample)

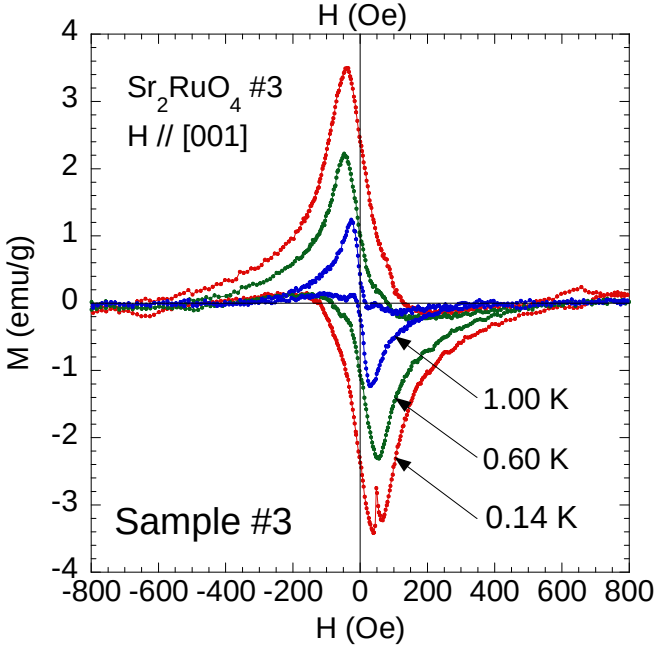
Strong field-gradient dependence of the hysteretic magnetization below the onset field of SMP.

