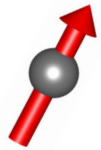
Quantum magnetism

classical and quantum spin states

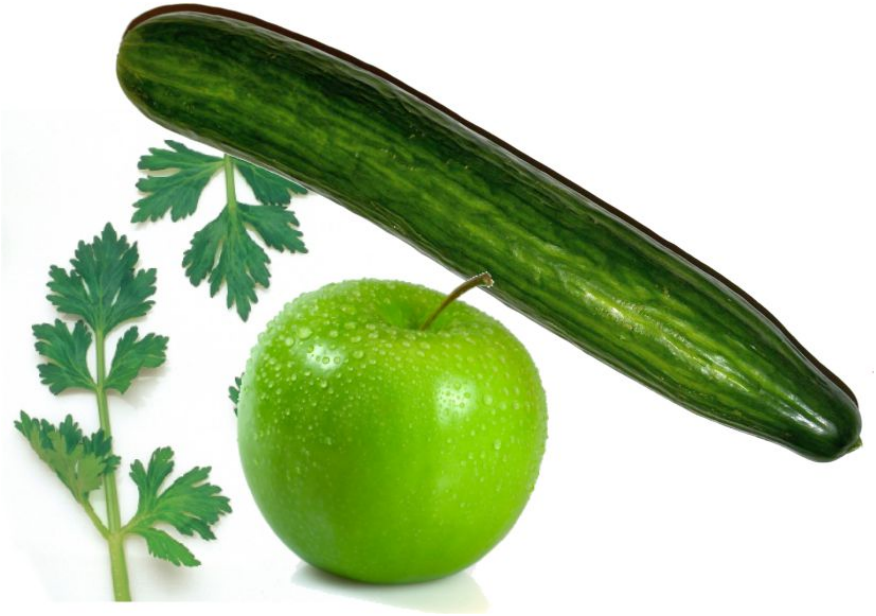
quantum tunneling of magnetization

molecular magnets



by Alexander Tsirlin, Leipzig University

Lecture 10: January 20, 2025



Classical states

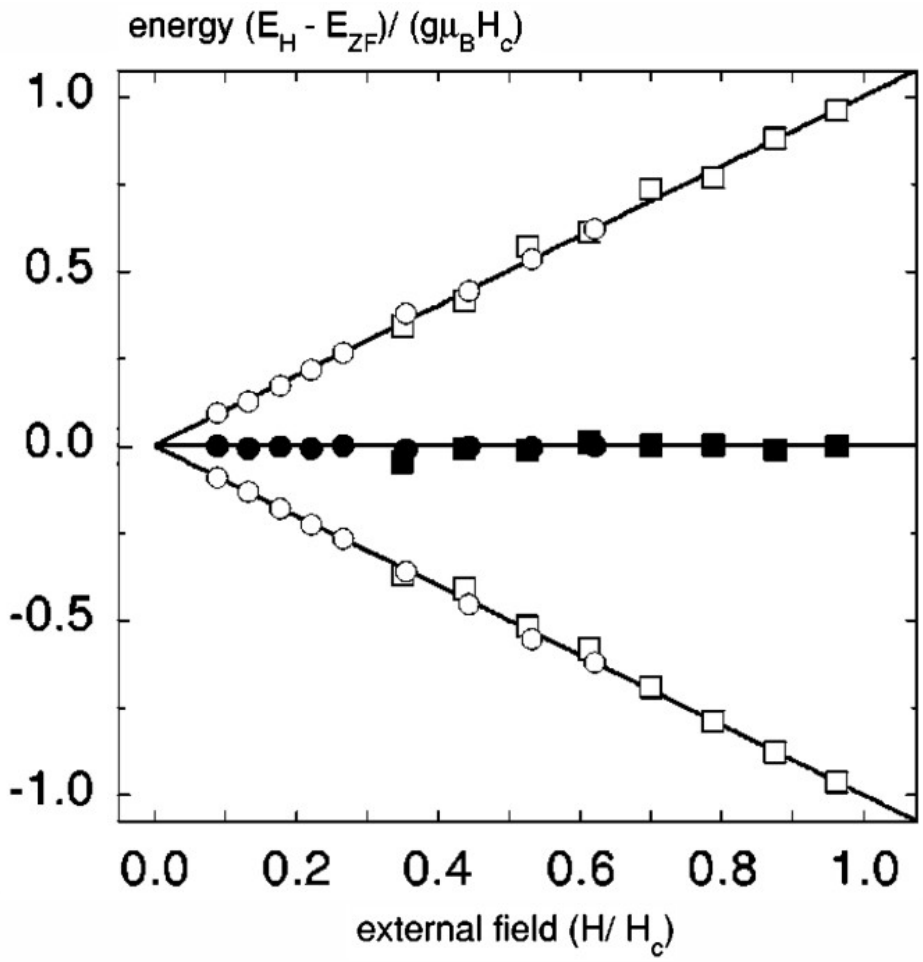
$|\uparrow\uparrow\rangle$, $|\downarrow\downarrow\rangle$, etc.

