公募研究：高速・高感度なイオン化検出による極低温多原子分子研究
Research on ultracold polyatomic molecules using fast and sensitive ionization detection

JST PRESTO, Kyoto University

Jun Kobayashi

Self-introduction

・Kyoto university, Takahashi lab. (Program-specific associate professor)

From 1.5 years ago, JST PRESTO Researcher

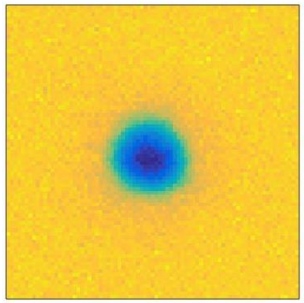
“Precision spectroscopy and chemical reactions using ultracold molecules”

C01 : Ultracold atom study of exotic phenomena bridging different hierarchies

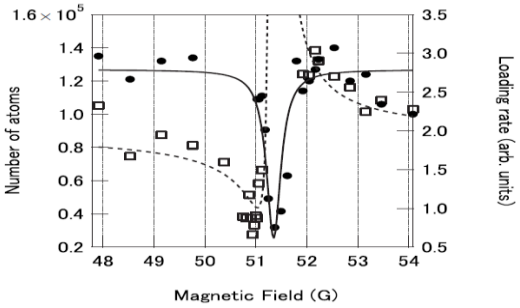
PI : Prof. Takahashi

Clusters & Hierarchies

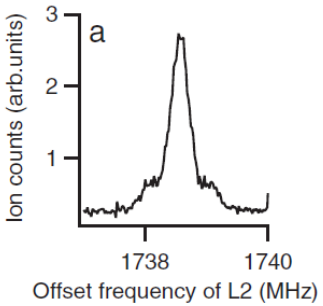
Experiments using ultracold atoms and molecules



