Quantum magnetism and the theory of strongly correlated electrons

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Helmholtz Zentrum Berlin

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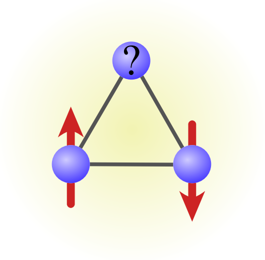

Outline

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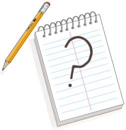
- Format of the seminar

- How to give a presentation

- How to search for scientific literature

- Possible topics for a presentation



Format of the seminar

Format of the seminar

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- Prepare a beamer presentation (∼45 min) about a topic in the field of quantum magnetism/ strongly correlated electrons

  Preparation includes:

  - search for literature (some initial reference will be given)
  - hand in a abstract (1 week before talk, will be announced on webpage)
  - one meeting with instructor (myself) before talk (optional)

- Present the talk in front of the seminar group

- Participation in discussion after each talk

source: sbs.ox.ac.uk

How to give a presentation

Giving a talk

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- Tell a story
- Motivate your topic. Why is this topic interesting?
- Keep things simple!
  - Use simple physical pictures/illustrations/graphs
  - Avoid complex formulas
- Fair citation
- Understand everything you present!

source: trainingsoutheast.blogspot.com

Consider the audience

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- Your talk is intended for students, not for specialists in the field
  - Be pedagogical (give introductions)
  - Repeat basics (if necessary)
- Engage the audience
  - Make eye contact
  - Move
  - Make the audience think and not just listen (e.g. ask a question, pause, then give the answer)

source: netrafic.com

Structure of the talk

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Timing of a 45 min talk ($\sim$ 2-3 min per slide):

- Title $\sim$1 min
- Contents 2-4 min
- Introduction 10-20 min
- Main body 20-30 min
- Conclusions 2-4 min
- Discussion after talk

source: jackmalcolm.com

Etiquette:

- Beginning: Thank organizers for invitation or opportunity to present work
- End: Thank for attention
- Acknowledgement (if applicable)

Preparation of slides/talk

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Slides:

- Limit amount of text/formulas
- No need for complete sentences
- Never over-crowd slides
- Make images and text large enough
- highlight keywords/ use colors

source: pixabay.com

Talk:

- Practice your talk (transition between slides)
- Do not read from slides
- Anticipate questions
  - you appear competent when you answer questions
  - but be honest if you don't know the answer

How to search for scientific literature

Scientific literature

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- Textbooks
- Journal articles
  - Regular research article
  - Review articles
  - Popular articles (Physics Today, Physik Journal, ...)

source: imgkid.com

Search for scientific literature

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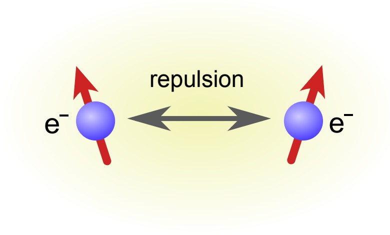
- General scientific database: www.webofknowledge.com
- Search engines of individual journals
  Common journals
  - Nature (Nature physics, Nature materials, Nature nanotechnology)
  - Science
  - APS journals (PRL, PRB, Rev. Mod. Phys.)
  - ...
- Preprint server arXiv (http://arXiv.org)
- Google

source: criticalproof.com

Possible topics for a presentation

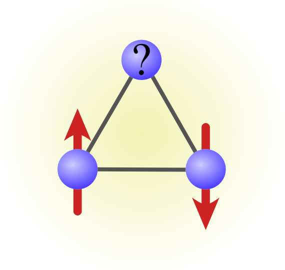
Quantum magnetism and the theory of strongly correlated electrons

strong interactions:



$\Longrightarrow$

magnetic phenomena:



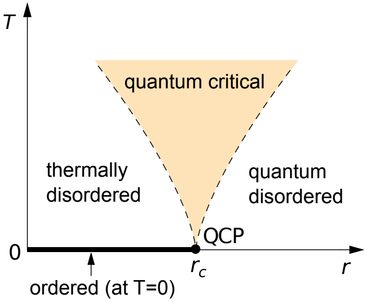
Mott insulators!

Talk 1:
Quantum phase transitions

Temperature driven phase transitions:

- solid - liquid
- ferromagnetic - paramagnetic

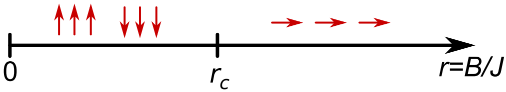
Quantum phase transitions: Only driven by quantum fluctuations at $T = 0$



Still affect properties at $T > 0$:
Quantum criticality

Example: Transverse field Ising model:

$H = \sum_i (-J S_i^z S_{i+1}^z + B S_i^x)$



magnetic $\Longleftrightarrow$ field aligned

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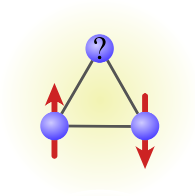
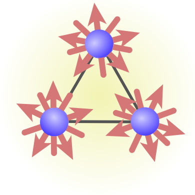
Spin liquids: General theory

Frustration: Competing spin interactions $+\vec{S}_i \vec{S}_j$ in certain arrangements of spins:



⟹ Can lead to destruction of magnetic long-range order:



⟹ Spin liquid: A spin state without any spontaneously broken symmetries.