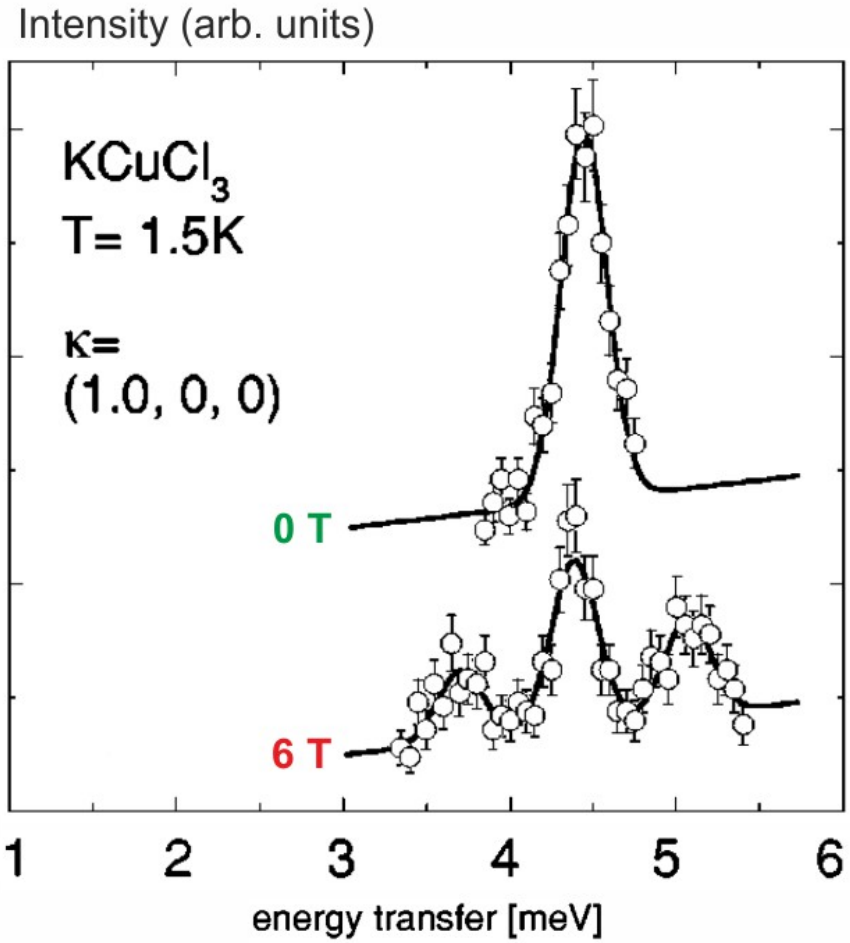
Quantum state

$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

Image credits: WiseMan42, Kiedd 07 (CC-BY-SA)