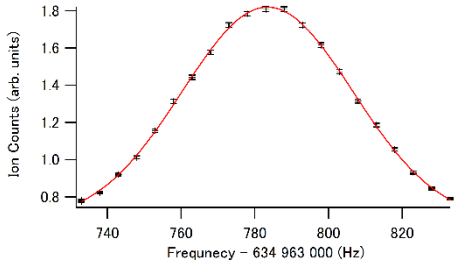
BEC



Feshbach Resonance

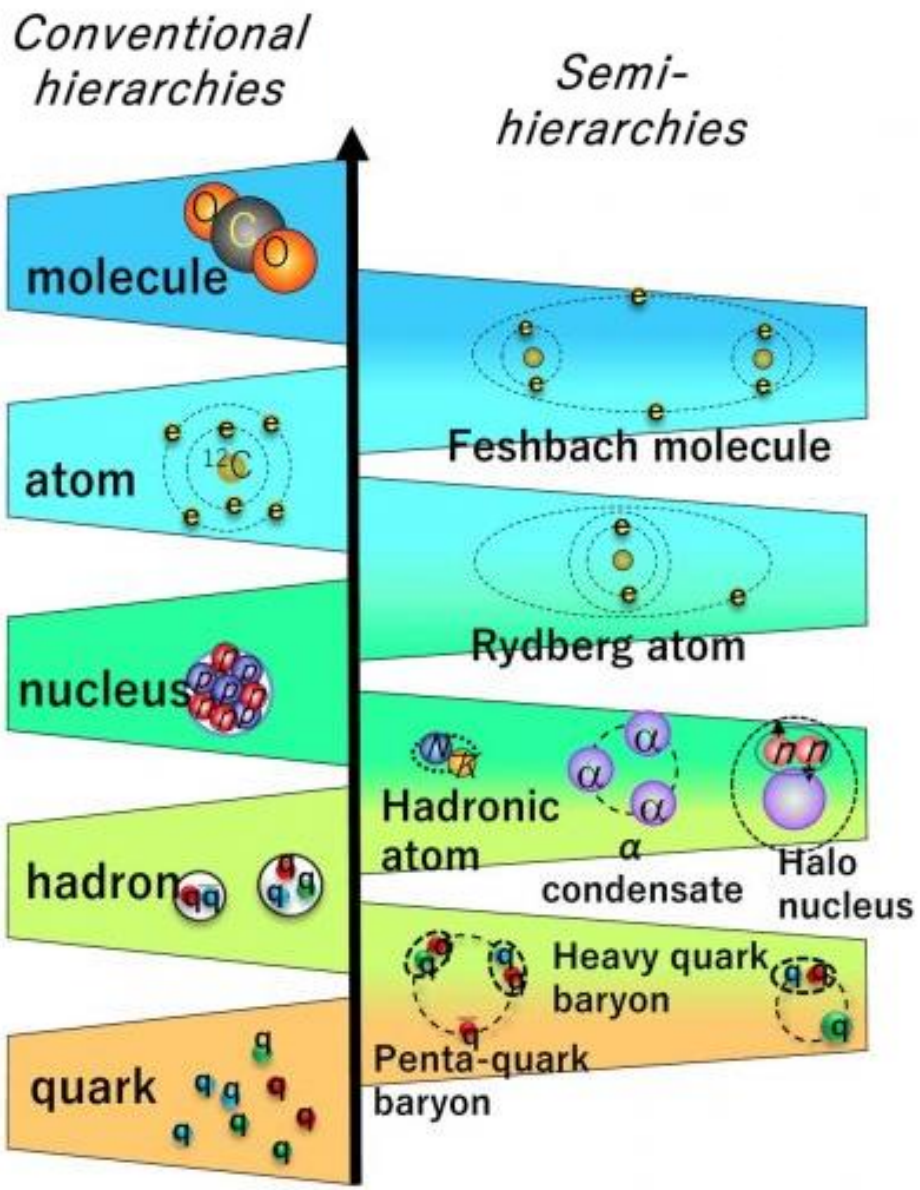


STIRAP

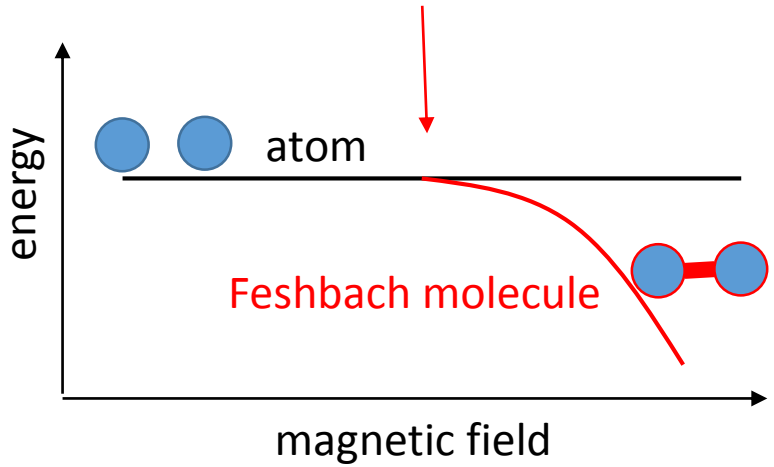


Precision spectroscopy

Hierarchical structure of matter



Feshbach resonance：
Resonance between atoms and molecule

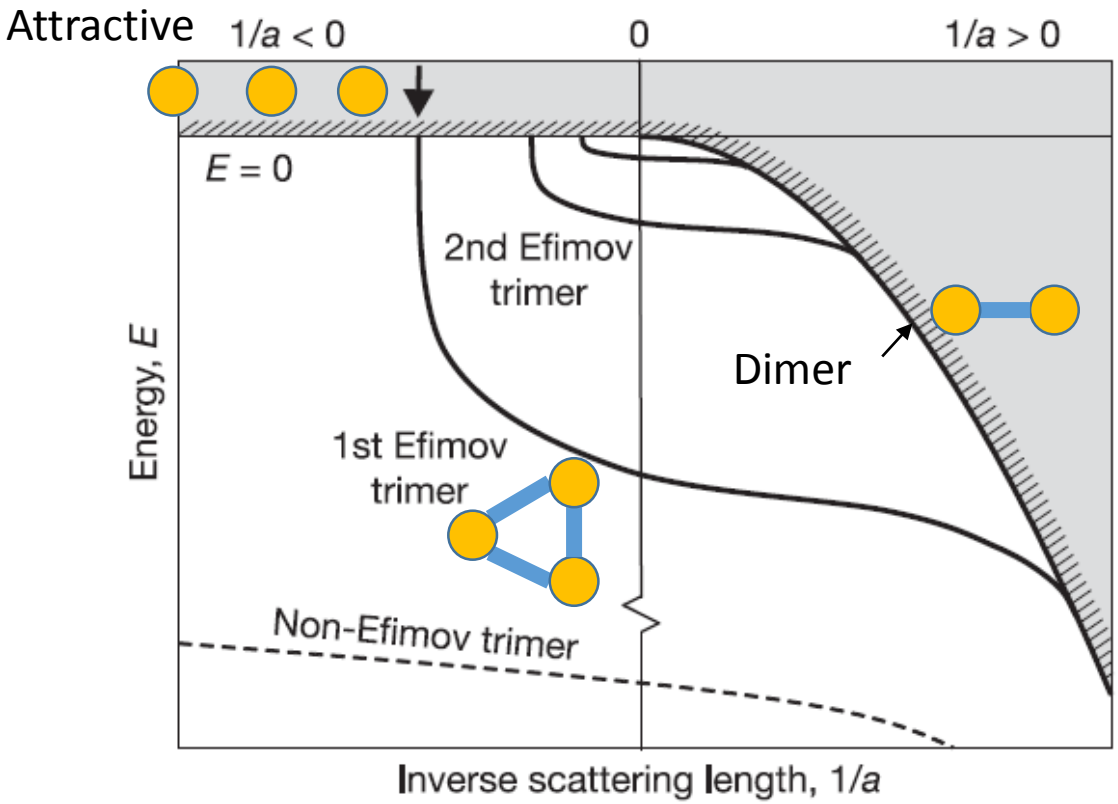


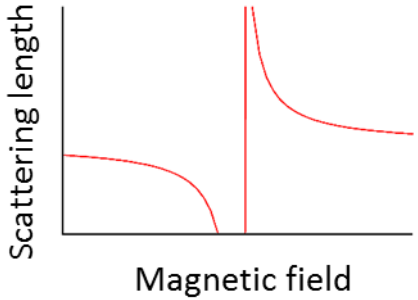
Atoms are adiabatically associated into molecules

⇨ Atoms can be resonant to N>2 atomic molecular states

Efimov state

Efimov states





[T. Kraemer et al., Nature 440 315 (2006)]

Efimov state is "Universal"

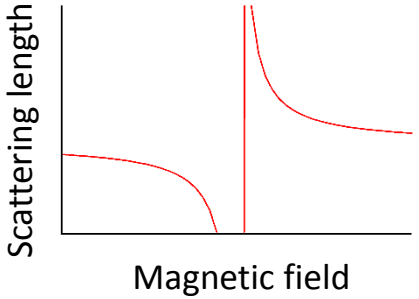
Any kind of particles with short range interactions