Still has hidden (topological) order and fractional spin excitations (spinons).

Talk 3:

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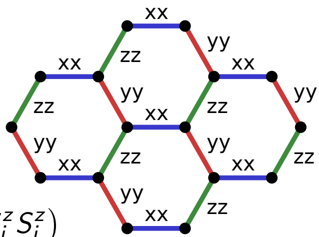
Spin liquids in Kitaev-honeycomb models

Hard to identify a spin liquid in a given spin Hamiltonian
$\Longrightarrow$ numerical approaches necessary!



Exception: Kitaev-honeycomb model:

$$H = J\Big(\sum_{xx-\text{links}} S_i^x S_j^x + \sum_{yy-\text{links}} S_i^y S_j^y + \sum_{zz-\text{links}} S_i^z S_j^z \Big)$$

Exactly solvable using Majorana fermions: $\gamma^\dagger = \gamma \implies \mathbb{Z}_2$ spin liquid.

Possible experimental realizations:

Iridate compounds Na_2IrO_3 and Li_2IrO_3.

Talk 4:

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Spin ice

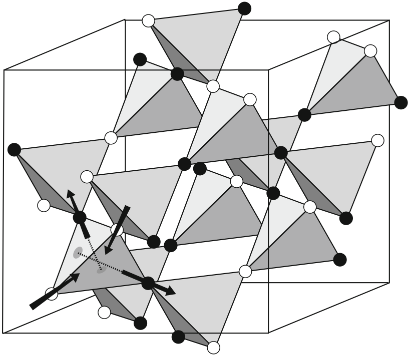
$Dy_2Ti_2O_7$, $Ho_2Ti_2O_7$:

Classical spins on a pyrochlore lattice

Point either in or out a tetrahedron

Ice rule: "two in two out"

⟹ Extensive ground-state degeneracy!



from Lacroix, Mendels, Mila: *Introduction to Frustrated Magnetism*

Emergent phenomena: magnetic monopoles, effective photons...

Talk 5:

Vortices in 2D spin systems

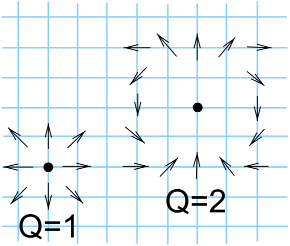
XY-model: $H = -J\sum_{ij}(S_i^x S_j^x + S_i^y S_j^y)$

classical spins in the x-y-plane.

Vortex generation above $T_{KT} \sim J$

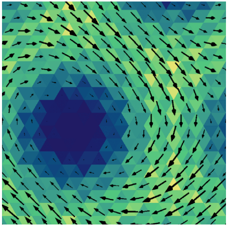
(Kosterlitz-Thouless transition)

($Q =$ topological charge)



from arXiv:0512356

In certain U(1) broken systems vortices can even exist at $T = 0$:

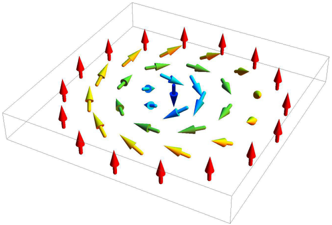


from arXiv:1409.6972

$\mathbb{Z}_2$ vortices with $Q = 0, 1$

Talk 6:

Magnetic skyrmions

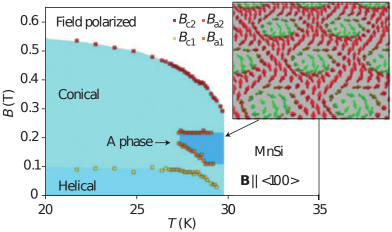


Skyrmions: Topological defects in non-centrosymmetric magnets (similar to vortices)

Stabilized in MnSi by

- Dzyaloshinkii-Moriya interactions $\sim \vec{D}(\vec{S}_i \times \vec{S}_j)$
- External magnetic field B
- finite temperature T

$\Longrightarrow$ form a skyrmion lattice



reproduced from
nature nanotechnology 2013.243

Talk 7:

High T_c-superconductivity

Certain cuprate compounds show superconductivity up to 138K

basis building block: CuO_2 planes

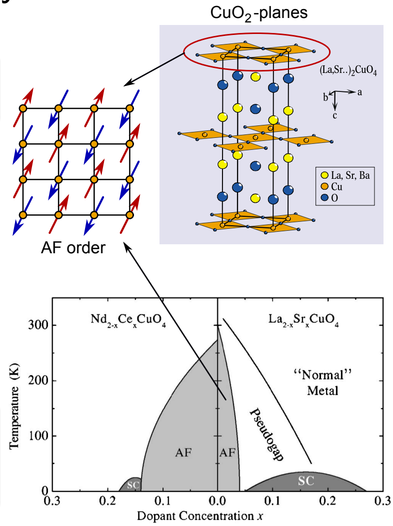
$\Longrightarrow$ described by antiferromagnetic Heisenberg model:

$$H = J \sum_{\langle ij \rangle} \vec{S}_i \vec{S}_j, \qquad J > 0$$

$\Longrightarrow$ long-range AF order

low electron or hole doping destroys AF order and generates superconductivity

UNEXPLAINED!!