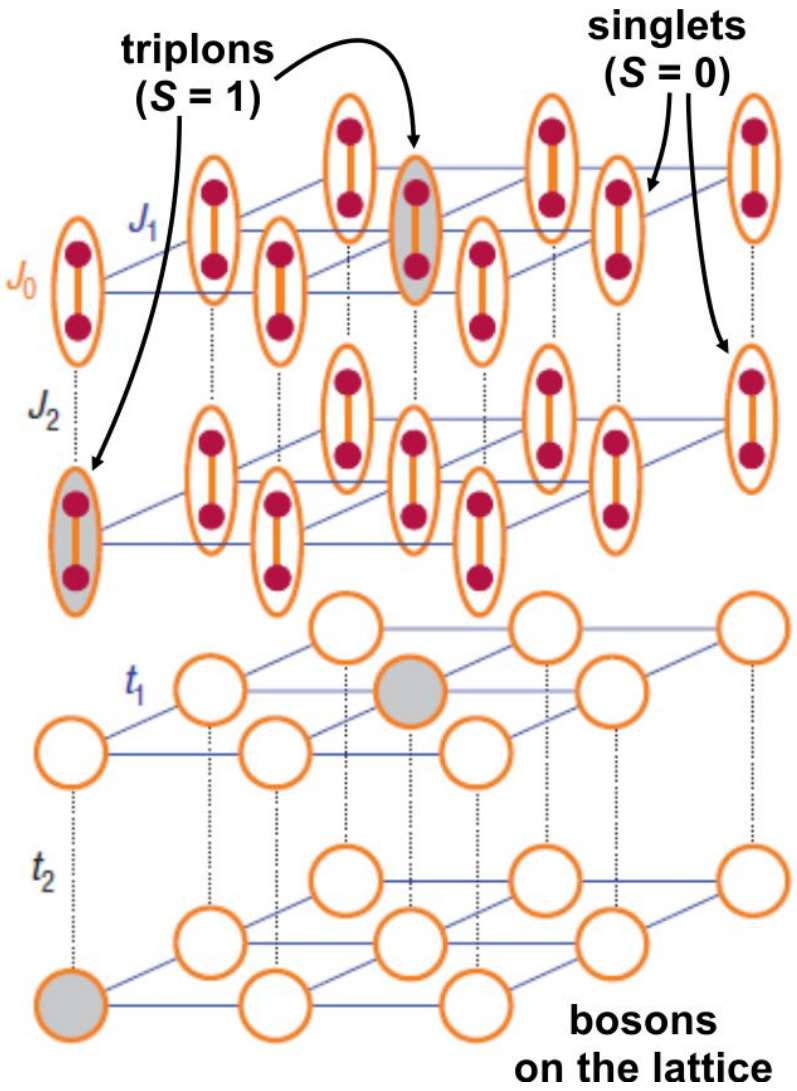
Dimer in the magnetic field



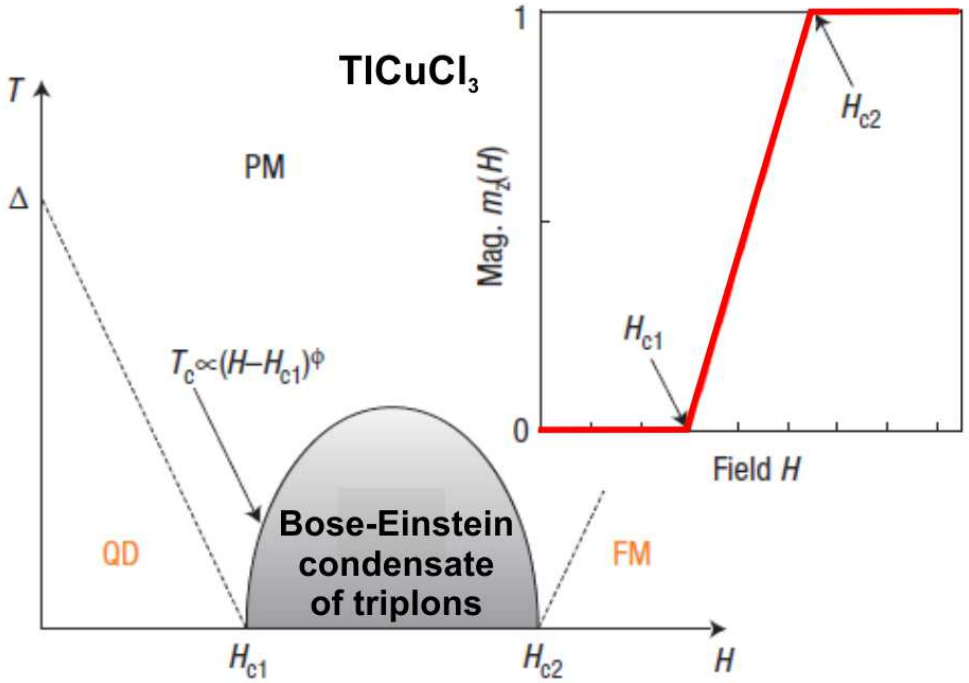


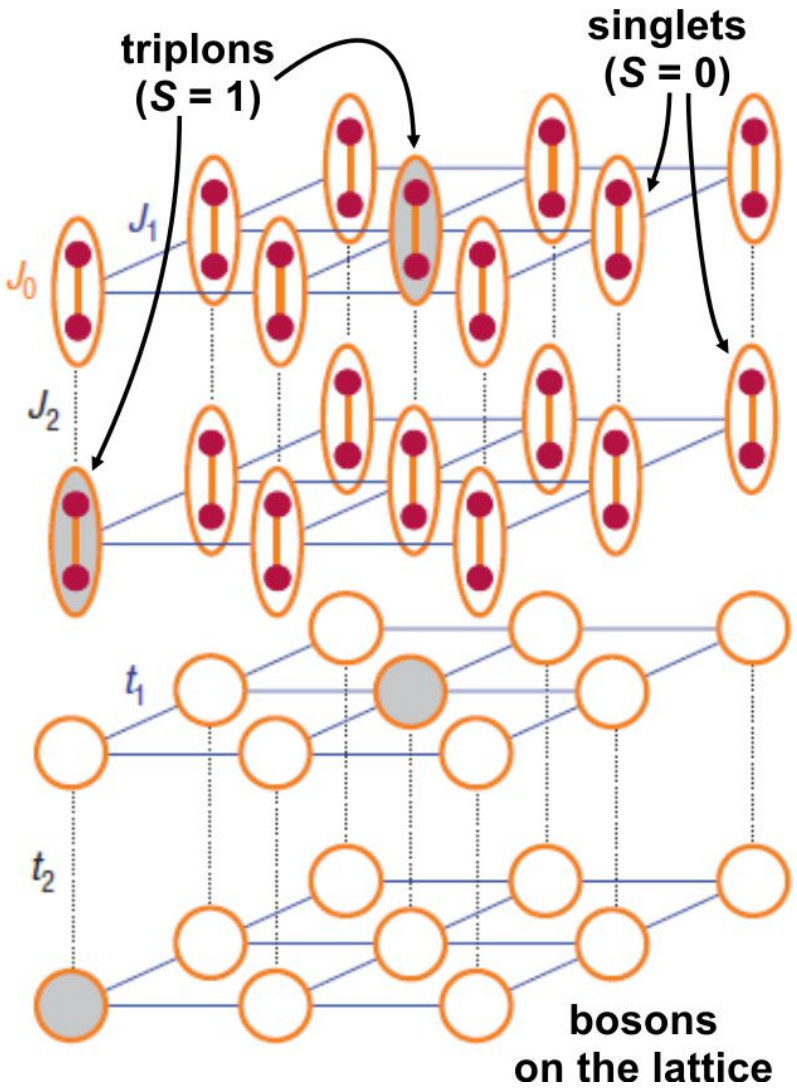
Phys. Rev B 65, 132415 (2002)

Triplon excitations



Nature Phys. 4, 198 (2008)





Tunable boson concentration

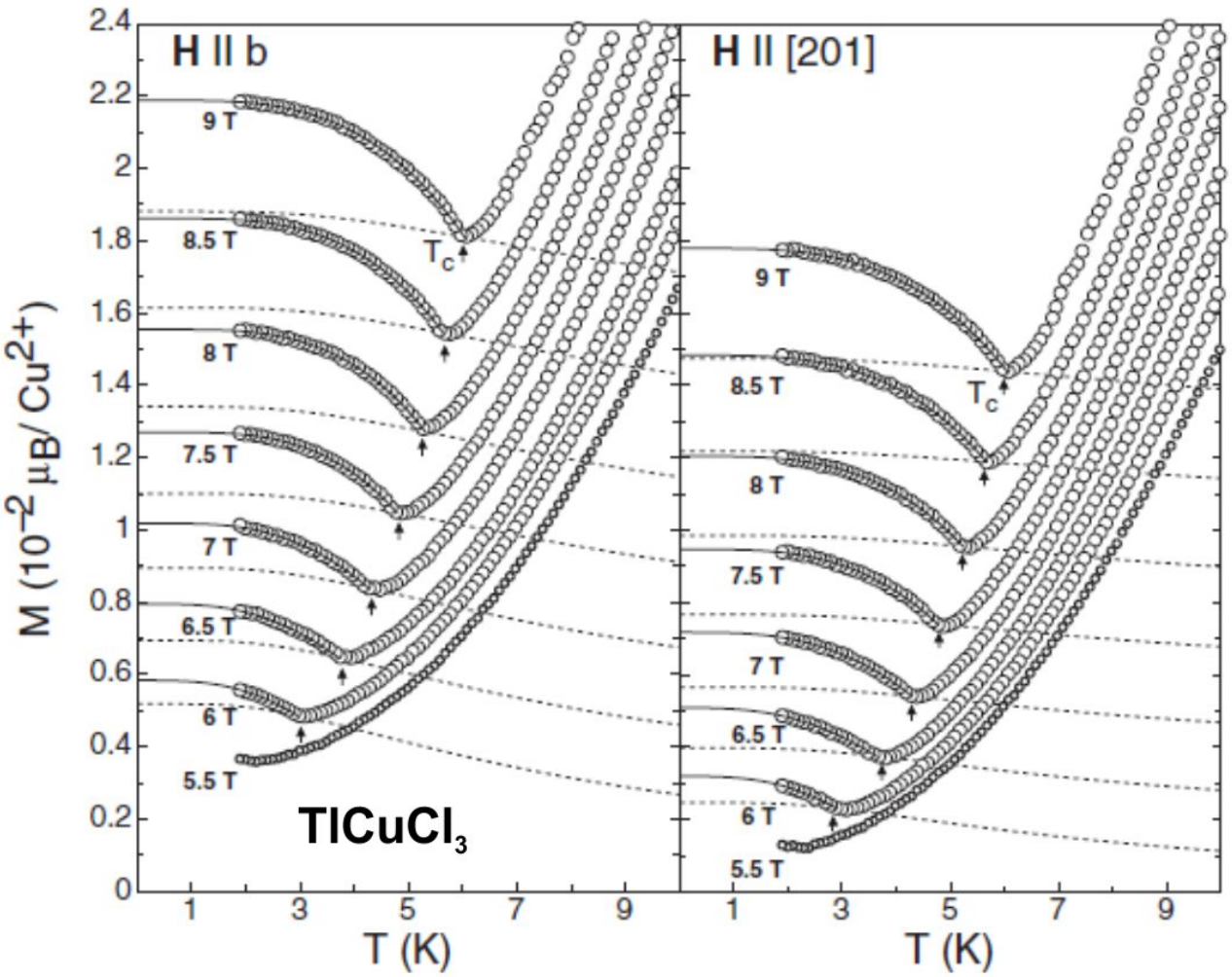
$\Rightarrow$ ordering at low-T

Bose-Einstein condensation
(bosonic language)

Field-induced magnetic order
(fermionic language)

Nature Phys. 4, 198 (2008)

