Magnetic phase transitions and magnetoelastic coupling in $Ba_3CoSb_2O_9$

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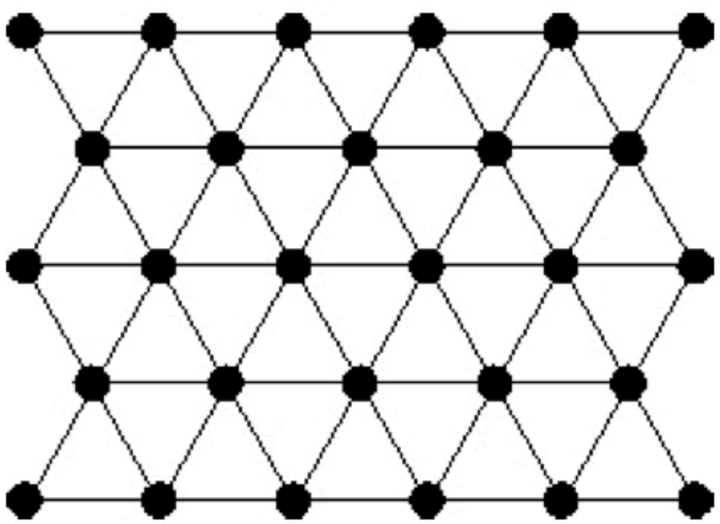
Degenerate ground states in frustrated antiferromagnets

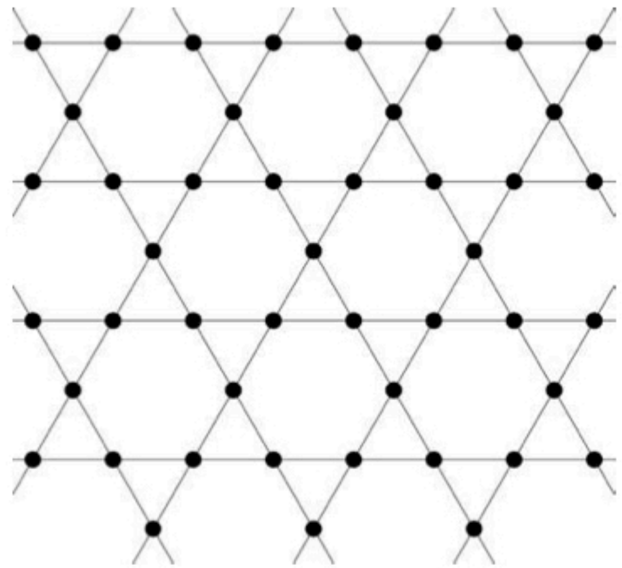
Triangular

(a)

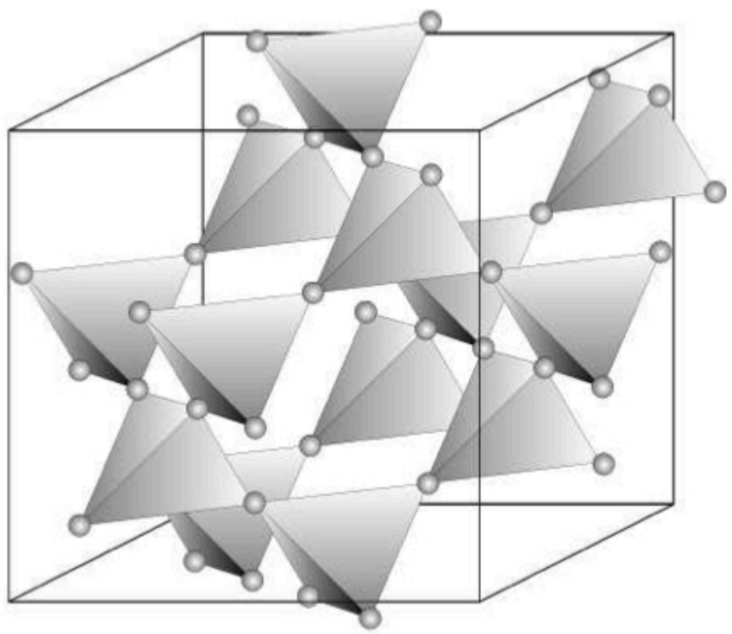


Kagomè

(b)

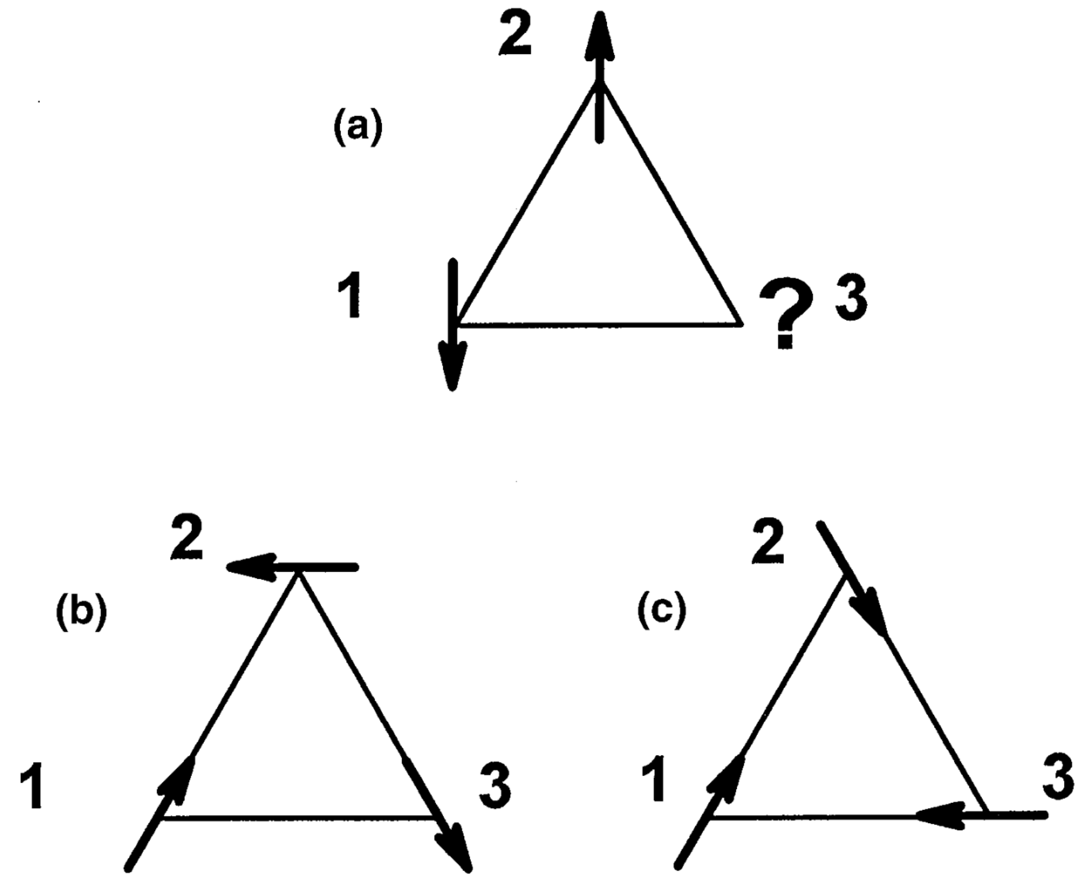


(c)



Pyrochlore

AF Frustration



Two 120° degenerate chiral states

Different properties from normal antiferromagnets
because of degenerate ground states

Properties and magnetic process of $Ba_3CoSb_2O_9$

Properties of $Ba_3CoSb_2O_9$
Stacked equilateral triangular lattice (Space group $P6_3/mmc$);
Magnetic ions Co^{2+} with effective 1/2 spin;
Quasi-2D crystal because of $J_c/J_{ab} \approx 0.027$;
Easy-plane anisotropy.

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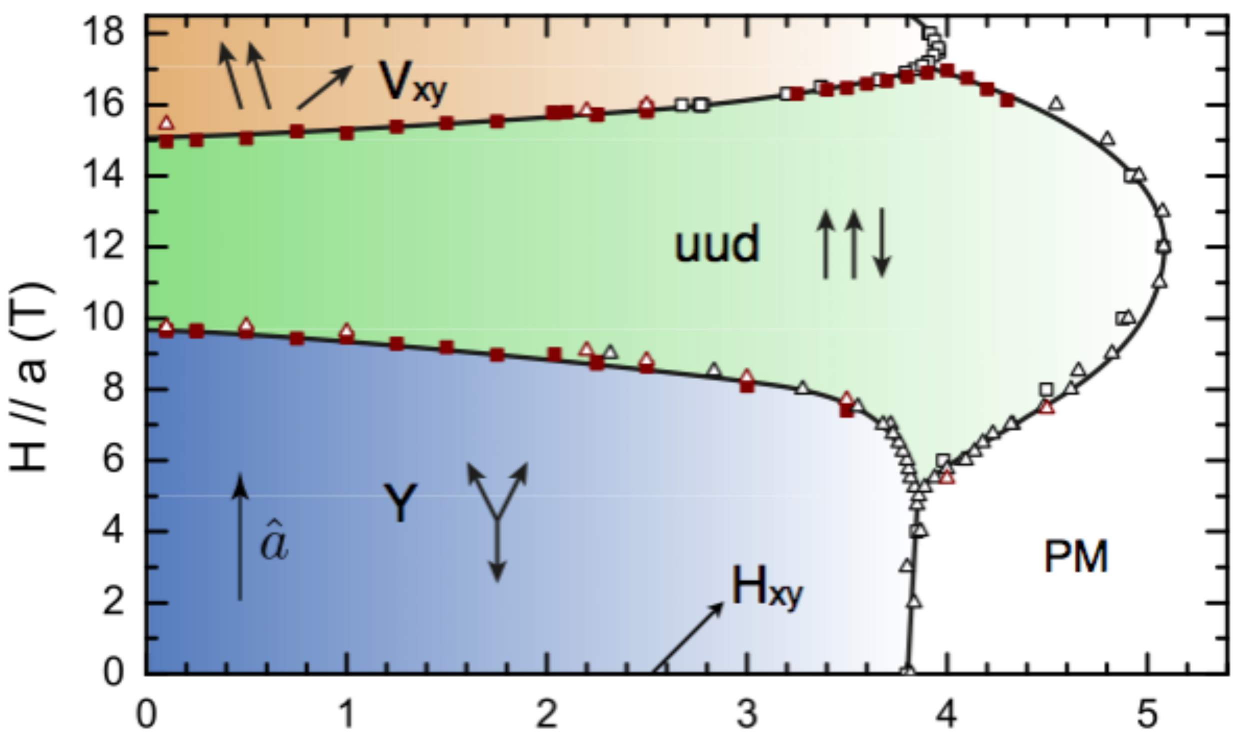
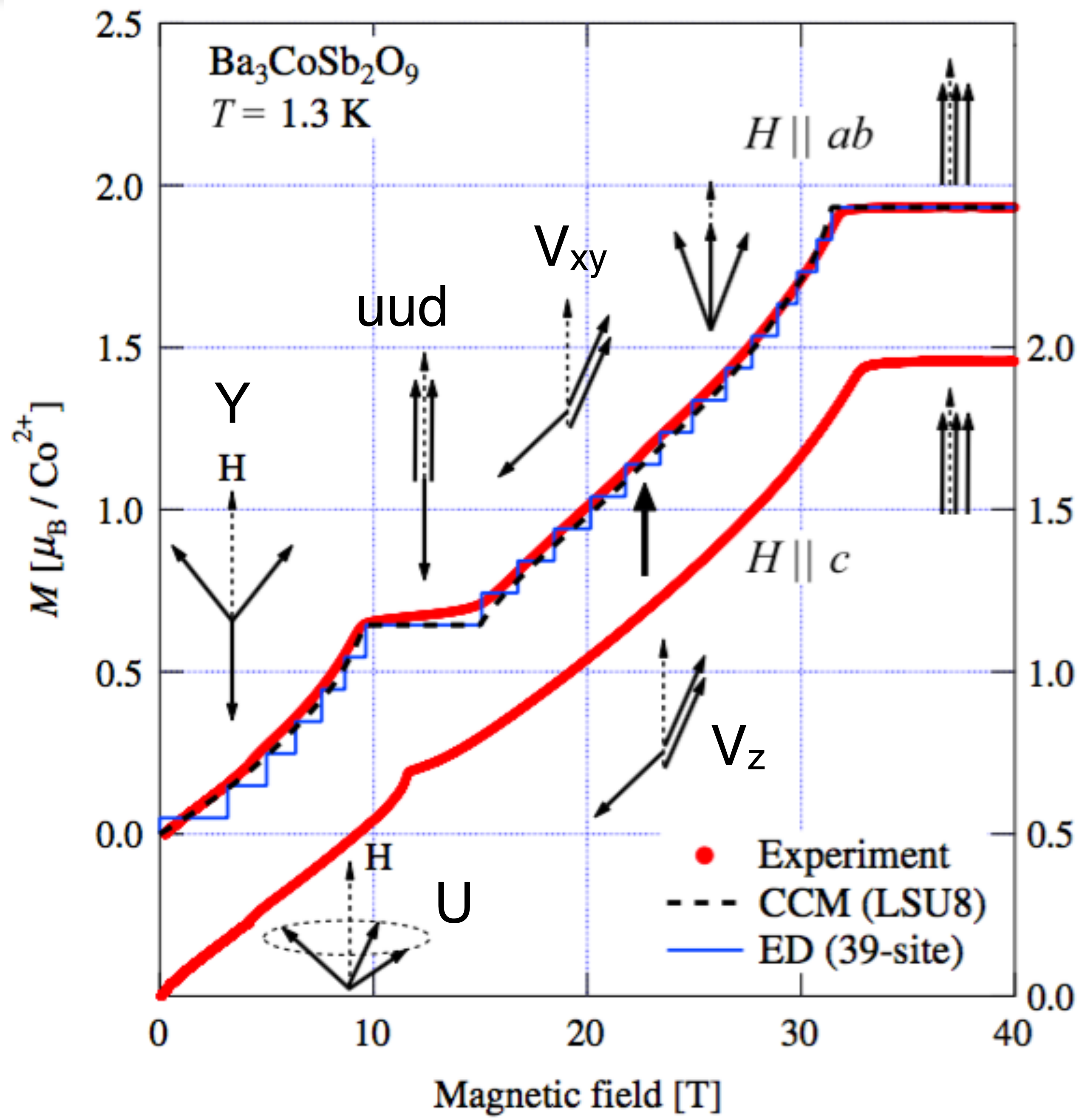


