Observation of second sound and more recent developments in ultracold Fermi gases

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degenerate Fermi gases

Periodic Table of the Elements

* Lanthanide Series
  58 Ce  59 Pr  60 Nd  61 Pm  62 Sm  63 Eu  64 Gd  65 Tb  66 Dy  67 Ho  68 Er  69 Tm  70 Yb  71 Lu

+ Actinide Series
  90 Th  91 Pa  92 U  93 Np  94 Pu  95 Am  96 Cm  97 Bk  98 Cf  99 Es  100 Fm  101 Md  102 No  103 Lr

2012  2013
degenerate Fermi gases

second sound

atom-dimer attraction

dipolar Fermi gas
superfluidity on YouTube!

Liquid helium II
1963 film by Alfred Leitner
https://www.youtube.com/watch?v=OlcFSHAz4E8

#2: enormous heat conductivity
#3: zero viscosity, or not zero?
#4: fountain effect
#5: Rollin film
#6: second sound

bizarre phenomena explained in terms of two-fluid hydrodynamics

Tisza (1938), Landau (1941)

(another famous effect: quantized vortices)
two-fluid model

normal part (carries all entropy)

superfluid part (no entropy)

temperature $\rightarrow$ superfluid fraction $\frac{s}{(n+s)}$

theoretical framework:
two-fluid hydrodynamics
Landau (1941)
sound
sound
sound
ordinary sound: pressure wave (adiabatic)
sound
sound
sound
sound

second sound: entropy wave (at constant pressure)
second sound in He II: detection

Figure 3. Detecting second sound. (a) Resonator used by Vasilii Peshkov in 1948 to study standing waves of second sound in helium II. The glass tube $G$ is closed at the bottom and acts as a resonator. The heater $H$ is mounted on a glass disk that can be moved up and down by the tube $A$. The thermometer $T$ is an open winding of phosphor bronze wire on a frame movable by tube $B$. An electrical current of frequency $f$ generates small temperature fluctuations of frequency $2f$. The thermometer $T$ can be moved up and down to trace out the standing wave patterns of second sound, from which the velocity of second sound can be measured. In 1960 Peshkov used a similar apparatus attached to a helium-3 refrigerator to reach temperatures as low as 0.4 K. (Adapted from ref. 6.) (b) Apparatus used at Yale University to detect second sound by Lars Onsager’s method. A thin lucite tube was inserted into liquid helium (blue) in a dewar surrounded by liquid nitrogen (pink). A heater $H$ at the bottom of the tube was excited at 1 kHz, and a microphone $M$ in the vapor above the liquid was tuned to 2 kHz and its signal rectified. As the liquid helium bath evaporated, the free surface fell and resonant peaks appeared from the microphone output, from which the velocity of second sound could be deduced. (Adapted from ref. 7.)
resonantly interacting spin mixture of $^{6}\text{Li}$

since the early experiments in 2003/04

a well-established system to study

BEC-BCS crossover, fermion superfluidity, and

many many many related topics

$^{6}\text{Li}$

hybrid trap:

optical conf. radially

magnetic conf. axially
Propagation of Sound in a Bose-Einstein Condensate

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 20 March 1997; revised manuscript received 27 May 1997)

FIG. 1. Excitations of wave packets in a Bose-Einstein condensate. A condensate is confined in the potential of a magnetic trap. At time $t = 0$, a focused, blue-detuned laser beam is suddenly switched on (a) or off (b) and, by the optical dipole force, creates, respectively, two positive or negative perturbations in density which propagate at the speed of sound.
Measurement of Sound Velocity in a Fermi Gas near a Feshbach Resonance

J. Joseph, B. Clancy, L. Luo, J. Kinast, A. Turlapov, and J. E. Thomas*

Department of Physics, Duke University, Durham, North Carolina, 27708, USA
(Received 21 December 2006; published 24 April 2007)

FIG. 1 (color online). Sound propagation at the Feshbach resonance: (Top) 2D density profile showing initial perturbation. (Bottom) Gray (red) solid curve: Axial density profiles of the cloud for different in-trap propagation times; black dashed curve: valleys (inverted).
ordinary (‘first’) sound
change excitation scheme
propagation of first and second sound

local heat pulse appears as a dip
pulse position vs. time
extracting the sound speeds

what can we learn from that?
Innsbruck-Trento team: expt. and theory!