Bose-Einstein condensation of triplons

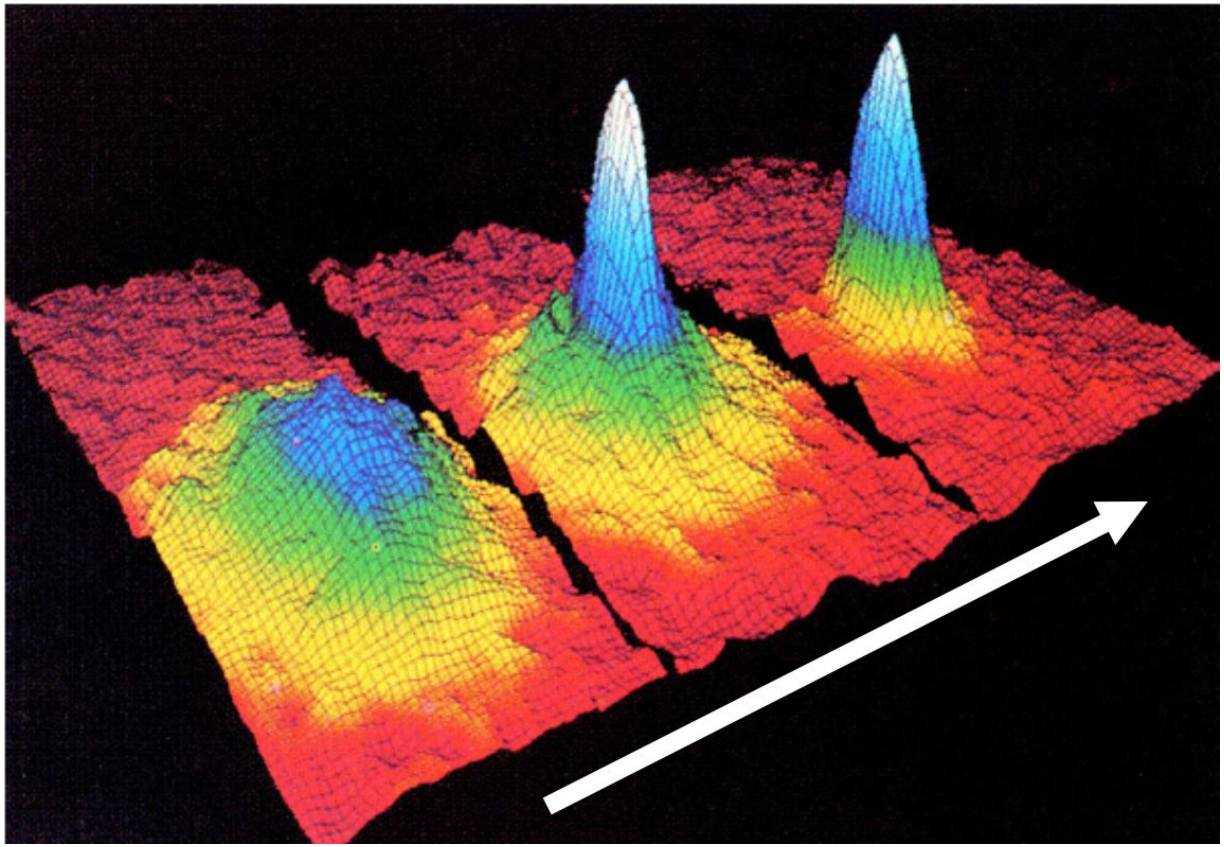


Zero field:
no magnetic order

Above H_c:
field-induced magnetic order

Phys. Rev. B 78, 224403 (2008)