G. Quirion, etc., Phys. Rev. B **51**, 014414 (2015).



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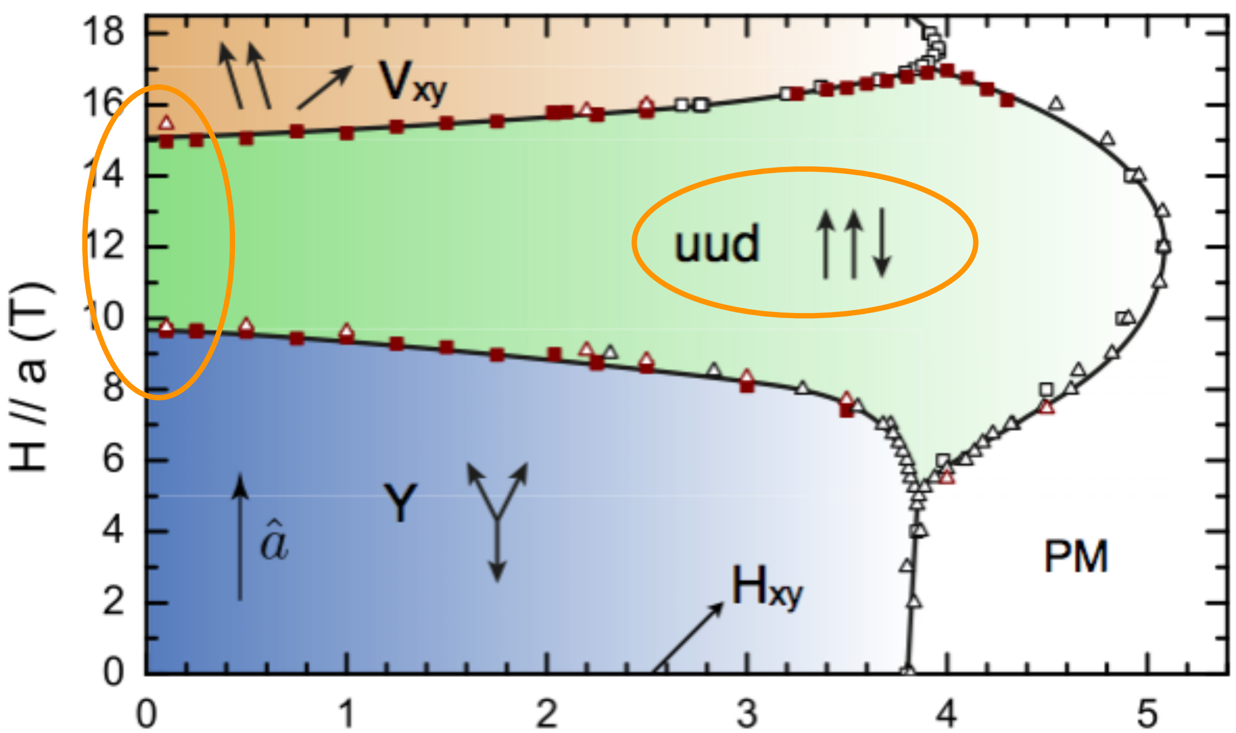

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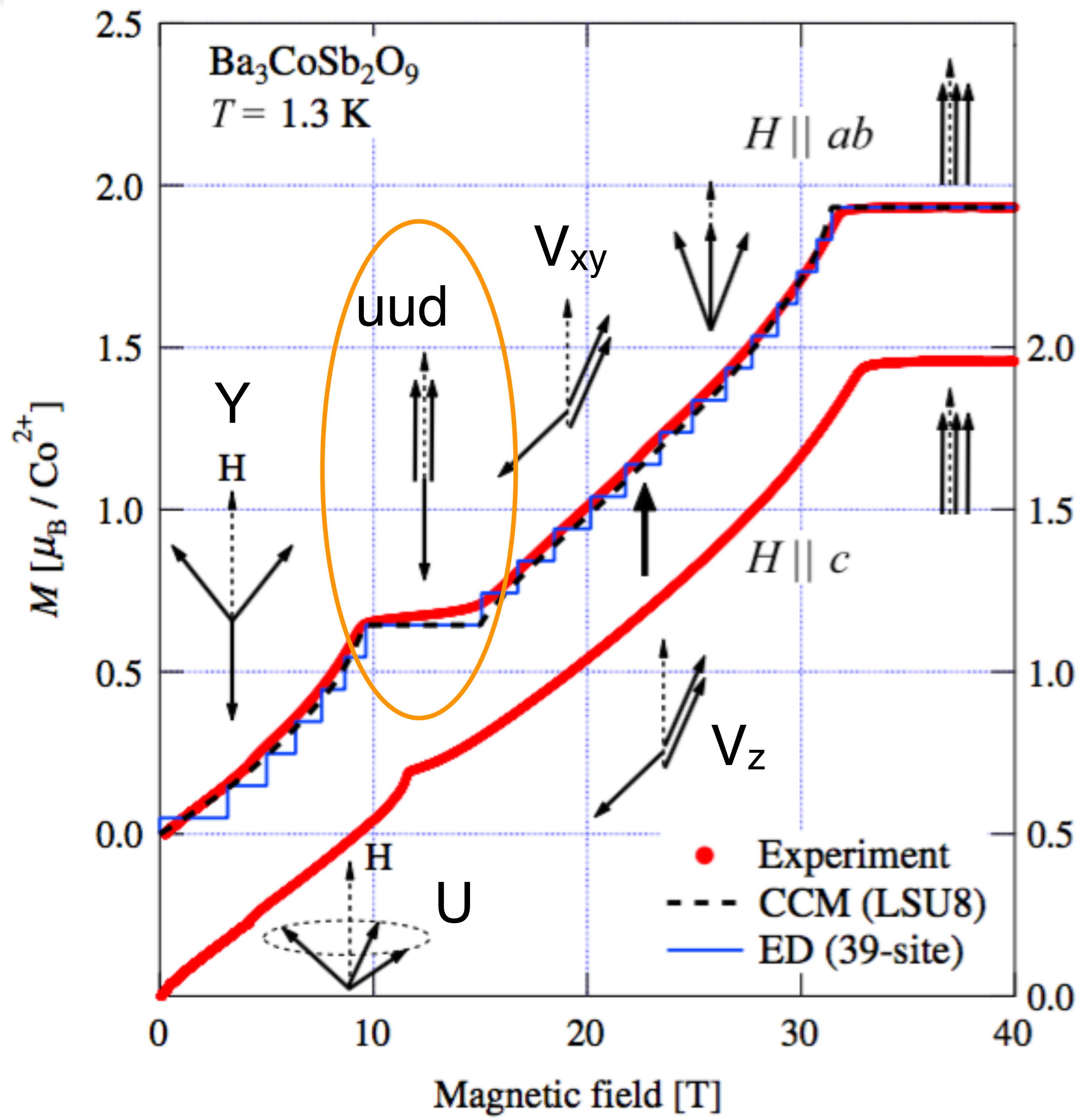

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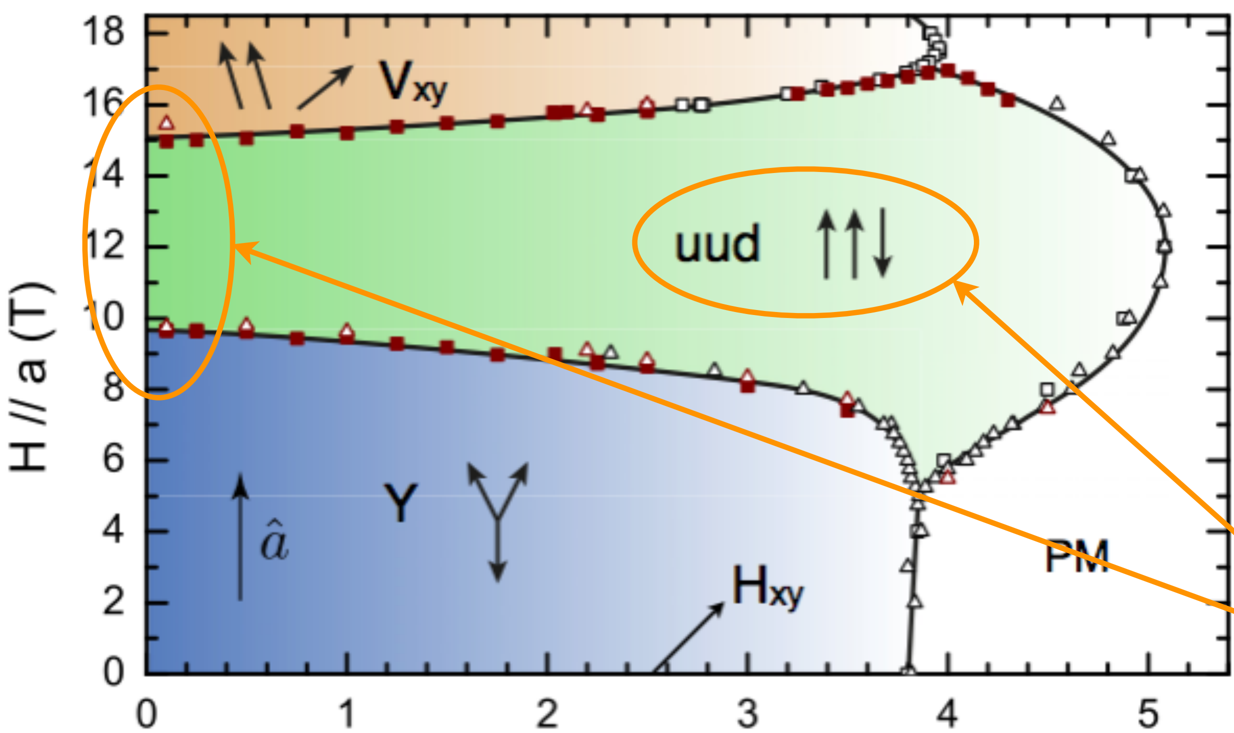

