Observation of the Efimov state of the helium trimer

Maksim Kunitski

614. Wilhelm und Else Heraeus-Seminar
Few-body Physics: Advances and Prospects in Theory and Experiment
Outline

1. Efimov effect & He trimer
2. Experimental method
3. Results on the Efimov state of He$_3$:
   - size
   - binding energy
   - structure
Outline

1. Efimov effect & He trimer
2. Experimental method
3. Results on the Efimov state of He$_3$:
   - size
   - binding energy
   - structure
Two body system

Potential scale 80
Two body system

Potential scale 60

Observation of the Efimov state of the helium trimer  M. Kunitski
Two body system

Potential scale 40

![Graph of potential scale 40 with interparticle distance in Angstroms and potential in Kelvin.](image)
Two body system

Potential scale 20

Observation of the Efimov state of the helium trimer

M. Kunitski
Two body system

Potential scale 4

Observation of the Efimov state of the helium trimer

M. Kunitzki
Two body system

Potential scale 4

![Graph showing potential scale for the two-body system.](image)
Two body system

Potential scale 2

Observation of the Efimov state of the helium trimer

M. Kunitski
Two body system

Potential scale 2
Two body system

Potential scale 1
Two body system

Potential scale

![Potential scale graph]

- Class: \( R_{\text{max}} \)
Two body system

Potential scale 1

Quantum Halos „Live in the tunnel“
Two body system

What happens to a 3 body system under this condition?
Efimov effect (prediction 1970)

Vitaly Efimov in front of the experimental setup (group of Prof. Grimm, Uni Innsbruck), on which the “Efimov” effect was observed 35 years after the theoretical prediction.
Efimov effect (prediction 1970)

Vitaly Efimov in front of the experimental setup (group of Prof. Grimm, Uni Innsbruck), on which the “Efimov” effect was observed 35 years after the theoretical prediction.

Observation of the Efimov state of the helium trimer

M. Kunitski
Efimov effect (prediction 1970)

Vitaly Efimov in front of the experimental setup (group of Prof. Grimm, Uni Innsbruck), on which the “Efimov” effect was observed 35 years after the theoretical prediction.
Efimov states

• **Universal** phenomenon (does not depend on the details of the underlying two-body interaction); nuclear, atomic, condensed matter and biological physics

• **Increase** in the two-body attraction leads to **decrease** in the number of Efimov states

• **Scaling:** binding energy (tiny) = $(22.7)^2$; size (huge) = 22.7
Experimental evidence for Efimov states, 2005

Evidence for Efimov quantum states in an ultracold gas of caesium atoms


Feshbach resonance

Tuning scattering length $a$ with magnetic field $B$

Efimov resonances

Observation of the Efimov state of the helium trimer

M. Kunitski
Experimental evidence for Efimov states, 2005

Evidence for Efimov quantum states in an ultracold gas of caesium atoms  

T. Kraemer\textsuperscript{1}, M. Mark\textsuperscript{1}, P. Waldburger\textsuperscript{1}, J. G. Danzl\textsuperscript{1}, C. Chin\textsuperscript{1,2}, B. Engeser\textsuperscript{1}, A. D. Lange\textsuperscript{1}, K. Pilch\textsuperscript{1}, A. Jaakkola\textsuperscript{1}, H.-C. Nägerl\textsuperscript{1} & R. Grimm\textsuperscript{1,3}

Feshbach resonance

Tuning scattering length $a$ with magnetic field $B$

Efimov resonances
Efimov State in the \(^4\)He Trimer

T. K. Lim, Sister Kathleen Duffy, and William C. Damert*
Department of Physics and Atmospheric Science, Drexel University, Philadelphia, Pennsylvania 19104
(Received 15 November 1976)

On the basis of a Faddeev calculation, an Efimov state is predicted to exist in \(^4\)He\(_3\). This discovery represents the first manifestation of the Efimov effect and may have far-reaching consequences in the statistical mechanics of \(^4\)He gas at low temperatures.

8 times larger than the ground state
Efimov effect & He trimer

Observation of the Efimov state of the helium trimer

M. Kunitski

8 / 26
\( ^4 \text{He} \) trimer & experiment

- **Preparation** (tiny binding energies and huge spatial extents)

- **Detection**: no rotational states, only two vibrational states (one transition, 2.66GHz, with a very weak Franck-Condon overlap), no dipole moment
Searching for the elusive $^4$He trimer

Observation of the Efimov state of the helium trimer

M. Kunitski

Oleg Kornilov and J. Peter Toennies


de-Broglie wavelength:

$$\lambda_{db} = \frac{h}{mv} = \frac{h}{Nm_{He}v}$$
Outline

1. Efimov effect & He trimer

2. Experimental method

3. Results on the Efimov state of He$_3$:
   - size
   - binding energy
   - structure
Experimental method: Preparation in a supersonic jet

- **VACUUM (Pb)**
- Nozzle
- 'Quitting surface'
- 'Zone of silence'
- Mach disc
- Shock system
- Skimmer
- Speed ratio $> 100$
- \( T_\infty < 1 \text{ mK} \)
- \( P_0 = 0.2-4\text{ bar} \)
- \( T_0 = 8\text{ K} \)

\[ d = 5\mu\text{m} \]

