Magnetization in superconducting Sr_2RuO_4

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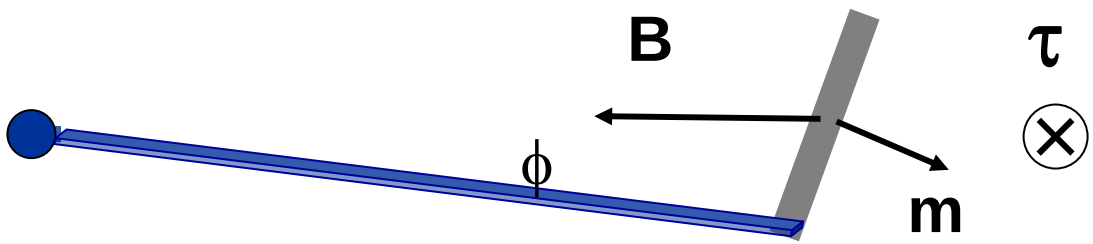
1. **Torque magnetometry**
2. ***M-H* curves with H||c**
3. **Competition with magnetic state (H||a)?**
4. **Anomalous critical-state reversibility**
5. **Dipole unlocking?**

Cantilever torque magnetometry

Torque on magnetic moment: $\tau = \mathbf{m} \times \mathbf{B}$



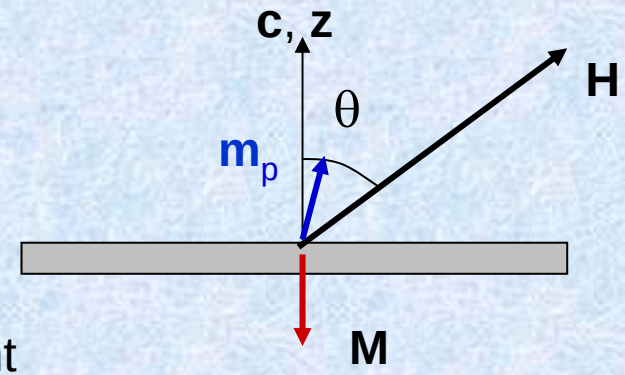
Deflection of cantilever: $\tau = k\,\phi$

Torque magnetometry

$$\tau = \mathbf{m_p} \times \mathbf{B} + \mathbf{MV} \times \mathbf{B}$$

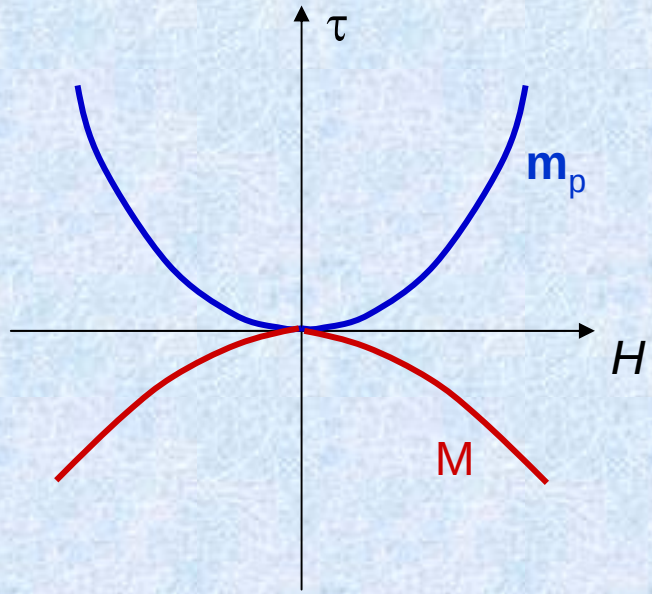
Paramagnetic moment

2D supercurrent



$$\tau/V = \chi_c H_x B_z - \chi_a H_z B_x + M B_x$$

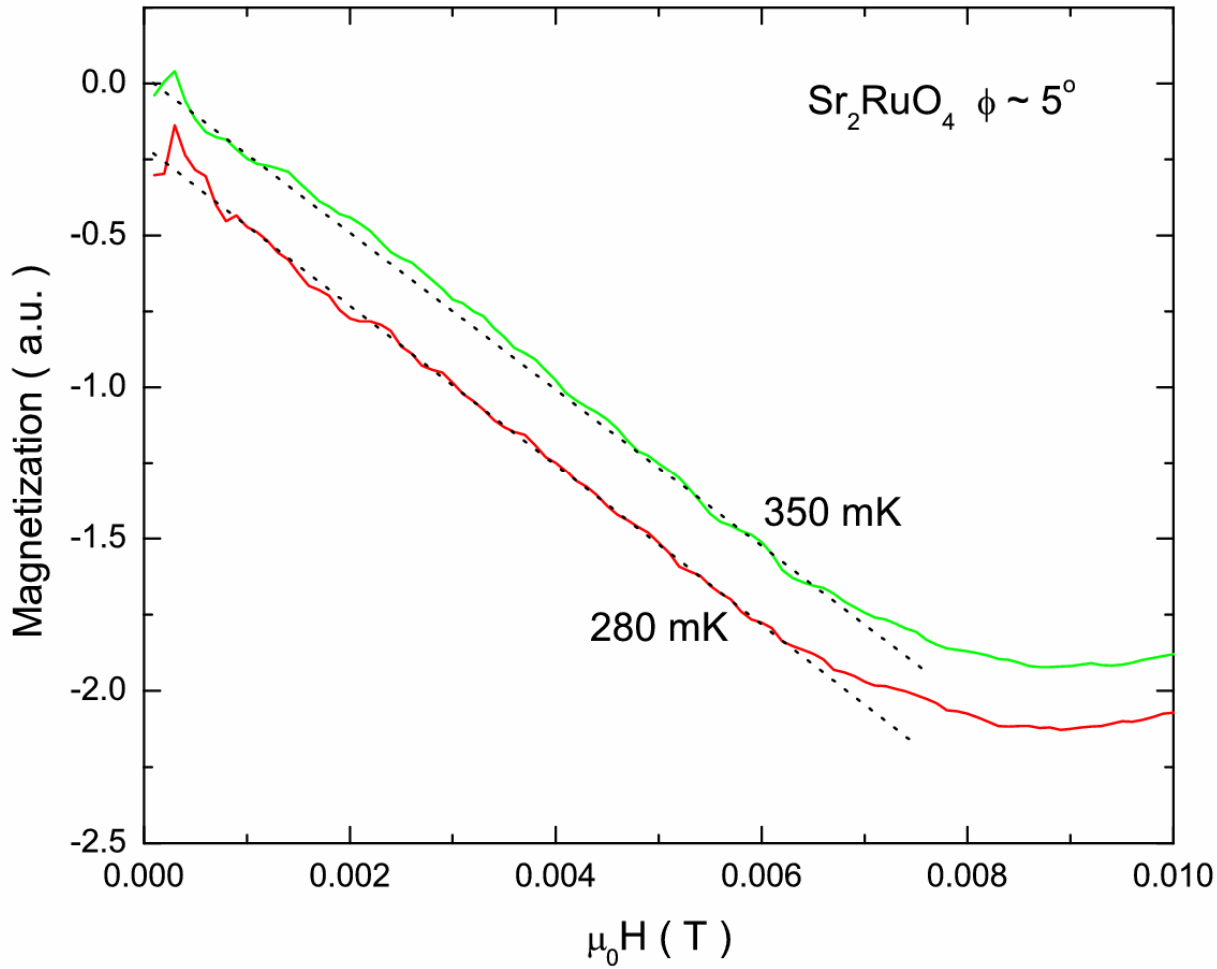
$$M_{eff} = \tau / VB_x = \Delta\chi_p H_z + M(H_z)$$