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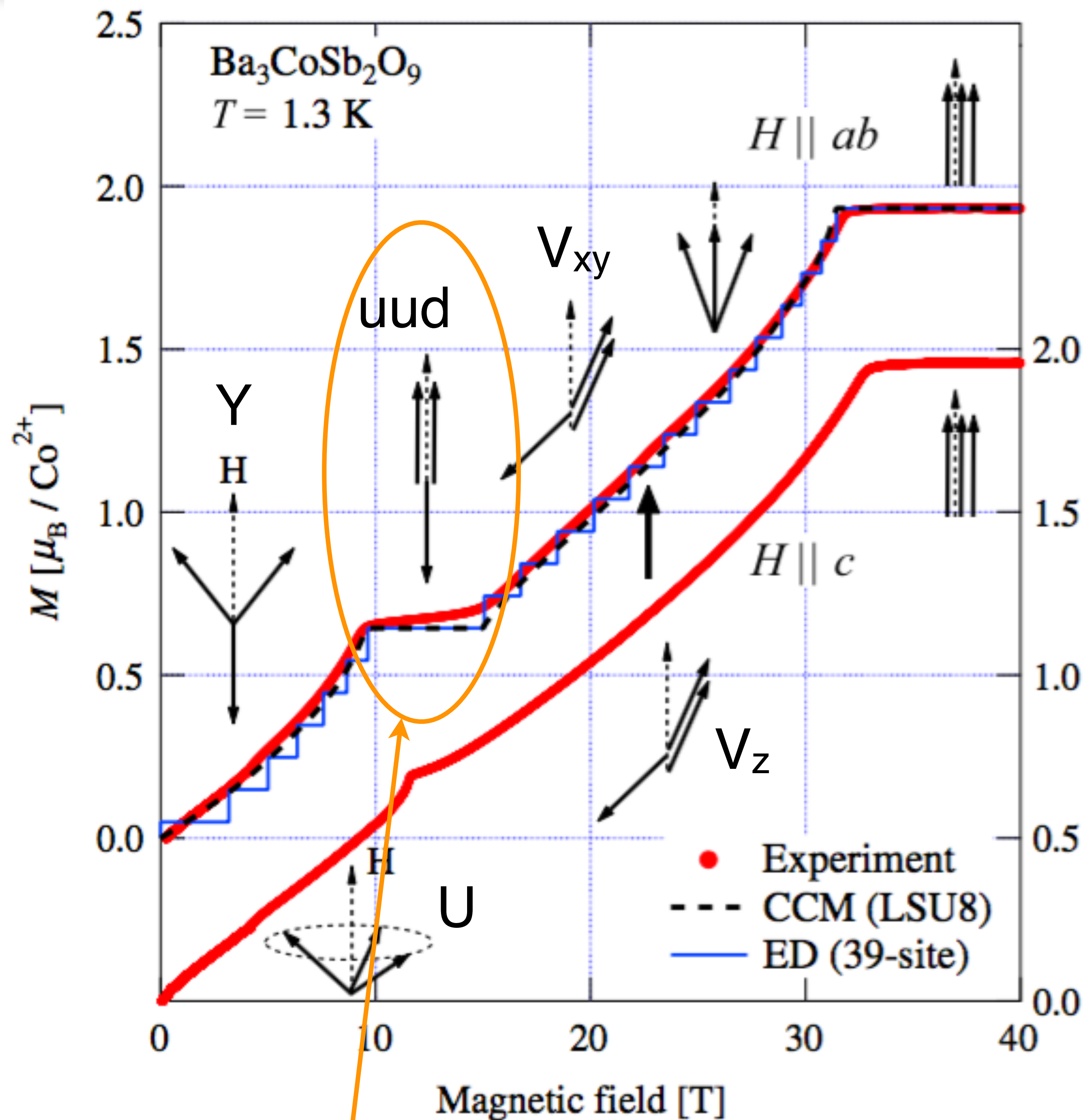

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Thermal and quantum fluctuation

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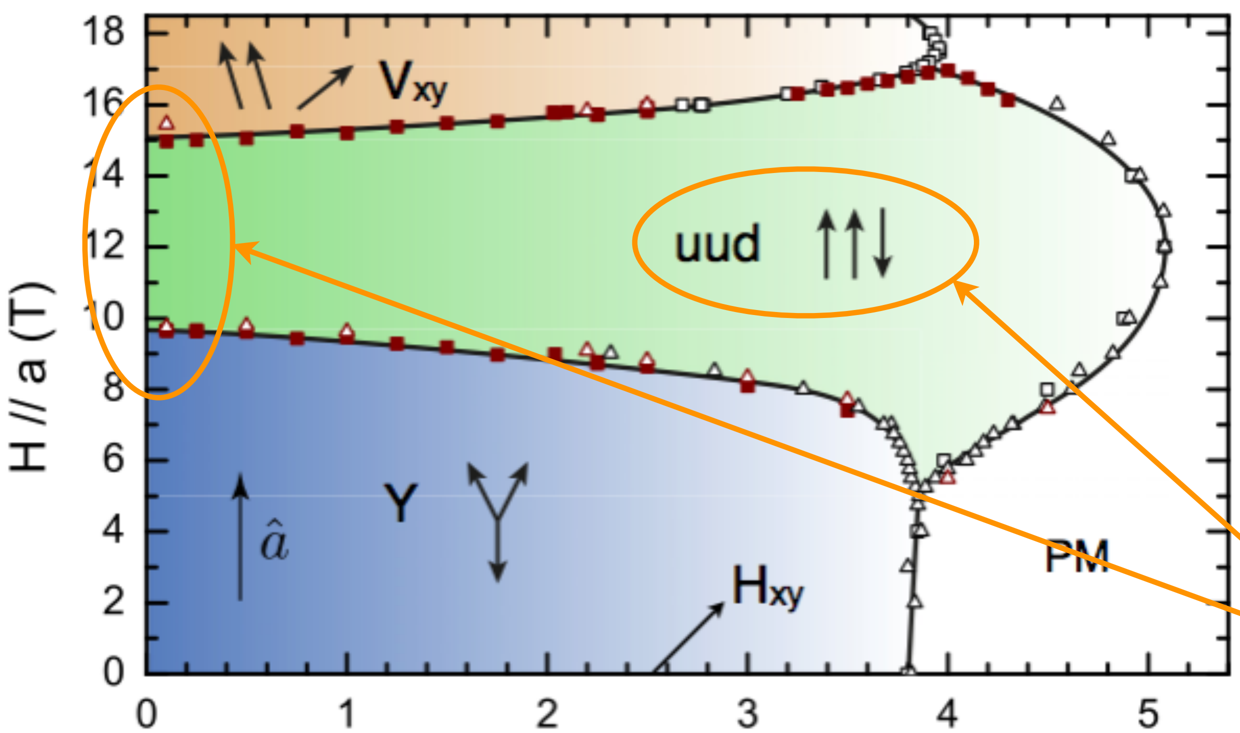

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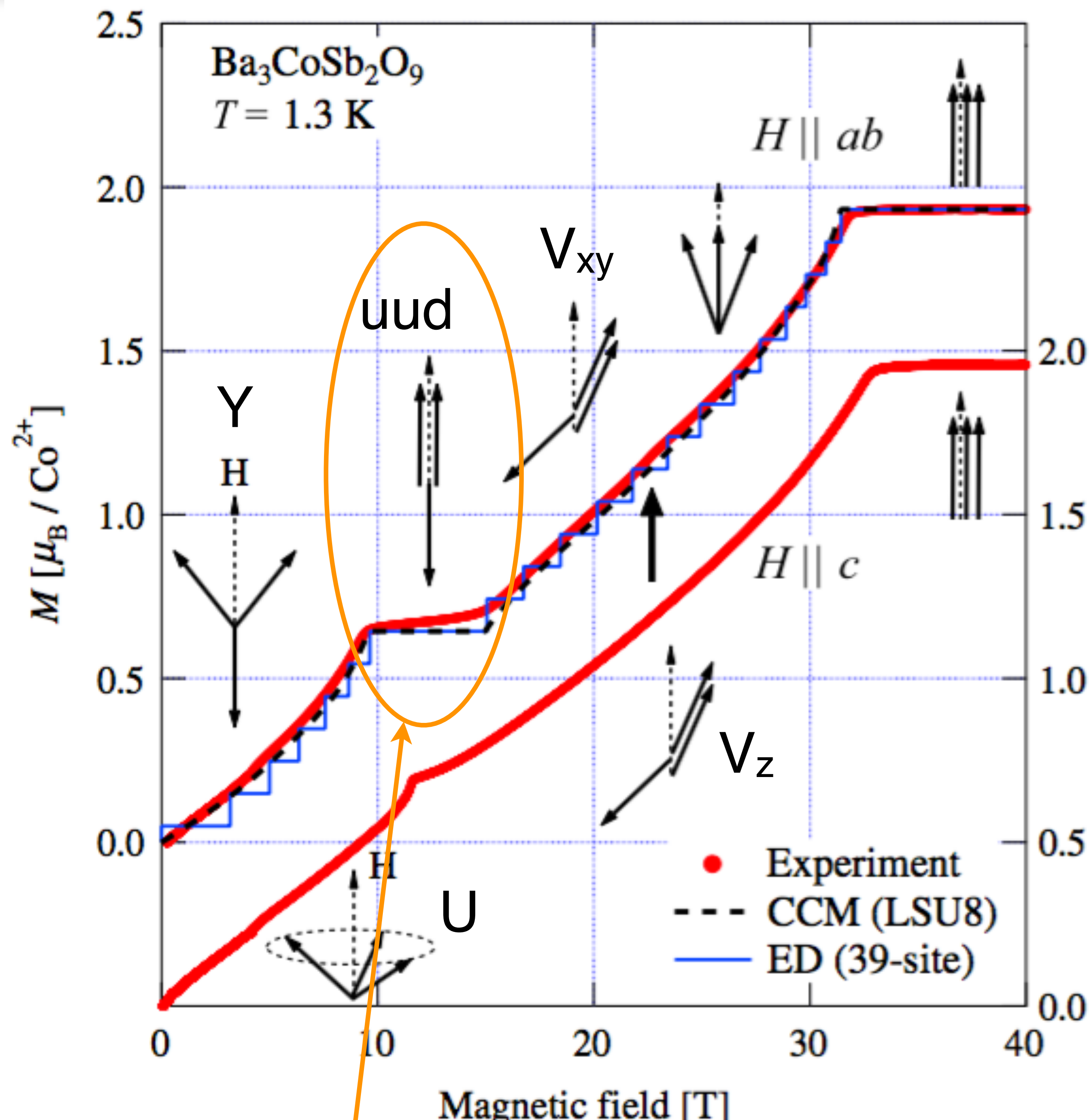

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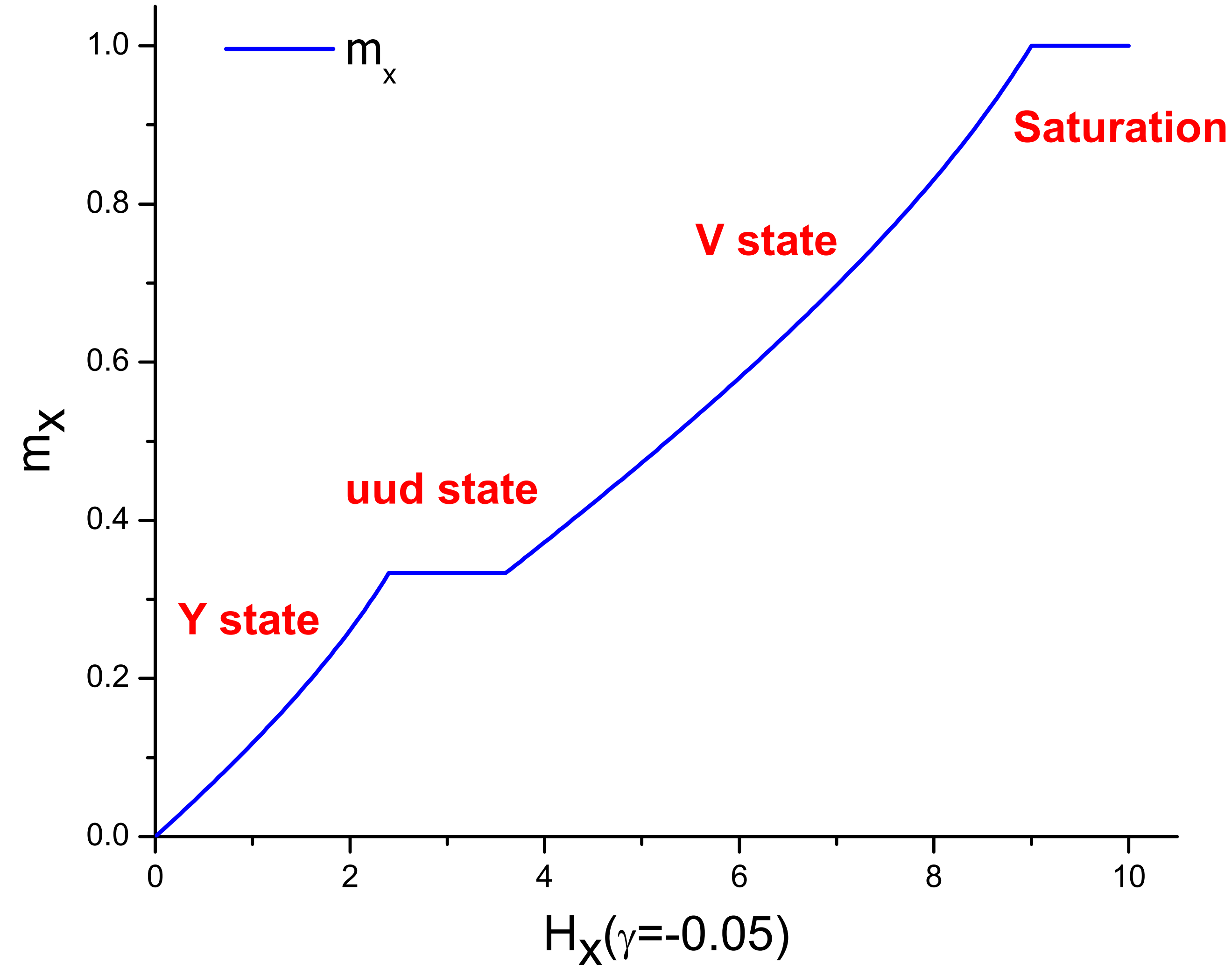
Thermal and quantum fluctuation

