Frustration-driven magnetic order on the Shastry-Sutherland lattice

Pinaki Sengupta
Nanyang Technological University
Singapore

Workshop on Current Trends in Frustrated Magnetism
Jawaharlal Nehru University, New Delhi

10th Feb., 2015

NANYANG TECHNOLOGICAL UNIVERSITY

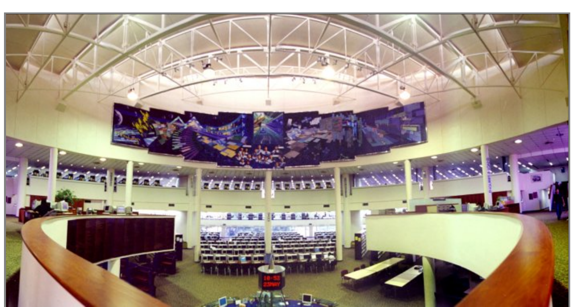
Collaborators

Theory:

- Keola Wierschem, NTU
- Zhifeng Zhang, NTU
- Naoki Kawashima, ISSP, U. Tokyo
- Takafumi Suzuki, U. Hyogo

Expt.:

- Christos Panagopoulos, NTU
- Sunku Sai Swaroop, NTU
- Tai Kong, Ames Lab, Iowa
- Paul Canfield, Ames Lab, Iowa



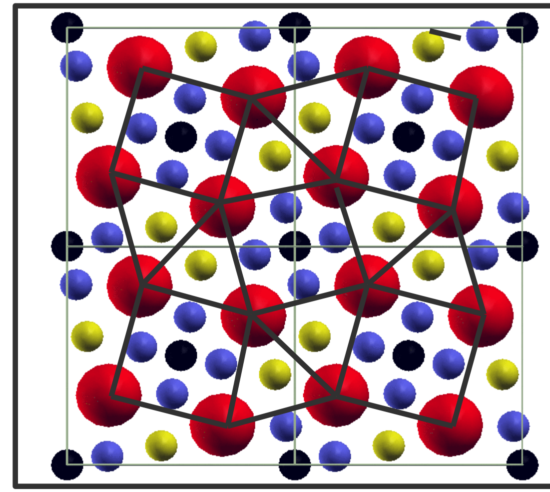
NANYANG TECHNOLOGICAL UNIVERSITY

Outline

- Rare earth tetraborides – a “new” family of Shastry-Sutherland compounds
- Generalized Shastry-Sutherland model
- Magnetization plateaus in TmB_4
- Spin supersolid in the generalized SSM
- Proliferation of plateaus in the generalized SSM
- Conclusion

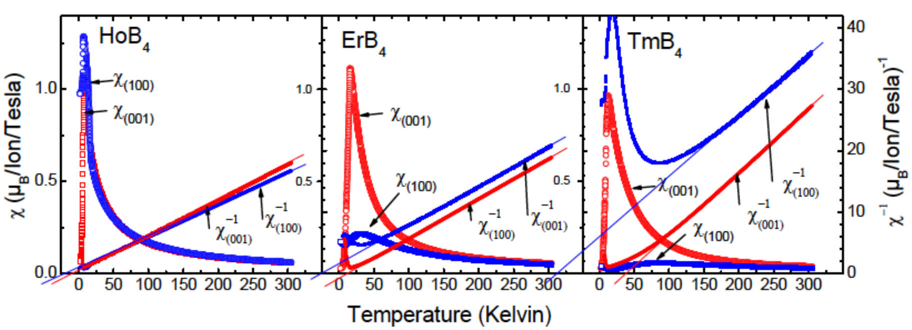
“Other” realizations of the SSL model

- Rare earth tetraborides:
  TmB_4, ErB_4, HoB_4, DyB_4, GdB_4, TbB_4
- R_2T_2M: Yb_2Pt_2Pb, Ce_2Pt_2Pb



- ❑ Weakly coupled layers
- ❑ R^{3+} ions arranged in SSL geometry

	ZF order	μ_{eff} (μ_B)	Θ (K)	T_{N1}	T_{N2}	ΣJ_{ij} (K)	D(K)
TmB_4	Ising-AFM (π,π)	6.6	-63	11.7	9.8	-4.8	-6.4
ErB_4	Ising-AFM (π,0)	8.4	-22.7	15.3		-1.4	-4.6
HoB_4	Ising-AFM (π,π)	9.2	-12.7	7.4	6.3	-1.3	0.3



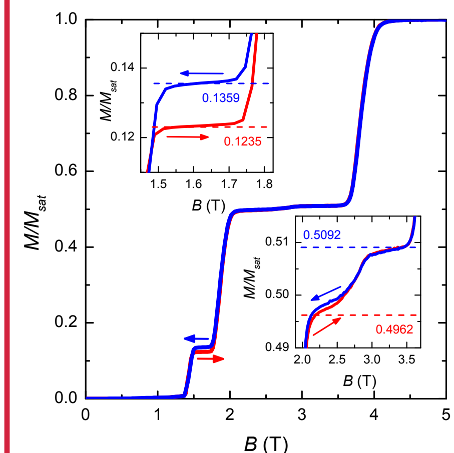
Mata’s. et.al., J. Phys: Conf. Ser., 200, 032041 (2010)