- Ultracold atoms
- He
- Nuclear
- Electron-atom
- ⋮

→ Interdisciplinary

Study on Efimov state with ultracold atoms

Ultracold atoms
- High controllability of the interaction
- Many atomic species



Single specie

Bosons

^{133}Cs - ^{133}Cs - ^{133}Cs

^{85}Rb - ^{85}Rb - ^{85}Rb

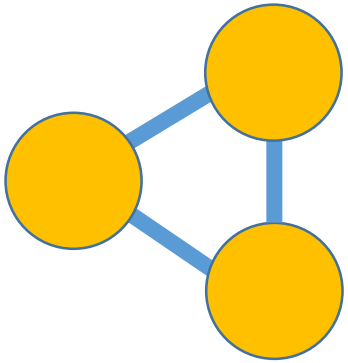
^{39}K - ^{39}K - ^{39}K

^{7}Li - ^{7}Li - ^{7}Li

Fermions

^{6}Li - ^{6}Li - ^{6}Li

in three spin states



Mixture of two species

Boson-Boson

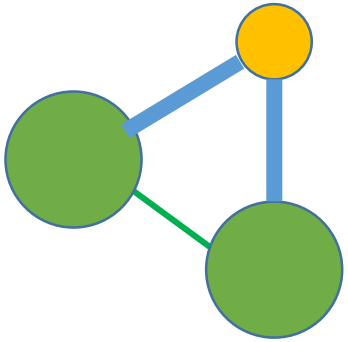
^{87}Rb - ^{87}Rb - ^{41}K

^{87}Rb - ^{87}Rb - ^{7}Li

Boson-Fermion

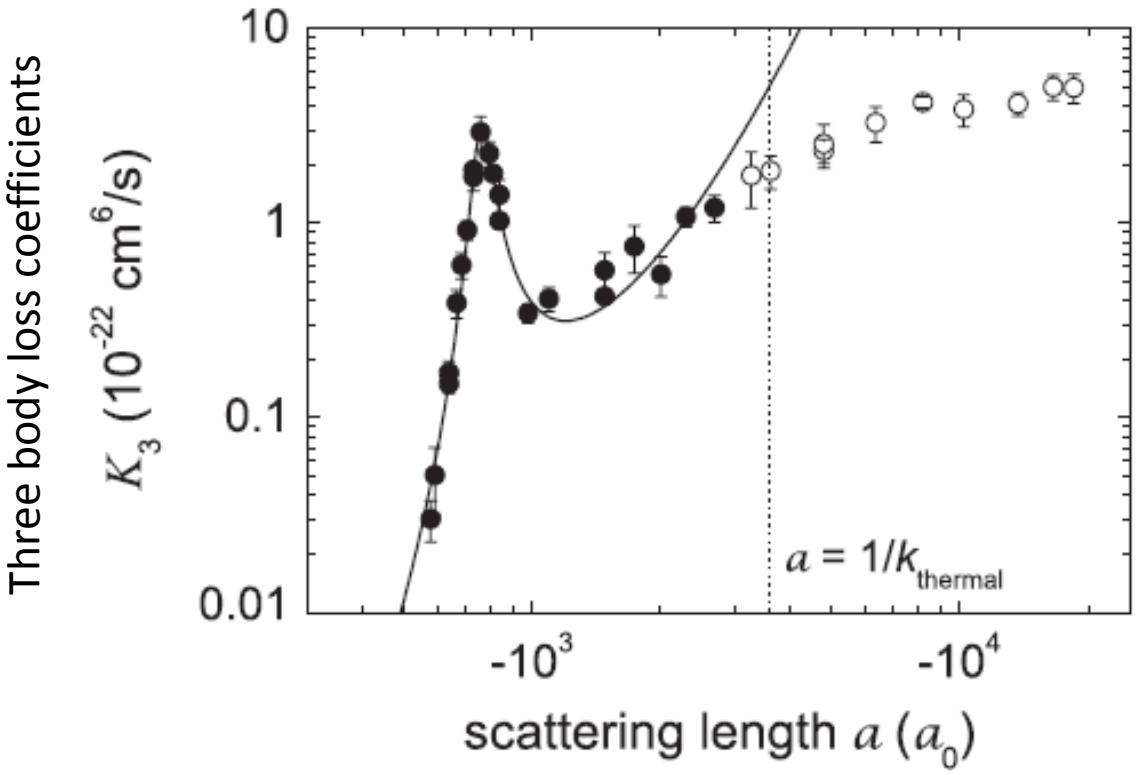
^{87}Rb - ^{87}Rb - ^{40}K

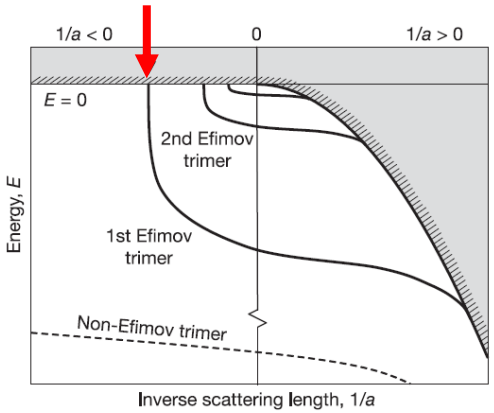
^{133}Cs - ^{133}Cs - ^{6}Li



Typical data of efimov resonance

$^{85}Rb_3$ [R.J. Wild et al., PRL 108 145305 (2012)]





At the Efimov resonance, atomic losses are enhanced.

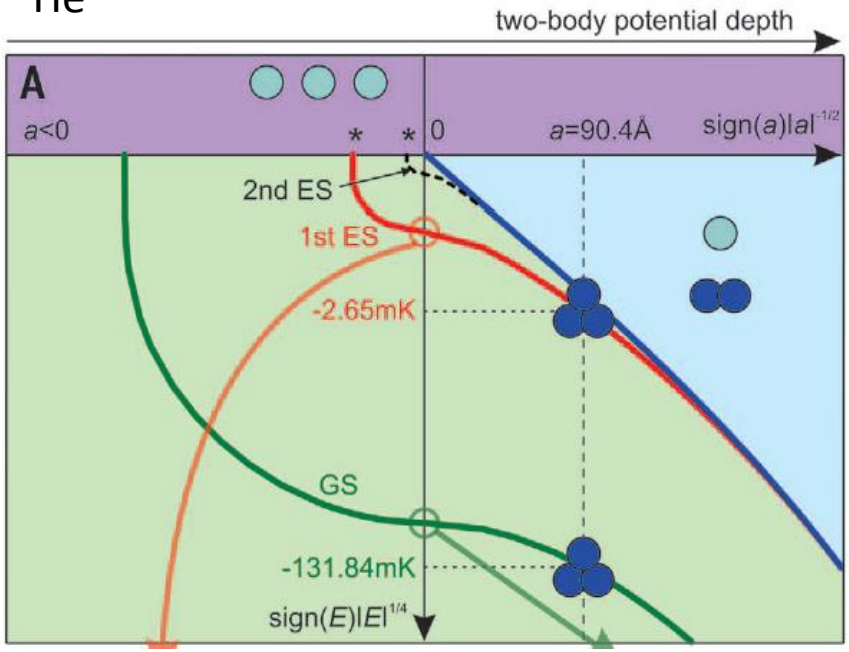
In the experiments with ultracold atoms, direct observation of the Efimov molecule is difficult.

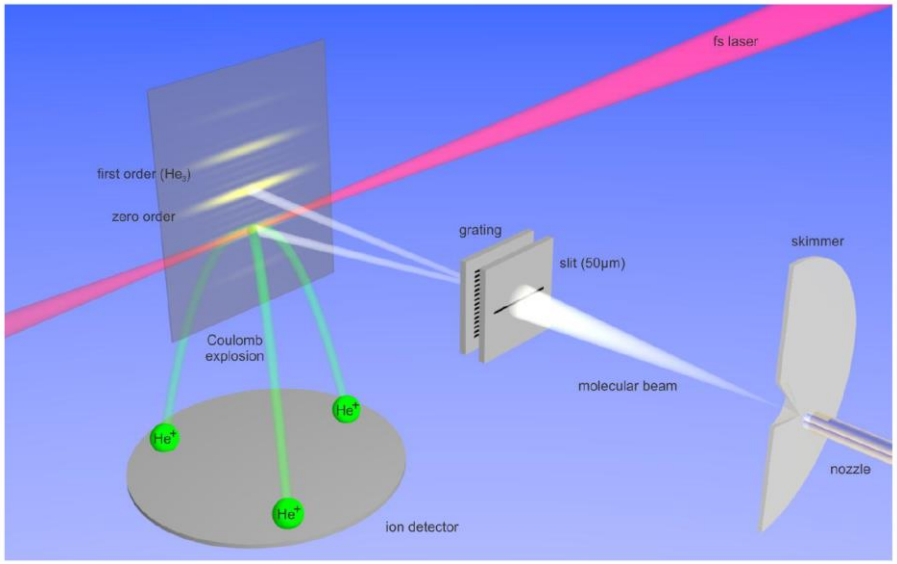
short lifetime
no cyclic optical transition

Direct observation of efimov state (He)

[M. Kunitski et al., Science 348 551 (2015)]

^{4}He





Efimov states are detected by ionization detection

No $^4He_2$ states below the trimers

⇩

Efimov trimer of $^4He_3$ is stable

Molecules used in ultracold atomic experiment have deeper binding states.

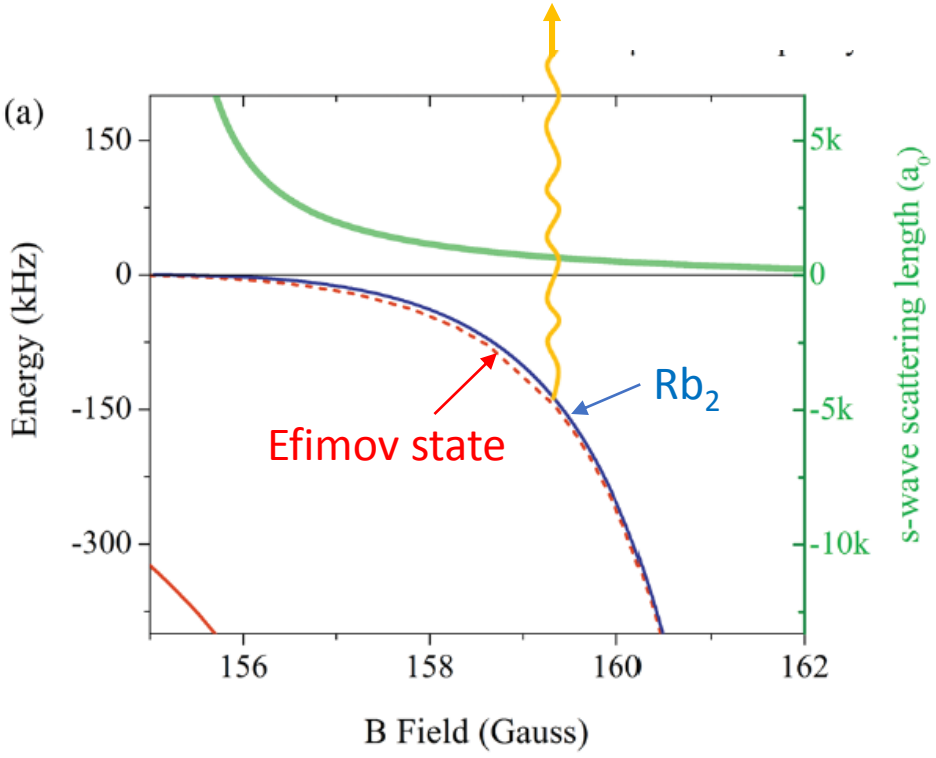
⇩

Trimers decay into dimer and atom in short time.

