Understand *strongly-correlated quantum matter*: one of greatest challenges in modern physics

Problems with ‘real’ systems

- Complex systems (what is necessary?)
- Imperfections (important?)
- Not versatile, can’t change interactions
- Very small length scales (typ. angstroms)
- Very short time scales (typ. femtoseconds)
- Hard to probe (neutron stars)

Construct synthetic, highly controllable quantum systems to simulate quantum systems of interests: **QUANTUM SIMULATION**

And I’m not happy with all the analyses that go with just the classical theory, because nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.

Quantum Matter of Ultracold Atoms

Typical models of quantum many-body physics (continuum, spin physics, etc.)

\[ \hat{H} = \sum_{i=1}^{N} \frac{\hat{p}_i^2}{2m} + \sum_{i=1}^{N} V_{\text{trap}}(\hat{r}_i) + \sum_{i<j} V_{\text{int}}(\hat{r}_i, \hat{r}_j) \]

\[ \hat{H} = \sum_{i} \frac{\hbar \Omega_i}{2} \hat{\sigma}_x^i + \sum_{i} \hbar \Delta_i \hat{n}_i + \sum_{i<j} V_{ij} \hat{n}_i \hat{n}_j \]

- Highly controllable external/internal degrees of freedom
- Tunable interactions
- Many observables

Programmable atomic painting

Box potentials (repulsive)

DMD/SLM

~ 10 μm

Rydberg dressing

Feshbach

- Density \[ \langle \hat{\Psi}^\dagger(\mathbf{r}) \hat{\Psi}(\mathbf{r}) \rangle \]
- Momentum distributions \[ \langle \hat{c}_k^\dagger \hat{c}_k \rangle \]
- Structure factor \[ S(\mathbf{q}, \omega) \]
- Spectral functions \[ A(\mathbf{k}, \omega) \]
- Elementary excitations \[ \epsilon(\mathbf{k}) \]
- Phases \[ \Delta \phi \]
- Quantum state tomography (single atoms)
Quantum Simulation @ UQM

**NEW**
(2017)

**‘Fermi lab’**
(SCL 20)

- **System.** Gas of $^6$Li atoms in programmable potentials

**Research themes**
- Superfluidity beyond weak coupling
- Exotic phases of strongly interacting matter
- Dynamics of rotating quantum fluids
- Turbulence in quantum fluids

**EVEN NEWER**
(2019)

**‘Sr lab’**
(SPL 20A)

- **System.** Single $^{88}$Sr atoms in array of optical tweezers

**Research themes**
- Models of quantum magnetism
- Dynamics of small quantum systems
- Quantum cellular automata
- Assembly of many-body states from ‘bottom-up’ (e.g. Mott)
Example of a fundamental question

**BCS theory** Celebrated theory of superconductivity
key ingredient: pairing

In a nutshell: order parameter is ‘fermion pairing field’

If OP nonzero: ‘condensate’ of fermion (Cooper) pairs

At the same time: gap opens in single-particle excitation spectrum

\[ E_k = \sqrt{(\epsilon_k - \mu)^2 + \Delta_{\text{gap}}^2} \]

**BCS prediction** \[ \Delta = \Delta_{\text{gap}} \] never tested

With uniform ultracold fermions, could measure both independently!

Fundamental follow-up: How does it hold beyond weak-coupling regime?
Strongly-interacting Fermions in a Box

- Ultracold Spin-$\frac{1}{2}$ fermions ($^6$Li) in Sloane Physics Lab

as of Nov 2019

- Expansion of uniform strongly-interacting superfluids (*preliminary*)

  \[ \text{decreasing } T \]

Unitary

BEC

\[ \text{First uniform mBEC?} \]
Sr Quantum Simulator

under construction in SPL 20A

2D MOT

Atomic source

3D MOT + single atoms

Synthesizing interactions via excitations to Rydberg states (~ 319 nm from $^3P_J$ manifold) (strong dipole-dipole interactions)

\{ Ground state $|g\rangle$ & Rydberg $|r\rangle$ \} map to pseudo spin 1/2

$$\hat{H} = \sum_i \frac{\hbar \Omega_i}{2} \hat{\sigma}_x^i + \sum_i \hbar \Delta_i \hat{n}_i^i + \sum_{i<j} V_{ij} \hat{n}_i^i \hat{n}_j^j$$

$\hat{\sigma}_x^i$ = $|g_i\rangle\langle r_i| + |r_i\rangle\langle g_i|$

$\hat{n}_i^i = |r_i\rangle \langle r_i|$

+ ulTRANarrow transition (~ mHz) for metrology + novel Rydberg dressing schemes
The team celebrating fermions in programmable potentials

Dec 2018: Bose-Einstein condensate of molecules $^6$Li$_2$

Franklin Grant
Jere
Gabriel Peter
Yunpeng
Tailored Spin Control for NMR and MRI of Solids

(A Surprising Route to “See Inside” Opaque Solids)

Sean Barrett (& MANY GREAT STUDENTS & COLLABORATORS!!)