Bose-Einstein condensation in cold gases



Evolution of the velocity distribution toward the condensate

Bose-Einstein condensation of ^{87}Rb atoms cooled to below 170 nK

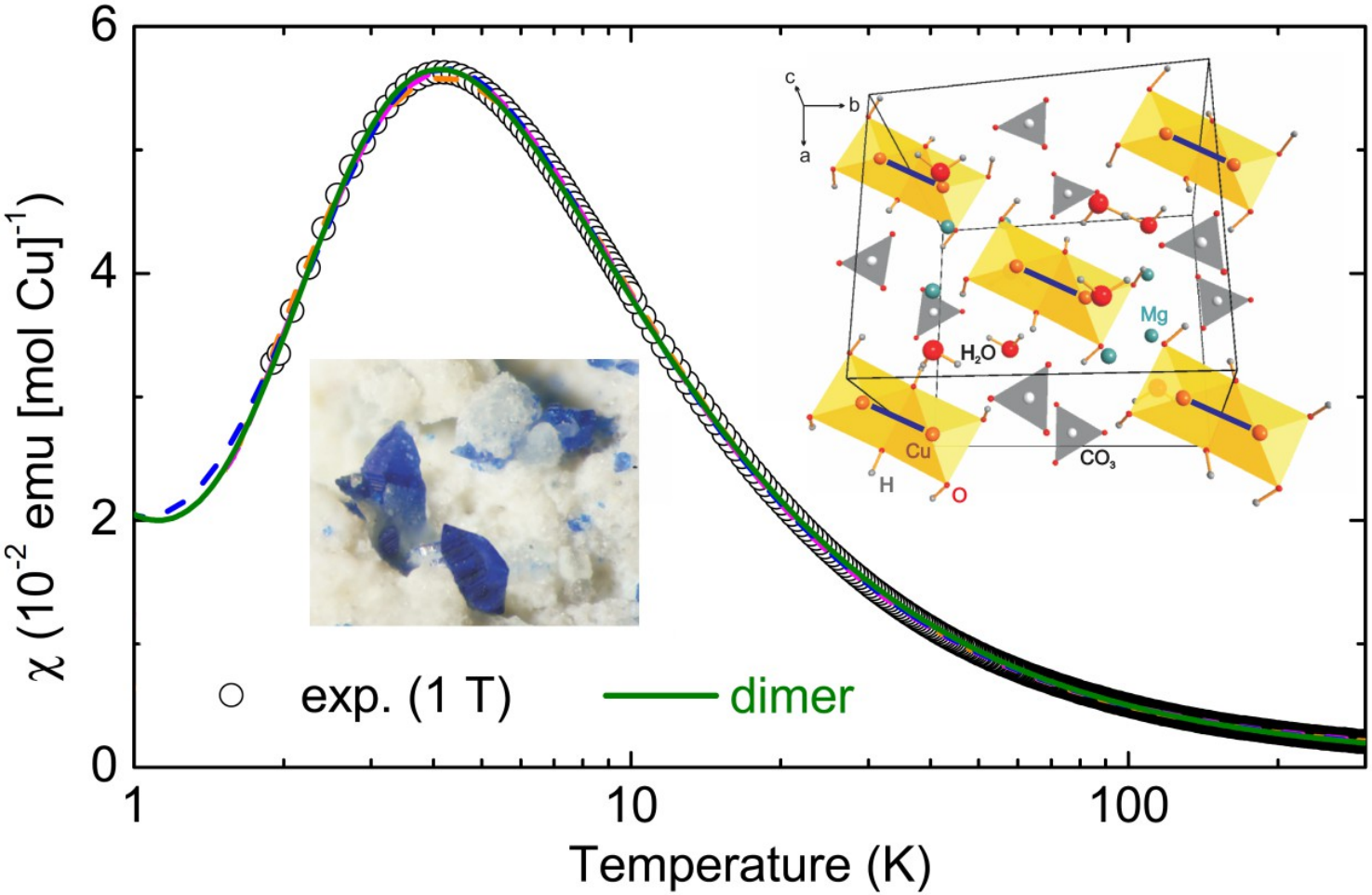
2001 Nobel prize in physics

Eric Cornell

Wolfgang Ketterle

Carl Wieman

M.H. Anderson *et al.* Science 269, 198 (1995) + Nobel committee summary



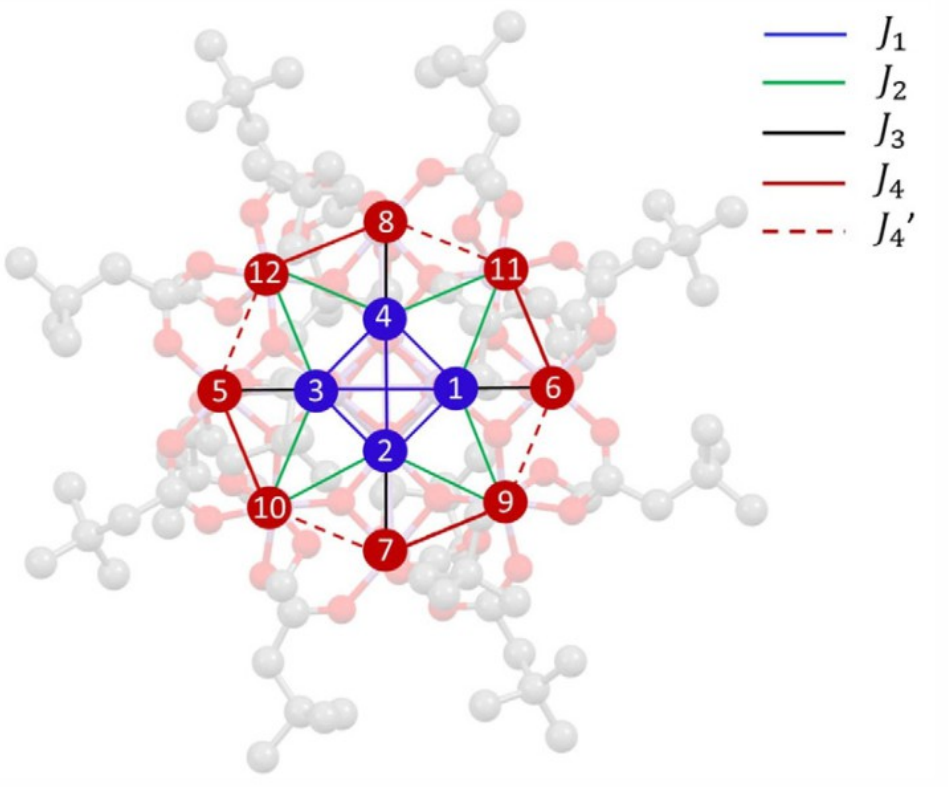
Callaghanite, $Cu_2Mg_2(CO_3)(OH)_6 \cdot 2H_2O$:

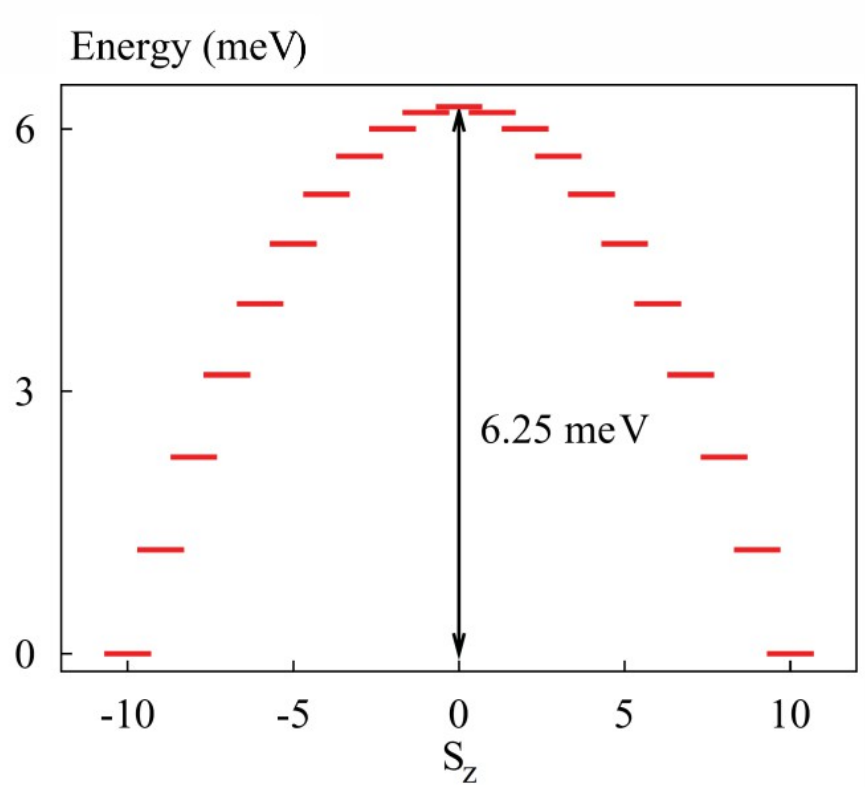
a spin-$\frac{1}{2}$ dimer with $J \simeq 7\,\mathrm{K}$

Phys. Rev. B 89, 165127 (2014)