RESULTS Magnetization

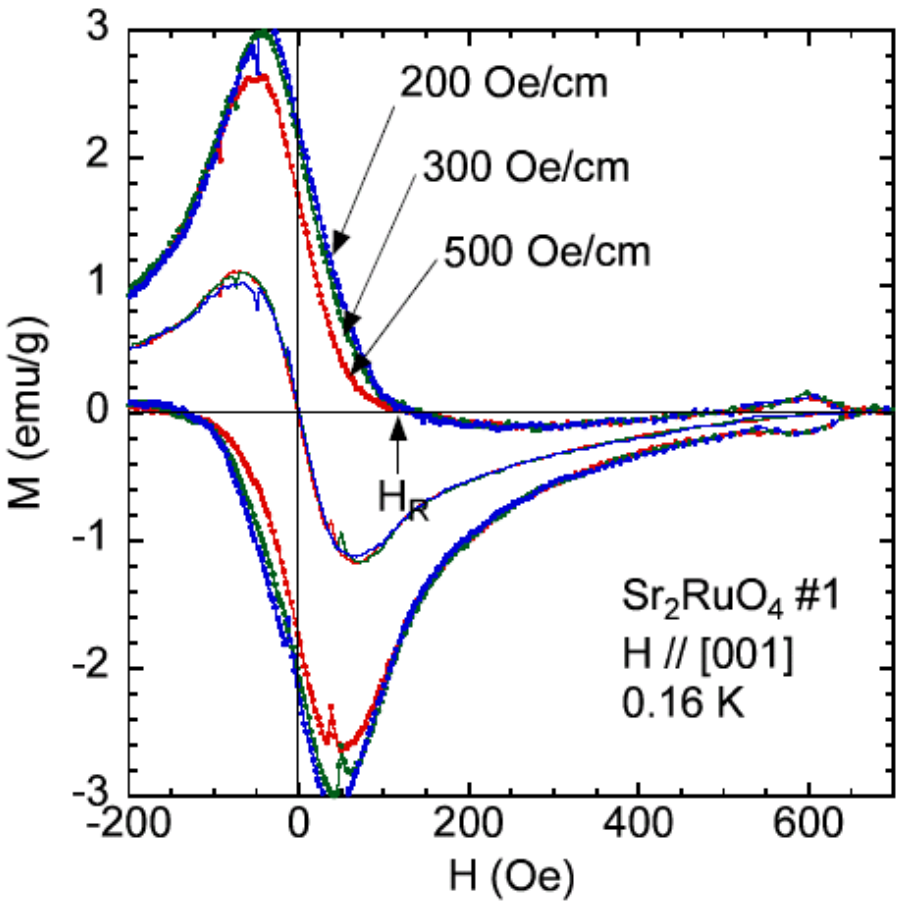
Successive tiny flux-jumps

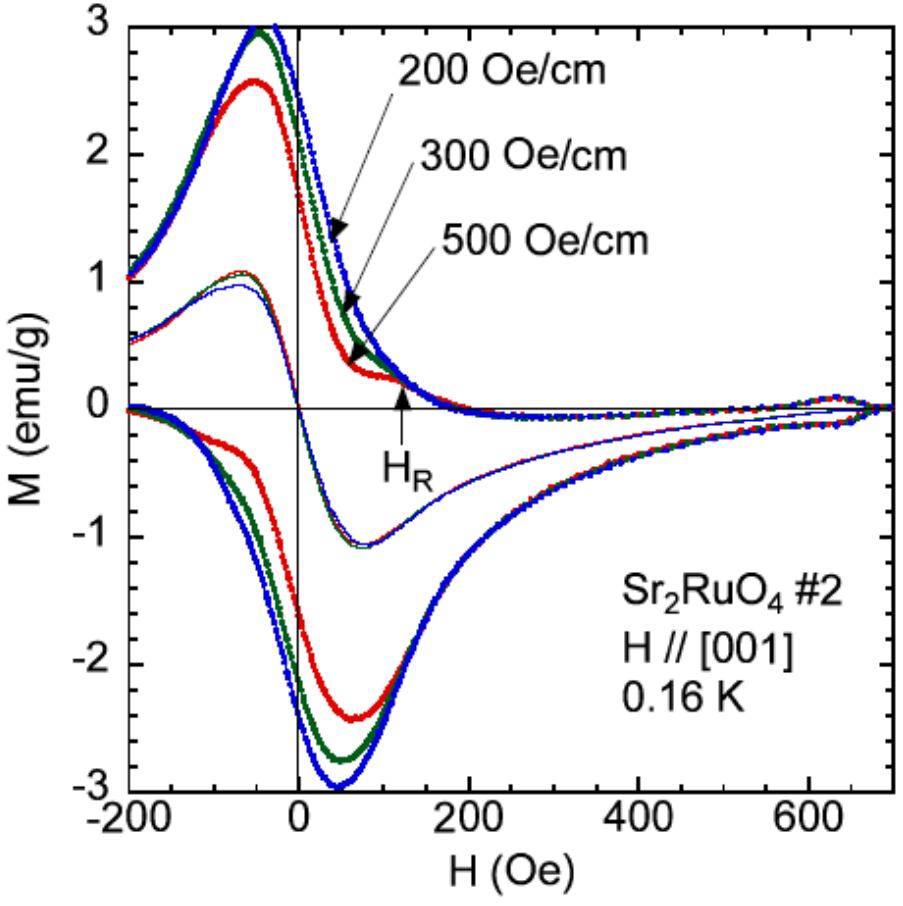




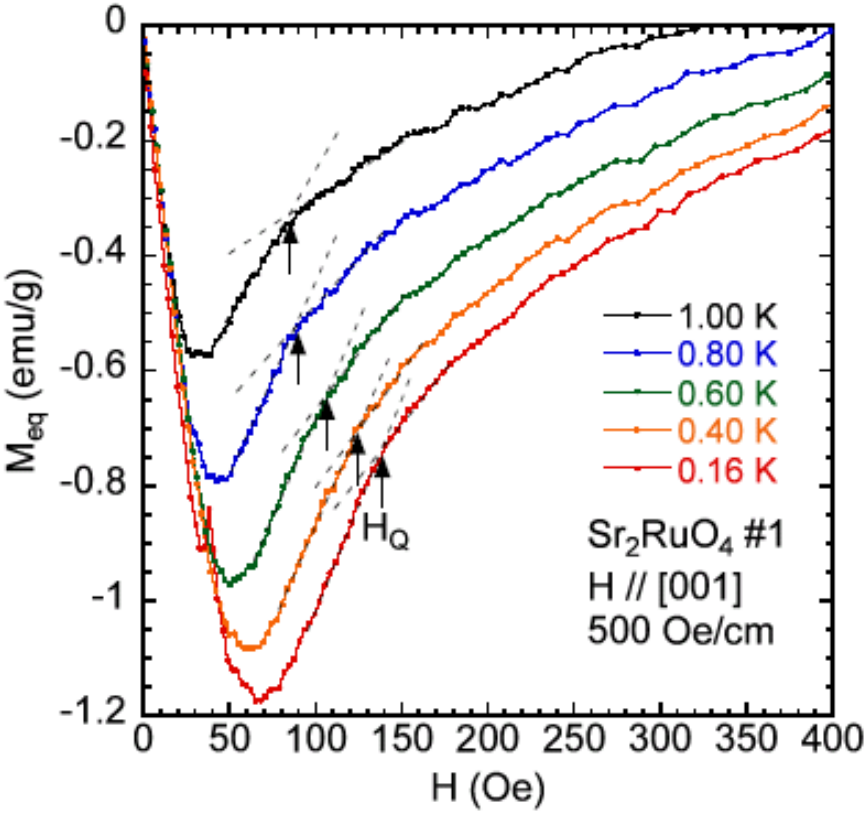


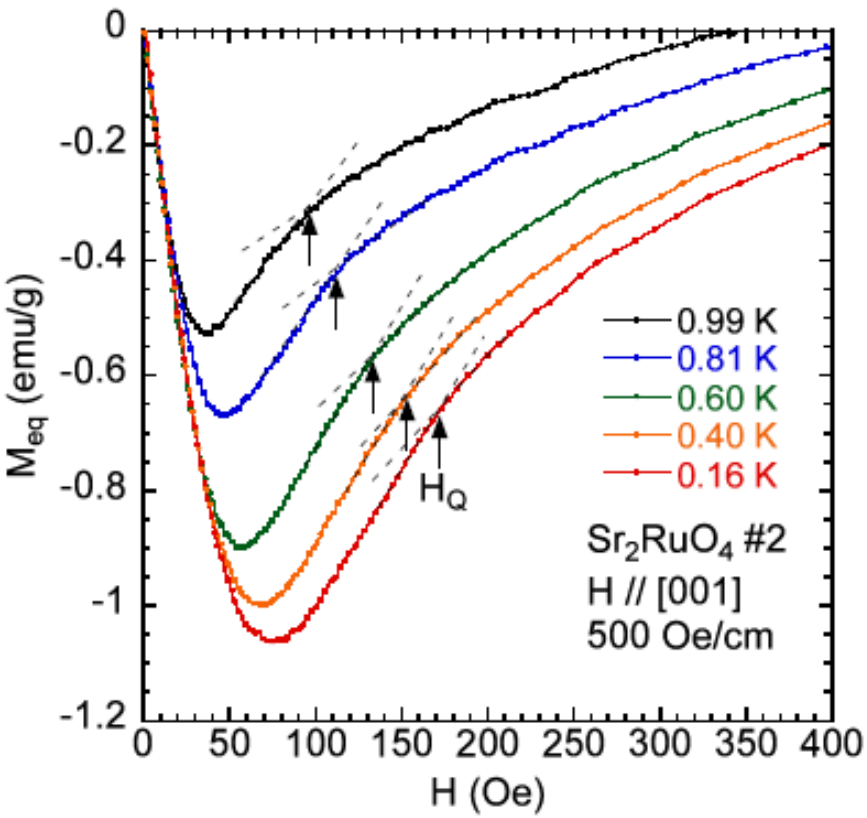
RESULTS Magnetization