NANYANG TECHNOLOGICAL UNIVERSITY

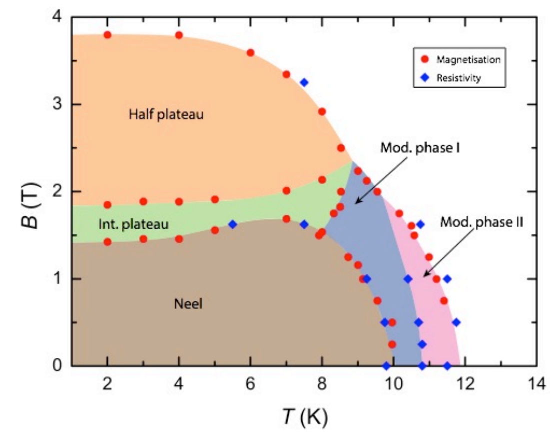
Magnetization plateaus in RB_4

- Ground state has long range magnetic ordering in most of the rare earth tetraborides
- Field-induced plateaus observed in all members
- Sequence of plateaus differ across the family
- Multi-step melting of magnetic order observed in many RB_4 compounds

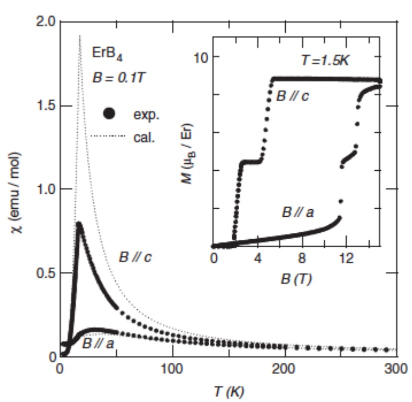
TmB_4



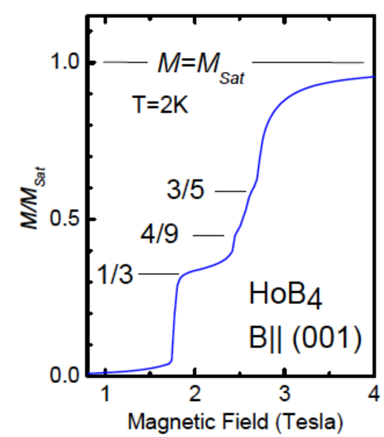
(a) magnetization plateaus,



(b) phase diagram



Uniform susceptibility and field dependent magnetization in ErB_4



Magnetization plateaus in HoB_4

NANYANG TECHNOLOGICAL UNIVERSITY

Rare earth tetraborides

Generic features

- Low saturation field (~ 10T) – low-T neutron scattering possible
- Span wide parameter regime including magnetic ground state at zero field
- Higher spins, single ion anisotropies ⟹ effective exchange anisotropy
- Additional interactions

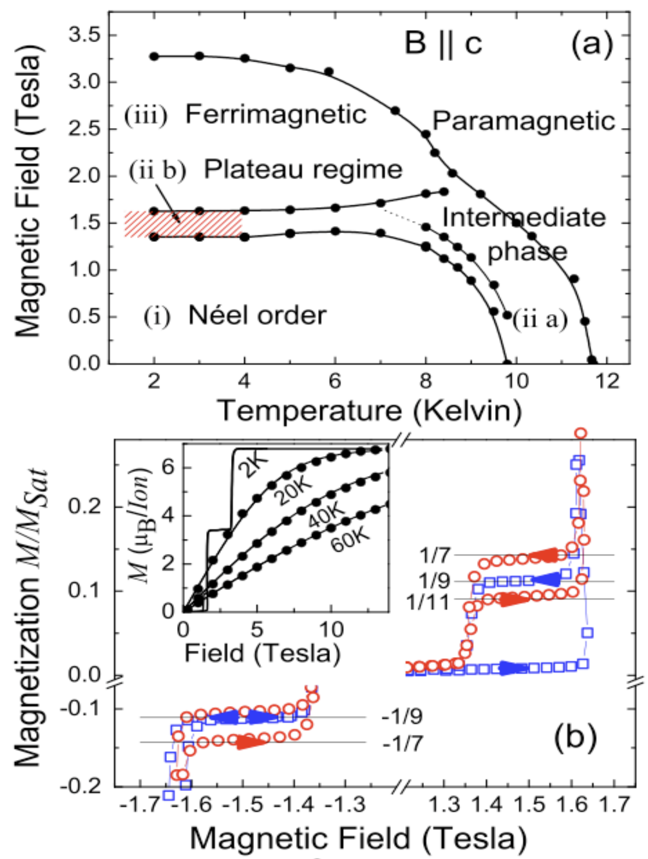
Extensive insight into the interplay of competing strong interactions and geometric frustration in the Shastry-Sutherland lattice