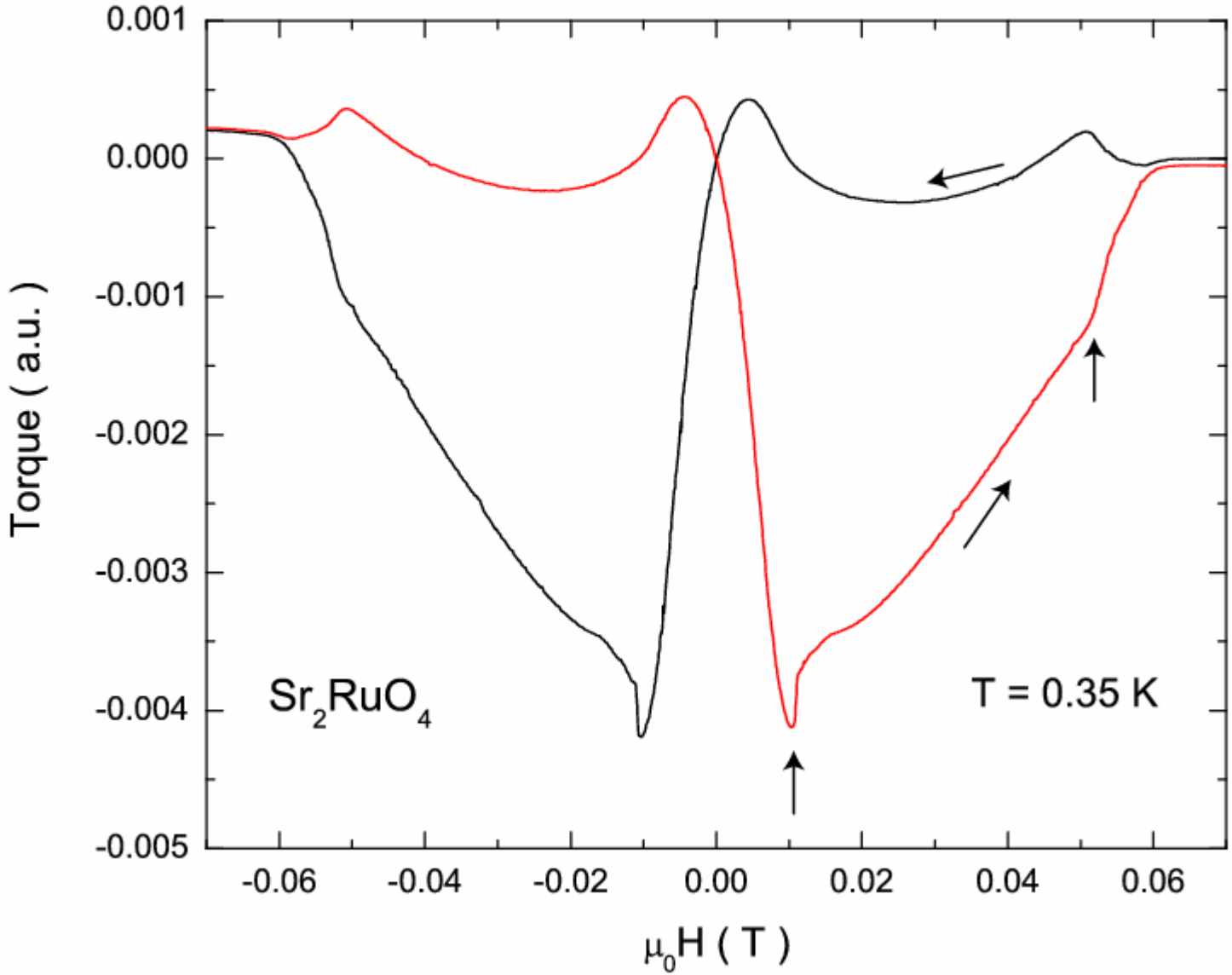
High sensitivity to 2D supercurrents

H_{c1} ~ 60 Oe at 280 mK (good agreemt w heat capacity)

