Observation of Efimov resonances in a mixture with extreme mass imbalance

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Seattle, May 13, 2014, „Few-body Universality in Atomic and Nuclear Physics: Recent Experimental and Theoretical Advances“
Universal few-body systems

- Scenario for >3
- Halo nuclei
- Analytical and numerical models
- Few fermion systems
- Lower and mixed dimensions
- Observables of universal features
- 3 particles with unequal masses

Innsbruck
LENS
ENS
Barllan
JILA
Rice
Heidelberg
Tokyo
...
Efimov physics with mass imbalance

\[ \text{Li} \quad \sim 22,2 \]

\[ \text{Cs} \quad \text{Cs} \]

| \( B-F \) | \( e^{\pi i s_0} \) | \( |a_{\text{min}}| \) | \( E_{\text{max}} \) (nK) | \( |a_{\text{min}}| \) | \( E_{\text{max}} \) (nK) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(^{133}\text{Cs} - ^{6}\text{Li}\) | 4.877 | \(3 \times 10^3\) | 1500 | \(2 \times 10^4\) | 60.0 |
| \(^{87}\text{Rb} - ^{6}\text{Li}\) | 6.856 | \(8 \times 10^3\) | 230 | \(6 \times 10^4\) | 5.00 |
| \(^{23}\text{Na} - ^{6}\text{Li}\) | 36.28 | \(9 \times 10^5\) | \(\ll 0.1\) | \(3 \times 10^7\) | \(\ll 0.1\) |
| \(^{7}\text{Li} - ^{6}\text{Li}\) | \(> 10^2\) | \(> 10^8\) | \(\ll 0.1\) | \(> 10^8\) | \(\ll 0.1\) |
| \(^{133}\text{Cs} - ^{40}\text{K}\) | 47.02 | \(2 \times 10^6\) | \(\ll 0.1\) | \(9 \times 10^7\) | \(\ll 0.1\) |
| \(^{87}\text{Rb} - ^{40}\text{K}\) | \(> 10^2\) | \(> 10^8\) | \(\ll 0.1\) | \(> 10^8\) | \(\ll 0.1\) |

Barontini et al., *Phys. Rev. Lett.* 103, 043201 (2009); Bloom et al., *Phys. Rev. Lett.* 111, 105301 (2013)

*D’Incao et al., Phys. Rev. A 73, 030703(R) (2006)*
1) Atom loss
2) Three-body loss rate
Feshbach resonances in Li-Cs

Repp et al., Phys. Rev. A 87, 010701(R) (2013)
Tung et al., Phys. Rev. A 87, 010702(R) (2013)

\[ a(B) = a_{bg} \left( \frac{\Delta}{B - B_{FR}} + 1 \right) \]

\[ B_{FR} = 842.99(4) \text{ G} \]
\[ \Delta = 60.4 \text{ G} \]

coupled-channels calculations by Eberhard Tiemann
Rf spectroscopy of dimers at 843 G

$B_{FR} = 842.90(20) \text{ G}$

$\Delta = 61.4(7) \text{ G}$

with rf spectroscopy of dimers
Experimental conditions

| frequencies | atom numbers | density       | temperature |
|-------------|--------------|---------------|-------------|
| Cs          | $2 \pi 54 \text{ Hz}$ | $1.6 \times 10^4$ | $4 \times 10^{11} \text{ cm}^{-3}$ | 0.4 $\mu$K |
| Li          | $2 \pi 141 \text{ Hz}$ | $4 \times 10^4$ | $0.8 \times 10^{11} \text{ cm}^{-3}$ | 0.4 $\mu$K |

→ at these temperatures: overlap $\approx 80 \%$ and gravitational sag $\approx 10 \mu$m
Feshbach resonances in Li-Cs

Repp et al., Phys. Rev. A 87, 010701(R) (2013)
Tung et al., Phys. Rev. A 87, 010702(R) (2013)

coupled-channels calculations by Eberhard Tiemann
Interaction around 843 G

Van der Waals

\[ r_{0}^{\text{LiCs}} = 45 \, a_0 \]
\[ r_{0}^{\text{Cs}} = 101 \, a_0 \]
Atom loss

Observation for $a < 0$:
Enhanced loss

$B_0 = 849.12(6)_{\text{stat}}(3)_{\text{sys}}$ G
$B_1 = 843.89(1)_{\text{stat}}(3)_{\text{sys}}$ G
$B_2 = 843.03(5)_{\text{stat}}(3)_{\text{sys}}$ G

Chin group, Tung et al., arXiv:1402.5943v1 (2014)