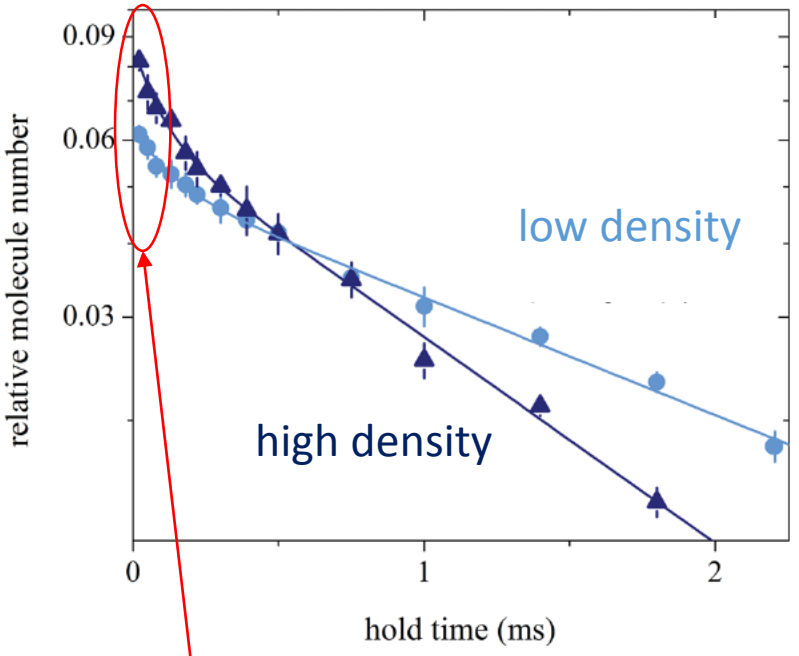
Observation of efimov state (Rb)

[C. E. Klauss et al., Phys. Rev. Lett 119 143401 (2017)]

Dissociation into atomic state by microwave transition



The efimov state and two-atomic molecules cannot be distinguished.



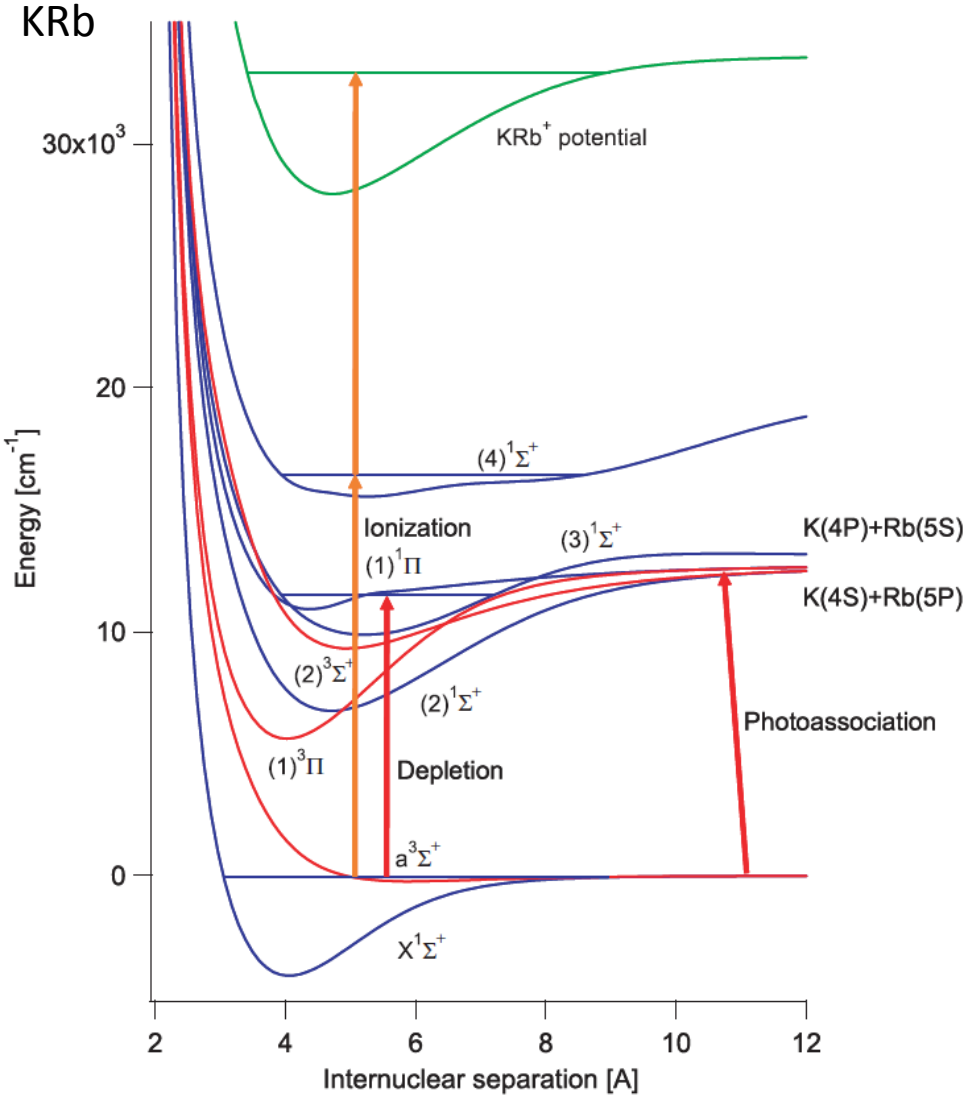
They say the fast loss is caused by the loss of efimov state

Lifetime ~ 100us

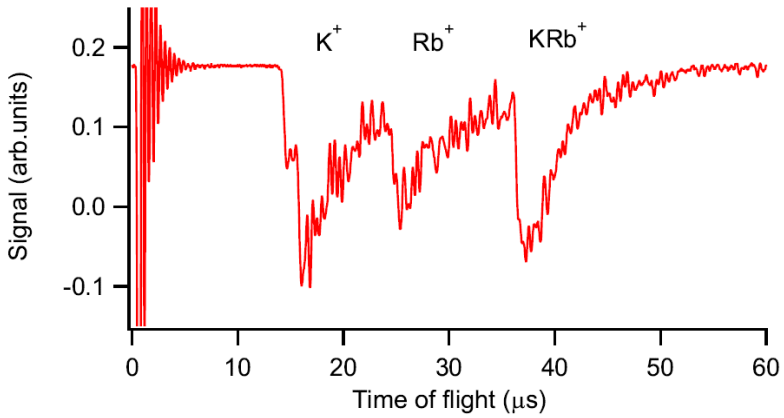
My idea : ionization detection of efimov sate