22.01.2013

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Rudi Grimm
Meng Khoon Tey
Yan-Hua Hou
Lev Pitaevskii
Sandro Stringari
Second sound and the superfluid fraction in a Fermi gas with resonant interactions

Leonid A. Sidorenkov$^{1,2}$, Meng Khoon Tey$^{1,2}$, Rudolf Grimm$^{1,2}$, Yan-Hua Hou$^3$, Lev Pitaevskii$^{3,4}$ & Sandro Stringari$^4$
personal connection to Landau

1956
two important theory papers from Trento

First and Second Sound in Cylindrically Trapped Gases

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(Received 29 January 2010; revised manuscript received 1 September 2010; published 4 October 2010)

effective 1D thermodynamic framework to solve Landau’s hydrodynamic equations for our trap geometry

First and second sound in a highly elongated Fermi gas at unitarity

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(Received 28 June 2013; published 21 October 2013)

describes behavior of 1D thermodyn. quantities based on EOS from MIT (Zwierlein group)
thermal expansion

Hou et al., PRA 88, 043630 (2013)

quite large!

this is why a local heat pulse appears as a density dip!
2D harmonic trap (uniform along z-axis)

on-axis Fermi energy: natural energy scale

\[ E_F = \left[ \frac{15\pi}{4} \left( \frac{\hbar^2}{2m} \right)^{3/2} m \omega^2 n_1 \right]^{2/5} \]

Bertaina et al., PRL 105, 150402 (2010)
3D harmonic trap (weak confinement along z-axis)

on-axis Fermi energy: natural energy scale

\[ E_F = \left[ \frac{15\pi}{4} \left( \frac{\hbar^2}{2m} \right)^{3/2} m\omega^2 n_1 \right]^{2/5} \]

Bertaina et al., PRL 105, 150402 (2010)
relevant Fermi temperature

3D harmonic trap (weak confinement along z-axis)

on-axis Fermi energy: natural energy scale

define corresponding Fermi temp. $T_F^{1D}(z)$

$E_F = \left[ \frac{15\pi}{4} \left( \frac{\hbar^2}{2m} \right)^{3/2} m\omega^2 n_1 \right]^{2/5}$

z-dependent
$T/T_F^{1D}$ varies along trap axis
sound speeds in terms of reduced quantities

**first-sound speed:**
excellent agreement with calculation based on known EOS

speed of the other signal:
strong temperature dependence, goes to zero near $T_c$
Обозначив общее значение $C_p$ и $C_v$ буквой $C$, а общее значение $(d\rho/d\rho)_T$ и $(d\rho/d\rho)_s$ просто как $d\rho/d\rho$, получаем из уравнения (8.9) две скорости звука $u_1$ и $u_2$ в виде

$$u_1^2 = \frac{d\rho}{d\rho}, \quad u_2^2 = \frac{TS^2\rho^2}{C\rho_n}.$$  

(8.10)

Таким образом, одна из скоростей ($u_1$) почти постоянна, а другая ($u_2$) сильно зависит от температуры, обращающаяся в нуль в $\lambda$-точке.

yes, this is exactly what we see !!!
sound speeds

according to effective 1D version of Landau‘s two-fluid theory

by Trento group

\[
\frac{u_1}{v_F^{1D}} = \sqrt{\frac{7}{10} \frac{P_1}{n_1 k_B T_F^{1D}}}
\]

\[
\frac{u_2}{v_F^{1D}} = \sqrt{\frac{T}{2 k_B T_F^{1D}} \frac{\tilde{s}_1^2}{\bar{c}_{p1}} \frac{n_{s1}}{n_{n1}}}
\]

where \( P_1 \) denotes the 1D pressure (unit of a force), \( \tilde{s}_1 = s_1/n_1 \) is the entropy per particle, and \( \bar{c}_{p1} = T (\partial \tilde{s}_1/\partial T)_{p1} \) is the isobaric heat capacity per particle.
superfluid fraction (1D)
superfluid fraction (uniform gas)

reconstruction based on universal thermodynamics

resonant Fermi gas remarkably close to liquid helium II

Dash & Taylor, Phys. Rev. 105, 7 (1957)
comparing with theory?