Material / Technology

molecular magnets

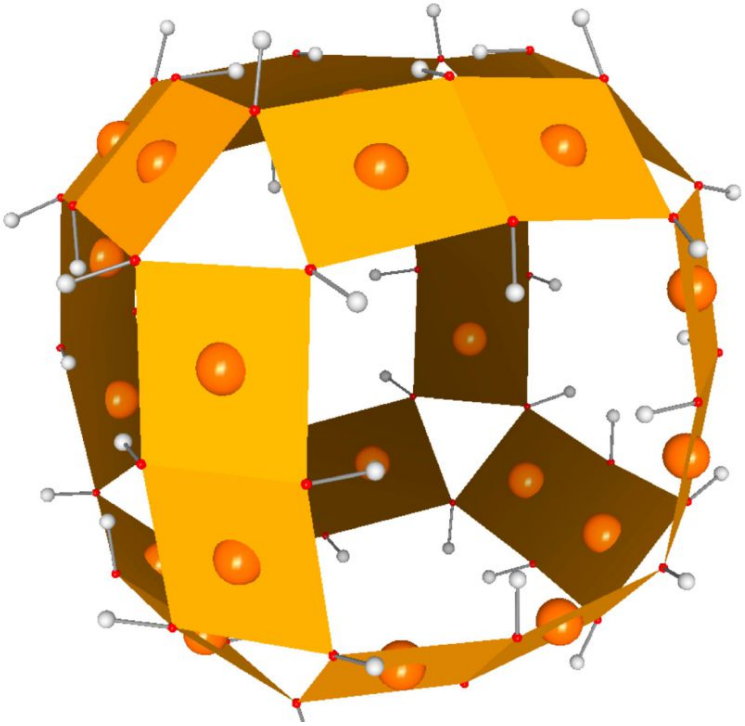




Mn_{12} family, e.g., $Mn_{12}O_{12}(CH_3COO)_{16}(H_2O)_4$,
one of the workhorses of molecular magnetism

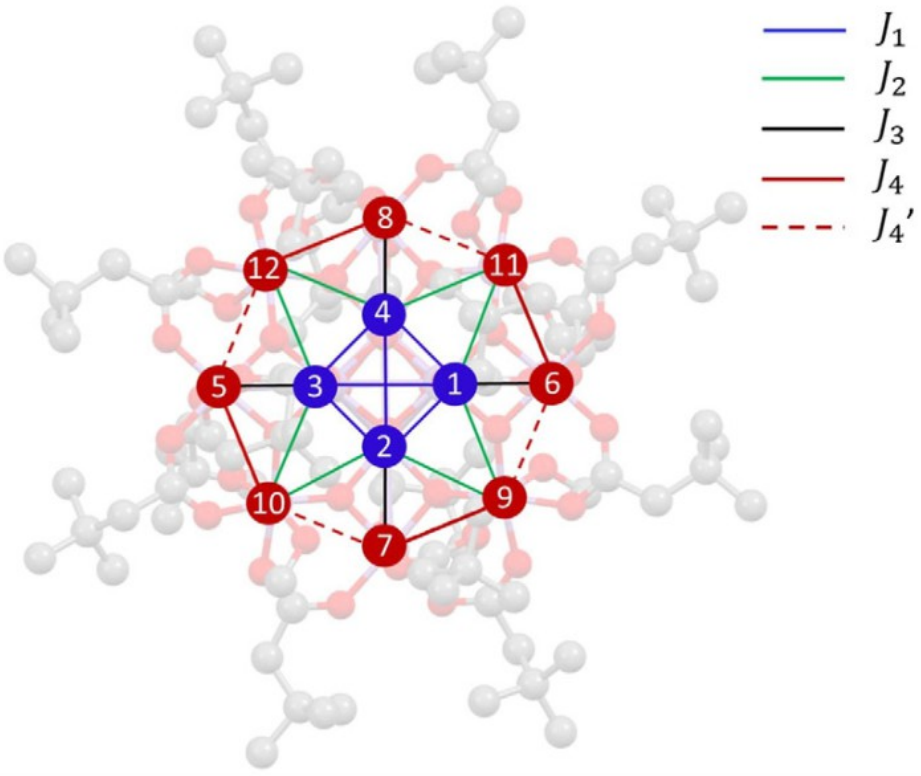
Phys. Rev. Lett. 119, 217202 (2017) and Phys. Rev. B 85, 245415 (2012)

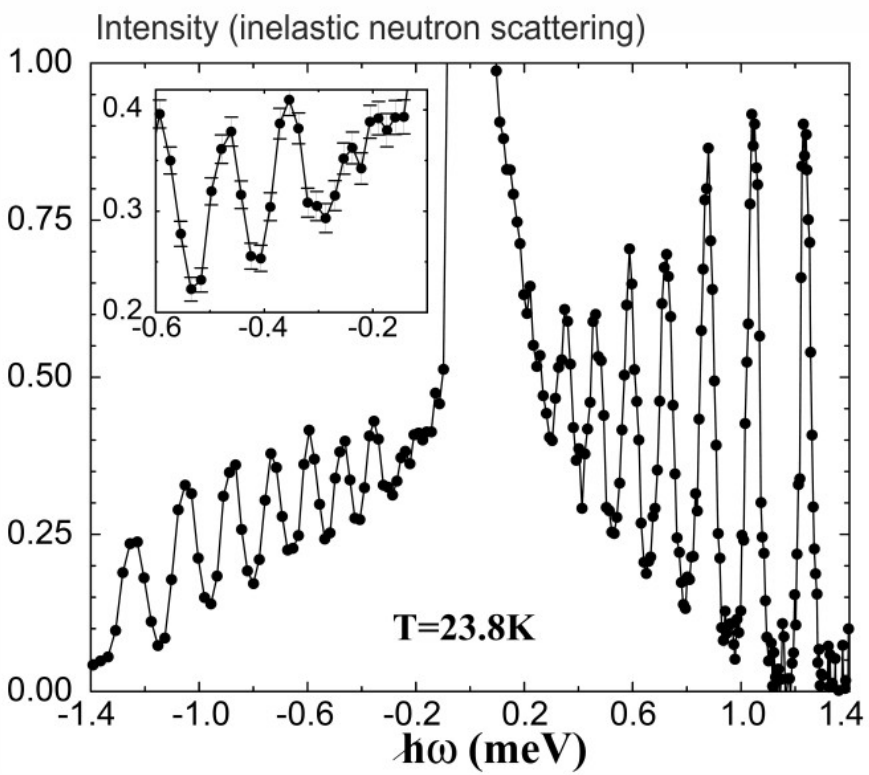
Even larger...