from Physik Journal 1 (2002) Nr. 1,
Rev. Mod. Phys. 78, 17 (2006)

Talk 8:

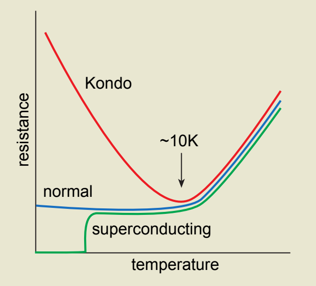
Kondo effect

Anomalous increase of resistance below T_K (Kondo temperature) in metals with magnetic impurities

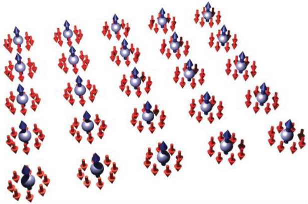
Explanation:

- screening of impurity spin by conduction electrons
- strong correlations between impurity spin and surrounding electrons (Kondo resonance, Kondo singlet $\frac{1}{\sqrt{2}}(|\uparrow_{\text{imp}}\downarrow_{\text{cond}}\rangle - |\downarrow_{\text{imp}}\uparrow_{\text{cond}}\rangle)$)

$\Longrightarrow$ many-body effect!



from Physics World 14, 33 (2001)



Source: www.st-andrews.ac.uk/~topnes/research/research_publications.php

Talk 9:

Fractional quantum Hall effect

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2D electron gas in a magnetic field
$\Longrightarrow$ integer quantum Hall effect:

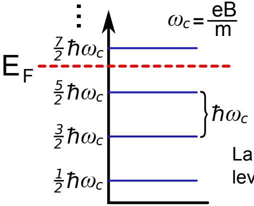
Plateaus in the Hall resistance R_H whenever the Fermi energy is between two Landau levels

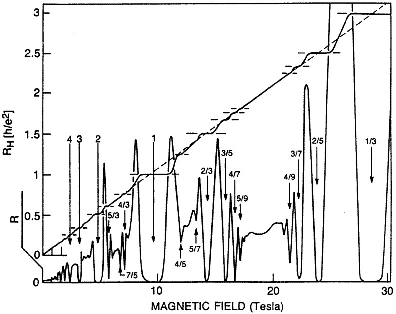
Effectively no kinetic energy in Landau levels

$\Longrightarrow$ very strong correlation effects

new many-body states can form due to strong interaction

additional plateaus at fractional filling





from Physica B 177, 401 (1992)

Talk 10:

Fractional Chern insulators

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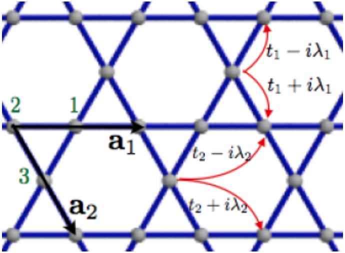
Similar to fractional quant. Hall effect

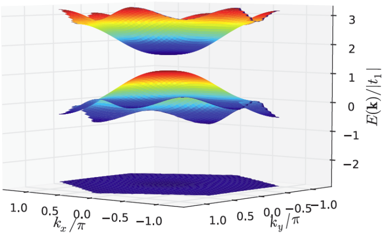
but: flat bands (Landau levels) not generated by magnetic field

instead: lattice tight binding models (e.g. Kagome lattice) with spin orbit coupling.

$\Longrightarrow$ proper choice of tight binding parameters can lead to flat bands

$\Longrightarrow$ fractional quantum Hall states!





from arXiv: 1308.0343

Talk 11:

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Many-body localization

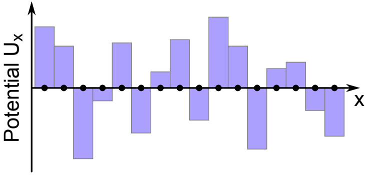
Anderson localization:

non-interacting tight-binding model:

$H = t \sum_x (c_x^\dagger c_{x+1} + c_{x+1}^\dagger c_x) + \sum_x U_x c_x^\dagger c_x$

U_x=random potential

$\Longrightarrow$ wave functions are localized!

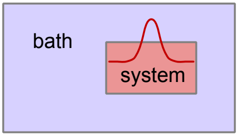


Localization also occurs in interacting systems: many-body localization

$H = J \sum_x \vec{S}_x \vec{S}_{x+1} + \sum_x h_x S_x^z$

h_x = random magnetic field

System does not thermalize when connected to a bath!



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Summary/conclusions...

Outlook...

Future directions of research...

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Acknowledgements

- Collaborators...

- Funding...

Thank you for your attention!