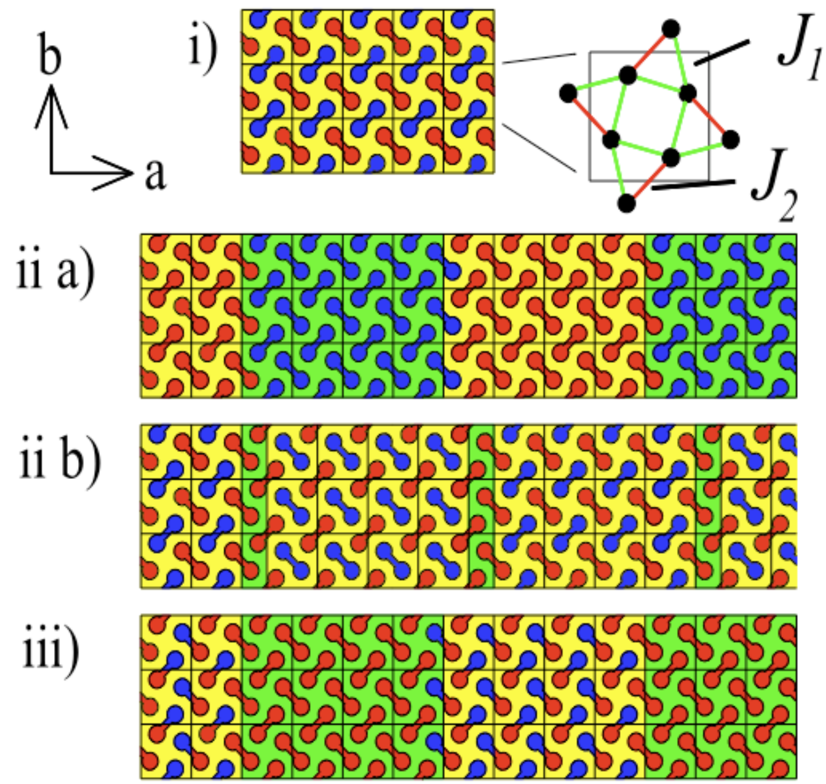
Metallic ground state – interaction of itinerant electrons with localized magnetic moments in a frustrated configuration – interesting magneto-electric effects

NANYANG TECHNOLOGICAL UNIVERSITY

Magnetization Plateaus in TmB_4

Stripe superstructures modulate underlying short-range structures



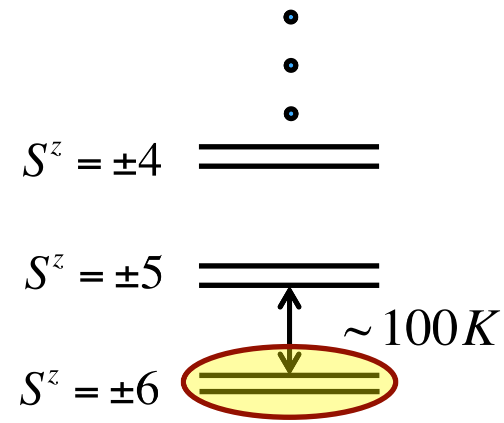


K. Siemensmeyer et. al., PRL **101**, 177201 (2008)

NANYANG TECHNOLOGICAL UNIVERSITY

Low energy effective model

- Large magnetic moment for Tm^{3+}: $S = 6$
- Large single-ion anisotropy: $-D\left(S_i^z\right)^2, D/J \approx 5$



Effective low energy model involving the lowest 2 levels

$$H = \sum_{\langle i,j \rangle} J_{ij}^z S_i^z S_j^z + J_{ij}^{xy}(S_i^x S_j^x + S_i^y S_j^y)$$

$$J_{ij}^{xy} < 0 \qquad J_{ij}^z \gg |J_{ij}^{xy}|$$ Ising limit

Ferromagnetic exchange term – sign problem in QMC simulations alleviated

Stochastic Series Expansion QMC algorithm used for simulation

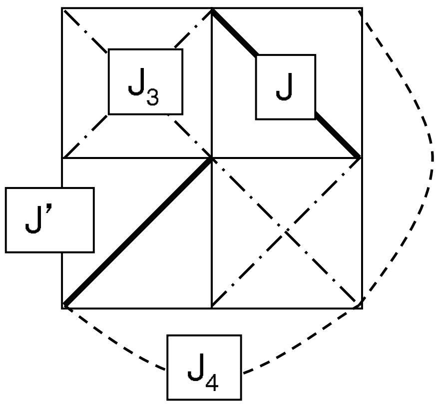
NANYANG TECHNOLOGICAL UNIVERSITY

Generalized Shastry-Sutherland model

- S=1/2 XXZ model with large Ising anisotropy
- J and J’ along the SSL lattice axes

Longer range interactions mediated by itinerant electrons

- NNN interaction (J_3) along the diagonals of the plaquettes with no J
- Additional 3^{rd} neighbor interaction J_4
- Same anisotropy for all interactions.