Boleite mineral, $KPb_{26}Ag_9Cu_{24}(OH)_{48}Cl_{62}$

Cu_{24} magnetic units





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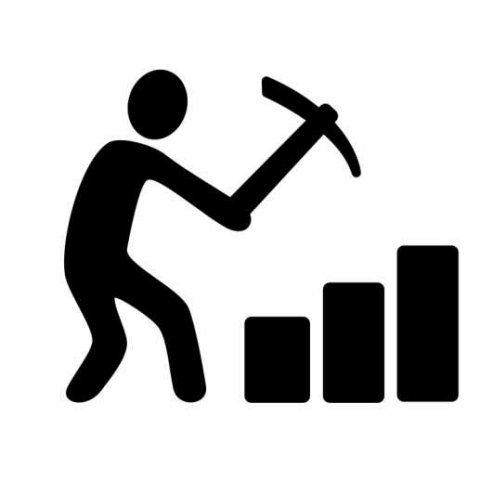
Phys. Rev. Lett. 119, 217202 (2017) and Phys. Rev. Lett. 83, 628 (1999)



Experiment

quantum tunneling of magnetization

Tunneling

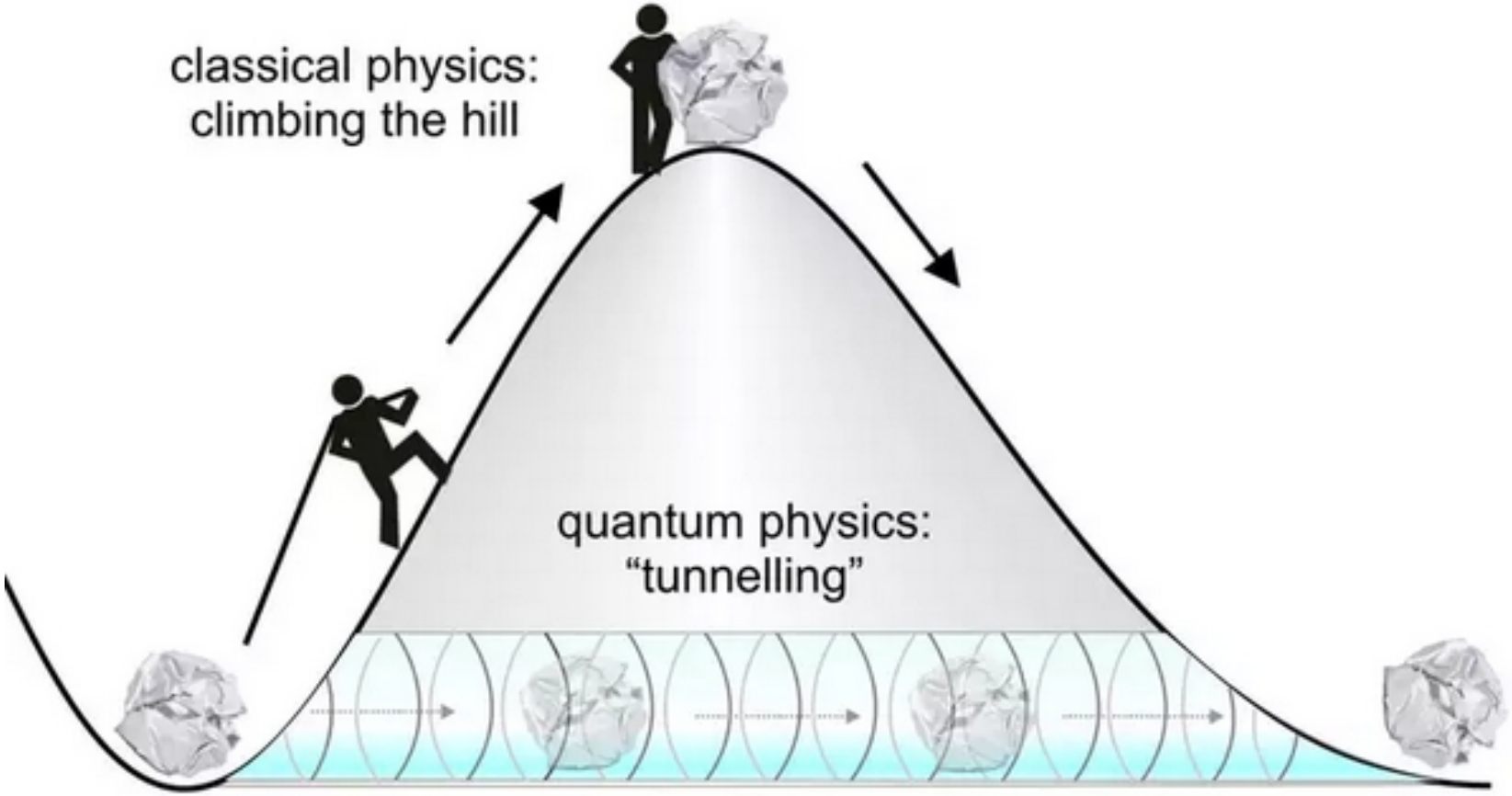
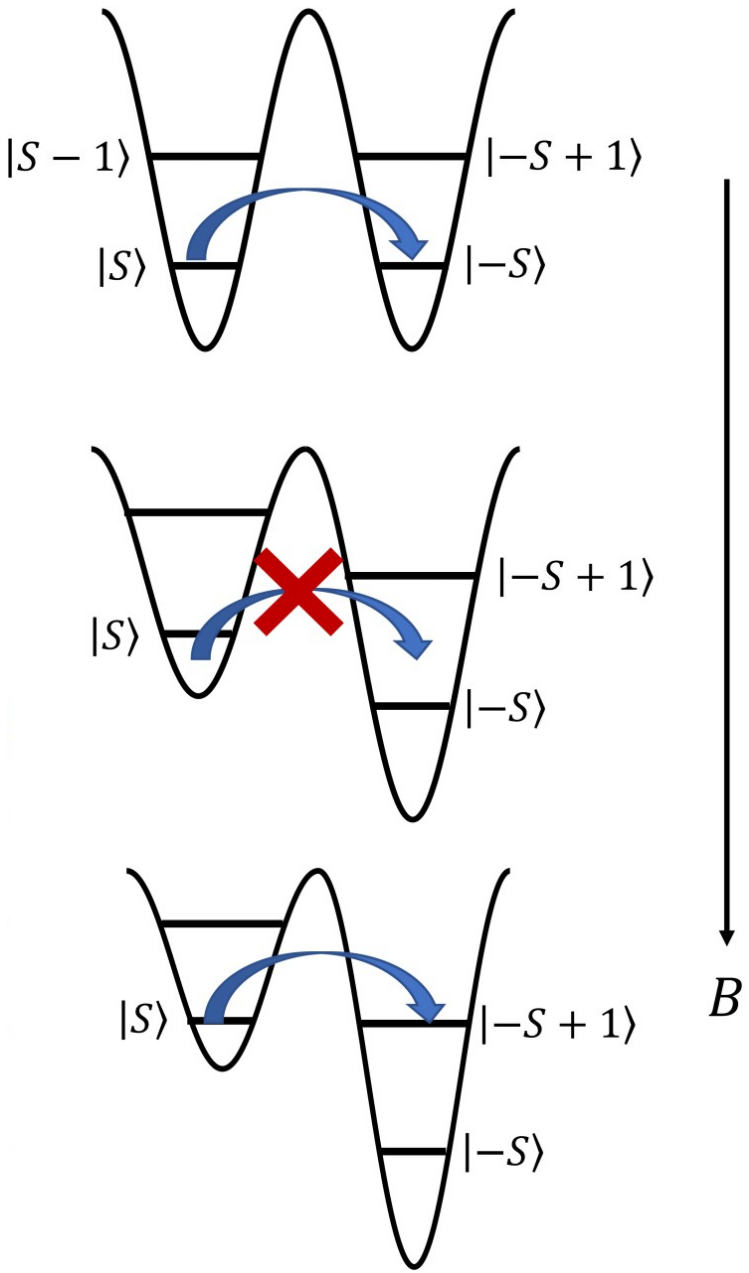
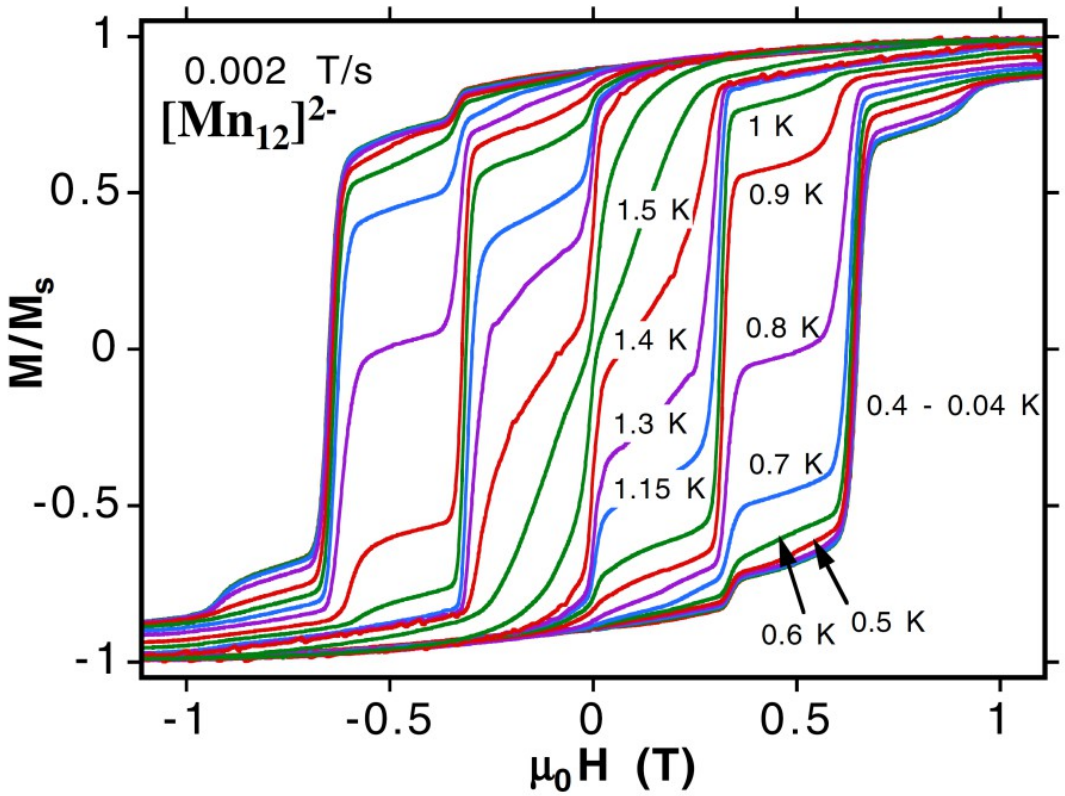