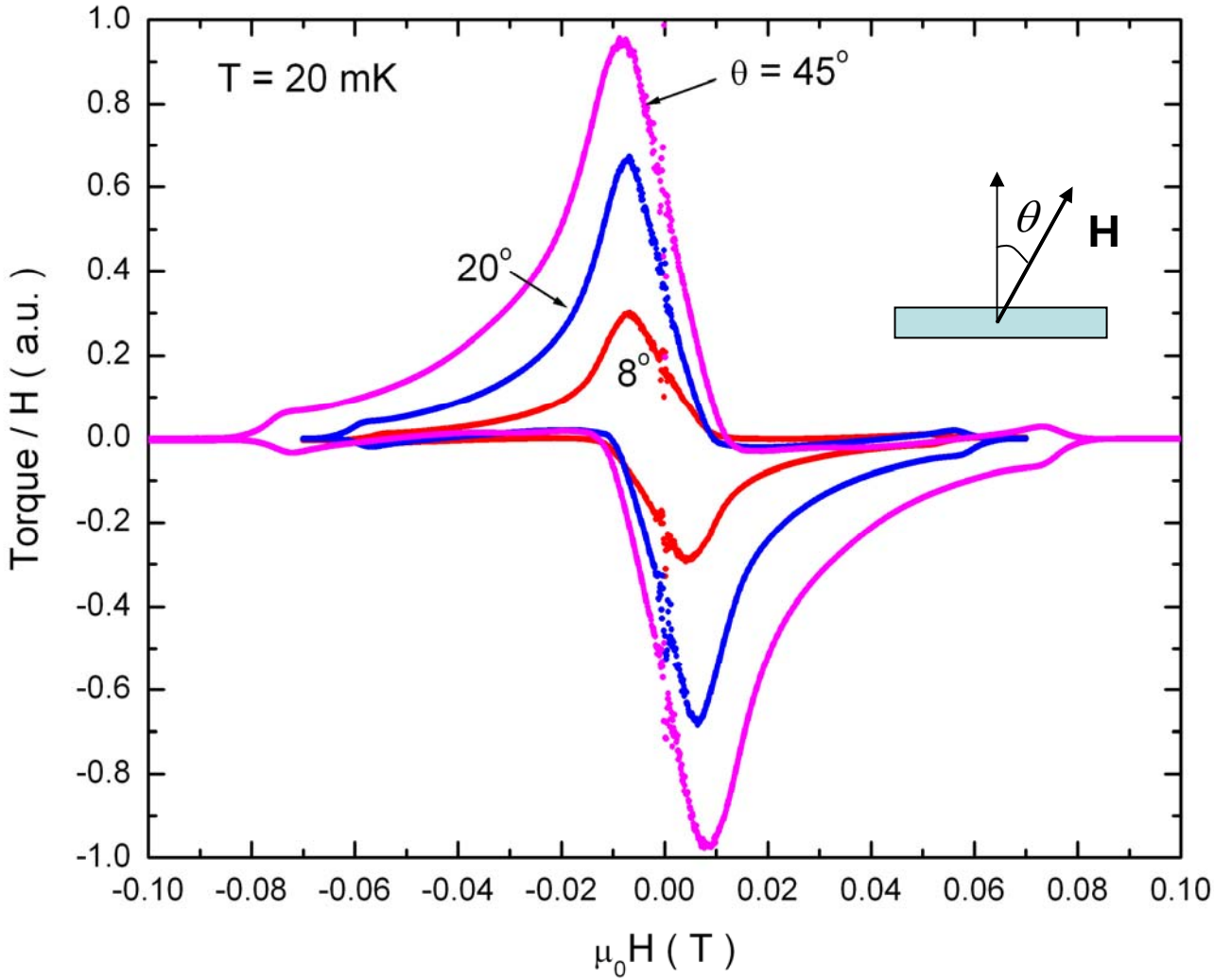
Initial M curves after ZFCool



Torque signal in Sr_2RuO_4 **H || c**

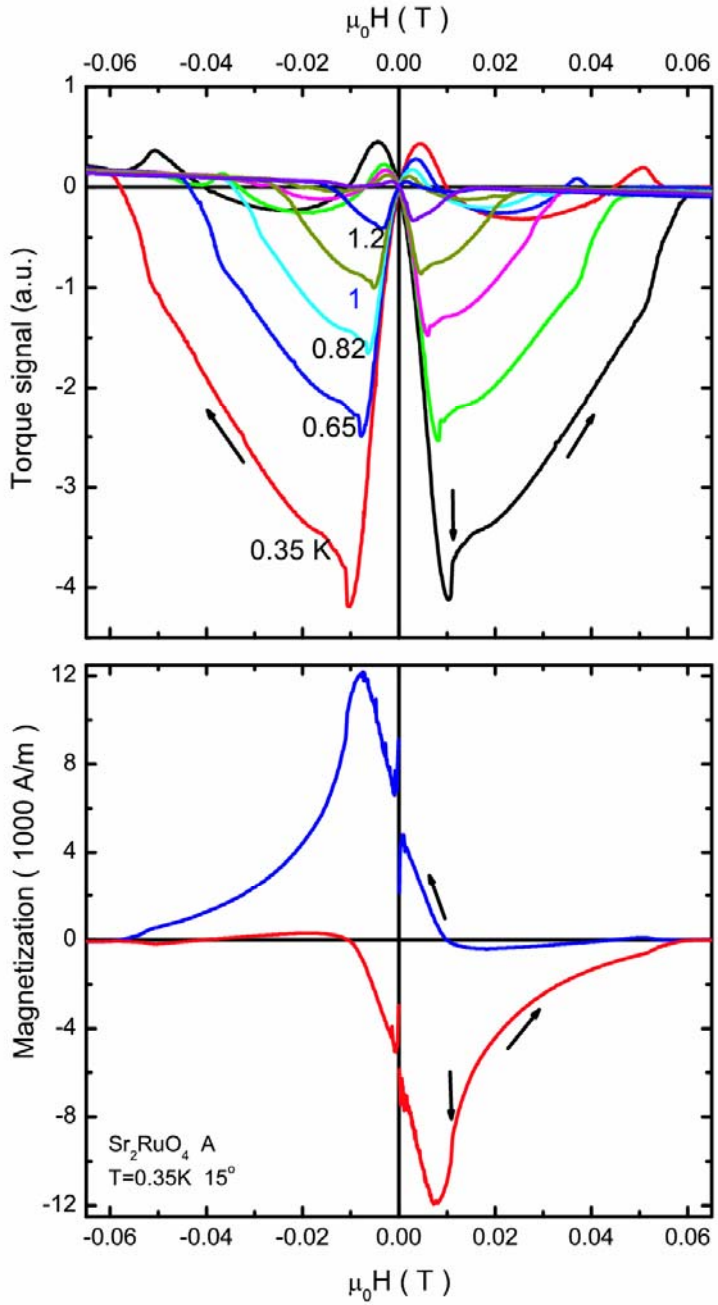


M vs H at selected tilt angles θ



Unusual features of *M-H* curves

1. Strongly skewed
2. Reversibility
3. Break in slope at H = 0