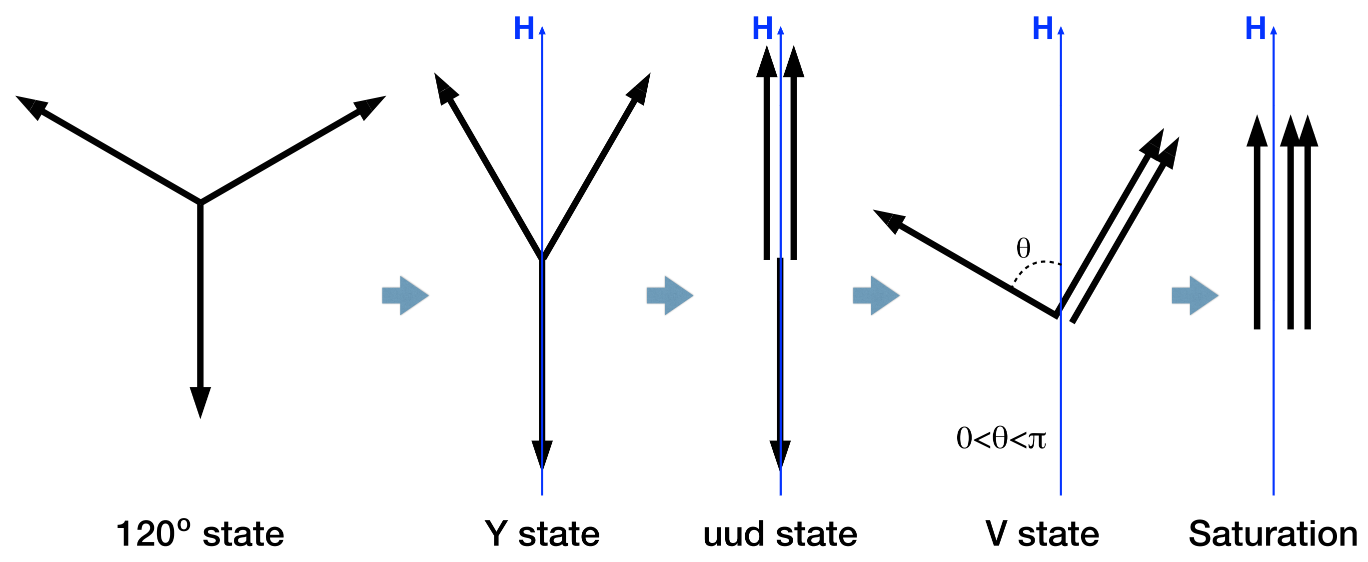
$$E \sim \sum_{ij} (S_i S_j)^2$$

M. E. Zhitomirsky, J. Phys.: Conf. Ser. 592, 012110(2015).

H_x dependence of magnetization

$$E/J = \sum_{i,j=A,B,C} \mathbf{S}_i \cdot \mathbf{S}_j + \gamma \sum_{\substack{i,j=A,B,C \\ i\neq j}} (\mathbf{S}_i \cdot \mathbf{S}_j)^2 - \frac{1}{3}\mathbf{H} \cdot \sum_{i=A,B,C} \mathbf{S}_i$$





Magnetoelastic coupling and bi-quadratic exchange

Magnetoelastic coupling is accounted for the variation of exchange constant ($\delta J = Ke$, where e is strain). With elastic energy, we conclude

$$F \sim JS^2 \rightarrow F = (J + Ke)S^2 + \frac{1}{2}Ce^2$$

For equilibrium,

$$\frac{\partial F}{\partial e} = KS^2 + Ce = 0$$

so that

$$e = -\frac{K}{C}S^2$$

therefore,

$$F = JS^2 - \frac{1}{2}\frac{K^2}{C}S^4$$

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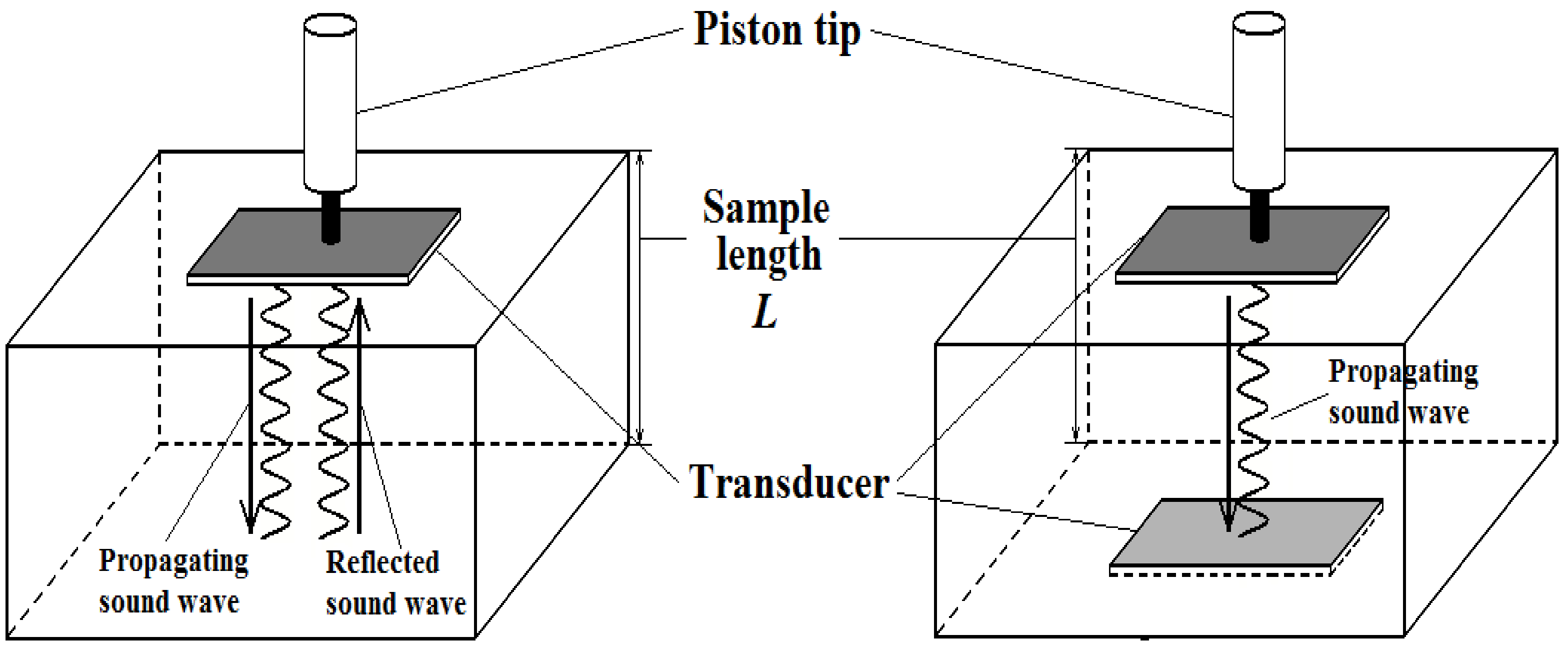
γ

Bi-quadratic exchange

Reflection and Transmission configuration



Phase difference Φ:

$$\Phi = \frac{2\pi t}{T} = \frac{2\pi L f}{v}$$

Ignoring thermal expansion and keeping the relative phase difference equal to zero:

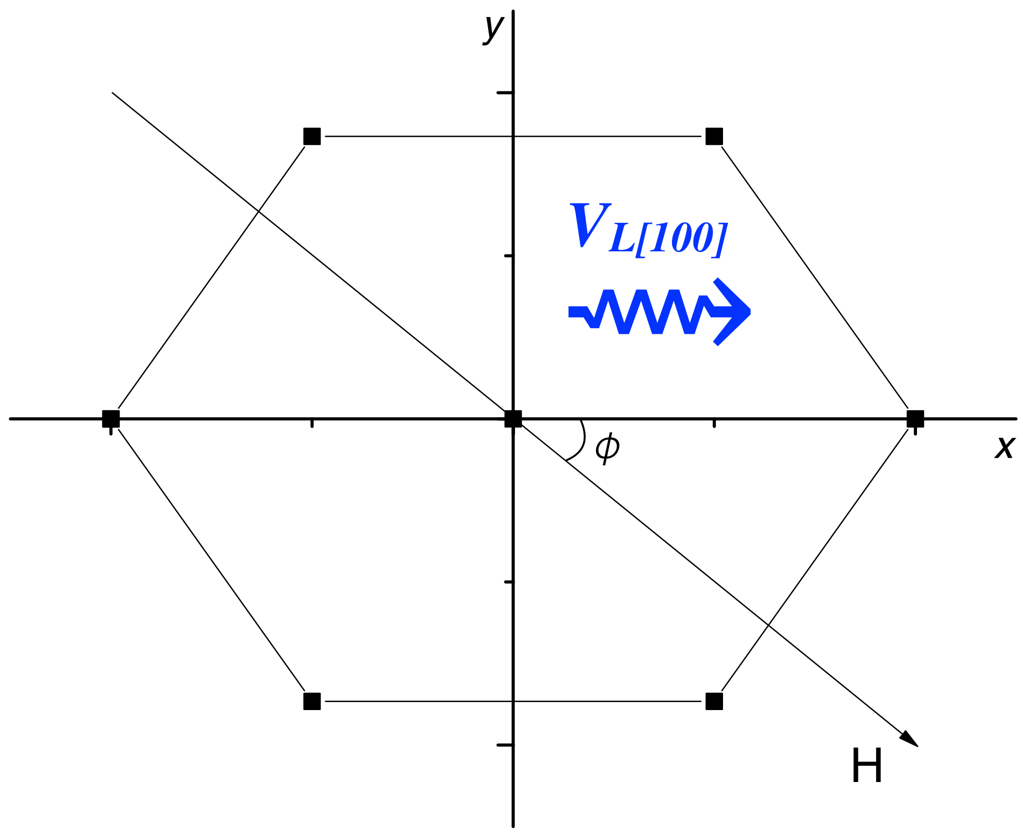
$$\frac{\Delta\Phi}{\Phi} = \frac{\Delta f}{f} - \frac{\Delta v}{v} = 0.$$

With $v = \sqrt{\frac{C}{\rho}}$, where C is elastic constant, ρ is mass density,

$$\frac{\Delta C}{2C} = \frac{\Delta v}{v} = \frac{\Delta f}{f}\,.$$

Angular dependence of $\Delta V/V$

Geometry of the experiment



$V_{L[100]} = \sqrt{C_{11}/\rho}$ as function of ϕ

$\phi = 0^\circ$ corresponds to $\mathbf{H} \parallel x$-axis

Period: 180° for hexagonal symmetry without distortion

Angular dependence of $\Delta V/V$

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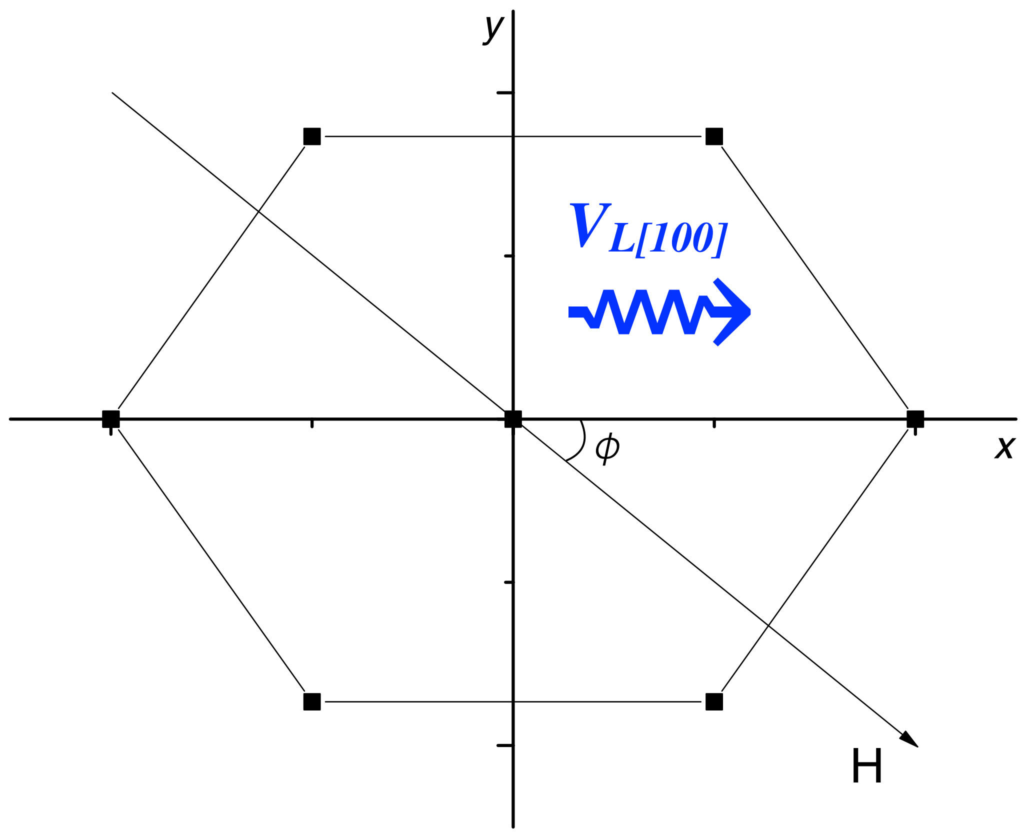