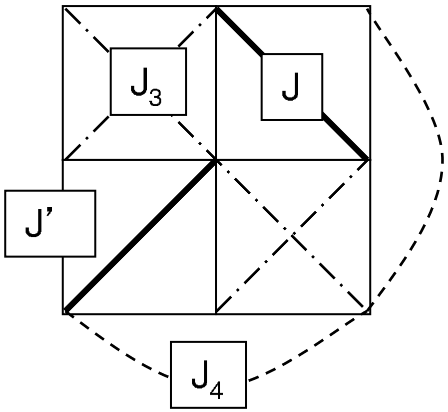
- ❑ Rich variety of magnetic phases
- ❑ Potentially realized in the different members of the rare-earth tetraborides

NANYANG TECHNOLOGICAL UNIVERSITY

Low energy effective model for TmB_4

Start with the generalized Shastry Sutherland model with J and J'

➡ inconsistency with experimental observation



Ising limit: Extended 1/3 plateau followed by a direct transition to full saturation

TmB_4: Extended ½ plateau, no 1/3 plateau

Need additional interactions

Longer range RKKY interactions mediated by itinerant electrons

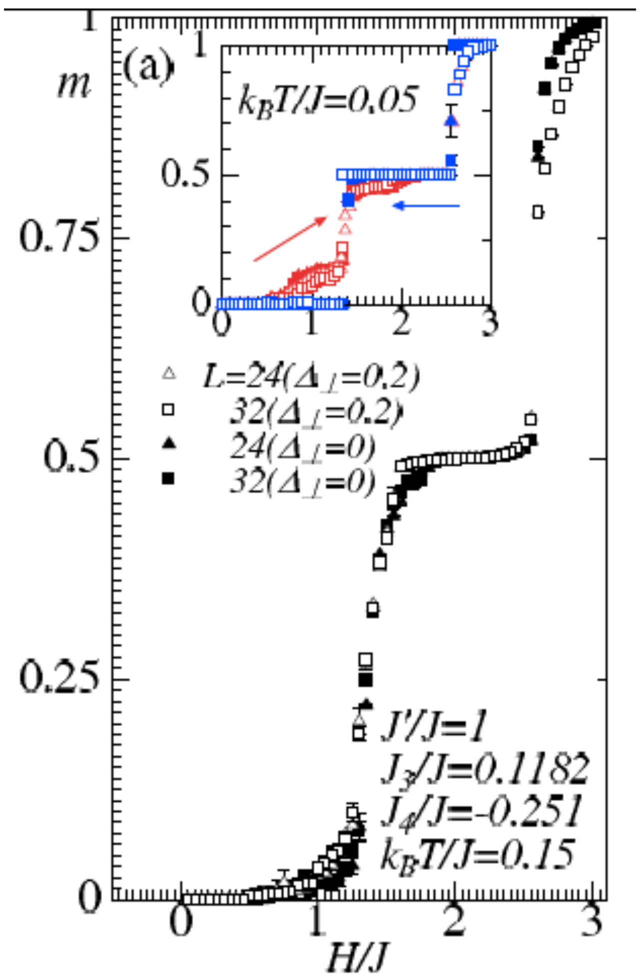
- AFM J_3 necessary to account for the appearance of ½ plateau
- FM J_4 necessary to explain the suppression of 1/3 plateau

Together they explain the principal plateau structure observed in TmB_4.

Suzuki, et. al., PRB **80**, 180405 (2009); PRB **82**, 214404 (2010)

NANYANG TECHNOLOGICAL UNIVERSITY

Modeling TmB_4

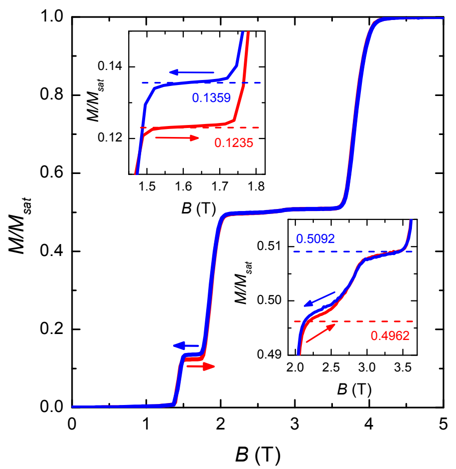


- ✓ Correct critical values for $m/m_s=1/2$ plateau reproduced
- ✓ Correct saturation field reproduced
- ✓ No evidence of lower magnetization plateaus for the current model
- ✓ No evidence for "hysteresis" effects.

