Magical magnetism and strange stuff
Thanks also to

The KITP faculty and staff, and our strong community supporters

Joe Polchinski

My friends and colleagues in the UCSB Physics and Materials departments

Many many past and present students, postdocs, and faculty visitors

research support from the NSF, DOE, ARO, and the Moore Foundation
sinan, ~ 200BC
SONOS PLAY:3

TEARDOWN
UCSB's powerful attraction
The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of star stuff.
The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of magnets.
“spin”
Ferromagnet
antiferromagnet

anti-parallel
1994 Nobel prize
space group: \(I\text{41m}(\text{tetragonal})\)

\(\text{RAlGe}\) (\(\text{R}\): rare-earth) – candidate of Weyl semimetal

Lattice (crystal structure) does not have inversion symmetry.

If magnetic moments on \(\text{R}\) ions align ferromagnetically, both inversion and time-reversal symmetries are broken.

\[
\begin{align*}
\text{atom position} & \quad \text{x} & \quad \text{y} & \quad \text{z} \\
\text{Ce} & \quad 4a & \quad 0 & \quad 0 & \quad 0.581 \\
\text{Al} & \quad 4a & \quad 0 & \quad 0 & \quad 0.166 \\
\text{Ge} & \quad 4a & \quad 0 & \quad 0 & \quad 0 \\
\end{align*}
\]

Crystal structure is polar but not chiral (because of the presence of mirror symmetry).

Joe Checkelsky

Lucile Savary

Takehito Suzuki

\(\mu_0H = 1.75\ T\)

\(T = 2\ K\)

\(6\ K\)
space group: I41md (tetragonal)

RAlGe (R: rare-earth) – candidate of Weyl semimetal

Location of symmetry operation

Lattice (crystal structure) does not have inversion symmetry. If magnetic moments on R ions align ferromagnetically, both inversion and time-reversal symmetries are broken.

atom position x y z

Ce 4a 0 0 0.581
Al 4a 0 0 0.166
Ge 4a 0 0 0

Crystal structure is polar but not chiral (because of the presence of mirror symmetry).

Joe Checkelsky
Takehito Suzuki
Jianpeng Liu

“domain wall”
“Quantum physics makes me so happy... it’s like looking at the universe naked”
Entanglement
Entanglement
Entanglement
Entanglement
Einstein-Podolsky-Rosen Pair
Einstein-Podolsky-Rosen Pair

“quantum non-locality”
Einstein-Podolsky-Rosen Pair

spukhafte Fernwirkung!
John Bell

Alain Aspect

no local realism

\[ S(\theta) \]

\[ -2 \leq S(\theta) \leq +2 \]

The indicated errors are ±2 standard deviations. The dashed curve is not a fit to the data, but Quantum Mechanical predictions for the actual experiment. For an ideal experiment, the curve would exactly reach the values ±2.828.

9.5. Timing experiment

As stressed in sections 6 and 7.5, an ideal test of Bell's inequalities would involve the possibility of switching at random times the orientation of each polarizer, since the locality condition would become a consequence of Einstein's causality. We have done a step towards such an ideal experiment by using the modified scheme shown on Figure 15. In that scheme, each (single-channel) polarizer is replaced by a setup involving a switching device followed by two polarizers in two different orientations:

- \( a \) and \( a' \) on side I,
- \( b \) and \( b' \) on side II.

The optical switch \( C_1 \) is able to rapidly redirect the incident light either to the polarizer in orientation \( a \), or to the polarizer in orientation \( a' \). This setup is thus equivalent to a variable polarizer switched between the two orientations \( a \) and \( a' \). A similar setup is implemented on the other side, and is equivalent to a polarizer switched between the two orientations \( b \) and \( b' \).

The switching of the light was effected by home built devices, based on the acousto-optical interaction of the light with an ultrasonic standing wave in water. The incidence angle (Bragg angle) and the acoustic power, were adjusted for a complete switching between the 0th and 1st order of diffraction. The switching function was then of the form

\[ \sin^2(\cos(\pi \theta/2)) \]

with the acoustic frequency \( \Omega \) of the order of 25 MHz.
Helium
Helium
Resonance

benzene

$C_6H_6$

Linus Pauling ~ 1930
Resonance

benzene

$\text{C}_6\text{H}_6$

chemical bond = EPR pair!