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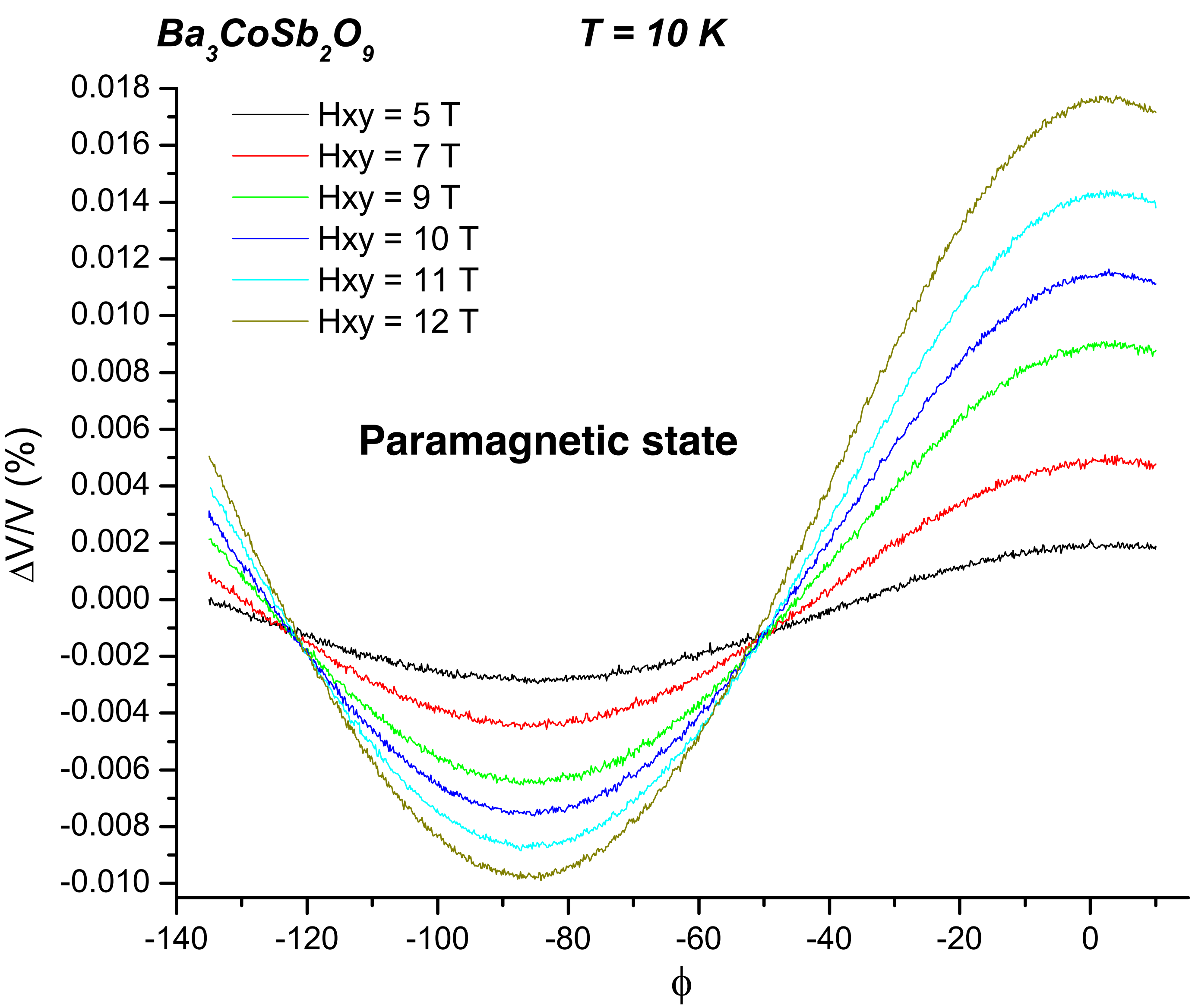


Linear-quadratic magnetoelastic coupling

The total free energy includes elastic coupling (*F(e)*), linear-quadratic magnetoelastic coupling (*F(m, e)*) and the magnetization contribution (*F(m)*):

$$F = F(e) + F(m, e) + F(m),$$

where (using the Voigt notation)

$$\begin{aligned} F(e) &= \frac{1}{2} C_{\alpha\beta} e_\alpha e_\beta, \\ F(m,e) &= K_{\alpha\beta} \mathcal{M}_\alpha e_\beta, \\ F(m) &= A_Q \mathbf{m}^2 - \mathbf{m}\ \mathbf{H}, \end{aligned}$$

$$\begin{array}{lllllll} \mathcal{M}_\alpha = \{ & m_x^2, & m_y^2, & m_z^2, & 2m_y m_z, & 2m_z m_x, & 2m_x m_y \}, \\ \alpha = \{ & 1, & 2, & 3, & 4, & 5, & 6 \}, \end{array}$$

$C_{\alpha\beta}$ (elastic tensor) and $K_{\alpha\beta}$ (l-q tensor) remain invariant under the symmetry operations I^2, C_y^2, C_z^2, C_z^3.

$\Delta C'_{11}/2C_{11}$ and distortion

The angular dependence of the new elastic tensor $C'(\phi)$ is obtained using

$$C'(\phi) = \frac{\partial^2 F}{\partial e_\alpha \partial e_\beta} - \frac{\frac{\partial^2 F}{\partial e_\alpha \partial m} \frac{\partial^2 F}{\partial e_\beta \partial m}}{\frac{\partial^2 F}{\partial m^2}}.$$

Therefore, the effect of linear-quadratic magnetoelastic coupling ($F(m, e)$) can be measured by

$$\frac{\Delta V_{L[100]}}{V_{L[100]}} \simeq \frac{\Delta C'_{11}(\phi)}{2C_{11}} \simeq \frac{C'_{11}(\phi) - C'_{11}(0)}{2C_{11}}$$
$$= A_{em} \sin^2(\phi) + B_{em} \sin^4(\phi)\,,$$

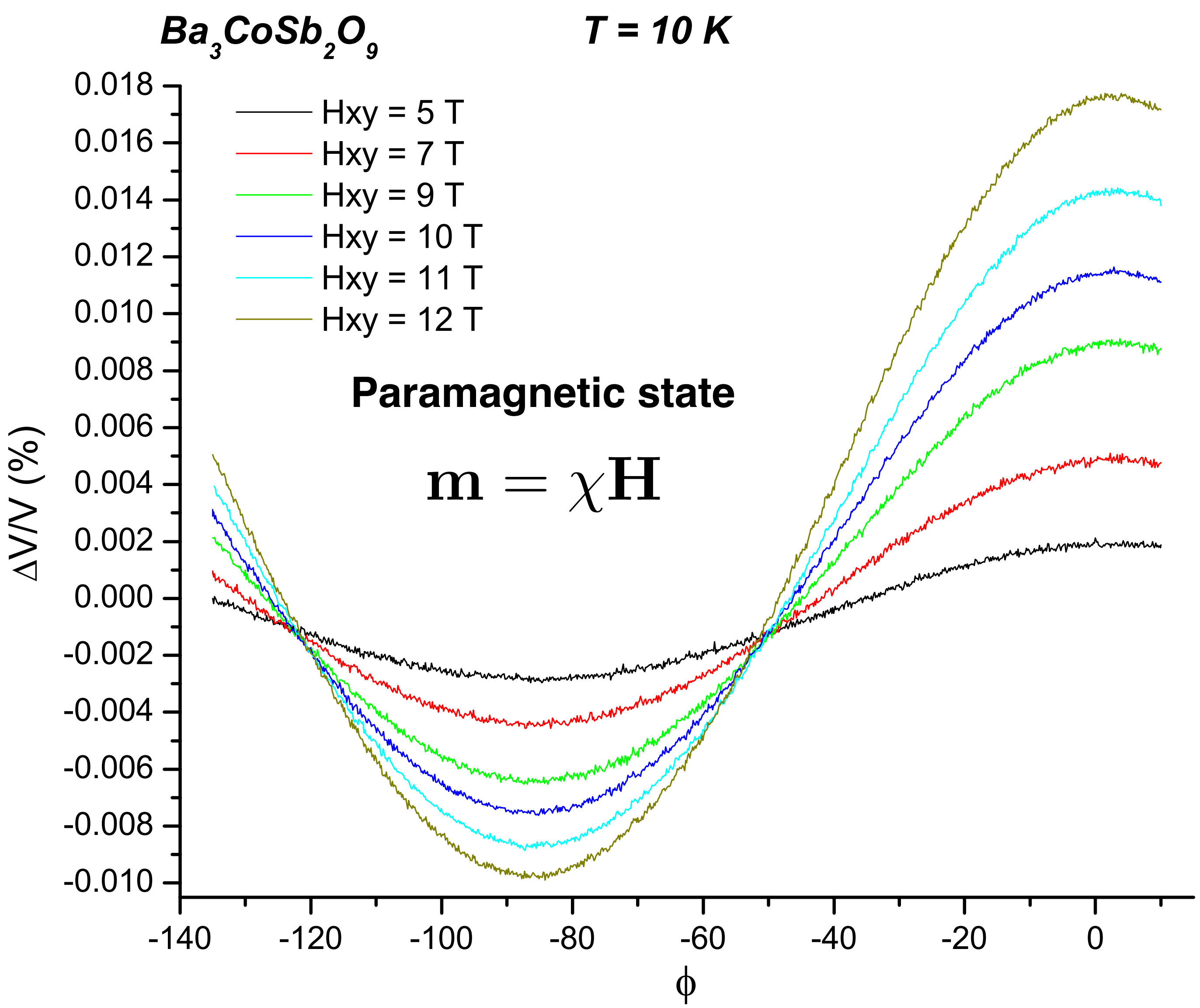
where

$$A_{em} = -\frac{8K_{m66}K_{m11}m^3}{C_{11}H}, \quad B_{em} = \frac{8K^2_{m66}m^3}{C_{11}H}$$

Strain:

$$e_1 - e_2 = -\frac{m^2 K_{m66}\cos(2\phi)}{C_{66}}\,, \quad e_6 = -\frac{m^2 K_{m66}\sin(2\phi)}{C_{66}}$$

Experimental results: angular dependence of *ΔV/V* at *T=10K*



$$A_{em} = -\frac{8K_{m66}K_{m11}\chi^3}{\mu_0^3 C_{11}}H^2$$

$$B_{em} = \frac{8K_{m66}^2\chi^3}{\mu_0^3 C_{11}}H^2$$

$$e_1 - e_2 = -\frac{\chi^2 K_{m66}}{\mu_0 C_{66}}H^2\cos(2\phi)$$

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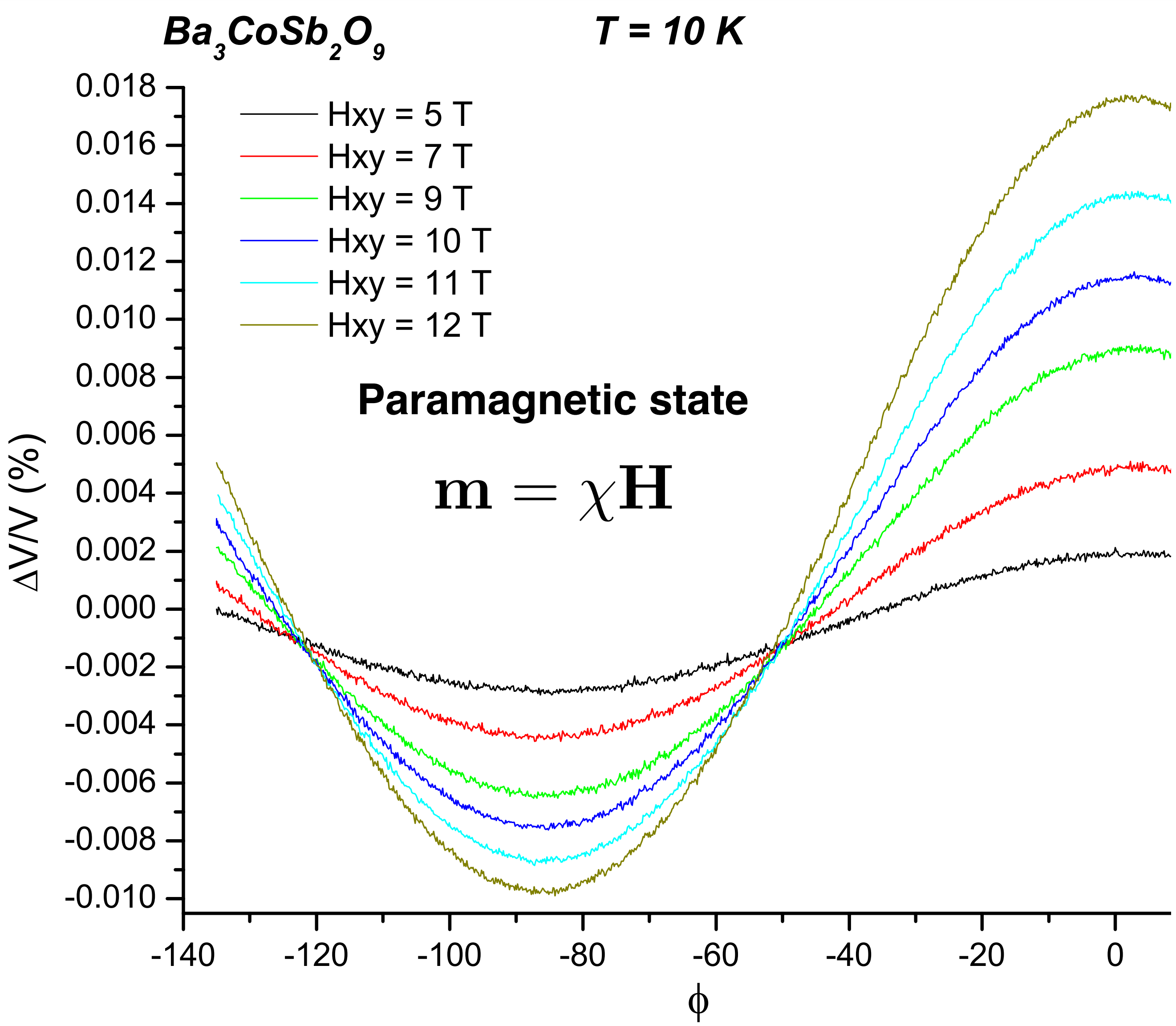