Taylor et al.,
PRA 77, 033608 (2008)

Salasnich,
PRA 83, 063619 (2010)

quantum Monte Carlo gives right $T_c$, but no information on superfluid fraction!
outlook

be inspired by He II

two-fluid hydrodynamics and transport phenomena revisited
e.g. transport through narrow channels (capillaries)

do things you cannot do with He II

second sound in the BEC-BCS crossover
controlled spin imbalance
low-D and lattices
more exotic superfluids
(e.g., mixed-species systems)
a barrier can really change things!
centrifugal barrier: two regimes

example $^{167}$Er: $p$-wave + vdW

molec. interactions

anything interesting here?

long-range interaction needed
Innsbruck erbium team

PI: Francesca Ferlaino
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Alexander Rietzler
PI: Francesca Ferlaino
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Rudi Grimm

Kiyotaka Aikawa
Michael Mark
Michael Springer

Simon Baier
centrifugal barrier: two regimes

example $^{167}$Er: $p$-wave + vdW

\[
E (\mu K) \quad R (100a_0)
\]
centrifugal barrier: two regimes

example $^{167}$Er: $p$-wave + vdW + DDI

long-range dipole-dipole interaction (Er with 7 $\mu_B$)
universal dipolar scattering

threshold value $\sigma = 6.702 \, D^2$

Bohn et al., NJP 11, 055039 (2013)

for identical fermions

$^{167}\text{Er}$

$D = 99 \, a_0$

$E_D = k_B \times 210 \, \mu K$

$\sigma \approx (260 \, a_0)^2$
Fermi degeneracy reached ($T/T_F \approx 0.2$)

FIG. 1: (color online) Time-of-flight absorption image of a degenerate Fermi gas of Er atoms at $T/T_F = 0.21(1)$ after $t_{\text{TOF}} = 12 \text{ ms}$ of expansion (a) and its density distribution integrated along the $z$ direction (upper panel) and $x$ direction (lower panel) (b). The observed profiles (circles) are well described by fitting a poly-logarithmic function to the data (solid lines), while they substantially deviate from a fit using a Gaussian distribution to the outer wings of the cloud, i.e. $w$ (dashed lines). The absorption image is averaged over six individual measurements.

Aikawa et al., PRL 111, xxxxxx (2013)
highly efficient evaporative cooling

Aikawa et al., PRL 111, xxxxxx (2013)

FIG. 2: (color online) Evaporation trajectory to Fermi degeneracy. (a) Temperature evolution during the evaporation ramp and (b) corresponding $T/T_F$ versus N. The ratio $T/T_F$ is obtained from the width $\sigma$ of the distribution (triangles) and from the fugacity (circles); see text. The error bars originate from statistical uncertainties in temperature, number of atoms, and trap frequencies for the width measurements and the standard deviations obtained from several independent measurements for the fugacity. The solid line is a linear fit to the data for $0.2 < T/T_F < 4$. 

evap. efficiency 3.5
no other spin states

Fig. 3: (color online) Absorption images of the atomic cloud with a Stern-Gerlach separation of the spin components. A magnetic field gradient of about 40 G/cm is applied during the expansion for about 7 ms. (a)-(e) Along the entire evaporative cooling sequence, atoms are always spin-polarized in the lowest hyperfine sublevel $|F = 19/2, m_F = -19/2\rangle$. $T/T_F$ of the atomic samples are indicated in each panel. In (f) the image is obtained right after RF mixing of the spin states for the sample at $T/T_F = 0.33(1)$. The three clouds correspond to the magnetic sublevels $m_F = -19/2, -17/2, \text{and} -15/2$ from bottom to top.

Aikawa et al., PRL 111, xxxxxx (2013)
FIG. 4: (color online) Effective elastic cross-section as a function of $T/T_F$ after thermalization. In the non-degenerate regime, the effective cross section is constant and gives a mean value of $2.0(5) \times 10^{-12}\text{cm}^2$. The error bars for each point contain the statistical uncertainties of the time constant for cross-dimensional thermalization, of the trap frequencies, and of the temperature. A typical cross-dimensional thermalization measurement with an exponential fit to the data is shown in the inset. $T_z$ is the temperature along the $z$-direction.