4. Abrupt jump at 110 Oe



Coexistence of superconductivity and hidden-order state in $CeCoIn_5$

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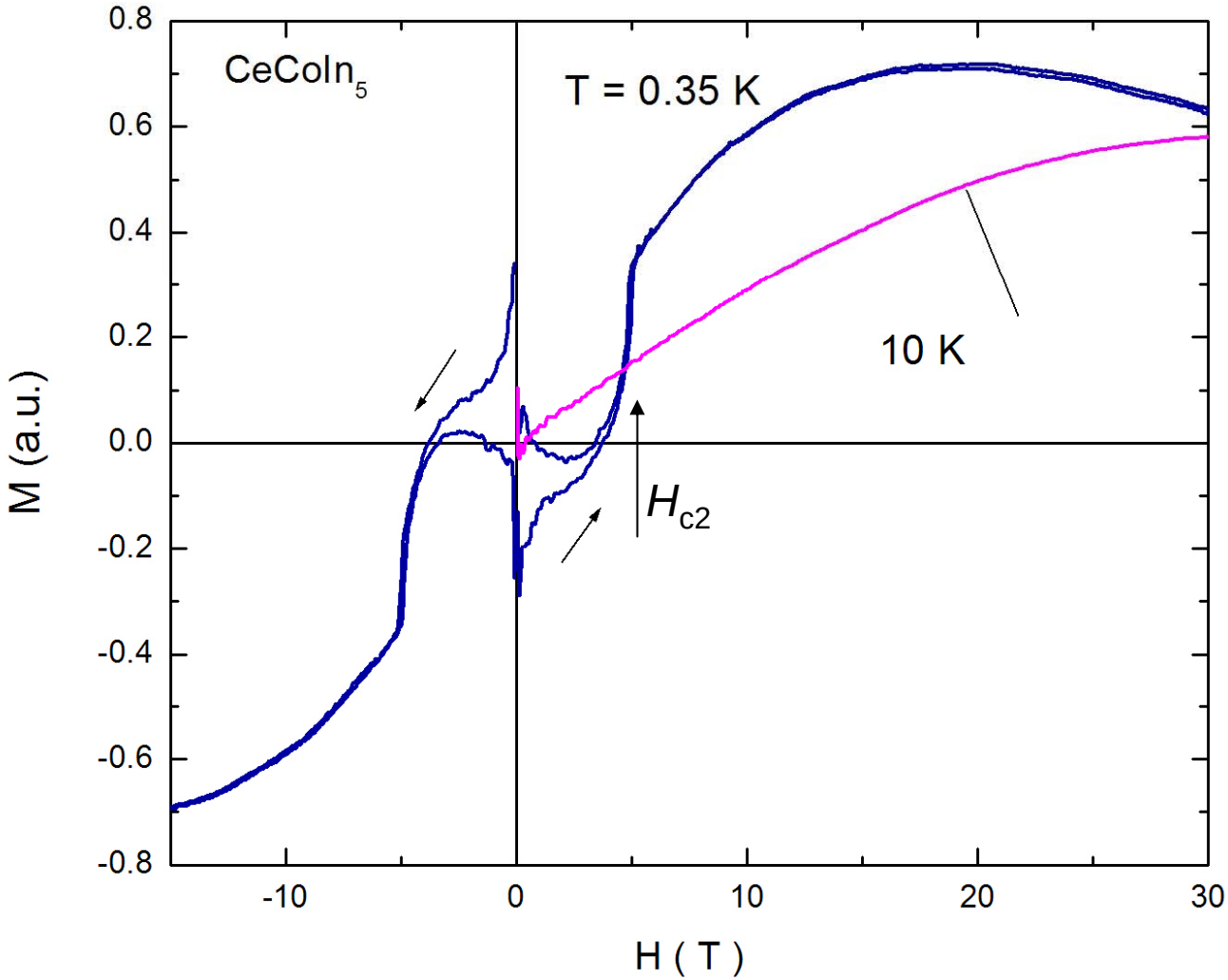
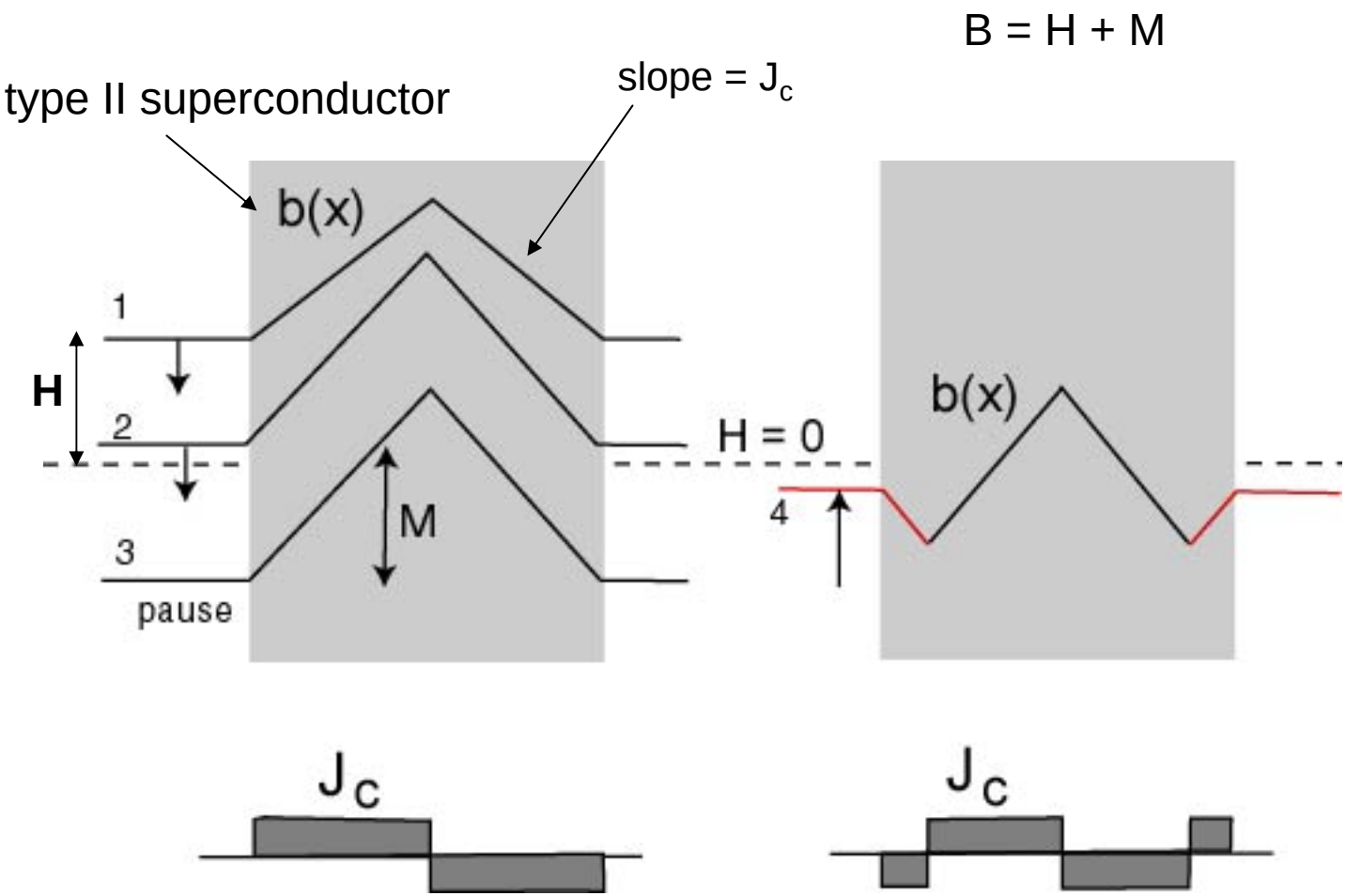
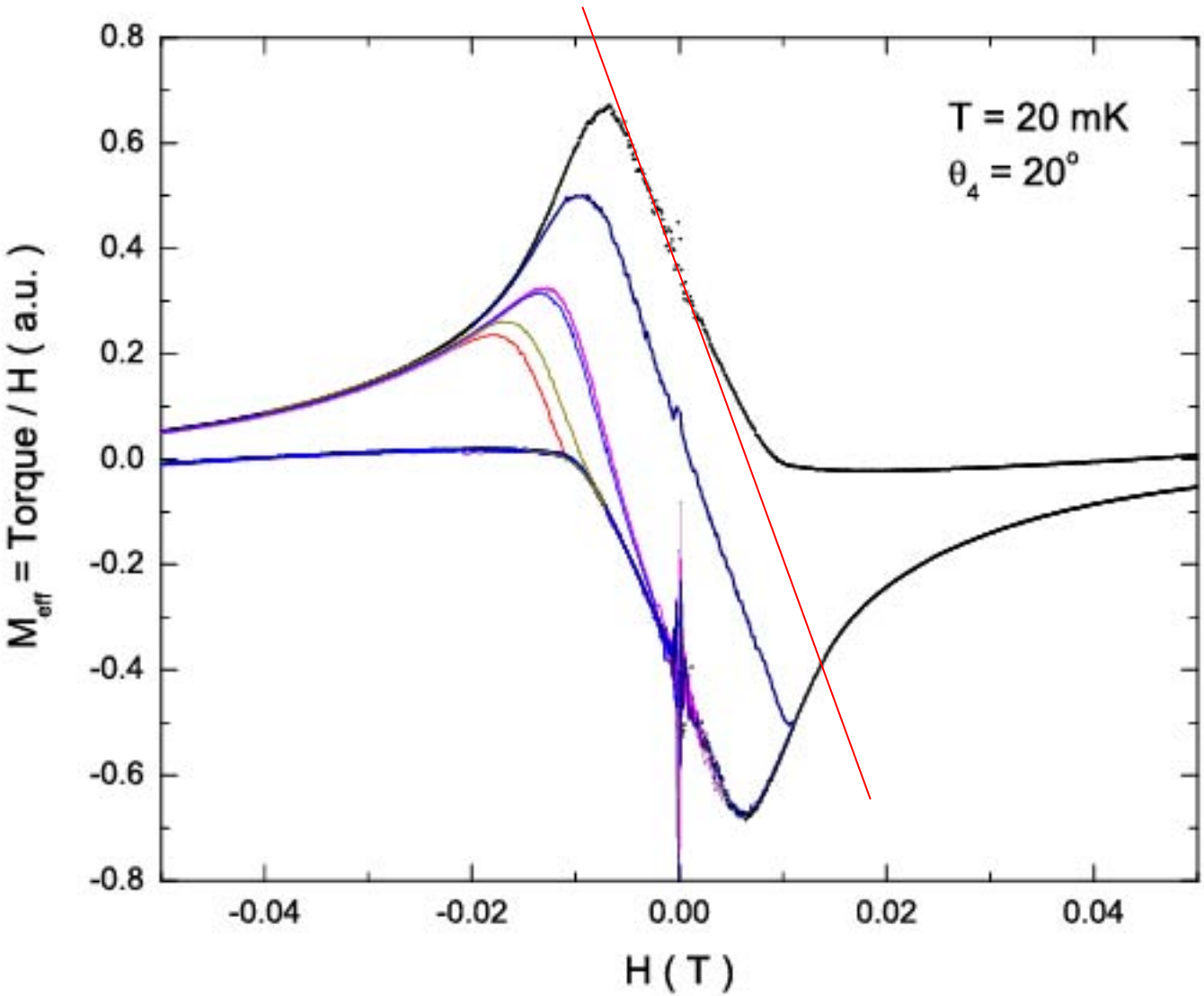