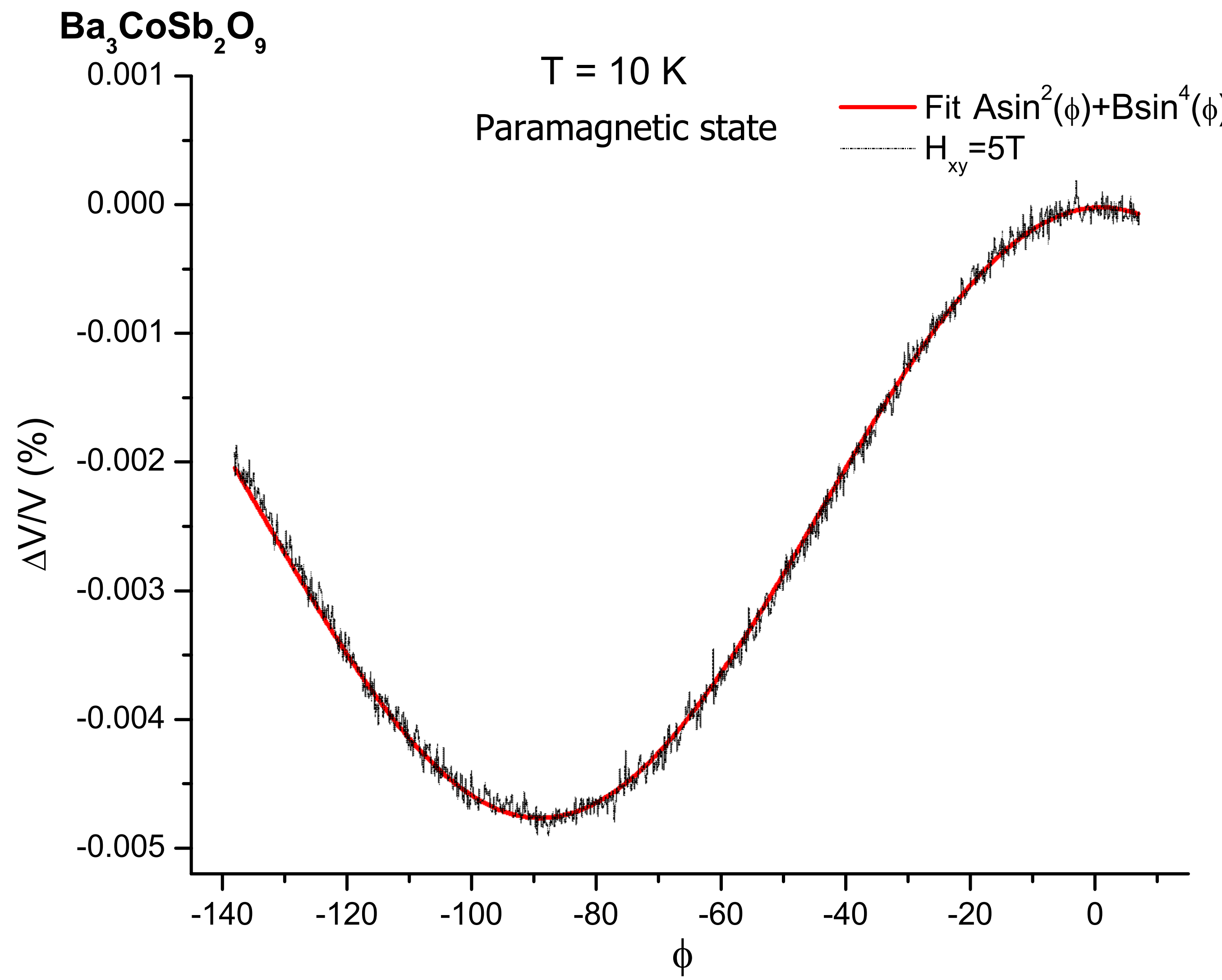

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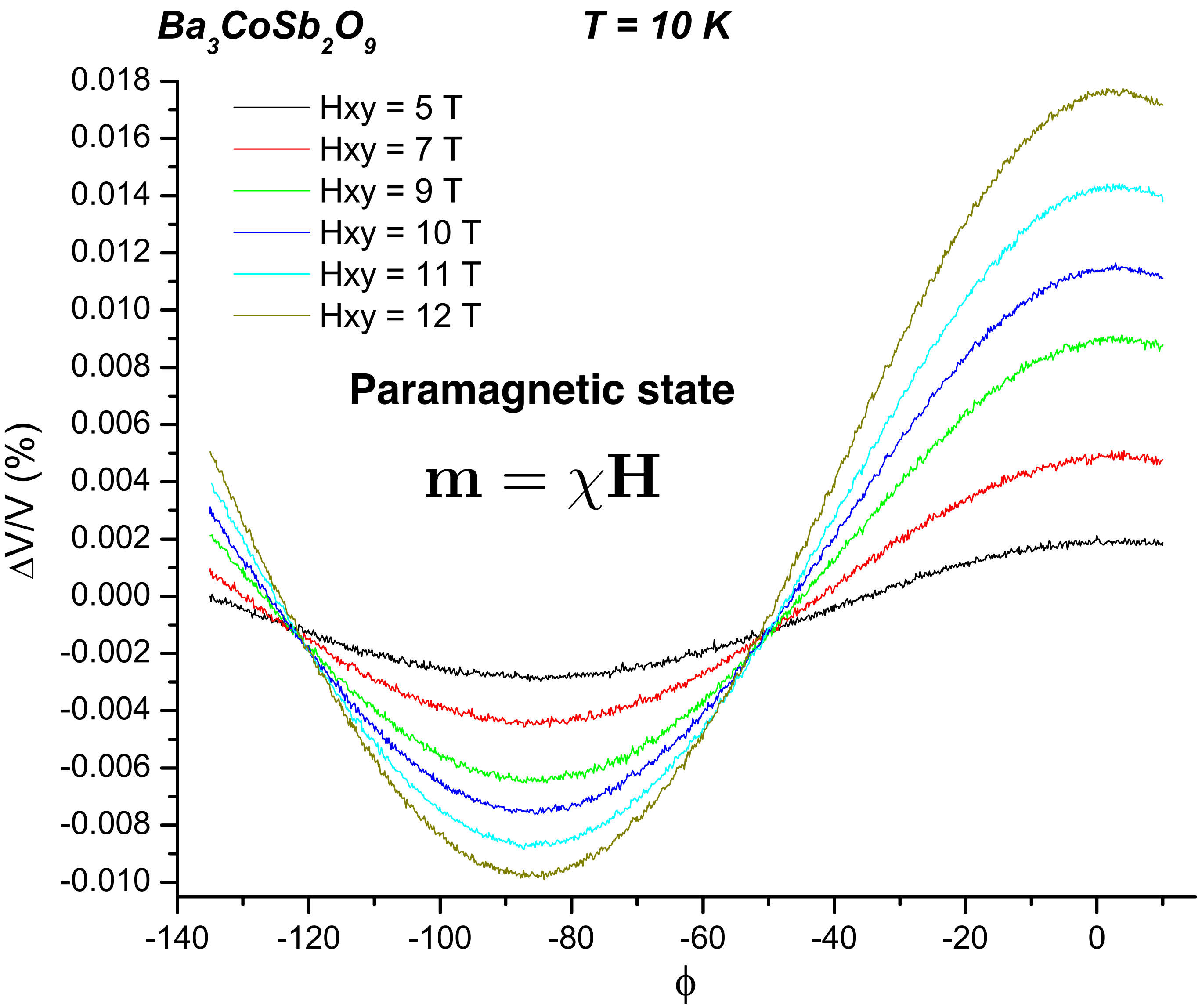