Resonance enhanced multi-photon ionization (REMPI) + MCP detection

KRb



TOF signal (our old experiment)



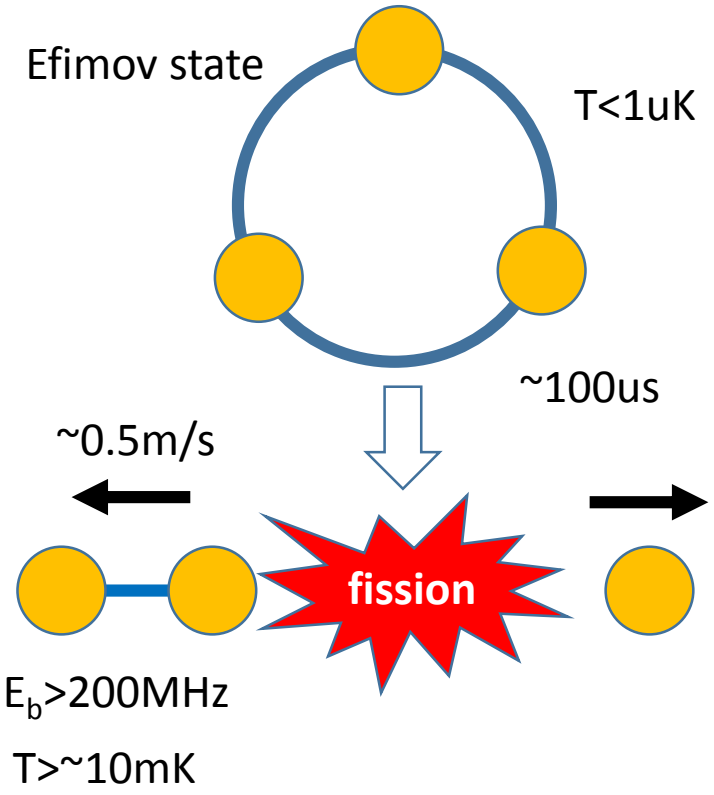
- Fast : 5ns pulse
- Sensitive : ~50% (MCP)
- Mass spectroscopy

⇩

Direct observation of Efimov trimer

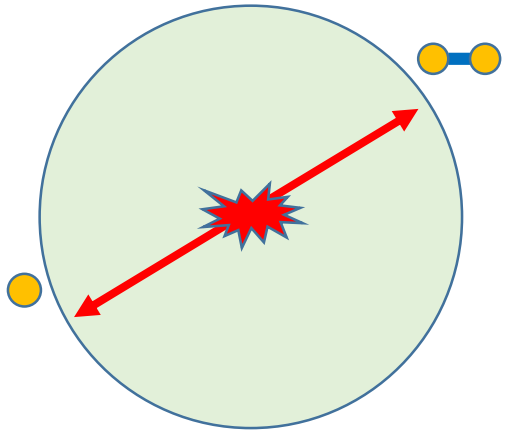
1. Study on decay process
2. Polyatomic cluster
3. Stable polyatomic molecule

1. Study on decay process



Ionization by pulsed laser

Beam diameter of pulsed laser : ~5mm



Observable period : ~5ms

The product molecules cannot be trapped.

Difficult to be observed by ordinary methods.

Study on decay process

Atoms $4x10^4$, $10^{13}cm^{-3}$

1ms

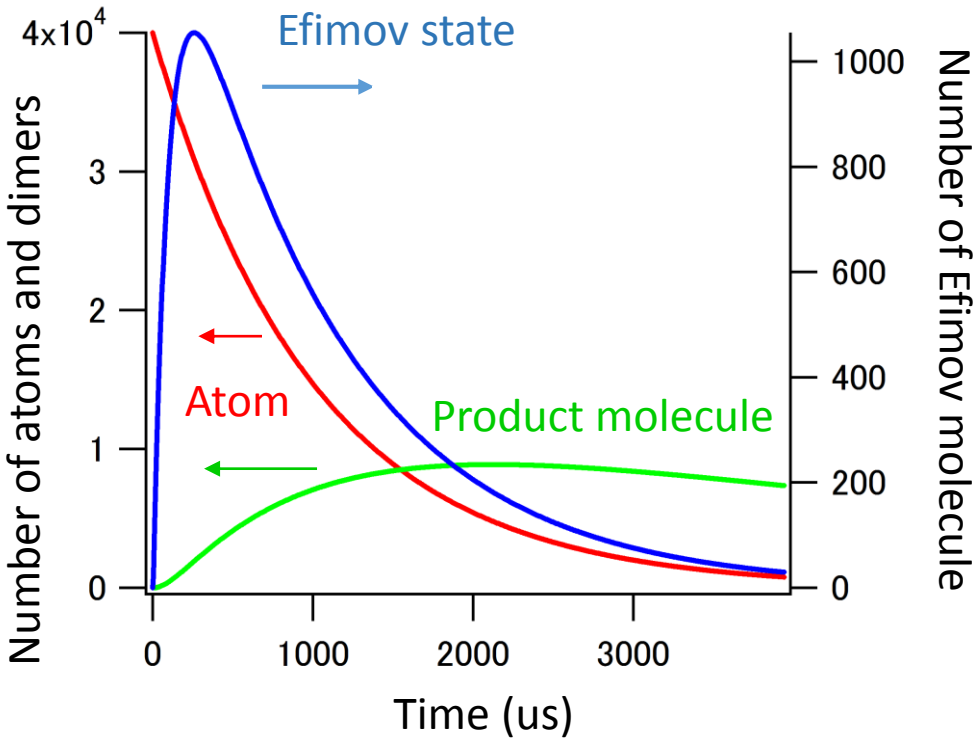
Efimov state

100us

Product molecule

5ms

out of detectable region



at maximum

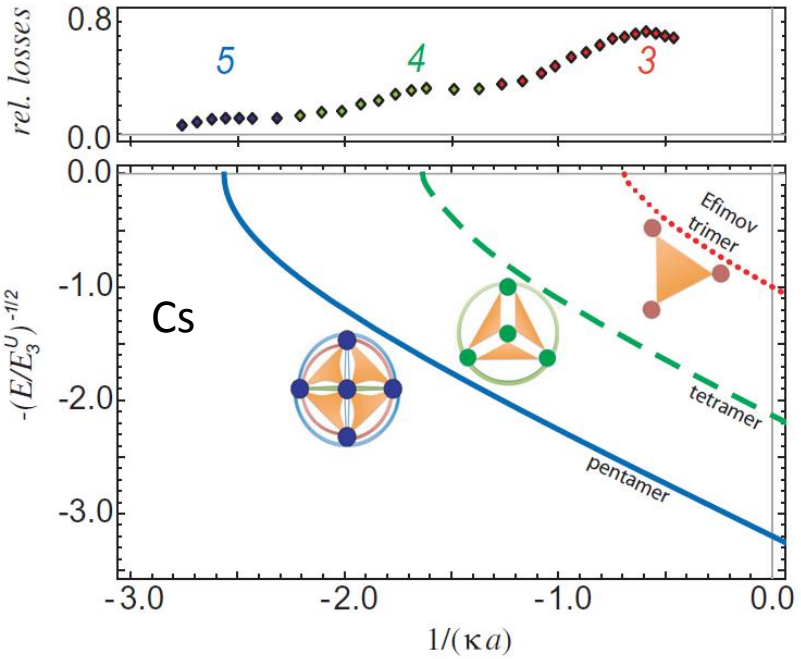
~10^3 Efimov states
~10^4 product molecules

→ Detectable by ionization detection

We can distinguish the vibrational state of the product molecule using a vibrational state selective optical transition.

