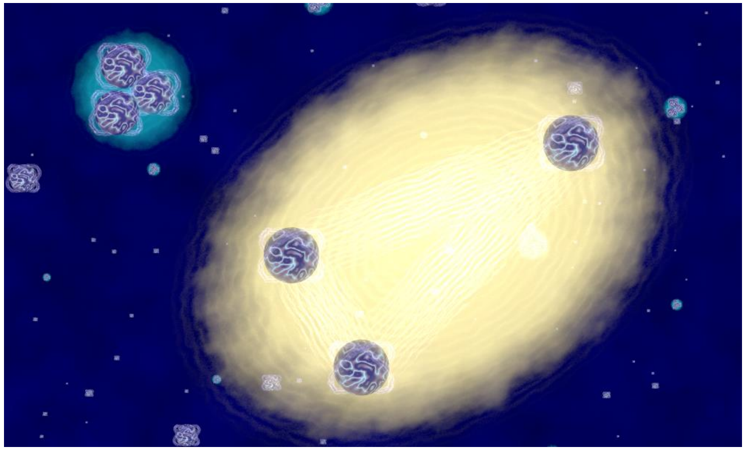
Observation of the Efimov state of the helium trimer



GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Maksim Kunitski

IKF Institut für Kernphysik Frankfurt

614. Wilhelm und Else Heraeus-Seminar
Few-body Physics: Advances and Prospects
in Theory and Experiment
19.04.2016

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
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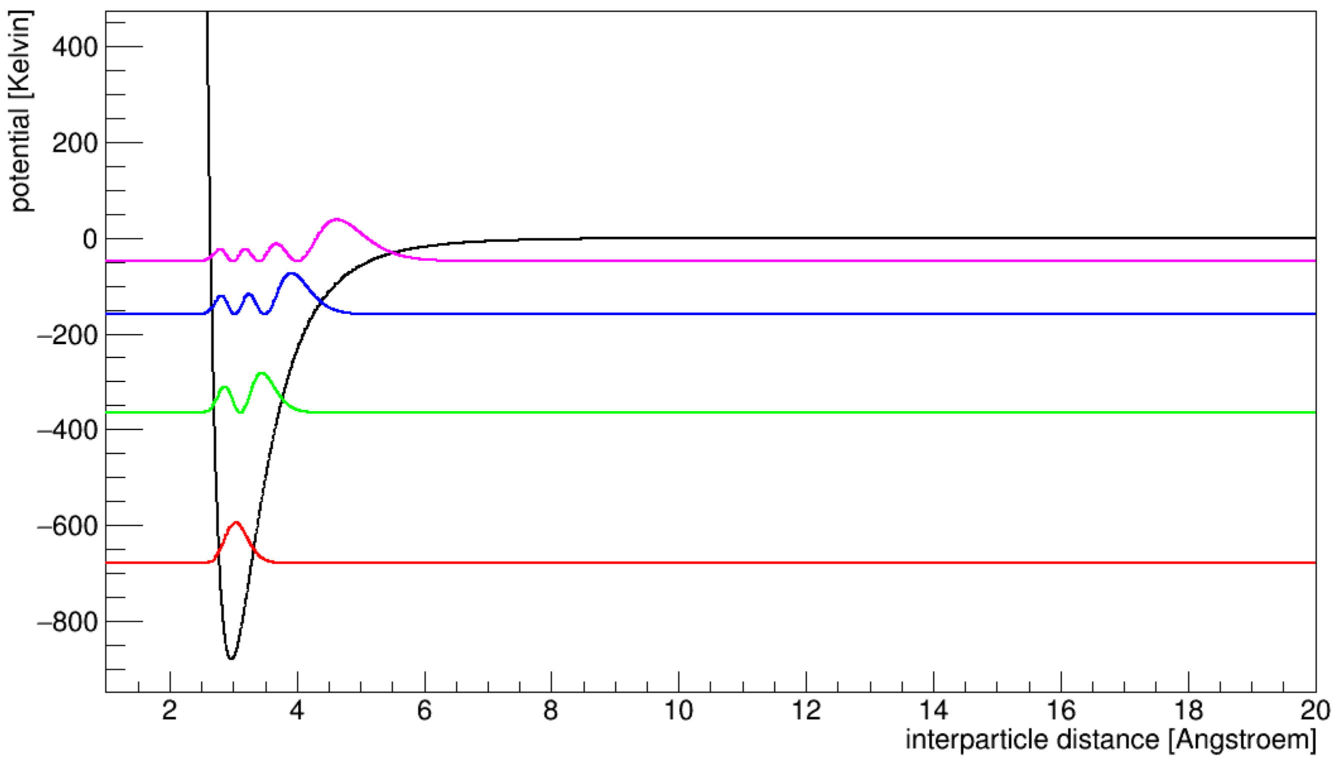
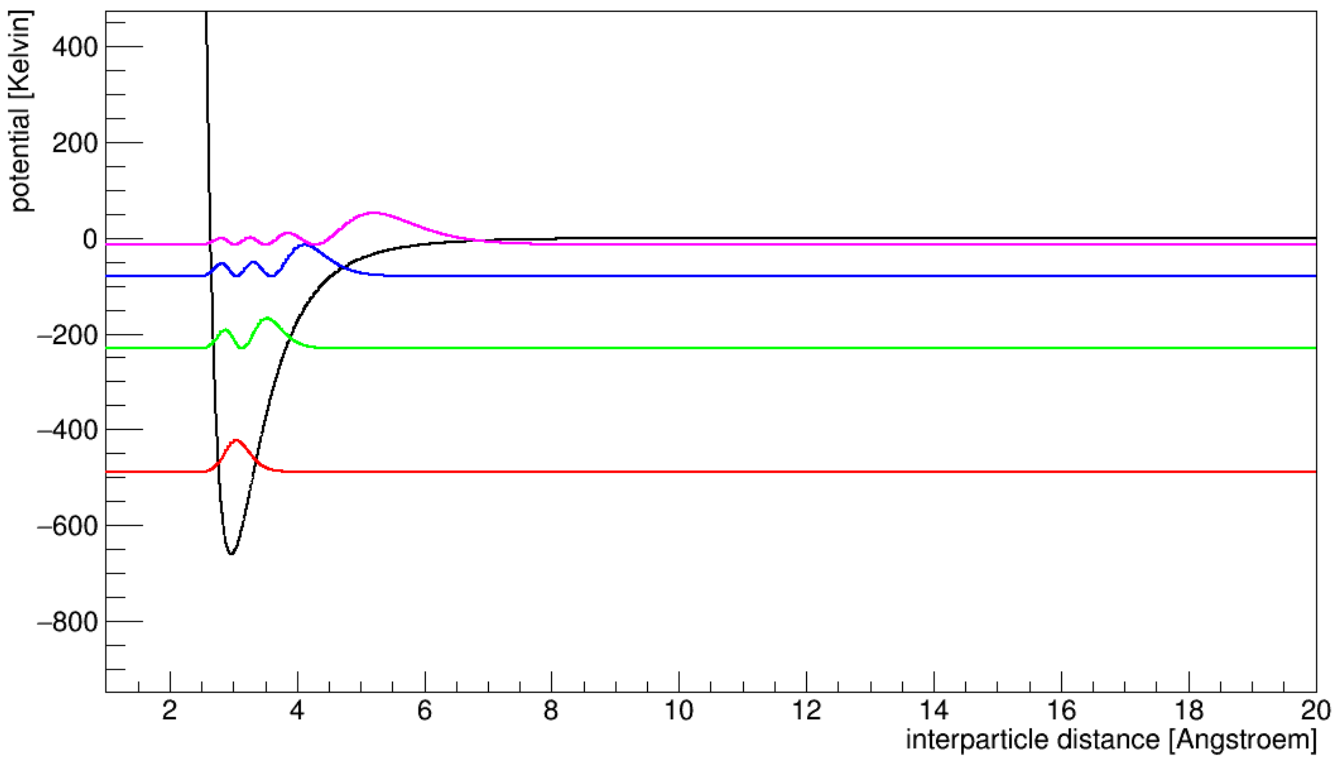
Two body system