RESULTS Magnetization



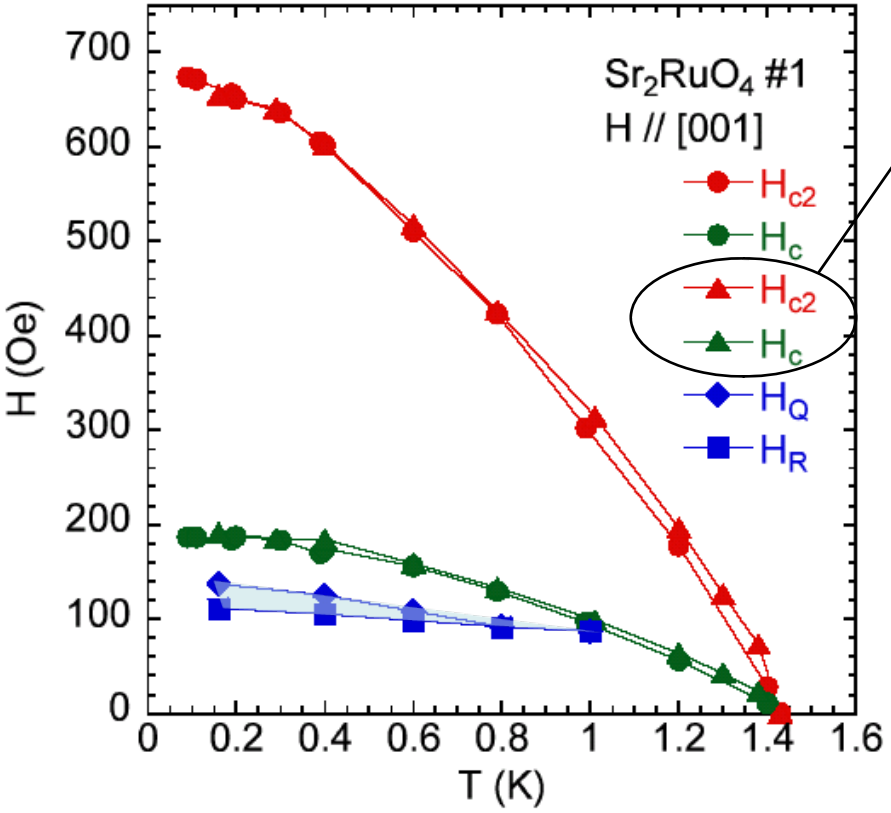


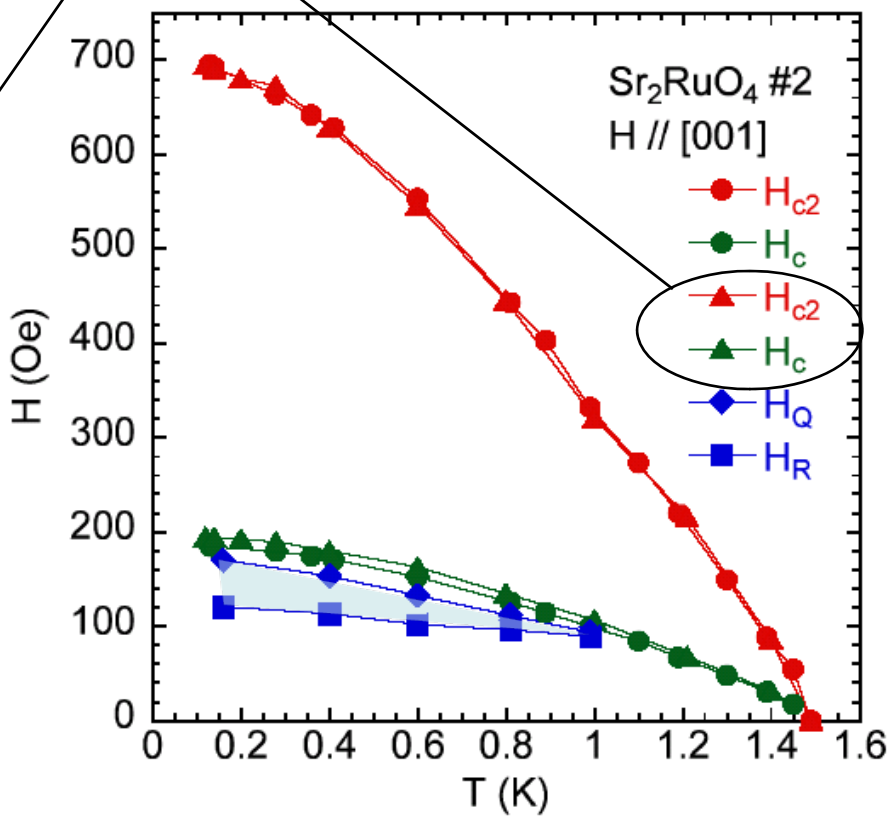
Equilibrium magnetization

$$M_{\mathrm{eq}}(H) = \frac{1}{2}\left[M_{\mathrm{inc}}(H) + M_{\mathrm{dec}}(H)\right]$$