2. Polyatomic cluster (efimov states with N>3)

[A. Zenesini et al., NJP 15 043040 (2013)]



N = 3, 4, and 5 atomic efimov resonances are observed by loss measurements.

Can we observe N>3 Efimov states directly?

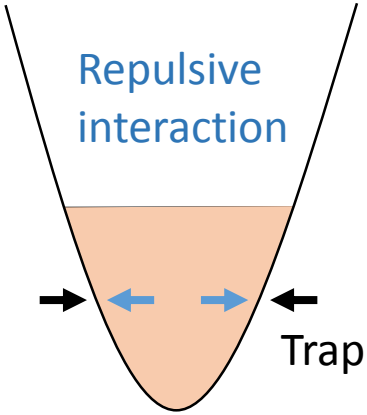
・Production rates are proportional to the n^{N-1}, where n is atomic density.

・Efimov states with N>3 should have shorter lifetime than N=3 states

We need higher density.

An instantaneous high density (>10^{15} cm^{-3})can be obtained by using a “collapse of a BEC with attractive interaction”

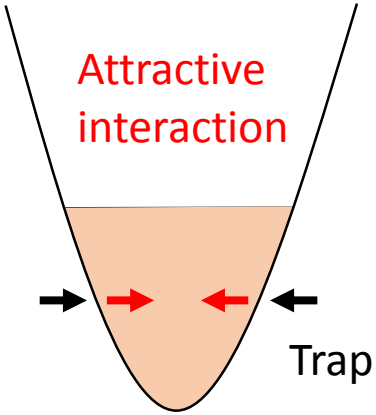
Collapse of a BEC with attractive interactions



The size of the BEC cloud is determined by the balance of the repulsive interaction and trap confinement.

Repulsive : Stable

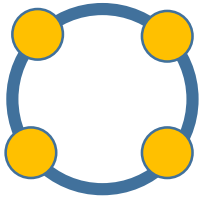
Switch the interaction to attractive



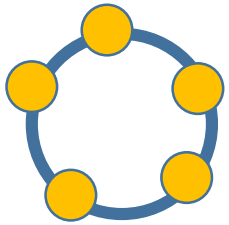
Collapse

Density is suddenly increased and the BEC is strongly heated by three-body recombination process.