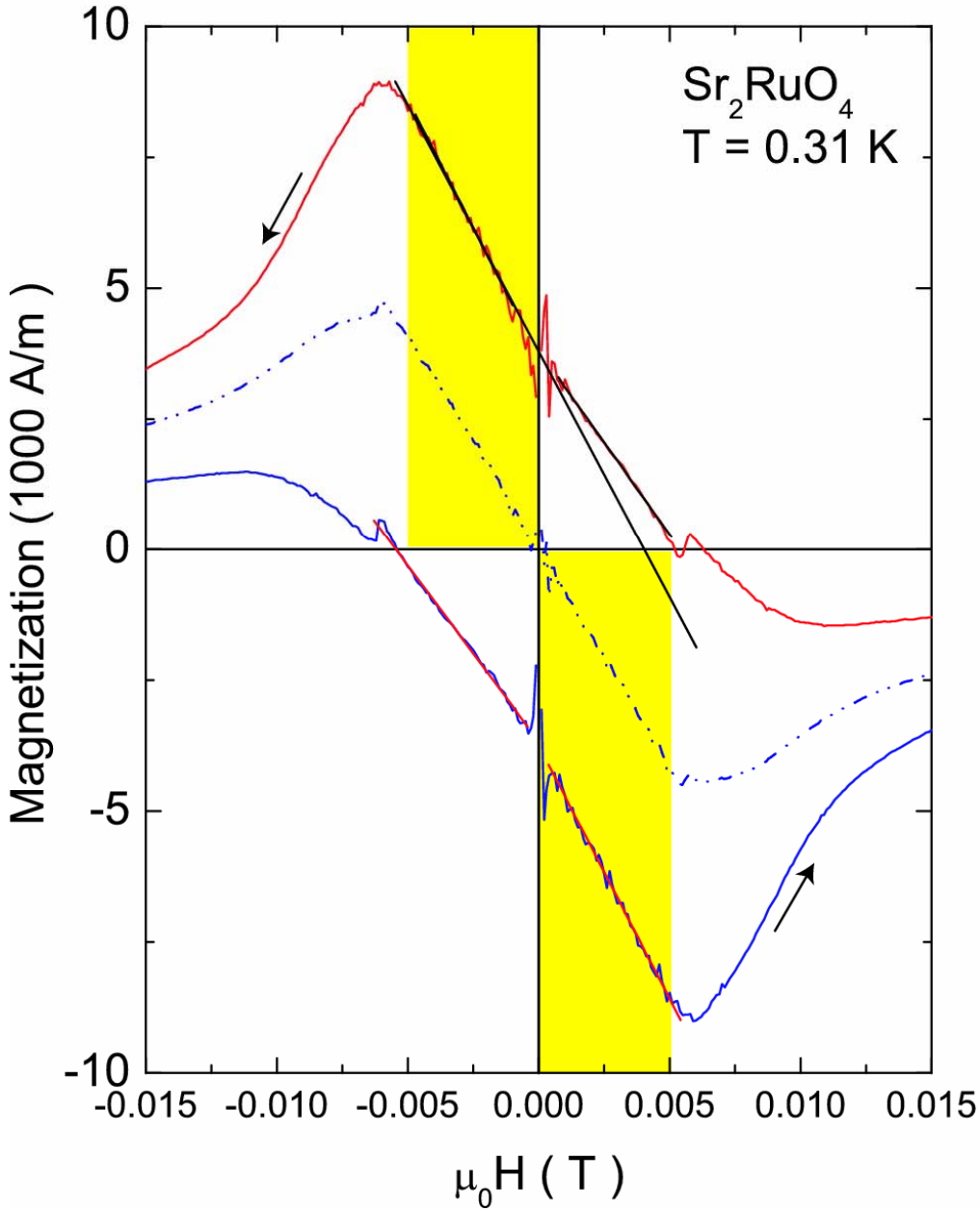
Hysteretic *M*-H curves in critical state (Bean model)