Suzuki, et. al., PRB **80**, 180405 (2009); PRB **82**, 214404 (2010)

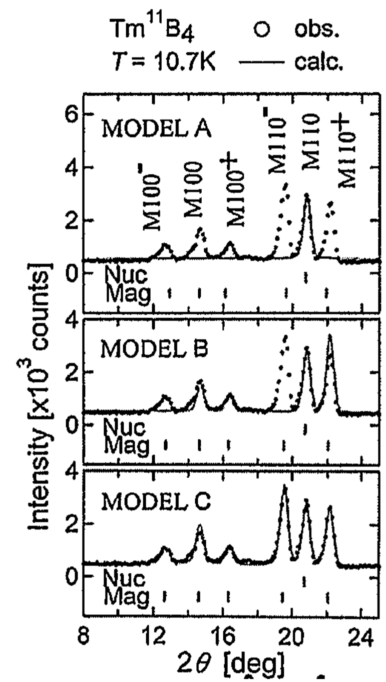
NANYANG TECHNOLOGICAL UNIVERSITY

Fractional plateau in TmB_4

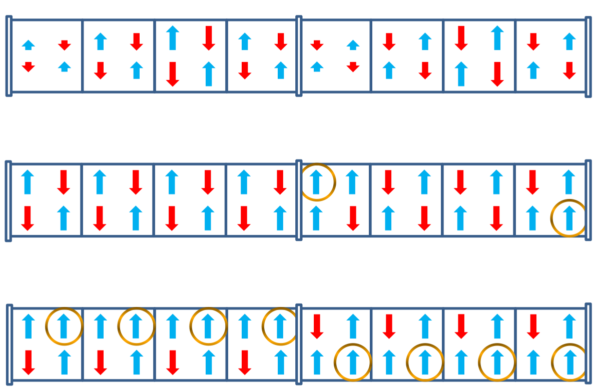


Fractional plateau and hysteresis in TmB_4

- Fractional plateau observed in TmB_4 at $m/m_s \sim 1/8$
- Magnetic hysteresis observed at the fractional plateau
- Neutron scattering → modulated AFM ground state with incommensurate periodicity
- Provides simple explanation for observed magnetic behaviour
- Predict modulated structure for both fractional and ½ plateaus – need to be confirmed experimentally