RESULTS Magnetization

Gradient Field = 500 Oe/cm

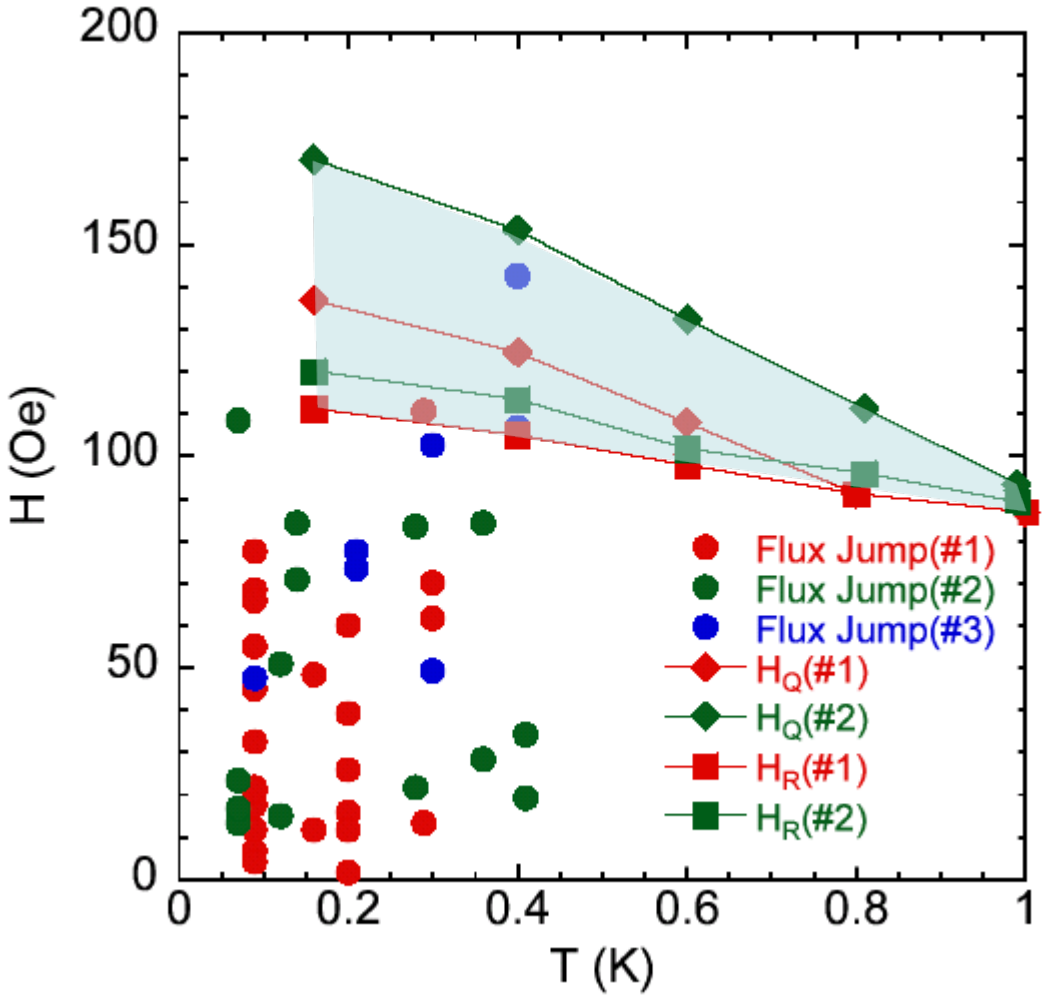




Thermodynamic critical field

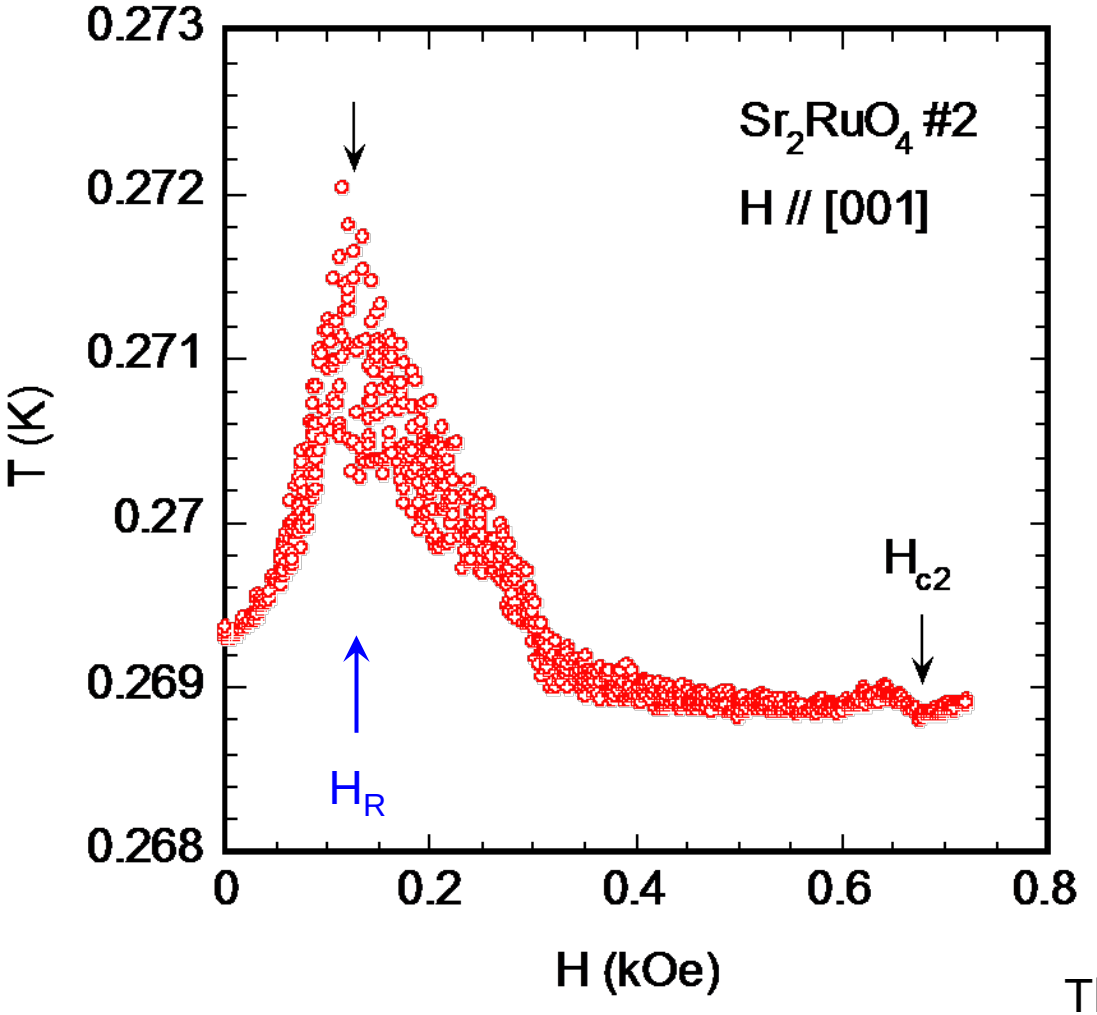
$$H_{\mathrm{c}} = \int_{0}^{H_{\mathrm{c2}}} \left[\frac{1}{2} \left\{ M_{\mathrm{inc}}(H) + M_{\mathrm{dec}}(H) \right\} - \chi_{\mathrm{n}} H \right] \mathrm{d}H$$