Aikawa et al., PRL 111, xxxxxx (2013)
some interesting numbers

optical dipole trap (1570nm light): $\bar{\omega}/2\pi = 380 \text{ Hz}$

number of atoms
$N \approx 6 \times 10^4$

peak number density
$n = 4 \times 10^{14} \text{ cm}^{-3}$

Fermi temperature
$T_F = k_B \times 1.3 \mu K$

three-body decay rate
$L_3 < 3 \times 10^{-30} \text{ cm}^6/\text{s}$

facilitates highly efficient evaporative cooling

physics behind that?
Centrifugal barrier: two regimes

Example \(^{167}\text{Er}: ~p\text{-wave} + \text{vdW} + \text{DDI}\)

![Graph showing E (\(\mu\)K) vs. R (100\(a_0\)) with labeled regions for lossy and shielded areas.](image)
optimum DDI strength

cross section too small

weak

breakdown of centrifugal barrier

strong
outlook

extreme number densities:
• what is the limit?
• p-wave superfluidity??

other systems:
• stable fermionic Feshbach molecules

\[
\begin{align*}
\text{\textsuperscript{39}K} & \quad \text{B} & \quad \text{F} \\
\text{\textsuperscript{41}K} & \quad \text{B} & \quad \text{F} \\
\text{\textsuperscript{167}Er} & \quad \text{B} & \quad \text{F} \\
\text{\textsuperscript{161}Dy} & \quad \text{B} & \quad \text{F} \\
\text{\textsuperscript{163}Dy} & \quad \text{B} & \quad \text{F} \\
\text{\textsuperscript{167}Er} & \quad \text{B} & \quad \text{F} \\
\text{\textsuperscript{162}Er} & \quad \text{B} & \quad \text{F} \\
\end{align*}
\]

• trimer or N-body states?

bosonic Er or Dy
three-body physics of two-fermion systems


Kartavtsev-Malykh trimer

Efimov states

we are here !

$^{40}\text{K} - ^6\text{Li}$
atom-dimer scattering

- $^6\text{Li}$
- $^{40}\text{K}$
- $^{40}\text{K}$
three-body process

Levinsen, Tiecke, Walraven, Petrov, PRL 103, 153202 (2009)
Levinsen, Petrov, EPJD 65, 67 (2011)

see also Alzetta, Combescot, Leyronas, PRA 86, 062708 (2012)
Born-Oppenheimer 3-body potentials

antisymmetric wavefunction

symmetric wavefunction

$2 m_{Li} a^2 V_{\text{eff}} / \hbar^2$

$\sim 1/R^2$
symmetry of AD wavefunction

antisym. wavefunction

\[ l = 0, 2, \ldots \]

symmetric wavefunction

\[ l = 1, 3, \ldots \]

\[ 2 m_{Li} a^2 V_{\text{eff}} / \hbar^2 \sim 1/R^2 \]
effective potentials in partial-wave channels

for 155G Li-K Feshbach resonance (880mG wide)

strong effect on $p$-wave barrier

strong atom-dimer attraction!
scattering amplitude

\[ \text{sign reversal} \]

\[ \text{s-waves only} \]

\[ \text{all partial waves} \]
scattering amplitude

\[ E_{\text{coll}} > \sim \frac{1}{10} E_b \]

**Sign reversal**

**s-waves only**

**all partial waves**
Fermi

Li

K

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Marko Cetina

Rudi Grimm

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Dima Petrov
mixture of heavy and light fermions: $^{40}\text{K} - ^6\text{Li}$
making weakly bound dimers (a>0)
flipping the spin state of the free atoms

$^{40}\text{K}$

- interacting spin state
- non-interacting spin state

$rf$ coupling
flipping the spin state of the free atoms

$^{40}\text{K}$

interacting spin state

non-interacting spin state

$rf$ coupling
flipping the spin state of the free atoms

Interacting spin state
Non-interacting spin state

rf coupling
radio-frequency spectroscopy

interacting spin state

non-interacting spin state

interaction with $^6\text{Li}^{40}\text{K}$ dimers

excellent tool to probe interaction shifts !!!
sample rf spectra

\[ B - B_0 = -20 \text{ mG} \]
broadening and shift

- $T_{eff} = 165 \text{ nK}$
- $T_{eff} = 232 \text{ nK}$
- $T_{eff} = 370 \text{ nK}$
sign reversal

\[ \delta \nu = \frac{\hbar \bar{n}_D a_{\text{eff}}}{\mu_3} \]

shift in terms of eff. sc. length

\[ -\text{Re} \langle f(0) \rangle (1000 \ a_0) \]

\[ T_{\text{eff}} = \]

- 165 nK
- 232 nK
- 370 nK

\[ a (1000 \ a_0) \]
why we are so excited!

mass imbalance: **qualitatively new** interaction properties

no-loss few-body effect

ultracold **paradigm shift**: physics beyond s-waves

potentially strong impact on many-body physics !!!
strongly interacting, mass-imbalanced mixtures

Periodic Table of the Elements

New project in Innsbruck: Dy-K mixtures
thank you for your attention