Neutron scattering data Michimura, et.al., 2009

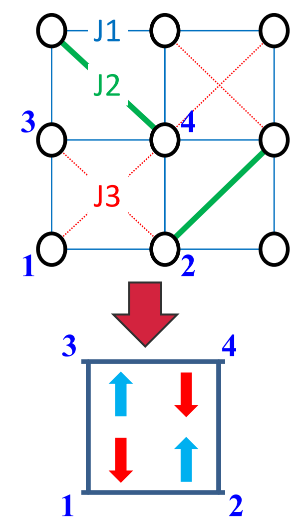


Modulated AFM

1/8 plateau

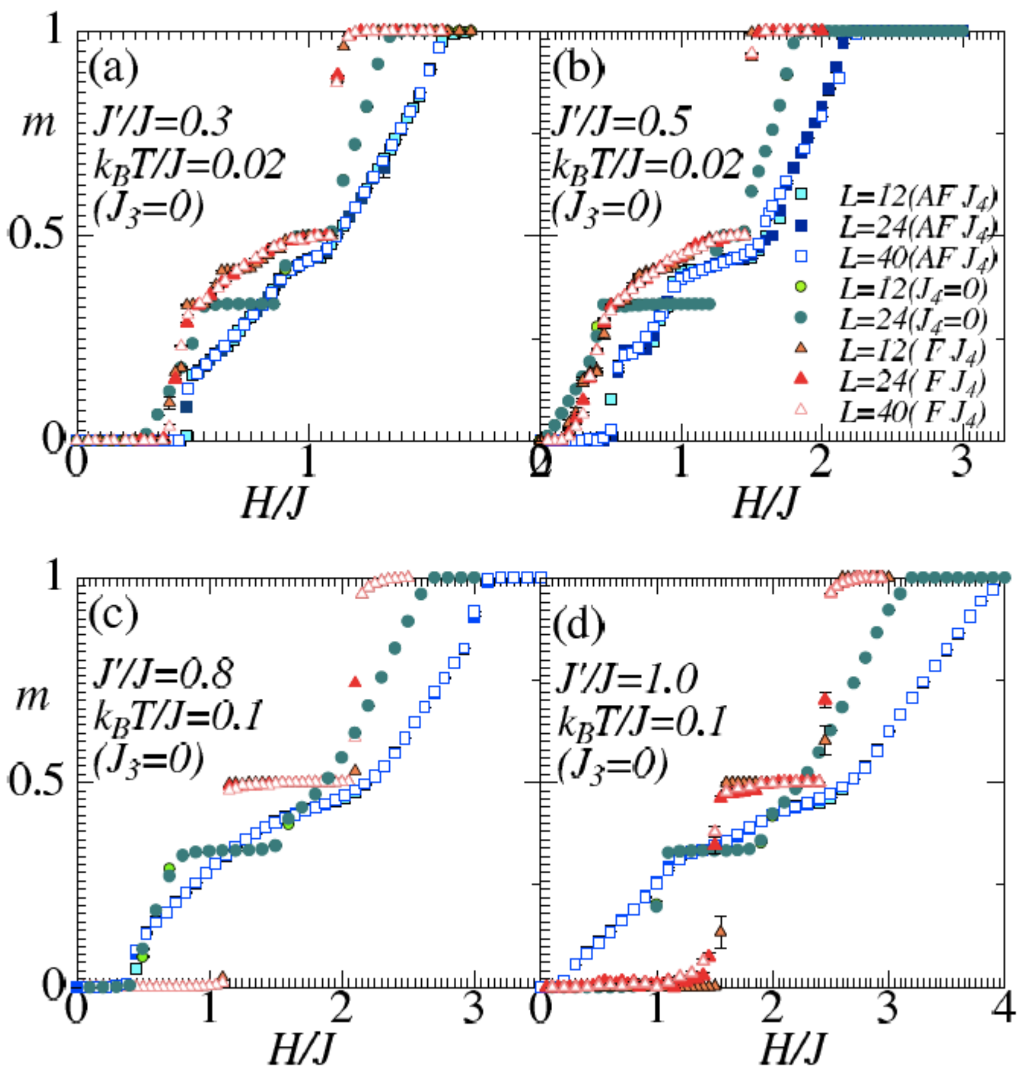
½ plateau

Schematic spin configuration



NANYANG TECHNOLOGICAL UNIVERSITY

Magnetization in generalized SSM

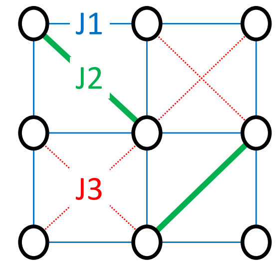


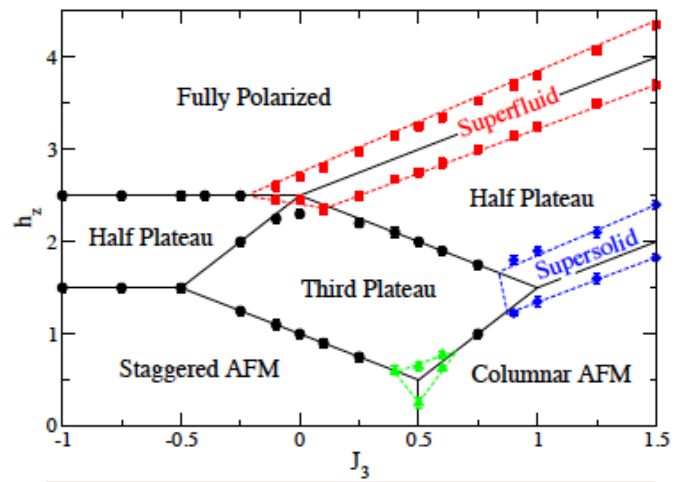
- Varied sequence of magnetization plateaus as the parameters are varied
- Fertile framework for investing frustration drivn field induced magnetic phases – plateaus, spins-supersolid (?)
- Potentially realizable in the different members of the rare earth tetraboride family of compounds
- Help identify dominant interactions driving observed magnetic phases

NANYANG TECHNOLOGICAL UNIVERSITY

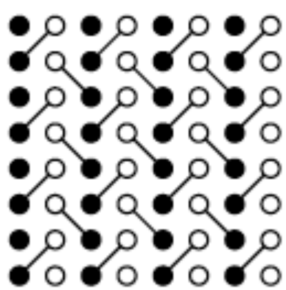
Magnetization plateaus in extended SSM

- Effect of J_3 explored in detail
- ZF: (π,π) AFM order for FM and weak AFM J_3 in the Ising limit
- (π,0) AFM order for moderate to strong AFM J_3 – observed in ErB4
- 1/3 plateau persists to finite J_3
- ½ plateau appears for any $J_3 \neq 0$
- Finite exchange interactions induce superfluidity at boundary between plateaus