critical current profile

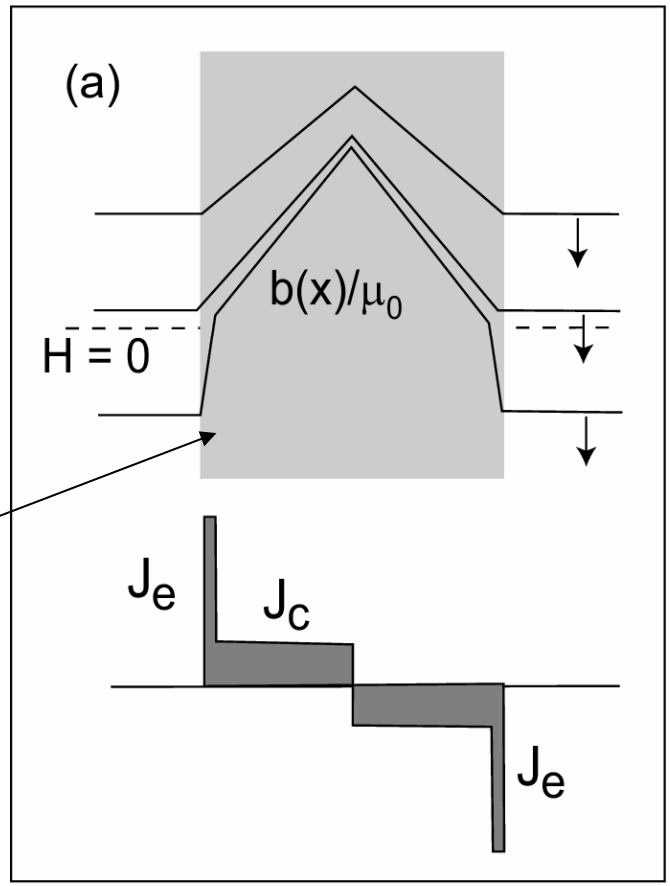

T = 20 mK
θ4 = 20°
M_eff = Torque / H (a.u.)
H (T)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-0.04
-0.02
0.00
0.02
0.04

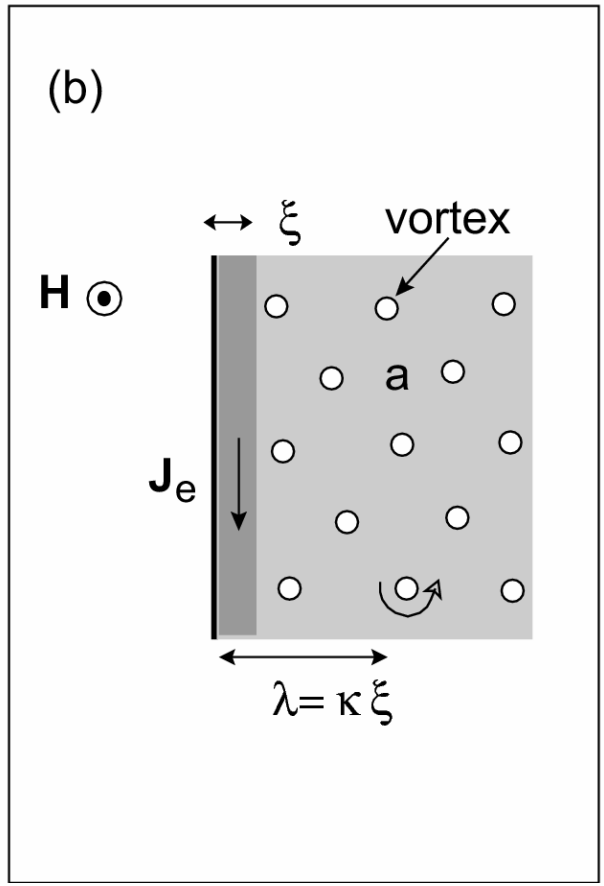
Anomalous break-in-slope at H = 0



Reversibility in the critical state?