Attractive : Collapse

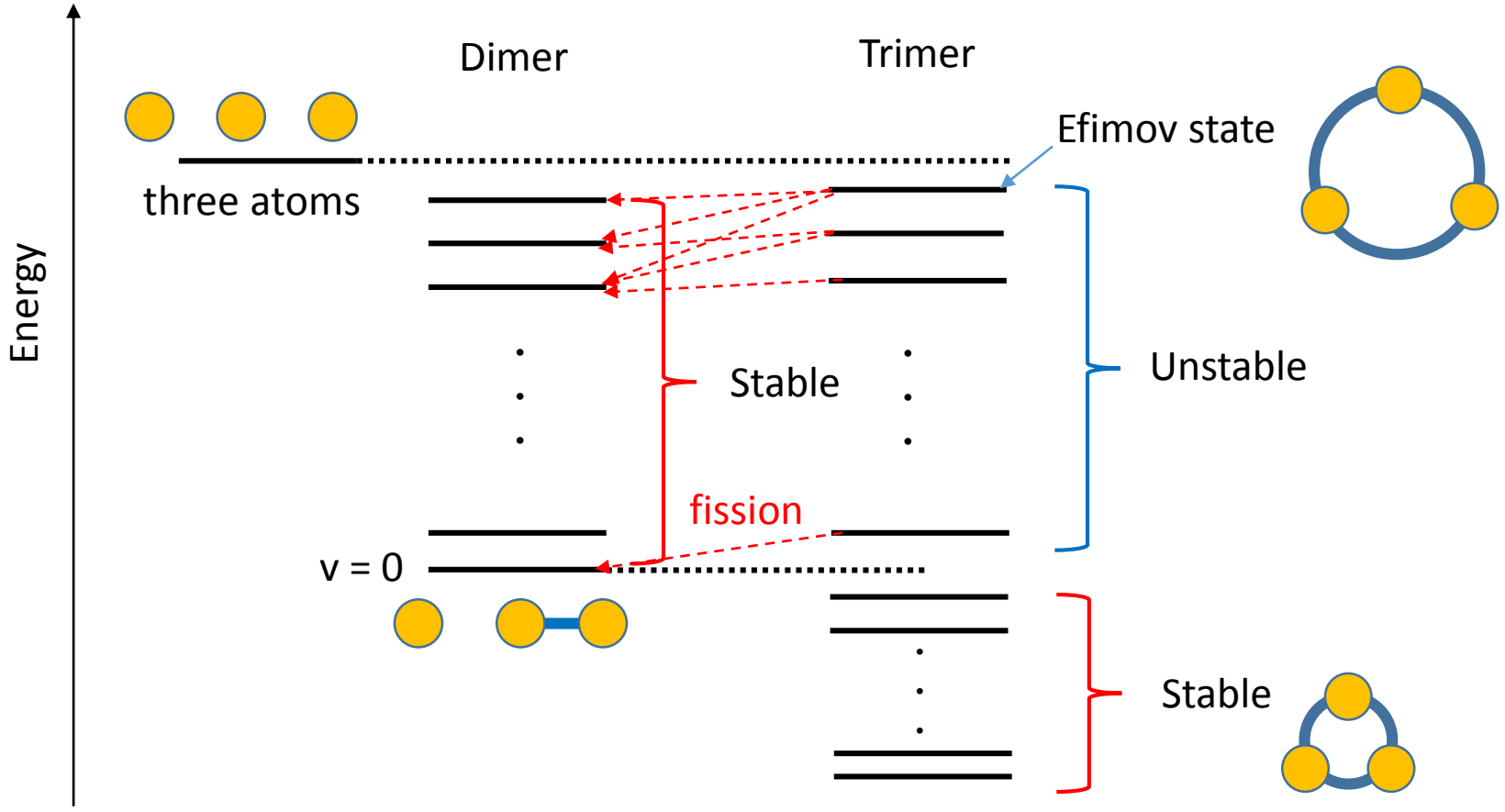


Tetramer



Pentamer

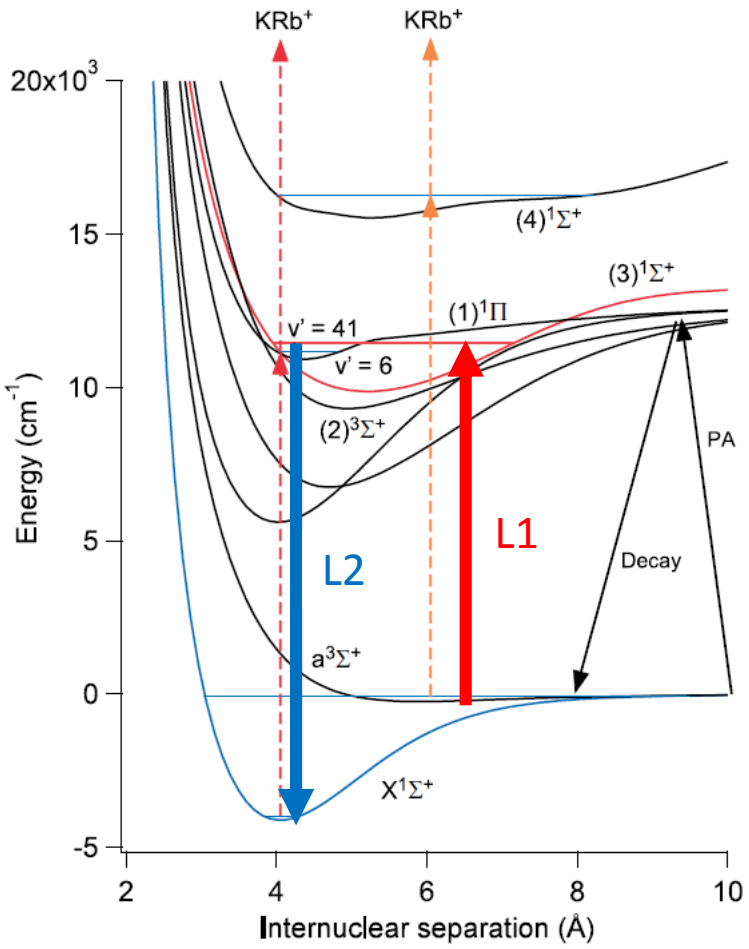
3. Stable polyatomic molecules



The fissions of molecules occurs only for three or more atomic molecules.

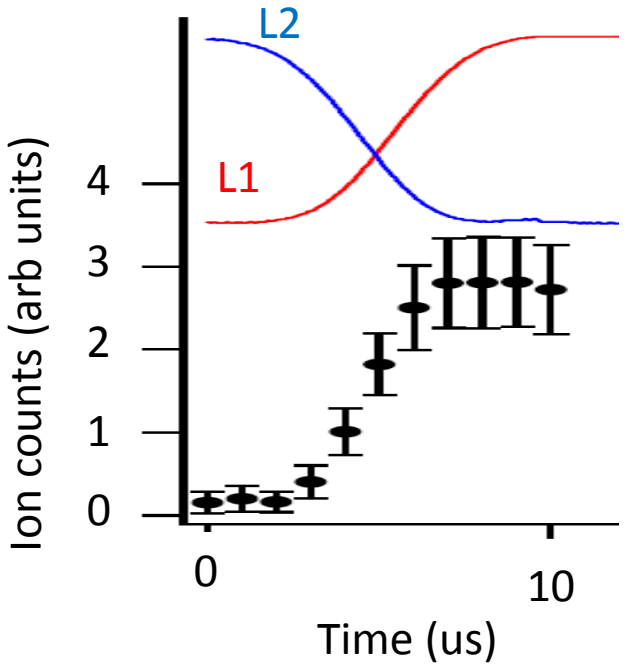
Transferring the efimov state to the stable three-atomic state gives a new way for making stable polyatomic molecules.

Vibrational state control of three-atomic molecule



[K. Aikawa PRL 105 203001 (2010)]

Vibrational states of two-atomic molecules can be arbitrary controlled by Raman transition.



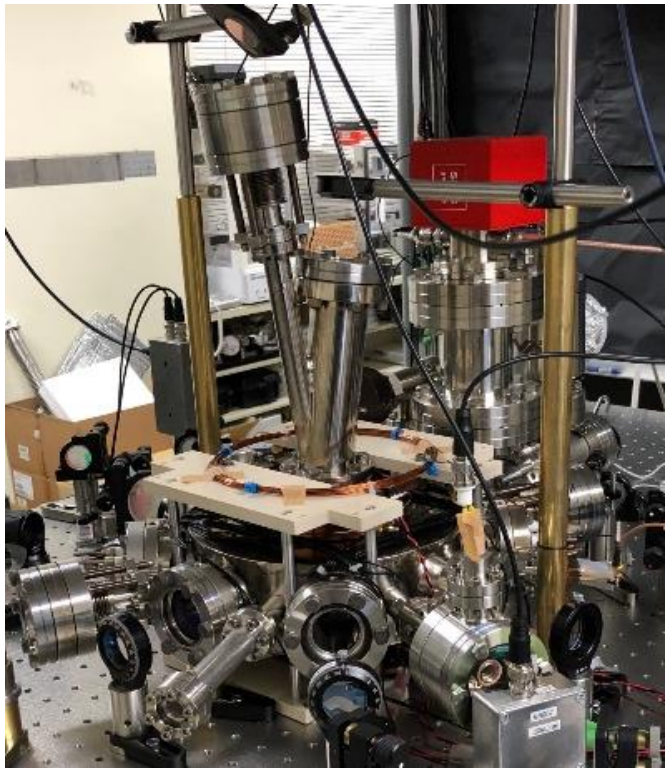
Transition can be done in less than 10 us.

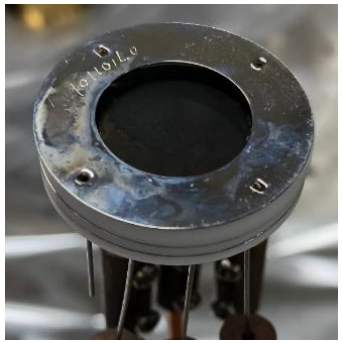
< Lifetime of efimov state: 100us

Control the vibrational states of trimers

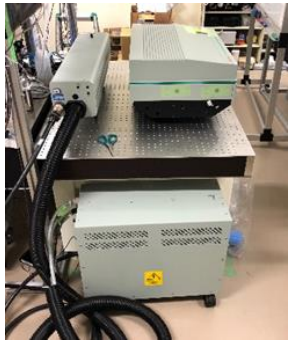
Current status of the experiment

In this 1.5 years, I have constructed a new experimental machine for the PRESTO research.



