Probing atomic gases with energetic atoms

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ITAMP workshop on
“Research frontiers in ultracold atoms and molecules: Unequal mass mixtures and dipolar molecules”
April 23-25 (2012)
Plan of this talk

1. Probing atomic gases with energetic atoms
   - New way to locally probe strongly-interacting atomic gases
   - Close connection to nuclear/particle physics
   - arXiv: 1110.5926 (Y.N.)

2. Beyond standard “Efimov effect”
   - 2-particles in any dimensions (1D, 2D, 3D)
   - Many advantages over standard one
     ⇒ further insights into Efimov physics
   - arXiv: 1202.3414 (Y.N. and Dean Lee)
Probing atomic gases with energetic atoms

- New way to locally probe strongly-interacting atomic gases
- Connection to nuclear/particle physics
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How to probe atomic gas?

Typically in ultracold atoms, light is used to probe atoms.
Probe atomic gas with atoms

Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate.

What can we learn from the scattering data on the (strongly-interacting) target atomic gas?
Probe atomic gas with atoms

Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate

Large $k \gg n^{1/3} \Rightarrow$ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = \cdots$$
Leading contribution

Shoot a probe atom into the target atomic gas and measure its differential scattering rate

Large $k \gg n^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + \cdots$$
Sub-leading contribution

Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate

Large $k \gg n^{1/3} \Rightarrow$ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta) \frac{C}{k^2} + \cdots$$
What is “C”?

Probability of finding 2 particles at small separation

- noninteracting gas: \( \langle \hat{n}(r)\hat{n}(0) \rangle = n^2 \)

- interacting gas: \( \langle \hat{n}(r)\hat{n}(0) \rangle \rightarrow \frac{C}{(4\pi|\mathbf{r}|)^2} \)

Anomally enhanced probability is quantified by the “contact density” \( C \)

Important characteristic of strongly-interacting atomic gases

Differential scattering rate

\[
\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta) \frac{C}{k^2} + \cdots
\]

Many-body physics

Few-body physics

Few-body physics plays an important role to probe many-body physics!
Differential scattering rate

\[
\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta, k/\kappa_*) \frac{C}{k^2} + \ldots
\]

For zero-range interactions

\[f(\theta)\]

\[g(\theta, 1.8)\]

For forward scattering \((\theta < 90°)\) only

For backward scattering \((\theta > 90°)\) possible

Efimov effect
Differential scattering rate

\[ \frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta, k/\kappa_*) \frac{C}{k^2} + \cdots \]

For zero-range interactions

\[ f(\theta) \]

\[ g(\theta, 1.8) \]

\[ \cos \theta \]

Efimov effect

Backward scattering rate measures contact density

New local probe of strongly-int atomic gases
Differential scattering rate

\[
\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta, k/\kappa_*) \frac{C}{k^2}
\]

\[
+ 16 \Theta(\cos \theta) \left( 2 \cos \theta \hat{k} + \hat{p} \right) \cdot \frac{\vec{j}}{k^2} + \cdots
\]

Azimuthal ($\varphi$) anisotropy reveals currents in many-body states
Ultracold atom “colliders”

Duke (2011)

MIT (2011)

NIST (2012)

Otago (2012)

C Schematic of scattering halo

Time (1 ms per frame)
Ultracold atom “colliders”

“A laser based accelerator for ultracold atoms”

University of Otago
(New Zeeland)
arXiv:1112.3650
Short summary 1

- Energetic atoms ⇒ New tool to locally probe strongly-interacting atomic gases
  ✓ backward scattering ⇒ contact density
  ✓ azimuthal anisotropy ⇒ current density

- Close connection to nuclear/particle physics
- Energetic atoms ⇒ New tool to locally probe strongly-interacting atomic gases
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- Close connection to nuclear/particle physics

“Hard probes” are useful to reveal short-range pair correlations both in nuclei and atomic gases
Beyond standard

“Efimov effect”

- 2-particles in any 1D, 2D, 3D
- Many advantages over standard one
  ⇒ further insights into Efimov physics
- arXiv:1202.3414 (Y.N. and Dean Lee)
Efimov effect

When 2 particles interact with “a=∞”, 3 always form a series of bound states

Discrete scale invariance
For the "Efimov effect" to happen, interaction needs to be scale invariant.

**Scale invariance**

in a zero-range interaction \((r_0=0)\)

with infinite scattering length \((a=\infty)\)

Quantum anomaly

Discrete scale invariance
When it happens?

For the “Efimov effect” to happen, interaction needs to be scale invariant

Zero-range interaction ($r_0=0$) becomes scale invariant when the scattering length is

• zero ($a=0$) $\Rightarrow$ no Efimov effect
• infinite ($a=\infty$) $\Rightarrow$ Efimov effect
• linear ($a=c|x|$) $\Rightarrow$ “Efimov effect”

Y. Nishida and D. Lee (2012)
We found ...

When 2 particles interact with “a = c|x|”, 2 always form a series of bound states.

\[ a = c|x| \]

Realizable in ultracold atoms by
- x-dependent magnetic/optical field
- x-dependent confinement length
We found ...

When 2 particles interact with “$a = c|x|$”, 2 always form a series of bound states

$a = c|x|$
We found ...

When 2 particles interact with “\(a = c|x|\)”, 2 always form a series of bound states.

\[a = c|x|\]

Discrete scale invariance
We found ...

When 2 particles interact with “a = c|x|”, 2 always form a series of bound states

Relative motion of the pair (E = -1/ma²) creates an effective 1/r² potential for the COM motion

Discrete scale invariance
## Comparison to Efimov effect

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**Pauli block**

**Spectroscopy**
### Comparison to Efimov effect

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**Sub-leading large k tail oscillates**

\[
\rho(k) \rightarrow \frac{C_2}{k^4} + C_3 \frac{\sin^2 \ln k}{k^5}
\]

**Leading large k tail oscillates**

\[
\rho(k) \rightarrow C \frac{\sin^2 \ln k}{k^3} + \cdots
\]

Y. Castin and F. Werner, PRA (2011)
E. Braaten, D. Kang, L. Platter PRL (2011)

TOF measurement
## Comparison to Efimov effect

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- **Sub-leading large k tail oscillates**
- **Leading large k tail oscillates**

- $\lambda = 22.7$ fixed
- $\lambda$ tunable by slope

### Many advantages!
Implication to Efimov physics

Q. Does discrete scale invariance persists for a larger number of particles?

A. Yes for N = 4

A. No for any N > 2 (bosons)

but can be yes for fermions

may be useful as a model system to develop insights into Efimov physics

G. Hanna and D. Blume (2006)
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