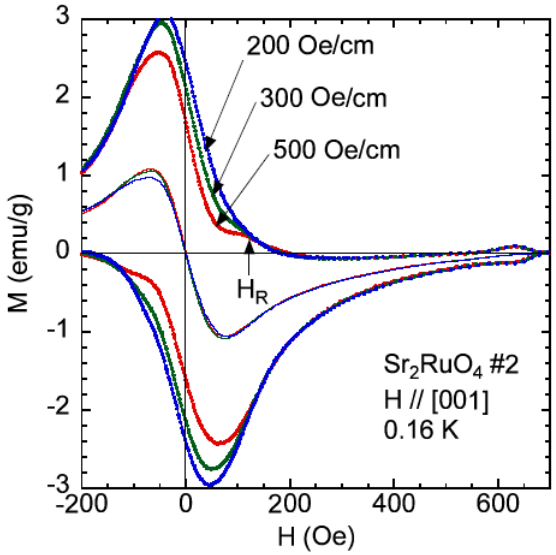
RESULTS Magnetization



Magnetic fields where tiny flux jumps are observed

RESULTS Magnetocaloric Effect





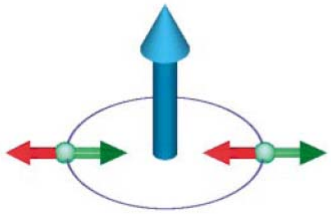
Magnetocaloric effect

Thermodynamic relation

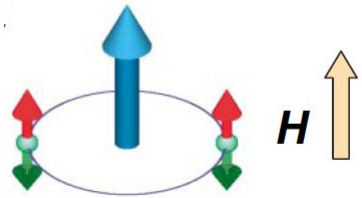
$$\Delta\left(\frac{\delta T}{\delta H}\right)_H = -\frac{T}{C}\Delta\left(\frac{\partial M}{\partial T}\right)_T \approx -\frac{T}{C}\Delta\left(\frac{\partial M}{\partial H}\right)_H \left(\frac{\mathrm{d}H}{\mathrm{d}T}\right)_T$$

DISCUSSIONS Field-gradient-dependent Magnetization

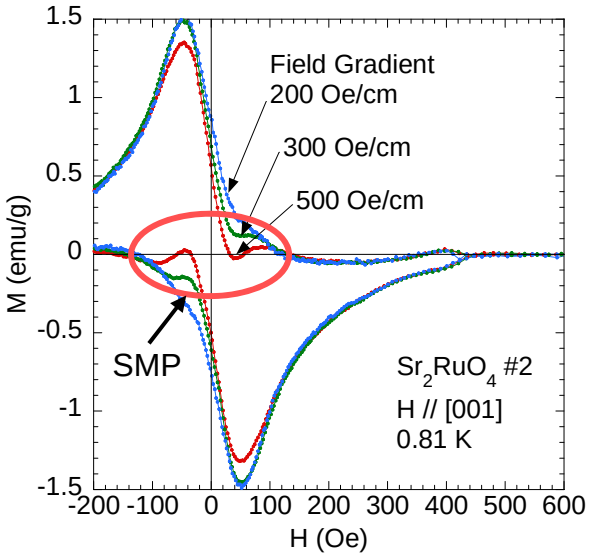
Second magnetization peak (SMP)

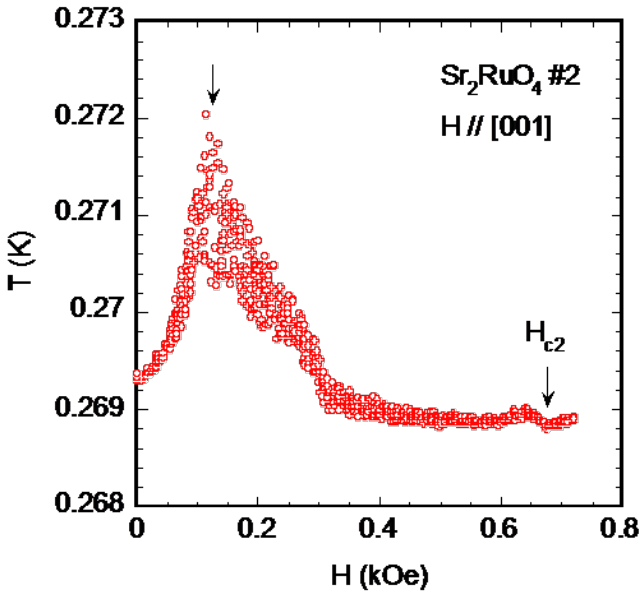


($H = 0$)



(H // c : H > 100 Oe)



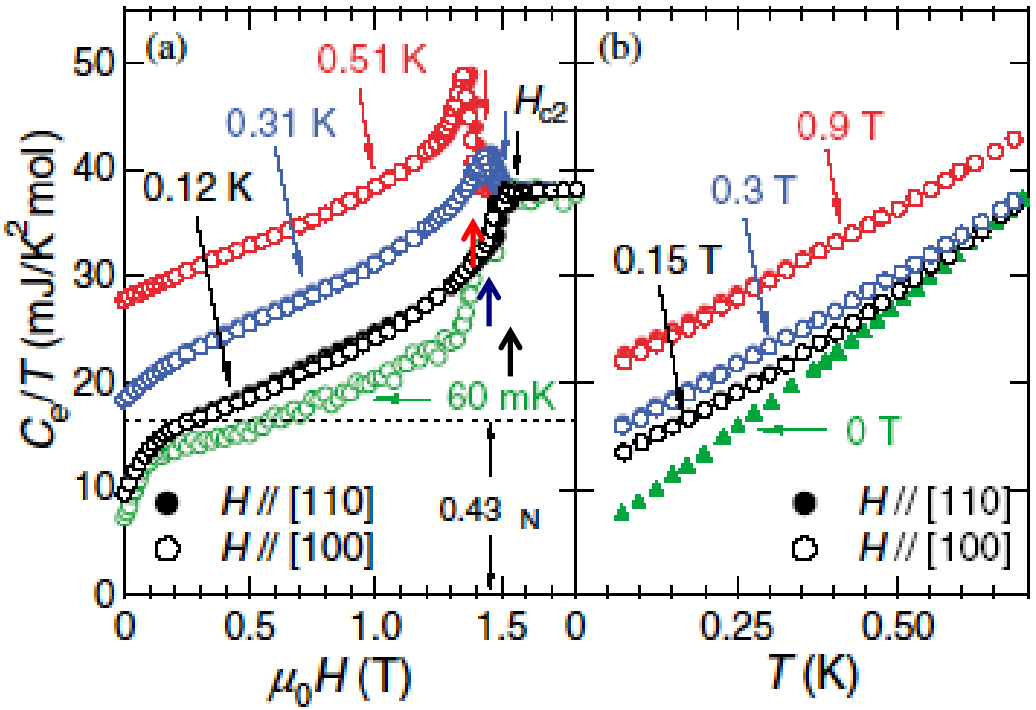


Strong field-gradient dependence of the hysteretic magnetization below the onset field of SMP.

➡ ***d***-vector flip ?