Linus Pauling ~ 1930
Strange Stuff

Phil Anderson, 1973

a “quantum liquid” of spins

\[ \Psi = \text{Resonating Valence Bond state} + \ldots \]
Quantum spin liquid

\[ \Psi = \text{[diagram]} + \text{[diagram]} + \ldots \]

For ~500 spins, there are more components than there are atoms in the visible universe!
“Schrödinger cat”

\[ \Psi = \begin{align*} + 
\end{align*} \]  

“Schrödinger kitten”
Strange stuff
Figure S1: Photographs, X-ray diffraction (XRD) patterns, and field dependence of magnetization of YbMgGaO$_4$.

a, Photographs of a representative YbMgGaO$_4$ single crystal.

b, XRD pattern of a YbMgGaO$_4$ single crystal from the cleaved surface.

c, Rocking curve of the (0, 0, 18) peak. The horizontal bar indicates the instrumental resolution.

d, Laue pattern of the YbMgGaO$_4$ single crystal viewed from the c axis.

e, Observed (red) and calculated (green) XRD diffraction intensities of ground single crystals. The X-ray has a wavelength of 1.54 Å.

f, Magnetic field dependence of magnetization at T = 2 K. Fitted g factors and Van Vleck susceptibility are shown in the figure.

Effect was also observed in the raw constant energy images (Fig. S2b-f), which were shown to be anisotropic, with slightly higher intensities occurring at approximately the same direction as that observed in the elastic incoherent scattering images. The self-attenuation can be corrected by normalizing the data with elastic incoherent scattering image. The normalized constant-energy images are presented in Fig. 2a-e, revealing nearly isotropic intensity distribution.

III. Spinon Fermi surface and dynamic spin structure factor.

Here, we describe the spinon mean-field state that is employed to explain the dynamic spin structure factor. Herbertsmithite, a natural mineral discovered in Chile YbMgGaO$_4$, synthesized 2015

Bi$_2$Se$_3$, a semiconductor used as a thermoelectric
herbertsmithite, a natural mineral discovered in Chile

YbMgGaO₄, synthesized 2015

Bi₂Se₃, a semiconductor used as a thermoelectric
Strange stuff → Peculiar particles
Strange stuff $\rightarrow$ Peculiar particles

"quasi-particles"
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III. Spinon Fermi surface and dynamic spin structure factor.

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Spin Liquid

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III. Spinon Fermi surface and dynamic spin structure factor.

Here, we describe the spinon mean-field state that is employed to explain the dynamic spin structure factor of the system.
Fundamental applications?
Can elementary particles and forces of our world emerge from entanglement?
Des recherches qui précèdent, il résultera:
1.° Que l'action, soit répulsive, soit attractive de deux globes électrisés, & par conséquent de deux molécules électriques, est en raison composée des densités du fluide électrique des deux molécules électrisées, & inverse du carré des distances.

Coulomb, 1785

\[ F_{12} = F_{21} = k \frac{q_1 q_2}{r^2} \]
Electromagnetism

James Clerk Maxwell
Photoelectric effect
"We’ve agreed to count it as both a wave and a particle for tax purposes."
Particle-wave duality
But where does electromagnetism come from?
Yb$_2$Ti$_2$O$_7$

**FIG. 2.** Detection of exotic quasiparticles by thermal conductivity measurements.

- **a**. Thermal conductivity divided by temperature $\kappa/T$ of Pr$_2$Zr$_2$O$_7$ as a function of temperature. Heat current $Q$ is applied along [1,-1,0] direction. Thermal conductivity shows characteristic behaviors in three different temperature regimes, I, II and III. Inset is a blowup of low-temperature region.

- **b**. $\kappa/T$ in regime II and its temperature derivative plotted on the left and right axes, respectively. $T_E$ represents the inflection point in the $T$-dependence of $\kappa/T$.

- **c**. $\kappa/T$ plotted against $1/T^2$ in a temperature range between 0.07 and 0.16 K.

Y. Matsuda group, unpublished
Gravity
There is no theory of quantum gravity
explaining gravity is explaining the emergence of space-time itself
electromagnetism

gravity?
Electrons

Black holes
Electrons

\[0.00000000000000000000000000000009 \text{kg}\]

Black holes

\[60000000000000000000000000000000000 \text{kg}\]
Sachdev-Ye-Kitaev Model
electromagnetism

1+1-dimensional gravity in anti-de Sitter space
$g = \tanh \theta$

$\nu = g \cos \tau$

$\nu = g \sin \tau$

$ds^2 = -d\tau^2 + d\theta^2$

$\tau = \cos \theta$
Thank you