Strongly interacting two-electron fermions at an orbital Feshbach resonance

Few-body Physics in Cold Atomic Gases
Beijing, April 15th 2016

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Two-electron $^{173}$Yb fermions

Two internal degrees of freedom with long coherence times:

- **Nuclear spin**
- **Electronic orbital**

### Nuclear spin
- $e$: 5/2, 3/2, 1/2, -1/2, -3/2, -5/2

### Electronic orbital
- $g$: 5/2, 3/2, 1/2, -1/2, -3/2, -5/2

$^3P_0$ and $^1S_0$ states are indicated.
Optical clock technology:

Collaboration with Yb clock team @ INRIM (Turin)

578nm clock transition (~10 mHz linewidth)
Remote stabilization of a spectroscopy laser

Frequency dissemination (traced to SI primary standards) beyond GPS

Absolute frequency measurement in a non-metrological lab (quantum gases)

Long-distance optical fiber link

INRIM-LENS optical fiber link (642 km)


Metrological institute
Primary SI standards

$^{173}$Yb ultracold fermions for quantum simulation
Long-distance optical fiber link

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Remote stabilization of a spectroscopy laser
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173Yb ultracold fermions for quantum simulation

Frequency vs. time (a)
Normalized atom number

Frequency offset vs. time (b)

Absolute frequency of $^{173}\text{Yb}$ clock transition

$$f = 518\,294\,576\,845\,268\,(10)\text{ Hz}$$

TABLE 1. Uncertainty budget of the $^{173}\text{Yb} \, ^1S_0-^3P_0$ absolute frequency, expressed in Hz at 578 nm.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Bias (Hz)</th>
<th>Uncertainty (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lorentzian fit (*)</td>
<td>–</td>
<td>0.8 – 5</td>
</tr>
<tr>
<td>Cs fountain statistical (*)</td>
<td>–</td>
<td>0.9 – 2</td>
</tr>
<tr>
<td>Comb INRIM statistical (*)</td>
<td>–</td>
<td>0.4 – 1.2</td>
</tr>
<tr>
<td>Comb LENS statistical (*)</td>
<td>–</td>
<td>1 – 3</td>
</tr>
<tr>
<td><strong>Total Type A (</strong>)</td>
<td></td>
<td><strong>1.9</strong></td>
</tr>
<tr>
<td>Cs fountain standard accuracy</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>Fiber link phase slips (*** )</td>
<td>–</td>
<td>0.1 – 5</td>
</tr>
<tr>
<td>Quadratic Zeeman</td>
<td>−0.59</td>
<td>0.03</td>
</tr>
<tr>
<td>Lattice Stark</td>
<td>−</td>
<td>8</td>
</tr>
<tr>
<td>Blackbody radiation</td>
<td>−1.24</td>
<td>0.05</td>
</tr>
<tr>
<td>Probe laser intensity</td>
<td>–</td>
<td>0.00015</td>
</tr>
<tr>
<td>Gravitational redshift</td>
<td>2.277</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Total Type B (</strong>* )</td>
<td></td>
<td><strong>9</strong></td>
</tr>
<tr>
<td><strong>Total (</strong>* )</td>
<td>0.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Non-metrological LENS setup (quantum gases, slow sample production cycle)

<2 Hz (4$x10^{-15}$) precision on averaging times of a few hours

x400 improvement on previous value of $^{173}\text{Yb}$ clock transition frequency (NIST, 2005)
Collisional physics

The interaction strength depends on the electronic state...

...but not on the nuclear spin:

SU(N) symmetry

Different scattering lengths for the two states:

Twoorbital spin exchange

Two fermions (g+e) in a trap

Antisymmetrization of the two-particle state:

\[
|\text{eg}^+\rangle \propto \left[ g_1 e_2 + e_1 g_2 \right] \left[ \uparrow_1 \downarrow_2 - \downarrow_1 \uparrow_2 \right]
\]

\[
|\text{eg}^-\rangle \propto \left[ g_1 e_2 - e_1 g_2 \right] \left[ \uparrow_1 \downarrow_2 + \downarrow_1 \uparrow_2 \right]
\]

orbital-antisymmetric spin-triplet
orbital-symmetric spin-singlet
Two fermions (g+e) in a trap

A local spin-exchange interaction between different "orbitals" arises:

Different scattering lengths for the two states:

\[ |eg^+\rangle \propto |\uparrow_g \downarrow_e\rangle - |\downarrow_g \uparrow_e\rangle \]
\[ |eg^-\rangle \propto |\uparrow_g \downarrow_e\rangle + |\downarrow_g \uparrow_e\rangle \]
A magnetic field $B$ induces a mixing between the two channels:

$$|\psi\rangle = \alpha |eg^-\rangle + \beta |eg^+\rangle$$

Spectrum of the 578nm clock transition in a magic-wavelength 3D optical lattice

see related work by S. Fölling group:
F. Scazza et al., Nat. Phys. 10, 779 (2014)
A magnetic field $B$ induces a mixing between the two channels:

$$|\psi\rangle = \alpha |eg^-\rangle + \beta |eg^+\rangle$$

B field quench + free evolution

$$|\psi(t)\rangle = \alpha |eg^-\rangle + \beta e^{-i2V_{ext}/\hbar} |eg^+\rangle$$

Ground-state magnetization:

$$|\langle g^\uparrow|\psi(t)\rangle|^2 = \frac{1}{2} + \alpha \beta \cos \left(\frac{2V_{ex}}{\hbar} t\right)$$

Two-orbital spin exchange

G. Cappellini et al., PRL 113, 120402 (2014)

see related work by S. Fölling group:
Two-orbital spin exchange

Spin-exchange energy in a 3D optical lattice:

Very large spin-exchange energy:
\[ 2V_{\text{ex}} = U_{\text{eg}^+} - U_{\text{eg}^-} > 10 \, \text{kHz} \gg k_B T \]

Very different scattering lengths:
\[ a_{\text{eg}^-} \sim +220 \, a_0 \]
\[ a_{\text{eg}^+} \sim +2000 \, a_0 \]

Orbital magnetism, Kondo physics, ...