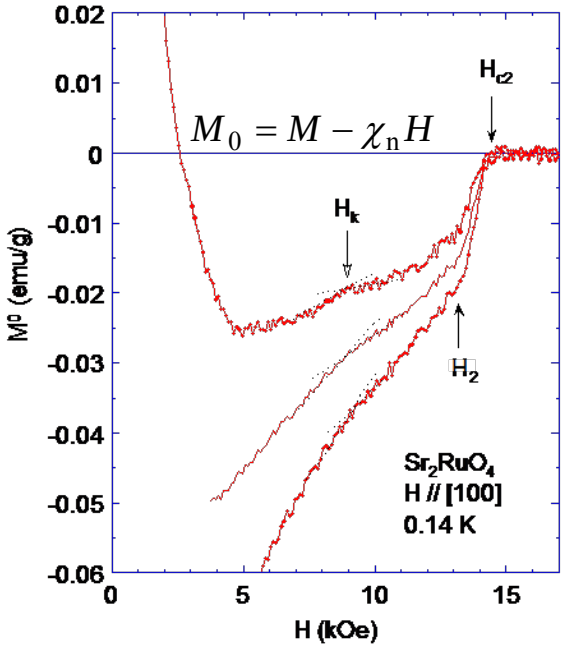
INTRODUCTION SC properties in Sr_2RuO_4

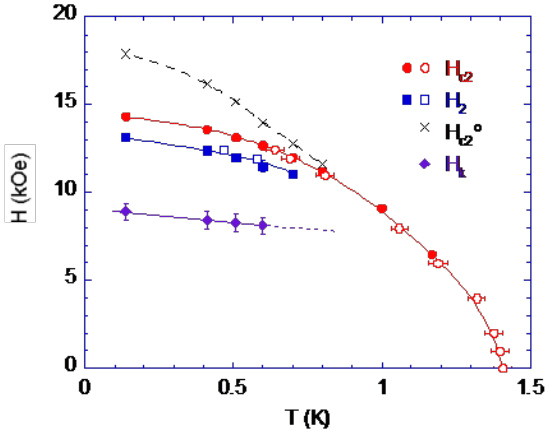
Specific heat under magnetic field ($H \perp c$)