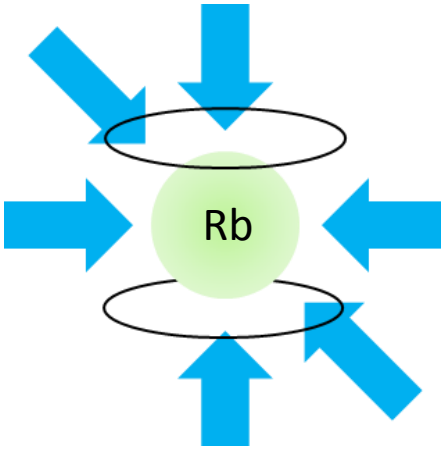


MCP

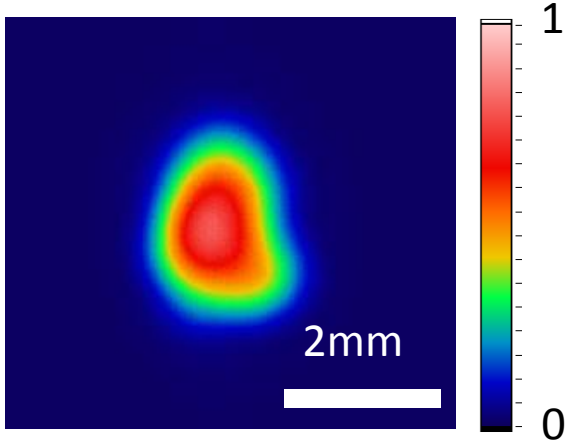


Pulsed laser

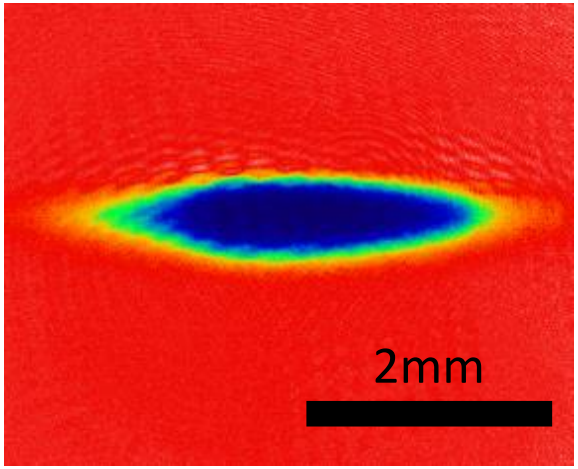
MOT



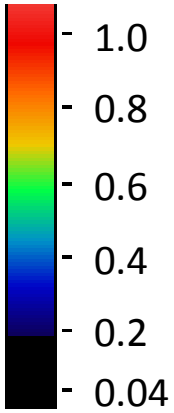
Fluorescence



Absorption imaging



Transmittance



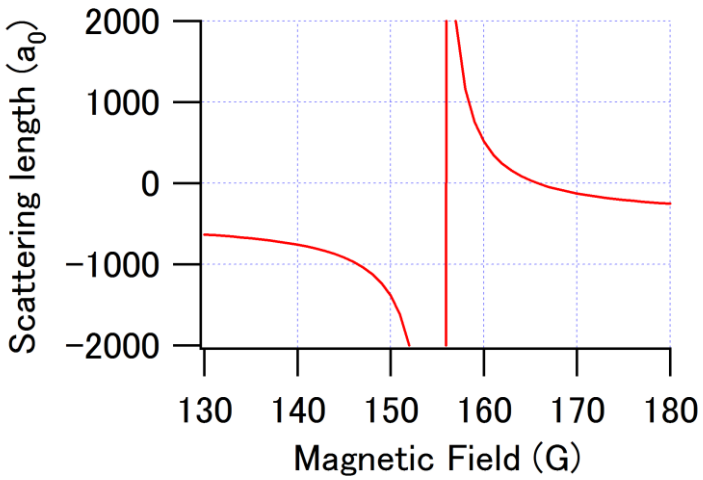
$N = 2 \times 10^{7}$

$T = 60$ uK

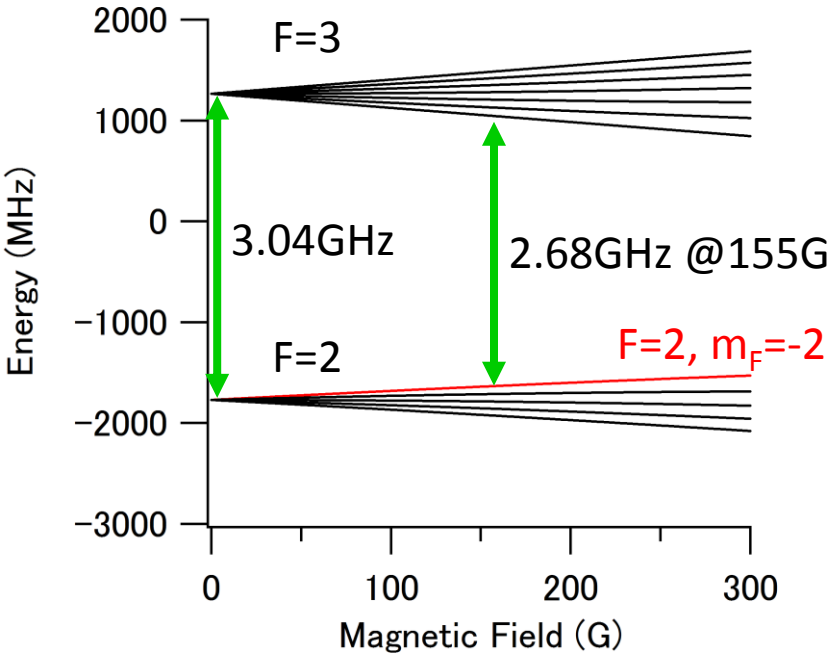
$n = 10^{11}$ cm^{-3}

Current status of the experiment

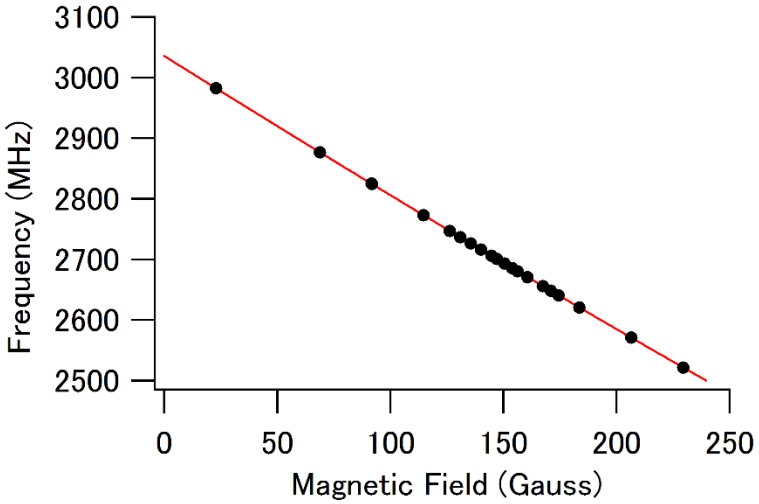
Feshbach resonance for ^{85}Rb F=2.m_F=-2



Zeeman shift



Observation of MW transition



Next to do

Optical pumping to F=2 m_F=-2

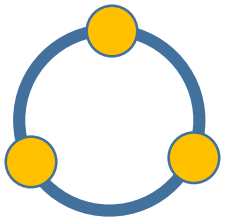
Cooling the atoms to get higher density

Ionization detection of molecules

Summary and outlook

Research on the “universal” efimov physics using ultracold atoms.

ultracold atoms, He, nuclear, atoms-electron, …

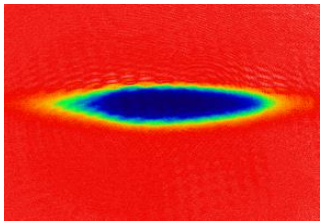


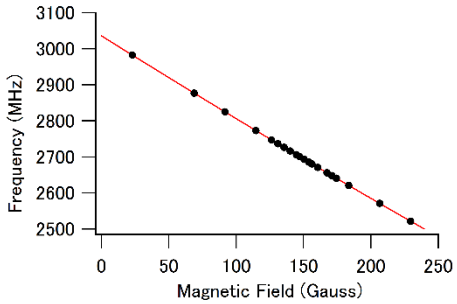
Direct detection of the efimov state using ionization detection.
(fast, sensitive, mass spectroscopy)

1. Study on the fission process of the efimov states by detecting product molecule.
2. Polyatomic efimov states using the collapse of the BEC with attractive interaction.
3. Stable three-atomic molecules using Raman transition (STIRAP).

Experiment

- ✓ Optical trapping of atoms
- ✓ Magnetic field for Feshbach resonance





Next

- Optical pumping
- Cooling the atoms
- Pulsed laser