Magnetic phases driven by J_3



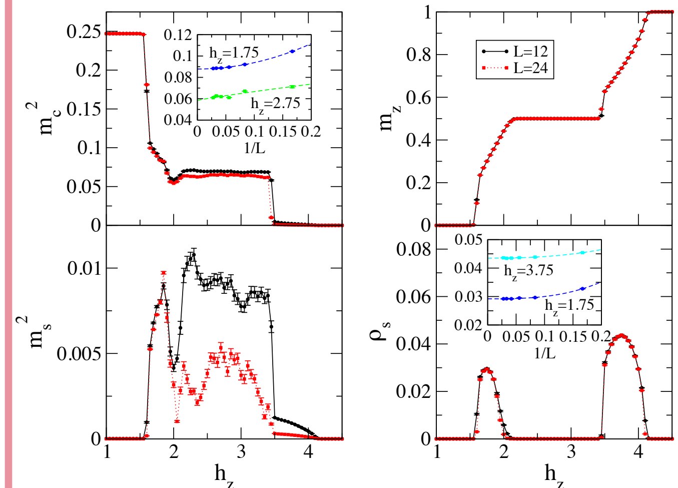
Columnar AFM order

K. Wierschem and P.S., PRL **110**, 207207 (2013)

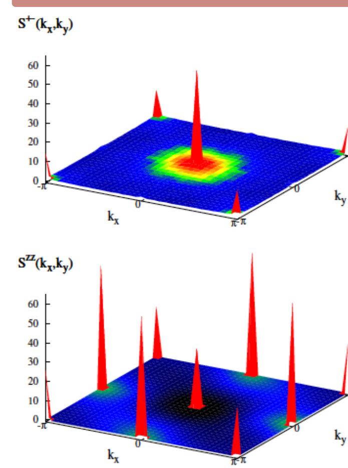
NANYANG TECHNOLOGICAL UNIVERSITY

Spin supersolid in extended SSM

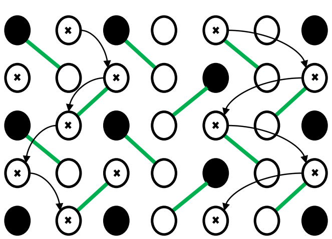
- Spin supersolid GS observed at densities close to, but less that half-filling
- Longitudinal AFM order at $(\pi,0)$ and (π,π)
- Transverse AFM order at (π,π)
- Simple mechanism based on delocalization of holes in the half-plateau by 1st order process
- Magnetization behaviour qualitatively similar to ErB4, but spin SSOL phase not yet reported



Simulation results showing the appearance of spin SSOL



Transverse and longitudinal structure factors in the spin SSOL phase



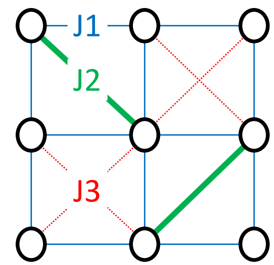
Delocalization of a single flipped spin at the ½ plateau

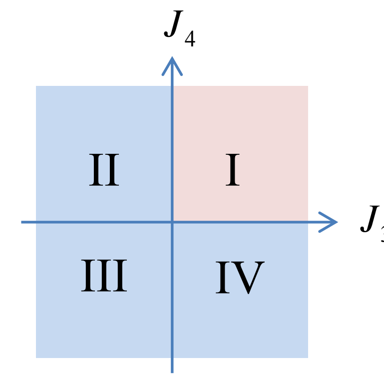
K. Wierschem and P.S., PRL **110**, 207207 (2013)

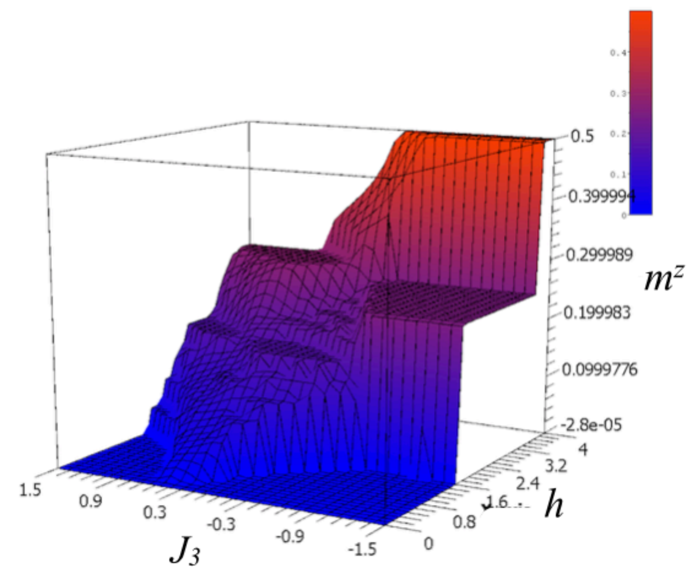
NANYANG TECHNOLOGICAL UNIVERSITY

Magnetic phases in generalized SSM

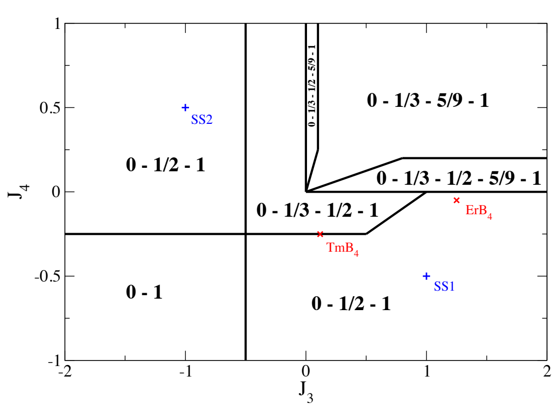
- Inclusion of J_4 changes plateau sequence significantly
- AFM J_3 and J_4 destabilises the ½ plateau – emergence of the 5/9 plateau
- Different structures for same plateau realised for different parameters
- Spin-SSOL stablised over extended parameter ranges