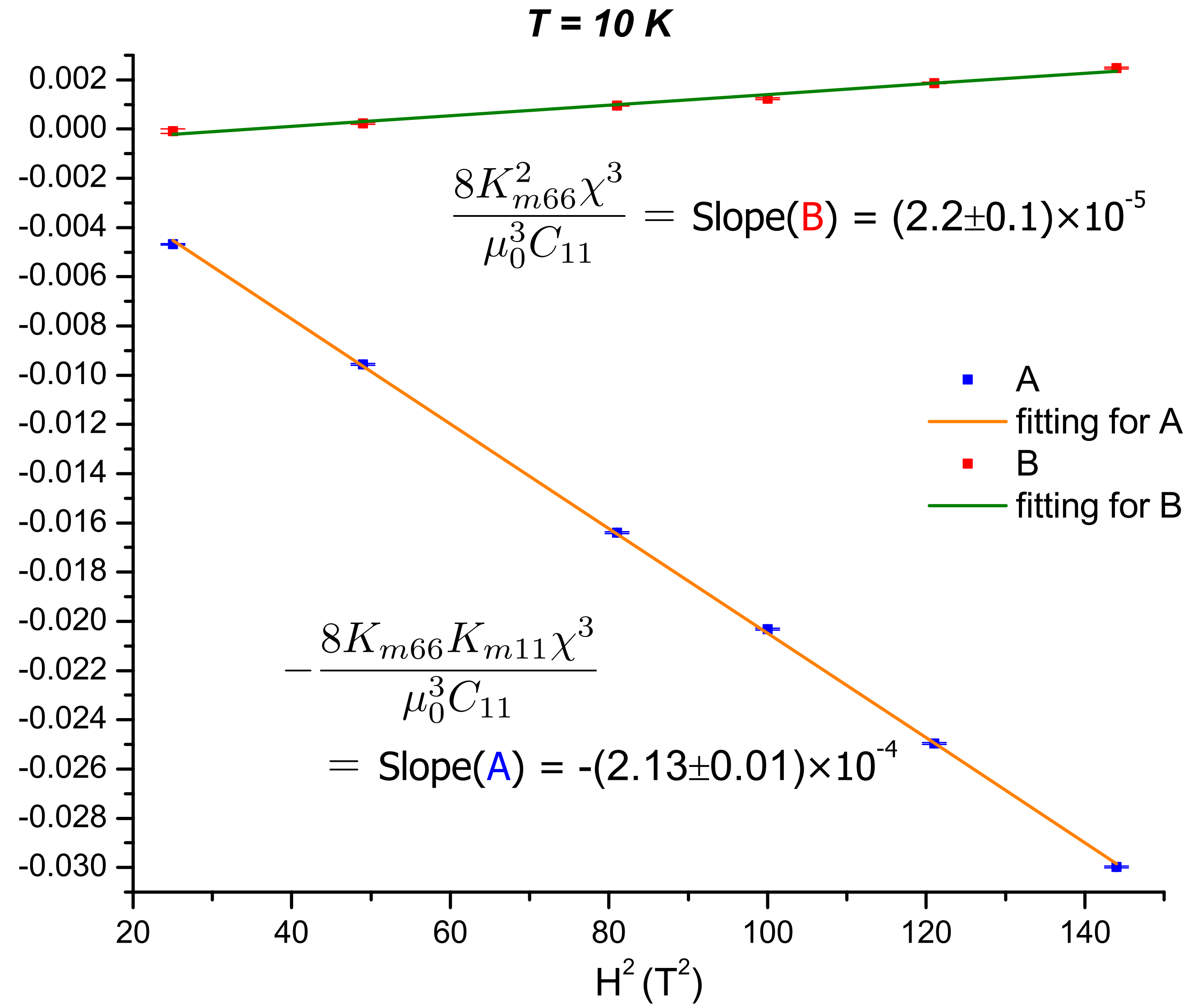

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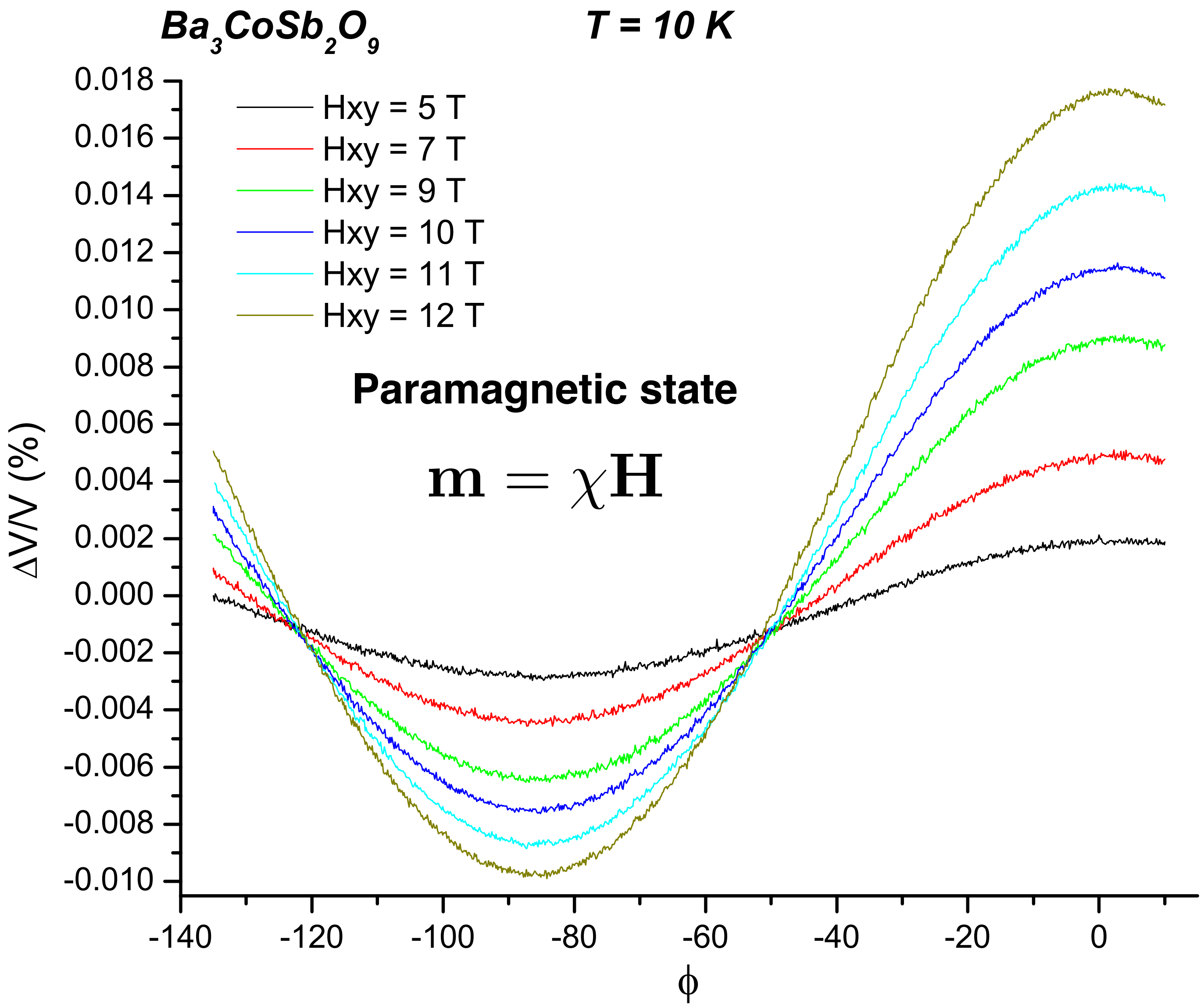

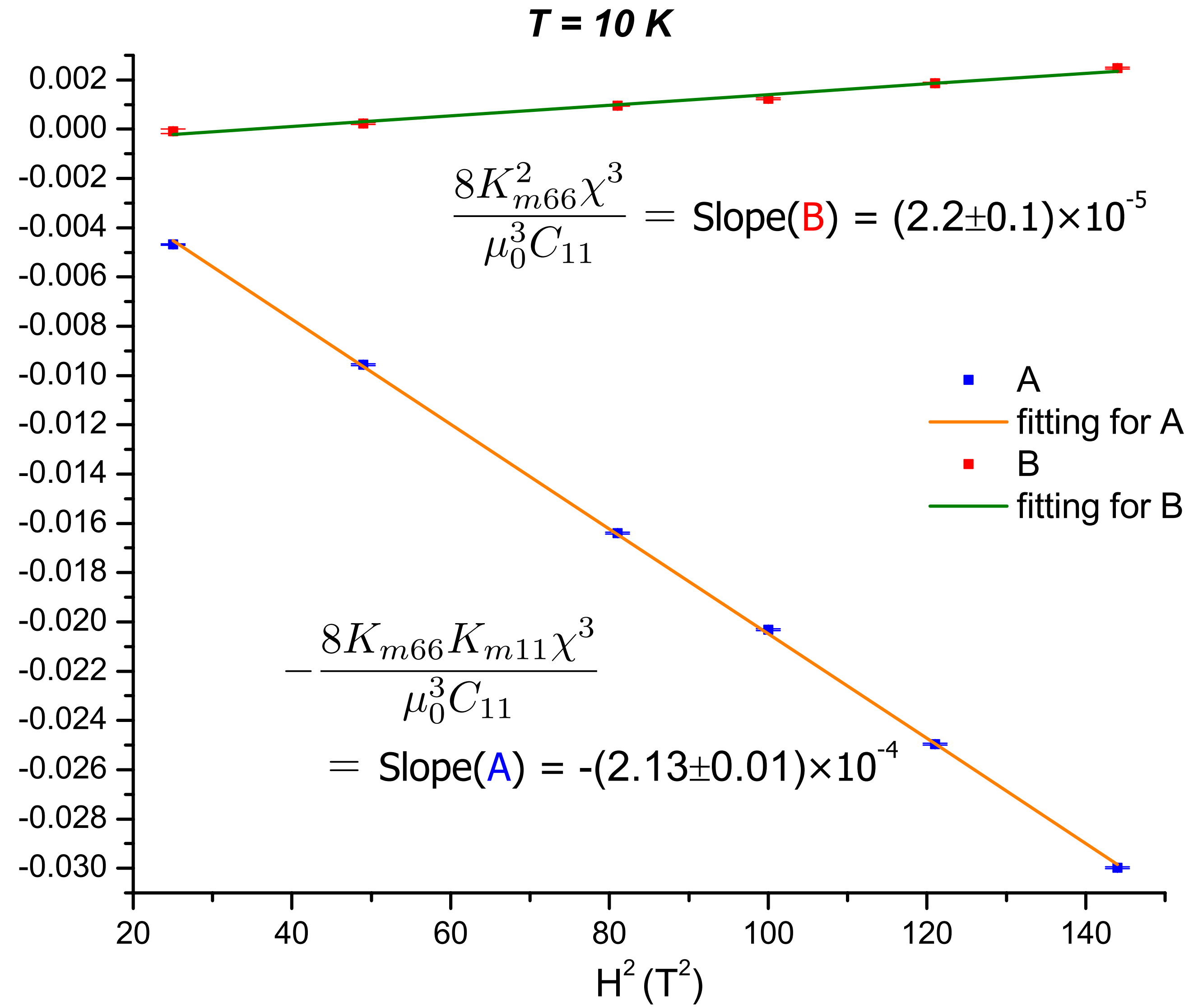

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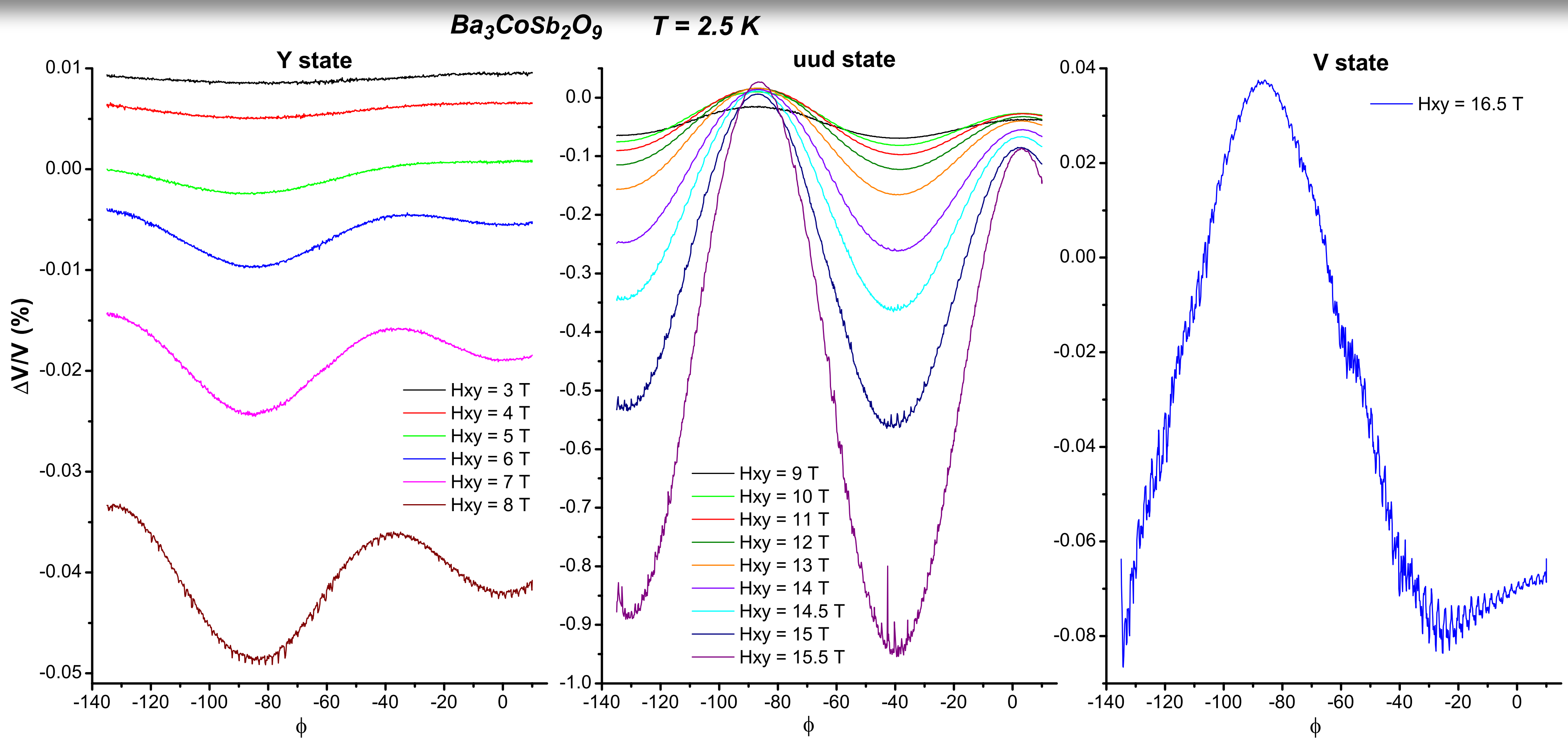
For $\boldsymbol{H} // \boldsymbol{x}$ and $1\,T < H < 20\,T$,
in paramagnetic state

$$10^{-6} \lesssim e_1 - e_2 \lesssim 10^{-4}$$

Experimental results: Angular dependence of *ΔV/V* at *T=2.5K*



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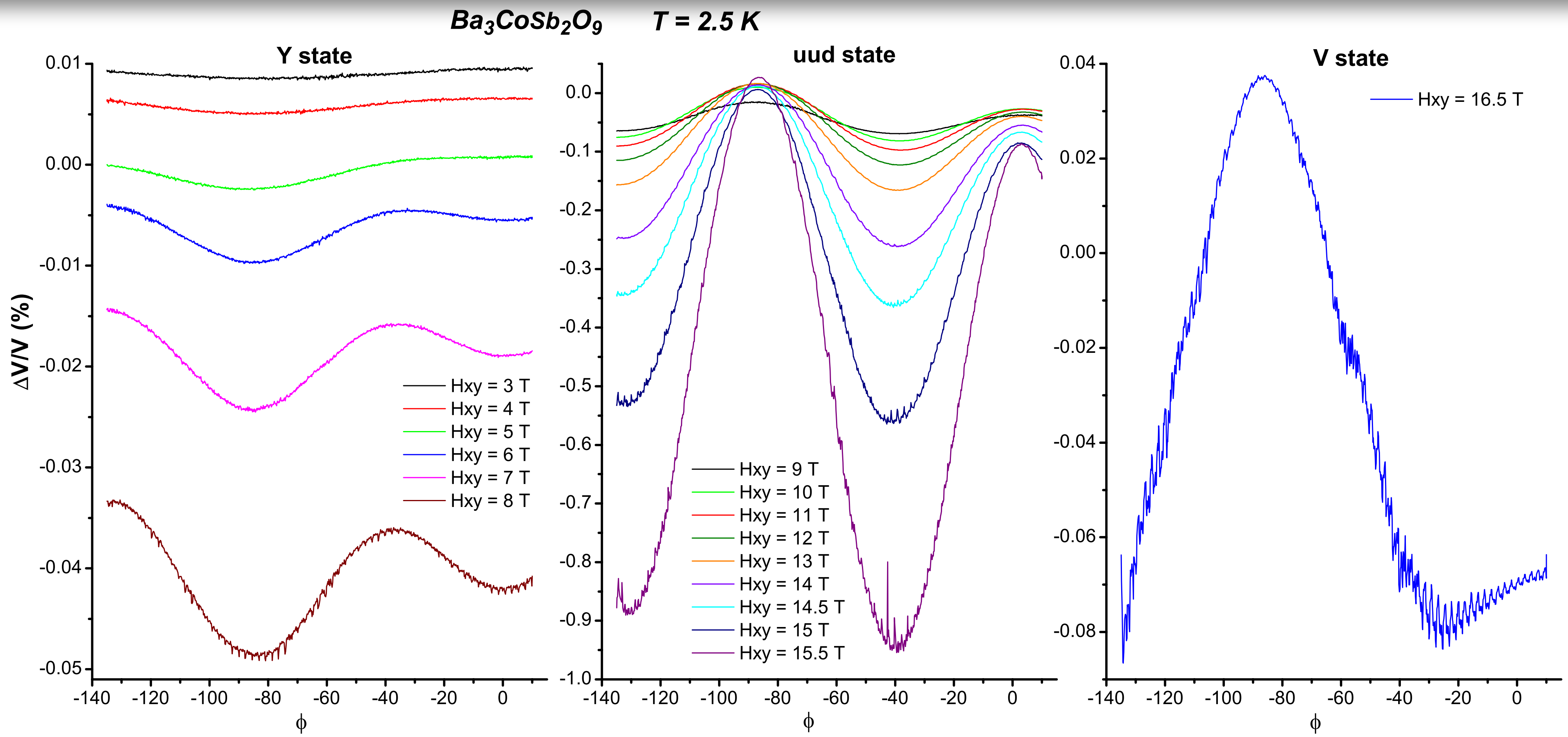

