Searching for Perfect Fluidity in a Cold Atomic Gas

John E. Thomas
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Quark-gluon plasma $T = 10^{12}$ K
Computer simulation of RHIC collision
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“JETLAB” Group

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Laser flash photography
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Laser flash photography

Ultracold atomic gas
$T = 10^{-7}$ K
Optical Traps – Bowls made of Light
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Our atom: $^6\text{Li}$
Optical Traps – Bowls made of Light

Our atom: $^6\text{Li}$

Mixture of Spin–up and Spin–down (like electrons—fermions)
Optical Traps – Bowls made of Light

Our atom: $^6\text{Li}$

Magnet coils

Mixture of Spin–up and Spin–down (like electrons—fermions)
Preparation of an Ultracold $^6$Li gas
Preparation of an Ultracold $^6$Li gas

Atoms precooled to 150 $\mu$K
Preparation of an Ultracold $^6$Li gas

Atoms precooled to 150 $\mu$K

CO$_2$ Laser: 2 MW/cm$^2$
CO₂ Laser Beam
CO$_2$ Laser Beam

Stable Commercial Laser

140 Watt CO$_2$ Laser
Invisible infrared beam $\lambda = 10.6$ $\mu$m
CO$_2$ Laser Beam
Experimental Apparatus
Experimental Apparatus
Experimental Apparatus
Tunable Strong Repulsion and Attraction
Tunable Strong Repulsion and Attraction
Tunable Strong Repulsion and Attraction

Interaction Strength

Magnetic Field (gauss)

Strong attraction
Tunable Strong Repulsion and Attraction
Tunable Strong Repulsion and Attraction

Interaction Strength vs. Magnetic Field (gauss)

Strong repulsion
Tunable Strong Repulsion and Attraction
Tunable Strong Repulsion and Attraction
The *Universal Regime*: *Natural Units and Rulers*
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Interparticle spacing $L$ becomes the *only* length scale.
A consequence of the *Heisenberg Uncertainty Principle*

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- Physical Properties, like Energy and Temperature have *Natural Units* determined by $L$
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- Physical Properties, like Energy and Temperature have *Natural Units* determined by $L$
- Viscosity?
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*Quantum Viscosity Unit*
Strongly Interacting Systems in Nature
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Strongly Interacting $^6\text{Li}$ gas
$T = 10^{-7} \text{ K}$

Strongly Interacting Systems in Nature

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Quark-gluon plasma $T = 10^{12} \text{ K}$
Strongly Interacting Systems in Nature

Strongly Interacting $^6$Li gas
$T = 10^{-7}$ K


Similar “Elliptic” Flow

Quark-gluon plasma $T = 10^{12}$ K
Strongly Interacting Systems in Nature

- Ultracold Atomic $^6$Li Gas
- Quark-Gluon Plasma
- High $T_c$ Superconductors
- Neutron Matter
- Black Holes in String Theory

Strongly Interacting $^6$Li gas
$T = 10^{-7}$ K


Similar “Elliptic” Flow

Quark-gluon plasma $T = 10^{12}$ K
The Minimum Viscosity Conjecture—String Theory
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\[
\frac{\text{viscosity}}{\text{entropy}} = \frac{\eta}{s} \geq \frac{1}{4\pi}
\]

Kovtun et al., PRL 2005
The Minimum Viscosity Conjecture—String Theory

Resistance to flow—hydrodynamic properties

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Disorder—thermodynamic properties

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The Minimum Viscosity Conjecture—String Theory

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Resistance to flow—hydrodynamic properties

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\frac{\text{viscosity}}{\text{entropy}} = \frac{\eta}{s} \geq \frac{1}{4\pi}
\]

Disorder—thermodynamic properties

Is a Strongly-interacting atomic \(^6\text{Li}\) gas a fluid with the minimum viscosity?
Measuring the Energy $E$ and Entropy $S$
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For a *universal* quantum gas, the energy $E$ is determined by the *cloud size*  

Measuring the Energy $E$ and Entropy $S$

For a \textit{universal} quantum gas, the energy $E$ is determined by the \textit{cloud size} \hspace{1cm} Duke, PRL (2005)

For a \textit{weakly interacting} quantum gas the entropy $S$ can always be determined from the \textit{cloud size} (textbook problem)
Measuring the Energy $E$ and Entropy $S$

For a universal quantum gas, the energy $E$ is determined by the cloud size


For a weakly interacting quantum gas the entropy $S$ can always be determined from the cloud size (textbook problem)
For a *universal* quantum gas, the energy $E$ is determined by the *cloud size*  


For a *weakly interacting* quantum gas, the entropy $S$ can always be determined from the *cloud size*  

(textbook problem)

**Experiment**

**Start**

*Universal strongly Interacting*
Measuring the Energy $E$ and Entropy $S$

For a *universal* quantum gas, the energy $E$ is determined by the *cloud size*  


For a *weakly interacting* quantum gas the entropy $S$ can always be determined from the *cloud size*  

(textbook problem)

**Experiment**

**Start**

Universal strongly Interacting

**Sweep** magnetic field


**End**

Weakly interacting
Energy versus Entropy
Energy versus Entropy
Energy versus Entropy

- Data: Strongly interacting $^6$Li gas
- Ideal gas
Energy versus Entropy

- Data: Strongly interacting $^6$Li gas
- --- Ideal gas
Energy versus Entropy

- Data: Strongly interacting $^6$Li gas
  - Ideal gas

Critical temperature for the superfluid transition $= 0.20$ (natural units)
Energy versus Entropy

Data: Strongly interacting $^6$Li gas

Ideal gas

Critical temperature for the superfluid transition $= 0.20$ (natural units)

Analog of a super-high temperature superconductor that would work at several thousand degrees!
Measuring Viscosity from the expansion of a rotating gas
Measuring Viscosity from the expansion of a rotating gas
Measuring Viscosity from the expansion of a rotating gas
Measure the angle of the cloud
Measure the **angle** of the cloud

Measure the **angle** of the **long** axis of the rotating cloud with respect to the laboratory axis
How low is the viscosity?
How low is the viscosity?

Rotates \textit{faster} as it \textit{expands}—opposite to the behavior of an ice-skater!
How low is the viscosity?
How low is the viscosity?

- Superfluid, $\Omega_0 = 178$ rad/s
How low is the viscosity?

- Superfluid, $\Omega_0 = 178$ rad/s
- Normal Fluid, $\Omega_0 = 178$ rad/s
How low is the viscosity?

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Theory—superfluid flow
How low is the viscosity?

Theory—superfluid flow

- Superfluid, $\Omega_0 = 178 \text{ rad/s}$
- Normal Fluid, $\Omega_0 = 178 \text{ rad/s}$
How low is the viscosity?

Superfluid, $\Omega_0 = 178$ rad/s

Normal Fluid, $\Omega_0 = 178$ rad/s

Theory—superfluid flow
Viscosity/Entropy (natural units)
Viscosity/Entropy (natural units)
Viscosity/Entropy (natural units)

[Graph showing data points with error bars for Viscosity/Entropy versus Energy, with a dashed line indicating the string theory limit.]
Viscosity/Entropy (natural units)

He near $\lambda$–point

String theory limit
Viscosity/Entropy (natural units)

- He near $\lambda$–point
- QGP simulations
- String theory limit
The 2008 Team
The 2008 Team
The 2008 Team

1st row: Willie Ong Chenglin Cao James Joseph Yingyi Zhang Le Luo Dave Weisberg

2nd row: Ethan Elliot John Thomas Xu Du

3rd row: Jessie Petricka Bason Clancy