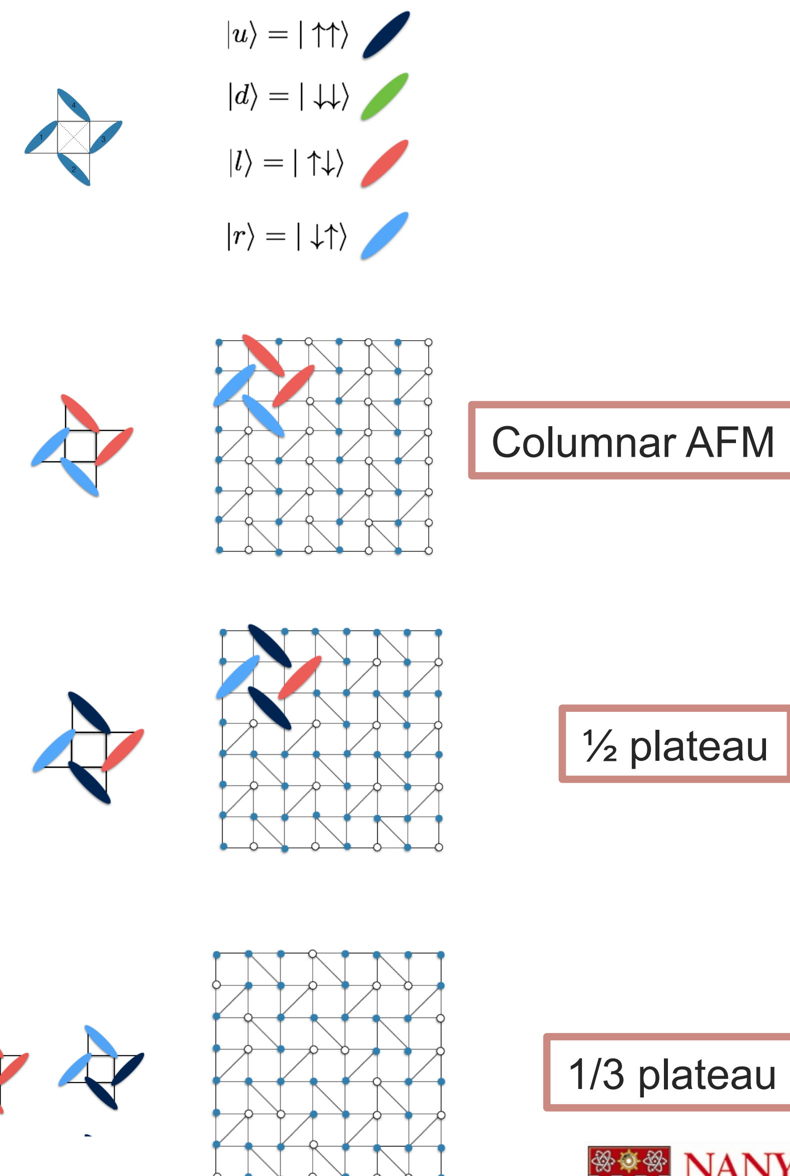
Evolution of plateau sequence for finite J4 in the XXZ model

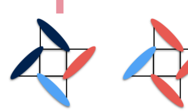


Plateau sequence in the Ising limit for finite J_4

Understanding plateaus in generalized SSM

- Explain spin textures at plateaus in terms of a plaquette unit cell
- Construct a “pinwheel” around a square with no diagonal bond
- Many different configurations possible (for Ising spins)
- Local dimer states determine nature of spin modulation
- Many possibilities for same plaquette magnetic moment
- Leads to multiple distinct plateaus with same magnetization
- Possible because of additional interactions
- Stable for finite exchange - Confirmed by QMC simulations in XXZ model





Electronic transport in rare earth tetraborides

- Itinerant electrons in rare earth tetraborides couple to local moments
- Electronic transport affected significantly by underlying magnetic texture
- Study within the framework of Shastry Sutherland Kondo lattice model (SSKLM)
- Control electronic transport by applied magnetic field and magnetism by driving current
- Small change in applied magnetic field changes magnetic structure – interesting magneto-electric phenomena

NANYANG TECHNOLOGICAL UNIVERSITY

Conclusions

- Interplay between geometric frustration, strong interaction and high magnetic field results in many novel quantum phases on the Shastry-Sutherland lattice

- Rare earth tetraborides present experimental realizations of many of these phases

- Metallicity makes these quantum magnets even more interesting

- Magnetic phases explored in great detail – transport promises new phases and phenomena

The best is yet to come !

NANYANG TECHNOLOGICAL UNIVERSITY