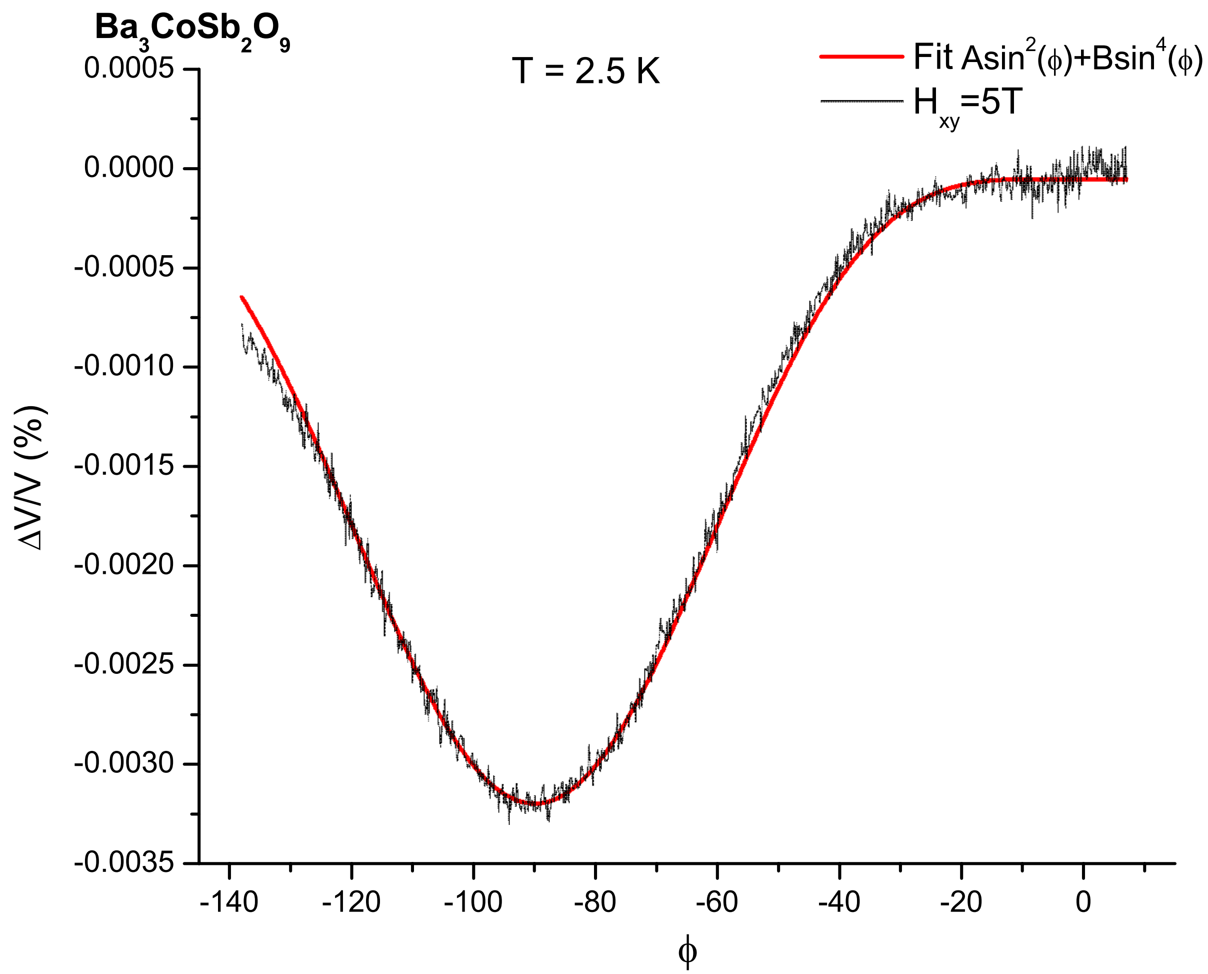

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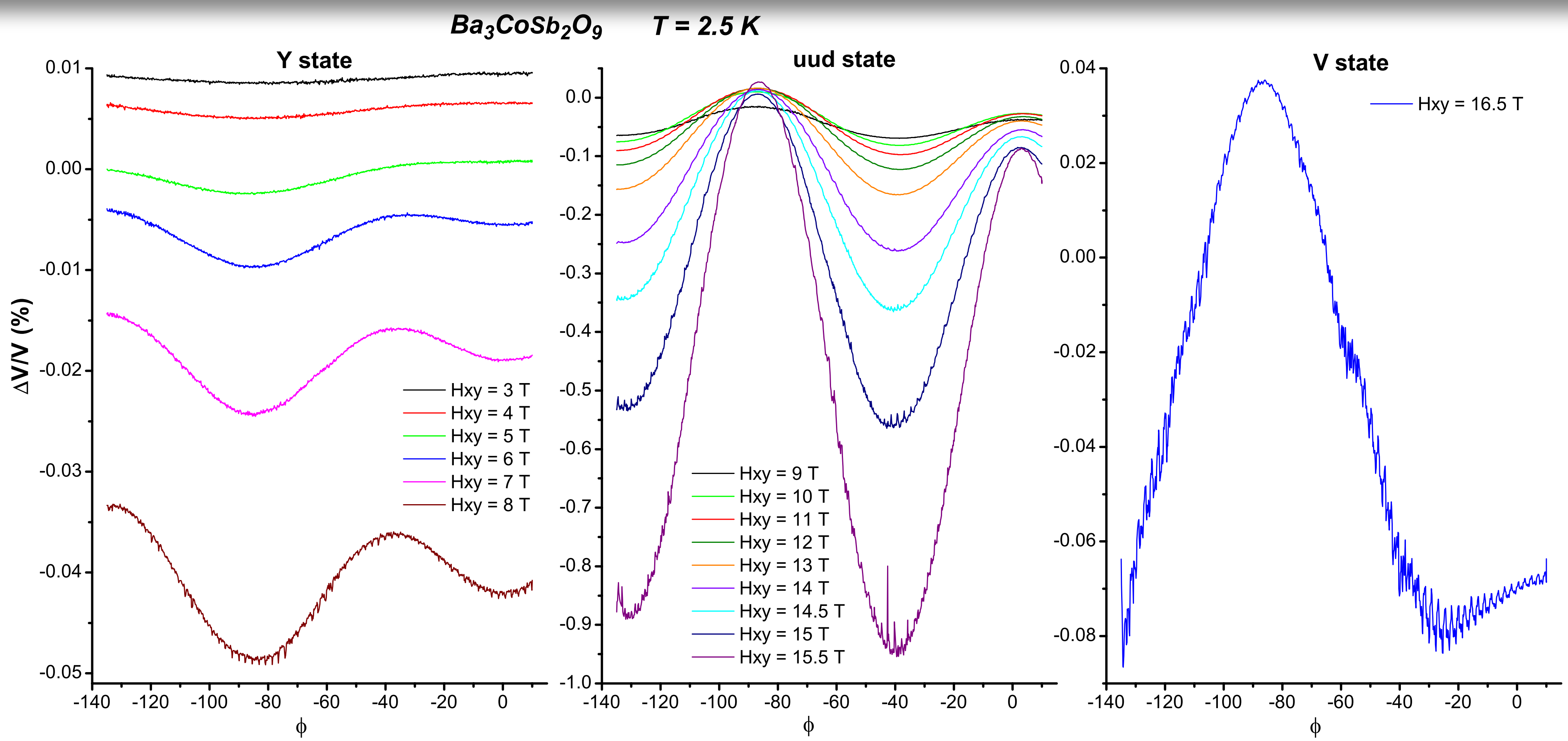

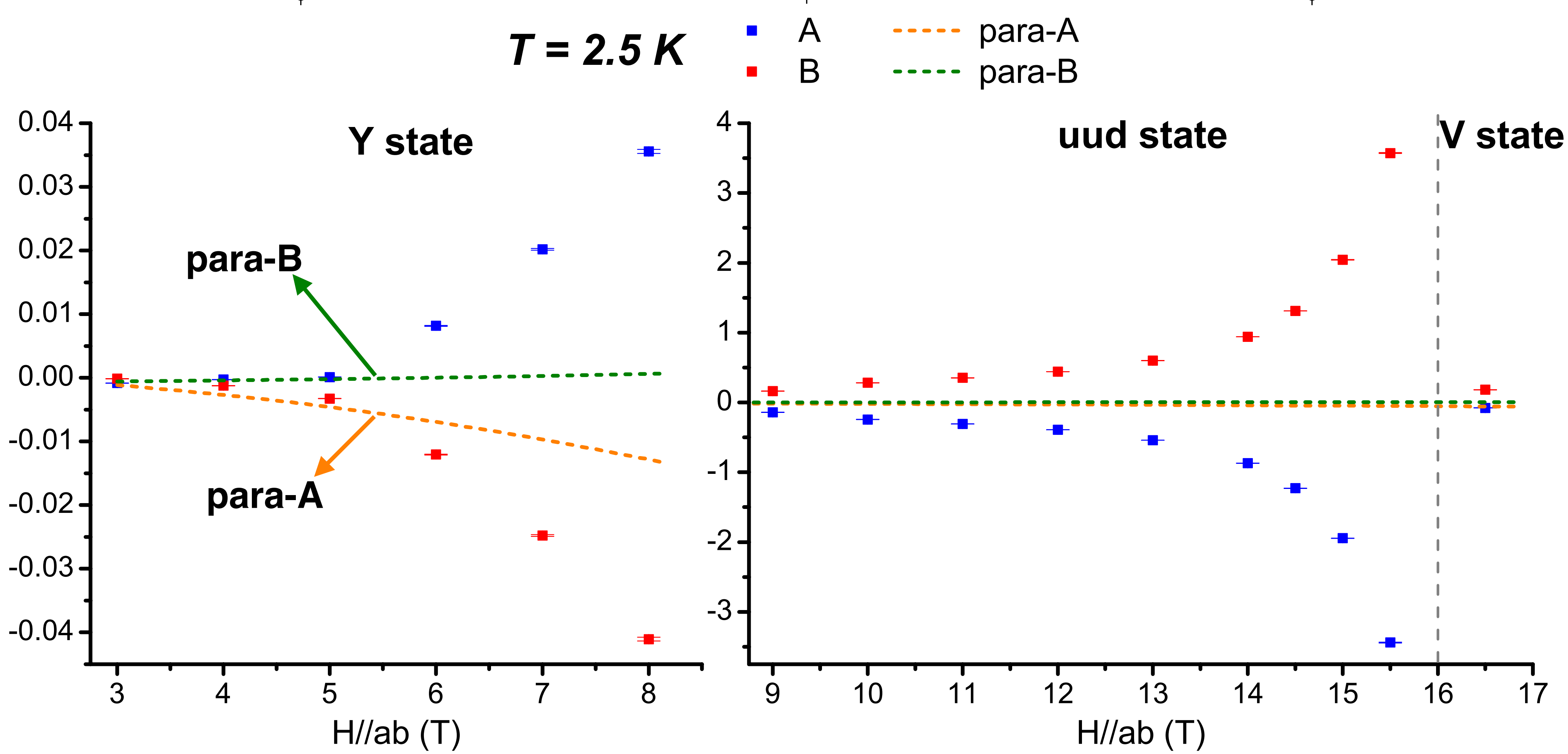

Conclusion and future work

1. Significant lattice distortions are included in paramagnetic state and ordered states as a function of the field;
2. The distortion is much larger in the ordered states than in paramagnetic state, especially in up-up-down state (magnetization plateau);
3. The direction of distortion might change from Y state to uud state;
4. Maintaining the magnetization plateau, lattice distortion works together with fluctuations, and some energy might be transferred from exchange coupling to elastic energy of lattice via spin-strain coupling;
5. A model is needed to analyze the spin-strain coupling in ordered states to explain the magnetization plateau;
6. Measurement of the distortions of $Ba_3CoSb_2O_9$ in paramagnetic state and ordered states as function of field is needed to confirm our conclusion.