Grimm group, Phys. Rev. Lett. 112, 190401 (2014)
Three-body loss rate

\[
\dot{n}_{\text{Cs}} = -L_1^{\text{Cs}} n_{\text{Cs}} - 2L_3^{\text{LiCsCs}} n_{\text{Li}} n_{\text{Cs}}^2 - L_3^{\text{Cs}} n_{\text{Cs}}^3
\]
\[
\dot{n}_{\text{Li}} = -L_1^{\text{Li}} n_{\text{Li}} - L_3^{\text{LiCsCs}} n_{\text{Li}} n_{\text{Cs}}^2
\]

Assumptions:

- Fermionic Li $\rightarrow$ suppression of $L_3^{\text{LiLiCs}}$ and $L_3^{\text{Li}}$
- Recompression of the trap stops residual evaporation $\rightarrow$ constant temperature
Three-body loss coefficient $L_{3}^{Cs}$

$L_{3}^{Cs}$ is roughly constant in the relevant field range 840 G to 852 G

Berninger et al., *Phys. Rev. Lett.* 107, 120401 (2011)
Three-body loss rate

\[ \dot{n}_{CS} = -L_1^{Cs} n_{CS} - 2L_3^{LiCsCs} n_{Li} n_{CS}^2 - L_3^{Cs} n_{CS}^3 \]

\[ \dot{n}_{Li} = -L_1^{Li} n_{Li} - L_3^{LiCsCs} n_{Li} n_{CS}^2 \]

Assumptions:

- Fermionic Li \( \rightarrow \) suppression of \( L_3^{LiLiCs} \) and \( L_3^{Li} \)
- Recompression of the trap stops residual evaporation \( \rightarrow \) constant temperature
- \( L_3^{Cs} \rightarrow \) constant
- More \( N_{Li} = 3 \times 10^4 \) than \( N_{Cs} = 2 \times 10^4 \), after wait time the loss of Li atoms \( \approx 30\% \) but all Cs atoms are lost \( \rightarrow \) constant \( n_{Li} \)

\[ \dot{n}_{CS} = -L_1^{Cs} n_{CS} - L_3^{LiCsCs} n_{Li} n_{CS}^2 - L_3^{Cs} n_{CS}^3 \]
Three-body loss coefficient $L_3^{LiCsCs}$

Conversion $N_{Cs} \rightarrow n_{Cs}$ depends on trap frequencies and temperatures of Li and Cs as well as on overlap.

\[
\dot{n}_{Cs} = -L_1^{Cs} n_{Cs} - L_3^{LiCsCs} n_{Li} n_{Cs}^2 - L_3^{Cs} n_{Cs}^3
\]
Three-body loss coefficient $L_3^{LiCsCs}$

Observation:
$B_0 = 848.90(6)_{\text{stat}}(3)_{\text{sys}} \ G$
$B_1 = 843.85(1)_{\text{stat}}(3)_{\text{sys}} \ G$

Comparison with atom loss
$B_0 = 849.12(6)_{\text{stat}}(3)_{\text{sys}} \ G$
$B_1 = 843.89(1)_{\text{stat}}(3)_{\text{sys}} \ G$

included: reduction due to 80% overlap
Three-body loss coefficient $L_3^{LiCsCs}$

Observation:
$B_0 = 848.90(6)_{\text{stat}}(3)_{\text{sys}} G$
$B_1 = 843.85(1)_{\text{stat}}(3)_{\text{sys}} G$

$$a(B) = a_{bg} \left( \frac{\Delta}{B - B_{FR}} + 1 \right)$$

$$a_0^{(0)} = -320(3)_{\text{stat}}(2)_{\text{sys}}(10)_{\text{rf}} a_0$$
$$a_0^{(1)} = -1871(19)_{\text{stat}}(58)_{\text{sys}}(388)_{\text{rf}} a_0$$

$B_{FR} = 842.90(20) G$
$\Delta = 61.4(7) G$

with rf spectroscopy of dimers
Three-body loss coefficient $L^\text{LiCsCs}_3$

\[ a^{(0)} = -320(3)_{\text{stat}}(2)_{\text{sys}}(10)_{\text{rf}} a_0 \]

\[ a^{(1)} = -1871(19)_{\text{stat}}(58)_{\text{sys}}(388)_{\text{rf}} a_0 \]

\[ \frac{a^{(1)}}{a^{(0)}} = 5.8(0.1)_{\text{stat}}(0.2)_{\text{sys}}(1.0)_{\text{rf}} \]
Summary

- Feshbach resonances in Li-Cs
- Atomic loss curves show loss features associated with Efimov states
- These features are measurable in both species
- Third resonance is in the deep universal regime
- Measurement of $L_3^{LiCsCs}$
- The first two resonances leads to a scaling $\frac{a_-^{(1)}}{a_-^{(0)}} = 5.8(0.1)_{stat}(0.2)_{sys}(1.0)_{rf}$
Outlook

- Binding energies of Feshbach dimers
- Mixture at lower temperatures: $L_3$ of the third resonance
- ... or need a finite-range correction?
- Binding energies of Efimov states
- ...
Li-Cs team

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