Department of Physics, Yale University

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Silicon doped with Phosphorous

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A group “selfie” showing: 2 PEB, 2 NSF GRFP, 2 Graduated Earlier (w/ great jobs!), 2 Newly Graduated (->postdocs w/me)!

Looking for 1-2 more...
Why do MRI of solids?

- Conventional MRI just looks at $^1\text{H}$ in water

- Challenges to MRI of solids:
  - Low spatial resolution
  - Very long imaging time
  - Low signal
Plasticity and toughness in bone
Robert O. Ritchie, Markus J. Buehler, and Paul Hansma; Fig. 1


Non-stoichiometric Hydroxyapatite
\[ Ca_{10}(OH)_2(PO_4)_6 \]
Brief Intro to NMR

• Most atomic nuclei have a non-zero spin, and this spin will precess in a magnetic field

\[ \omega_0 = -\gamma B_0 \]
Brief Intro to MRI

- In order to do imaging, you need **spatial information**, which is encoded by applying gradients – magnetic fields that vary (usually linearly) over space – along with the large constant magnetic field.

![Diagram of Magnetic Field and Signal](image)

Linear change in B-field due to gradient in x-direction.
Why is it hard to do high resolution MRI of solids?

- For good spatial resolution, we need a narrow frequency spectrum, this limits the types of samples we ordinarily image to liquids.

Linear change in B-field due to gradient in x-direction.
We use a quadratic echo pulse sequence which narrows the broad linewidth of solids to look like that of a liquid.

(a Serendipitous Discovery)
Novel Approaches to Spin Control: From Qubits to Skull and Bones

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Ben Deen
Suyog Bhandari
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Sean Barrett

Supported by ARO/ARDA/NSA and NSF-ITR/FRG research grants


Silicon doped with Phosphorous
“Beating T2*” -- Hahn’s Spin Echo

A 90x-tau-180y-tau-echo
This “pancake” echo has ~all of FID’s amplitude
Our Line-Narrowing Block:

- Relevant Hamiltonian parts (in rotating frame)...

Zeeman: \[ H_Z = \Omega_z I_z \]  
Spin interaction with local magnetic field (due to nearby electrons, chemical bonds, etc.)

Dipolar: \[ H_{ZZ} = \sum_{j>i}^N B_{ij} \left( 3I_{z_i} I_{z_j} - \vec{I}_i \cdot \vec{I}_j \right) \]  
Spin-spin interaction with other nuclei of same type
Our Line-Narrowing Block:

Zeeman: $H_Z\Delta$

Dipolar: $H_{ZZ}\Delta$

$0 = -H_Z\Delta$

$- (\frac{1}{2} H_{ZZ}) 4\Delta = 0$

$H_{ZZ}\Delta = 0$

Linewidth Reduction of $70,000$ for Si-29:

Linewidth is reduced from 200 Hz to 0.003Hz ($\sim 10^{-5}$ ppm).

$T_2^{\text{effective}}$ is increased from 1.6ms to 111s $\sim 1/3T_1$. 
The Quest for **Faster** Imaging, **Higher** Resolution, and **Stronger** Signal In MRI of Solids

Merideth Frey

Yale University
Physics Department
Dry Bovine Bone

1 mm
What about $^{31}$P MRI of soft tissues?

Metabolites (e.g., ATP)
DNA+RNA
Cell Membranes
Mouse Brain
Latest News-

1) New Equipment at Yale CBIC (~12 Tesla, fastest gradients, state-of-art spectrometer, optimized for our experiments)

2) Discrete (or Floquet) “Time Crystal” Physics
Crates have been arriving since in Feb. 2018...working to bring the full system online!

Most advanced NMR spectrometer on the Yale campus. First to be optimized for our MRI of solids experiments...
Our DTC work:
- Why do DTC signatures look so similar across a wide range of systems?
- DTC echo reveals new details about state created by DTC sequence.
4. TC Phase Region

![Graph showing TC Phase Region with time and phase angle parameters.](image)
Summary and Future Directions...

- New approach (from research on Quantum Computing!) to do high resolution P-31 MRI on hard and soft solids
  - Currently *ex vivo* because of rapidly changing gradients and high power rf pulses
  - We are extending these methods to other materials, and other nuclei
  - This method of Hamiltonian manipulation is not restricted to NMR and can be used in any spin (or pseudo-spin) system with a similar Hamiltonian
- Only a small portion of the experimental parameter space has been explored to date, so we have not yet reached the ultimate limits of this approach
Doing more with less:
Accelerating multidimensional NMR and MRI experiments using iterated maps

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“Accelerating multidimensional NMR and MRI experiments using iterated maps”,
M.A. Frey, Z.M. Sethna, G.A. Manley, S. Sengupta, K.W. Zilm, J.P. Loria, S.E. Barett,
1D Implementation