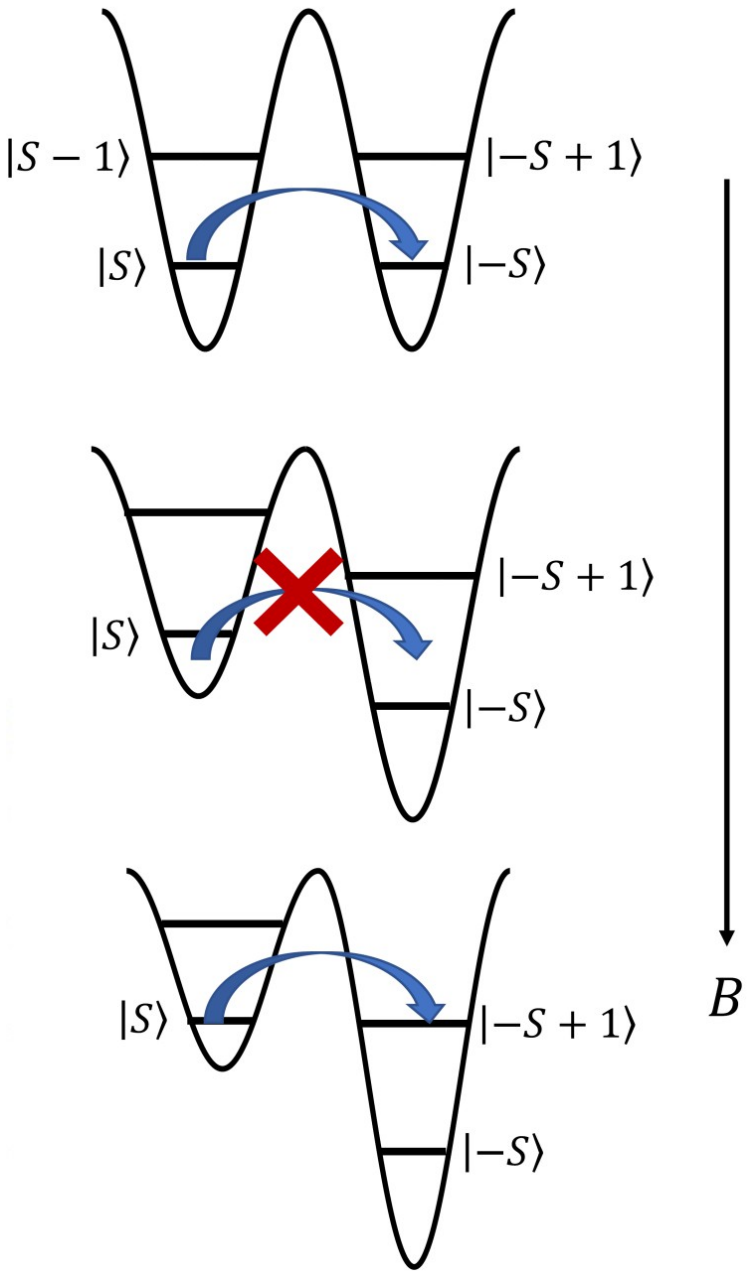
Image credit: MPI for Quantum Optics

Tunneling



Rep. Prog. Phys. 87, 034501 (2024)





Magnetization steps due to the tunneling

$\Rightarrow$ applications in quantum computing?

Rep. Prog. Phys. 87, 034501 (2024) and Phys. Rev. Lett. 95, 037203 (2005)