K. Deguchi *et al*. (2004)

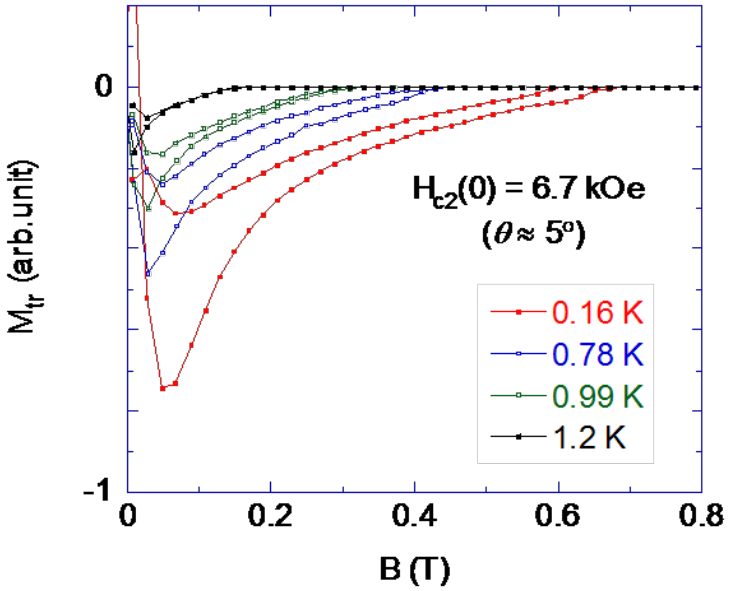
Magnetization



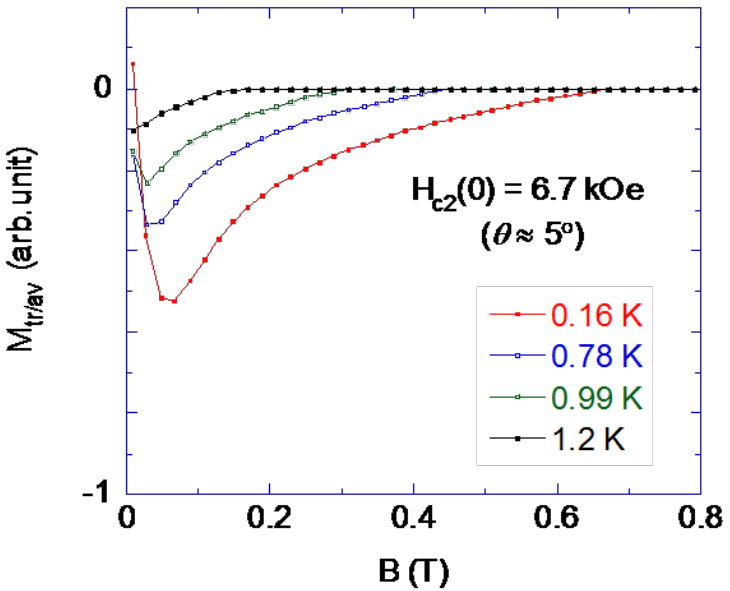


Anomalous behaviors just below H_{c2}^{ab}

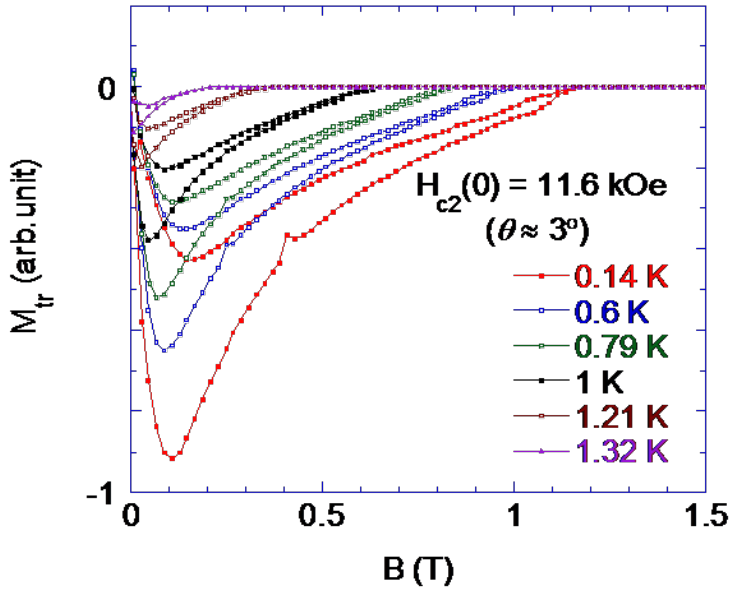
RESULTS Magnetic torque & magnetization



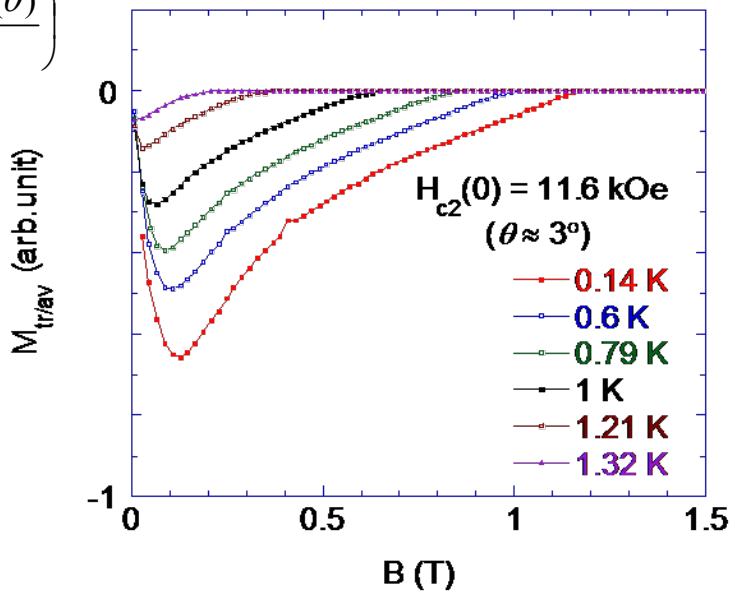
averaging



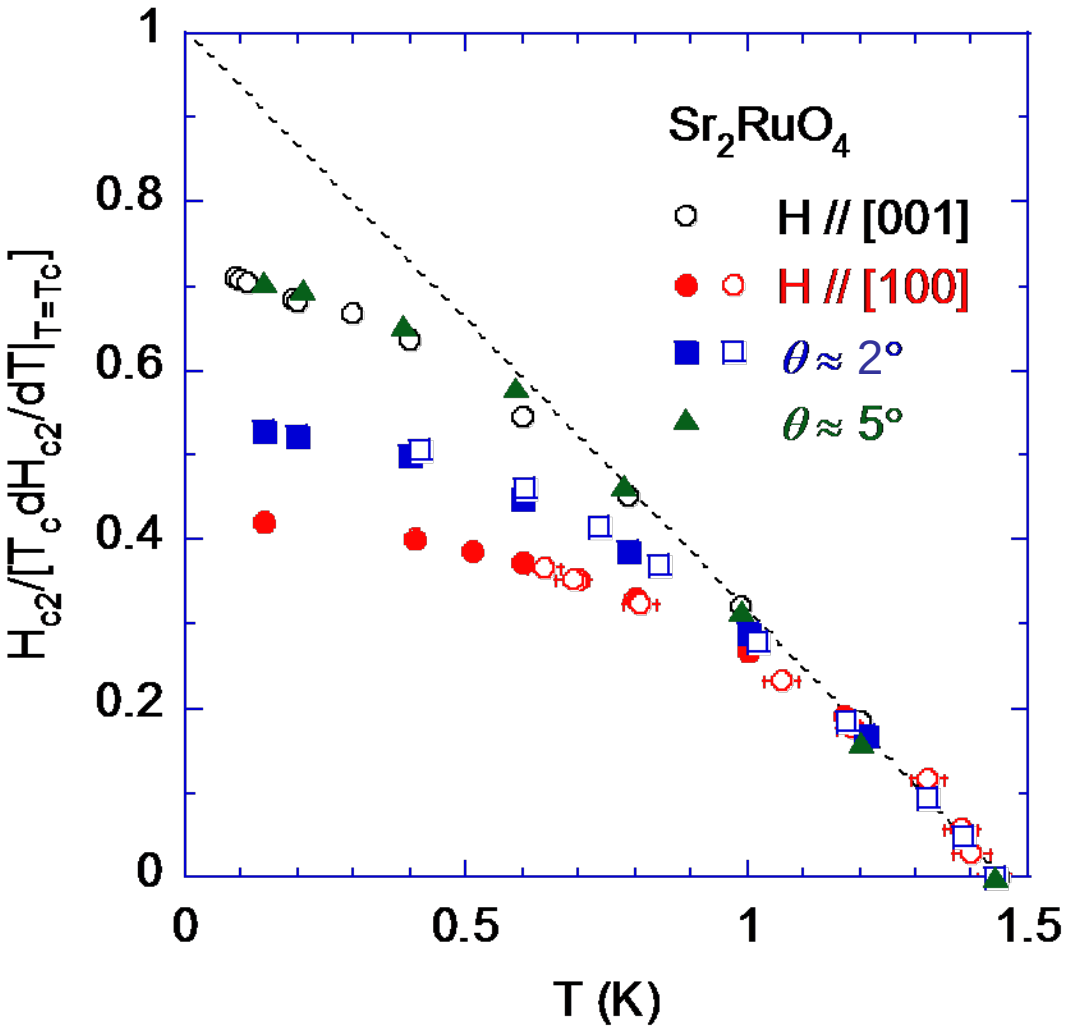
$$M_{\mathrm{tr}} \propto \frac{1}{[\lambda(\theta)]^2} \log\left(\frac{\eta H_{c2}(\theta)}{H}\right)$$