**Graphs:**
- Final temperature vs. source pressure
- Speed ratio vs. source pressure

**References:**
Experimental method: Detection by Coulomb Explosion Imaging

acquired momenta (or KER) → structural information
Experimental method: Detection by Coulomb Explosion Imaging

Kinetic Energy Release (KER) $\equiv E_1 + E_2 + E_3 = \frac{1}{R_{12}} + \frac{1}{R_{13}} + \frac{1}{R_{23}}$

acquired momenta (or KER) $\rightarrow$ structural information
Experimental: COLd Target Recoil Ion Momentum Spectroscopy (COLTRIMS ≡ Reaction Microscope)

- **single molecule** experiment
- **coincident** measurement of **3D momenta** of **all charged** products after ionization
Experimental method: cluster separation + COLTRIMS

Separation of different He clusters

Momenta of ions measured by COLTRIMS
Outline

1. Efimov effect & He trimer
2. Experimental method
3. Results on the Efimov state of He$_3$:
   - size
   - binding energy
   - structure
Results: nozzle temperature $T_0=8$K

$\text{KER} \equiv E_1 + E_2 + E_3 = \frac{1}{R_{12}} + \frac{1}{R_{13}} + \frac{1}{R_{23}}$

$P_0 = 1.39$ bar

$\text{He}_2 + \text{He}$
Results: nozzle temperature $T_0 = 8K$

KER $\equiv E_1 + E_2 + E_3 = \frac{1}{R_{12}} + \frac{1}{R_{13}} + \frac{1}{R_{23}}$

- $P_0 = 1.39 \text{ bar}$
- $P_0 = 0.33 \text{ bar}$

**Ground state**

He$_2$+He

Observation of the Efimov state of the helium trimer

M. Kunitski
Results: nozzle temperature $T_0 = 8K$

$\text{KER} \equiv E_1 + E_2 + E_3 = \frac{1}{R_{12}} + \frac{1}{R_{13}} + \frac{1}{R_{23}}$

- $P_0 = 1.39 \text{ bar}$
- $P_0 = 0.33 \text{ bar}$

- Approximately 50 events per hour, ~80 Å
- 1% with respect to the ground state

Observation of the Efimov state of the helium trimer

M. Kunitski
Results: $T_0=8\text{K}$, $\text{KER}=E_1+E_2+E_3$

Science, 348, p.551, 2015
Results: $T_0=8K$, $\text{KER}=E_1+E_2+E_3$

Science, 348, p.551, 2015
Results: $T_0 = 8K, \ KER = E_1 + E_2 + E_3$

The excited state is about 8 times larger than the ground state.
Observation of the Efimov state of the helium trimer

M. Kunitski
Results: $T_0=8\text{K}$, pressure scan

He$_2$ + He$_2$ $\leftrightarrow$ He$_3^*$ + He

Observation of the Efimov state of the helium trimer

M. Kunitski

Science, 348, p.551, 2015
Observation of the Efimov state of the helium trimer

He-He pair distance distribution

Science, 348, p.551, 2015
He-He pair distance distribution

Science, 348, p.551, 2015

Observation of the Efimov state of the helium trimer

M. Kunitski
The binding energy of the excited state of He$_3$

\[ \Delta B = 0.084 \mu eV = 0.98 \text{mK} \pm 0.2 \text{mK} \]

\[ P_{\text{pair}}(R) \propto e^{-2\sqrt{2\mu \Delta B / \hbar^2} R} \]

\[ \Delta B = B(\text{He}_3^*) - B(\text{He}_2) \]

\[ B(\text{He}_3^*) = 2.6 \pm 0.2 \text{mK} \]
Observation of the Efimov state of the helium trimer

M. Kunitski

22 / 26
Observation of the Efimov state of the helium trimer

M. Kunitski

Structures

excited state: theory

excited state: experiment

ground state: theory

zoom x10
Observation of the Efimov state of the helium trimer

M. Kunitski
Structures
Structures

Observation of the Efimov state of the helium trimer

M. Kunitski
Structures
Structure of \( \text{He}_3^* \): shortest & longest bonds

![Graph showing the distribution of shortest and longest bond lengths for \( \text{He}_3^* \). The graph compares experimental (red squares) and theoretical (blue line) data, with the x-axis representing He-He pair distance in Angstroms and the y-axis representing counts.]
Structure of $\text{He}_3^*$: shortest & longest bonds
Structure of an Efimov state
Structure of an Efimov state
$R_{\text{min}}/R_{\text{max}}$ distribution of He$_3$

Observation of the Efimov state of the helium trimer

M. Kunitski
Conclusions

- The Efimov state of the helium trimer has been observed.
- The structure of the Efimov state spread out over 300\(\text{Å}\).
- The binding energy of the Efimov state of \(\text{He}_3\) is determined to be \(2.6\pm0.2\text{mK}\).
- The typical shape of the Efimov state of \(\text{He}_3\) is the \(\text{He}_2\) with the third He atom attached farther away.

Science, 348, p.551, 2015
Acknowledgments

Dörte Blume

Thank you for your attention!