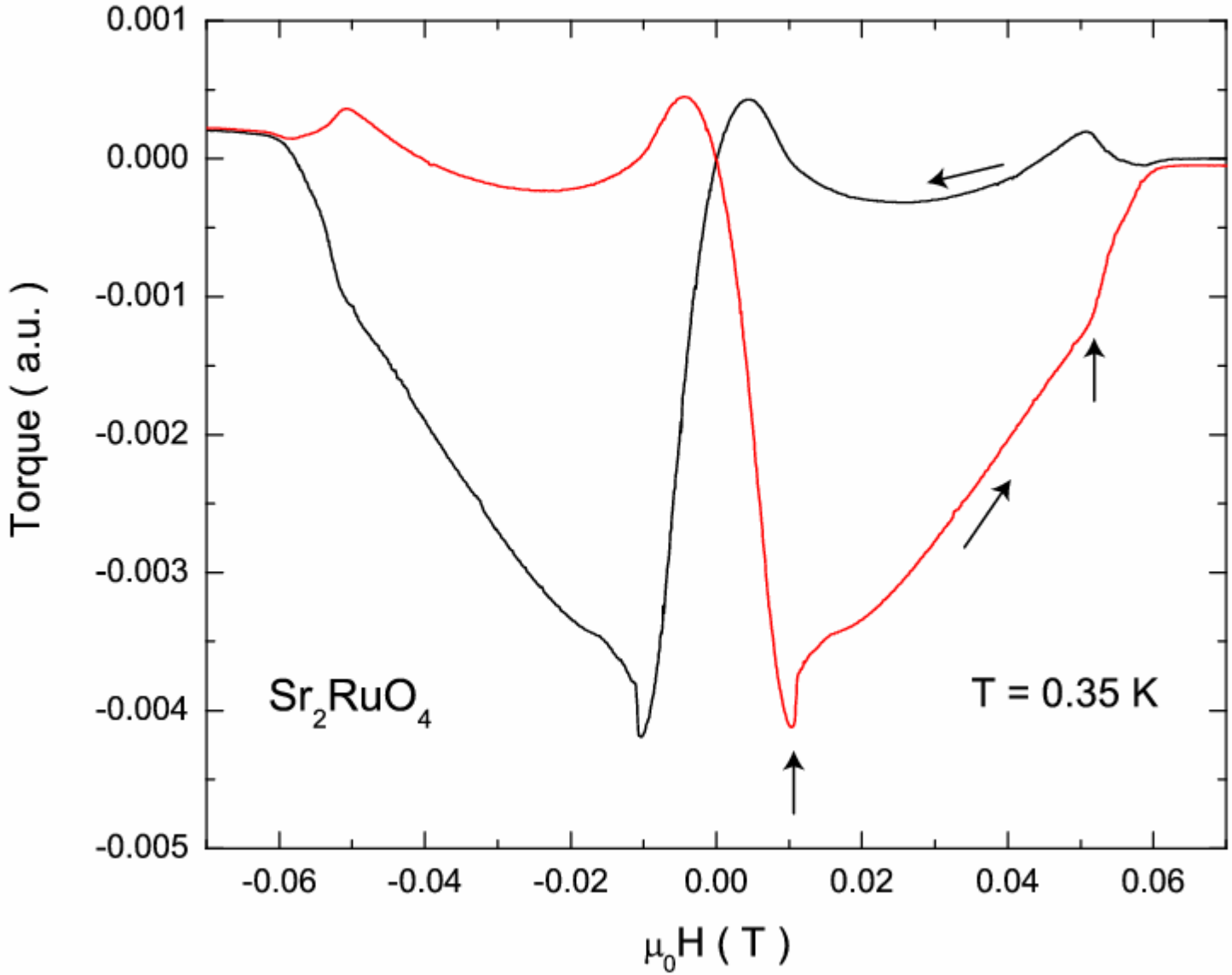
Reversible behavior





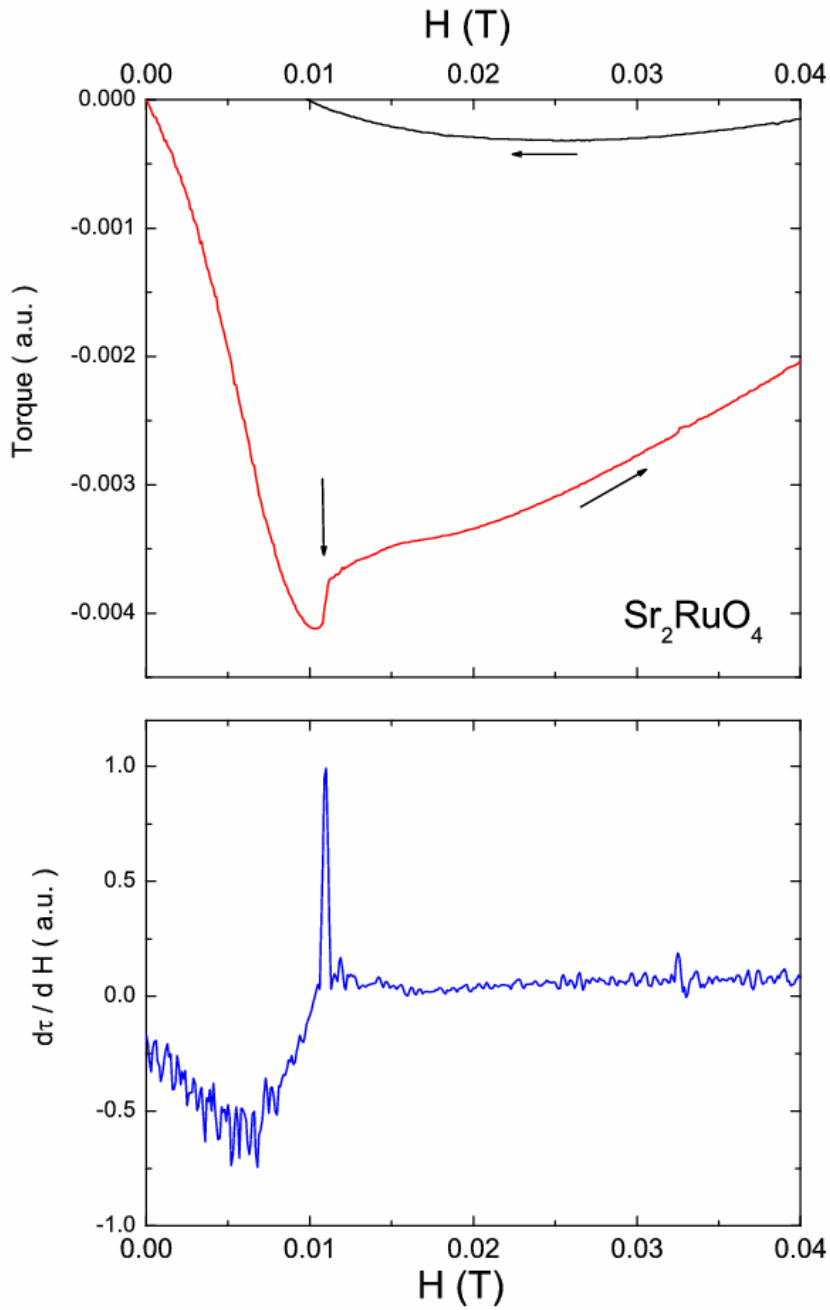
$$\mathbf{J}_\ell = \nabla \times \left(\rho_s \vec{\ell} \right)$$

Torque signal in Sr_2RuO_4 **H || c**

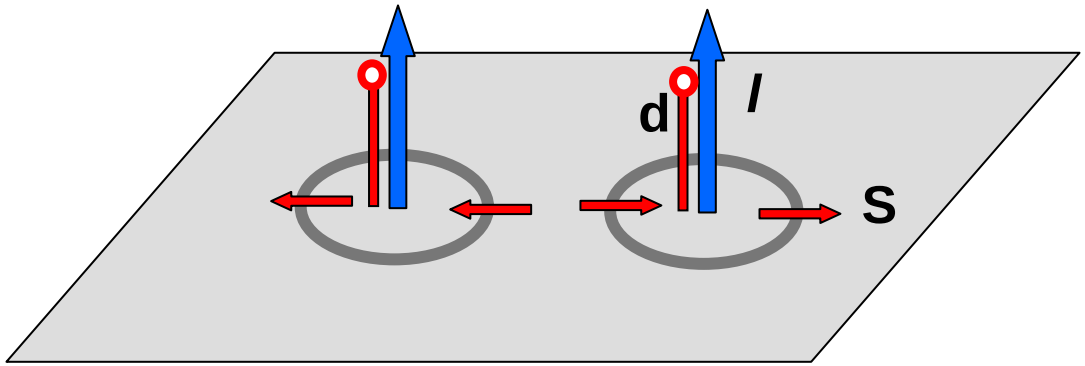


Sharp transition
In magnetic fied
H ~ 120 Gauss

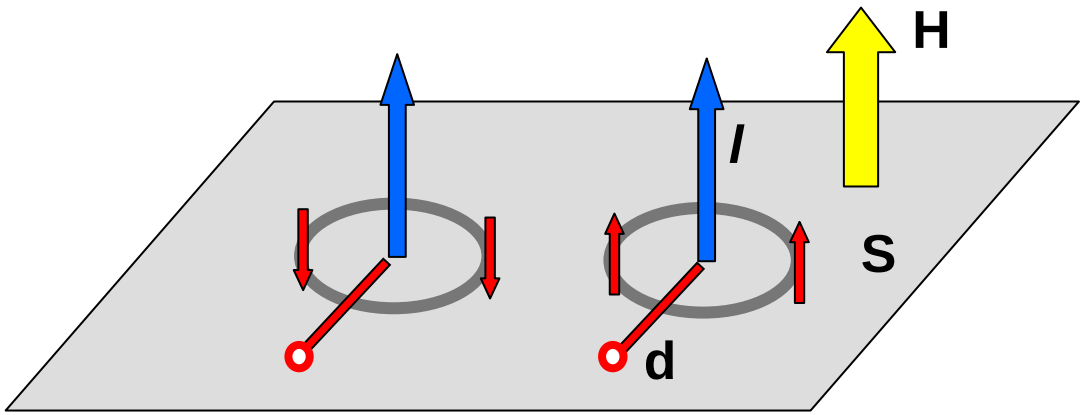
Dipole unlocking
Transition?