G. Cappellini et al., PRL 113, 120402 (2014)
Two-orbital spin exchange

Test of SU(N) symmetry:

same spin-exchange frequency verified at $3 \times 10^{-3}$ level
A new kind of Feshbach resonance between atoms in different nuclear and electronic states, driven by the two-orbital spin-exchange interaction very small, but finite, differential Zeeman shift $113 \Delta m \text{ Hz/G}$
Preparation of a two-orbital Fermi gas in the open-channel mixture:
Preparation of a two-orbital Fermi gas in the open-channel mixture:

Orbital Feshbach resonance

G. Pagano et al., PRL 115, 265301 (2015)
Preparation of a two-orbital Fermi gas in the open-channel mixture:
Orbital Feshbach resonance

Preparation of a two-orbital Fermi gas in the open-channel mixture:

Anisotropic hydrodynamic expansion of the Fermi gas:

C. Menotti, P. Pedri, S. Stringari

A strongly interacting gas of two-orbital fermions

G. Pagano et al., PRL 115, 265301 (2015)
A new tool for controlling interactions in two-orbital Fermi gases

Aspect ratio vs $B$:

Scattering length vs $B$:

related work by S. Fölling group:
Orbital Feshbach resonance

Atom loss rate vs B:

Measured 1/e lifetime at resonance $\sim 400$ ms
Atomic density $\sim 6 \times 10^{13}$ at/cm$^3$
Orbital Feshbach resonance

Feshbach resonance vs. $\Delta m$

Resonance condition:  $\Delta m \delta g \mu_N B = E_C$

$SU(N)$ symmetry $\rightarrow$ Same bound state energy $E_C$ for different $\Delta m$ $\rightarrow$ $B \sim \Delta m^{-1}$
Feshbach resonance vs. $\Delta m$

Resonance condition:

$$\Delta m \delta g \mu_N B = E_C$$

**SU(N) symmetry**  $\rightarrow$  Same bound state energy $E_C$ for different $\Delta m$  $\rightarrow$  $B \sim \Delta m^{-1}$
A new tool for controlling interactions in two-orbital Fermi gases


narrow Feshbach resonance

\[
T_c/T_F = f\left(\frac{1}{k_Fa_s}\right)
\]

BEC-BCS crossover?
A new tool for controlling interactions in two-orbital Fermi gases

Outlook

A new tool for controlling interactions in two-orbital Fermi gases


narrow Feshbach resonance

spin-orbit coupling

BEC-BCS crossover?

Topological superfluids?
Credits

Funding from ERC (CoG 2016), EU, MIUR, INFN

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C. Clivati, M. Pizzocaro, D. Calonico, F. Levi
Outlook

Two-orbital quantum magnetism
G. Cappellini et al., *PRL* 113, 120402 (2014)

Orbital Feshbach resonance

Strongly interacting 1D SU(N) fermions

Fermions in synthetic dimensions and edge states
M. Mancini et al., *Science* 349, 1510 (2015)

Optical-fiber absolute frequency dissemination
Coupling nuclear spins

$\text{g}$

$\frac{5}{2}$ $\frac{3}{2}$ $\frac{1}{2}$ $\frac{-1}{2}$ $\frac{-3}{2}$ $\frac{-5}{2}$

$\text{^1S_0}$
Coupling nuclear spins

Raman transitions coupling coherently different nuclear spin states:

\[ \pi \sigma^+ \pi \sigma^+ \pi \sigma^+ \pi \sigma^+ \pi \]

\[ g \quad 5/2 \quad 3/2 \quad 1/2 \quad -1/2 \quad -3/2 \quad -5/2 \]

\[ \sim 6 \text{ GHz} \]

\[ \gamma \sim 100 \text{ kHz} \]

\[ ^1S_0 \]

\[ ^3P_1 \]
Simulating an "extra dimension"

Analogous to coherent tunnelling coupling in a lattice

O. Boada et al., PRL 108, 133001 (2012)
Gauge fields and edge states

An atomic Hall ribbon in a real+synthetic space

Visualization of cyclotron skipping-orbits

A hallmark of quantum Hall physics
Gauge fields and edge states

A hallmark of quantum Hall physics

M. Mancini et al., Science 349, 1510 (2015)

A. Celi et al., PRL 112, 043001 (2014)

Visualization of cyclotron skipping-orbits

An atomic Hall ribbon in a real+synthetic space
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Optical-fiber absolute frequency dissemination
1D multicolor SU(N) fermions

Momentum distribution of repulsive SU(N) 1D fermions measured after time-of-flight expansion:
1D breathing mode

For $N \rightarrow \infty$ the breathing frequency approaches that of spinless bosons

«bosonization» of large-spin 1D fermions

C. N. Yang et al., CPL 28, 020503 (2011)
X.-W. Guan et al., PRA 85, 033633 (2012)
Thank you!

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G. Cappellini et al., *PRL* 113, 120402 (2014)

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