averaging

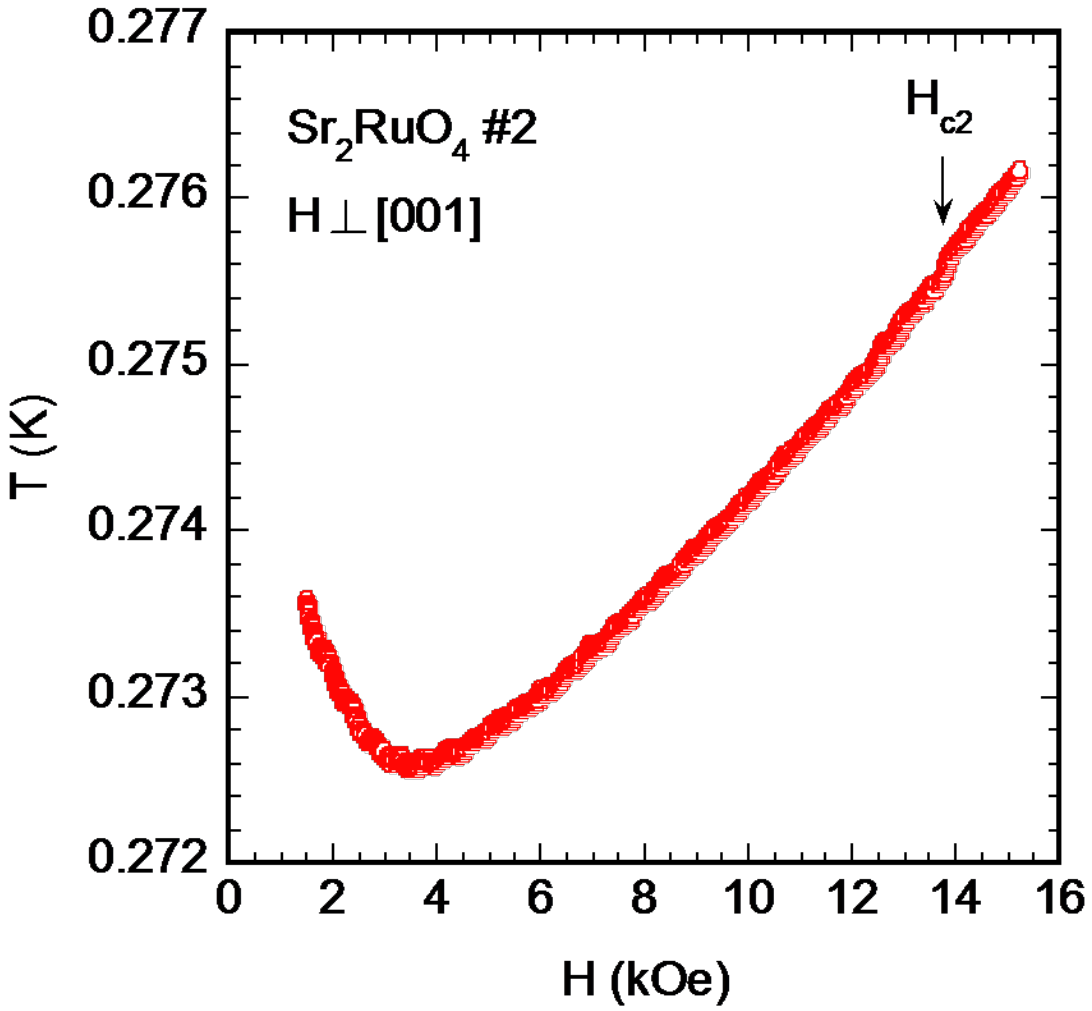


RESULTS Magnetic torque & magnetization

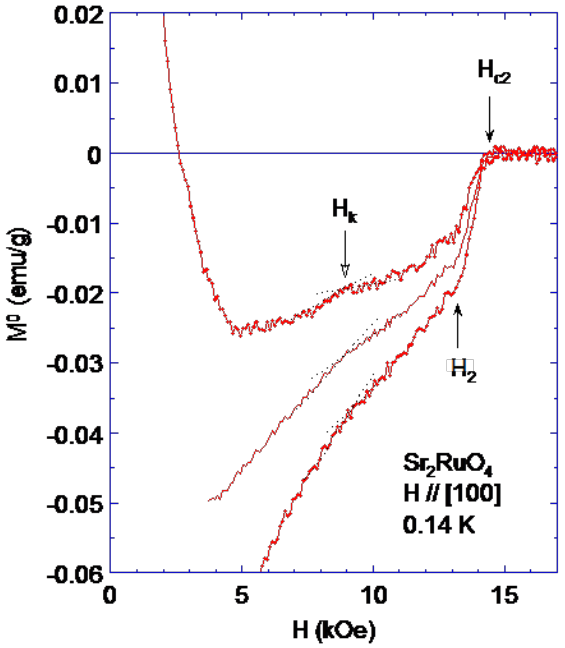


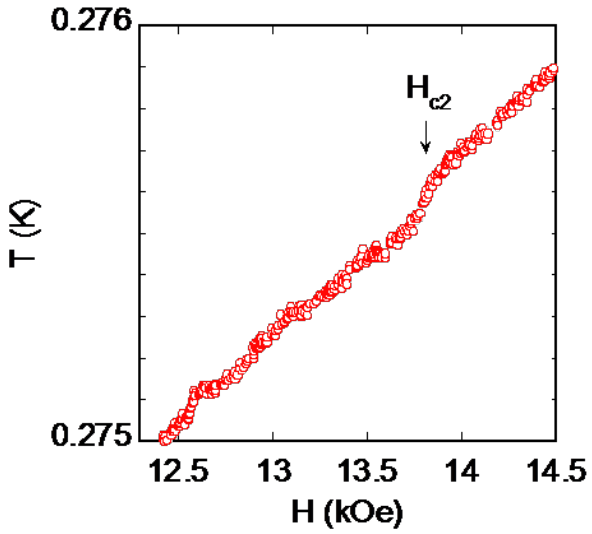
$\theta \geq 5°$: No SC suppression at low temperatures

RESULTS Magnetocaloric Effect



Magnetocaloric effect





Summary

- Detailed magnetization measurements for *H* // [001] are performed in the SC state of Sr_2RuO_4. Anomalous vortex-pinning behaviors are observed at weak fields.
- Second magnetization peak (SMP) anomalies are also observed at low fields. Tiny anomalies are observed in the equilibrium magnetization curves as well.
- The hysteretic magnetization below the SMP-field strongly depend on the field-gradient.
- Possible origins of these anomalous pinning behaviors are ***d***-vector flipping.
- Anomalous tiny flux-jumps are observed only below the SMP field.
- Magnetocaloric effects measurements are performed for *H* // [001].
- Future works
  - Detailed magnetocaloric effect measurements
  - Magnetic striction measurements