Cooper pairs in p-wave superconductor (and ^{3}He A-phase)



Equal spin pairing
Dipole-locked
(***l*** || **d**)

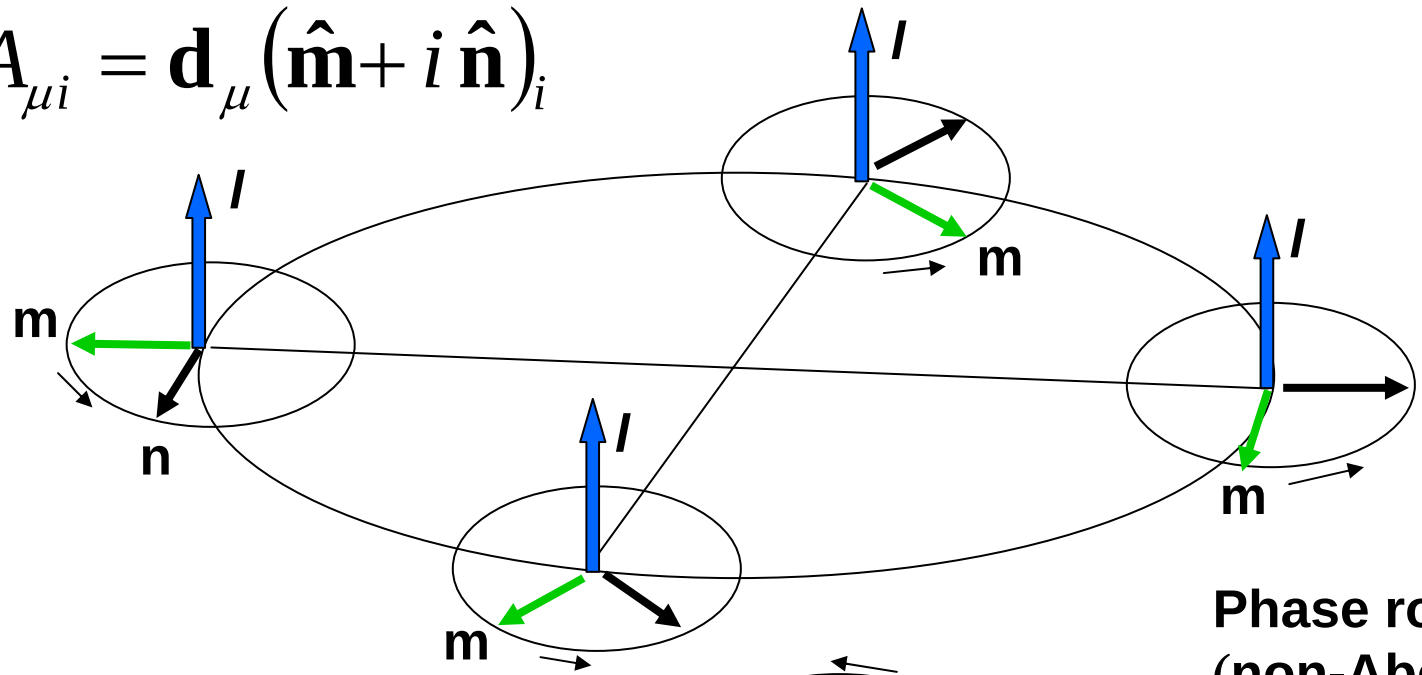


Magnetic field H
drives
dipole unlocking
transition

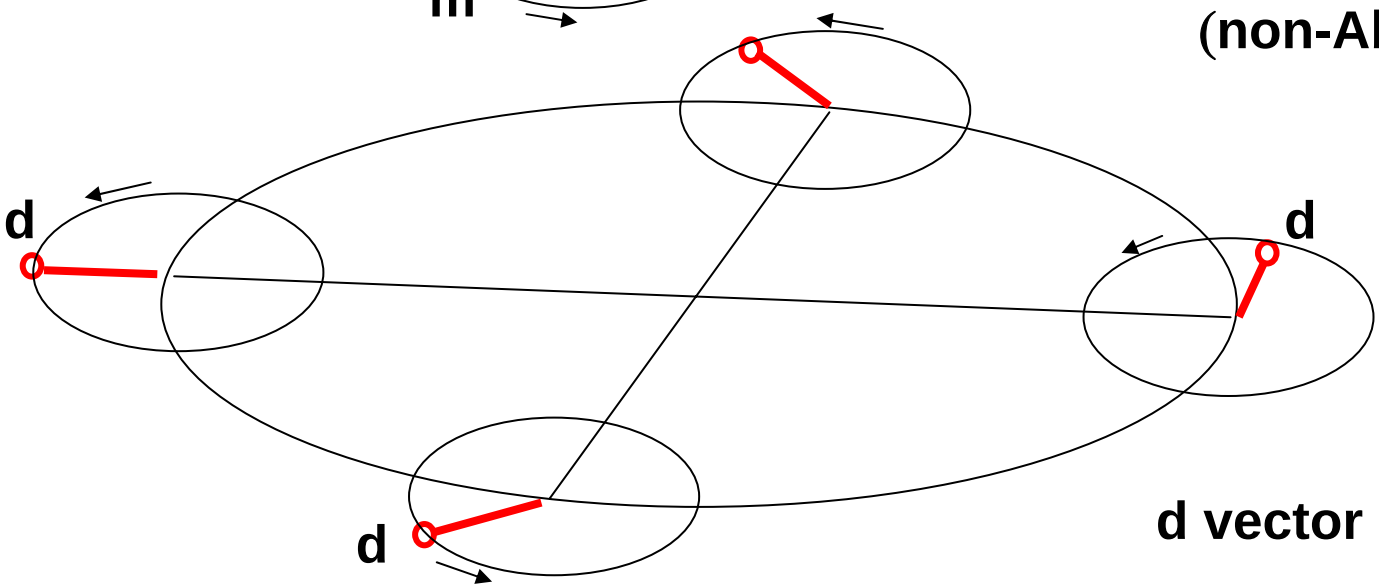
Half-vortex may be energet. favored

Circulation around a half-vortex

$$A_{\mu i} = \mathbf{d}_{\mu}\left(\hat{\mathbf{m}} + i\,\hat{\mathbf{n}}\right)_i$$



Phase rotates by π (non-Abelian)



d vector rotates by π

Summary

1. ***M-H*** **curve with H||c anomalously skewed.**

2. **Large break-in-slope d*M*/d*H* at *H* = 0 in critical state.**

3. ***M*** **is “reversible”**

4. **Some samples show abrupt jump at 110 Oe.**
   Unlocking of d from l?