Potential scale 80



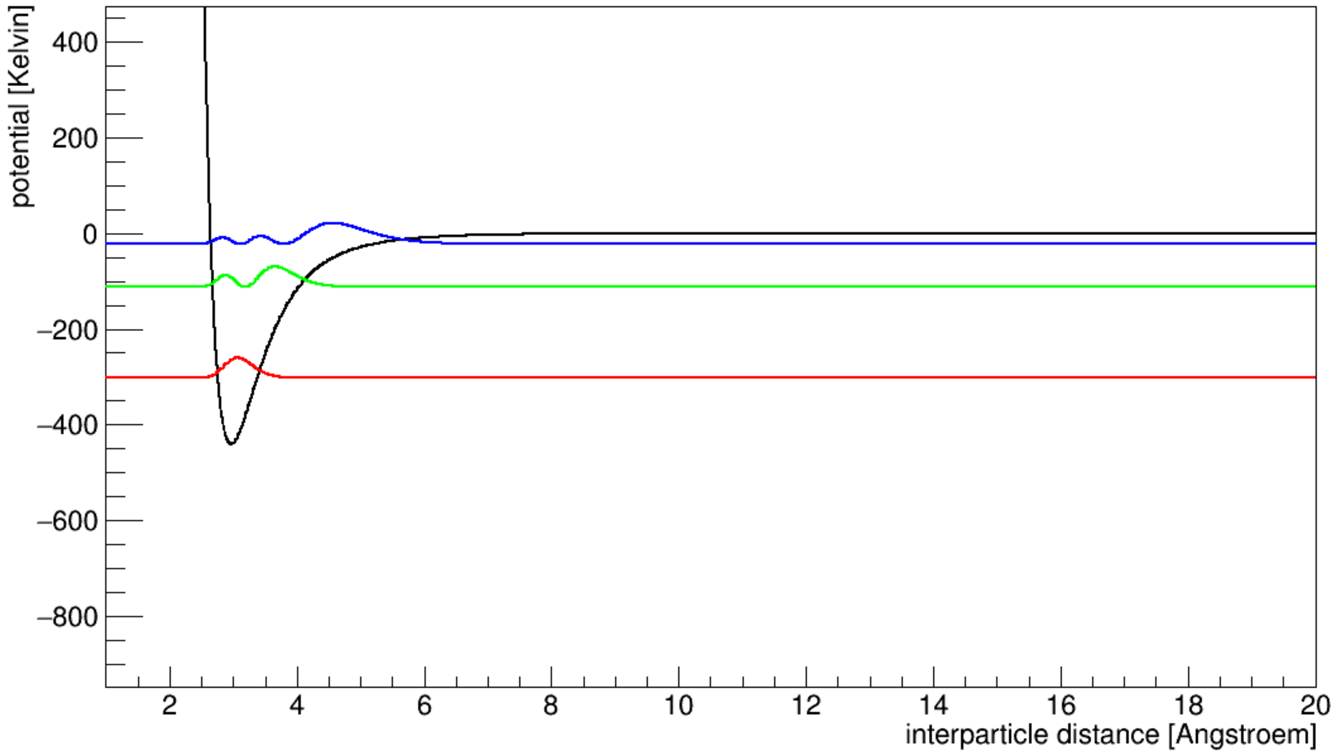
Two body system

Potential scale 60



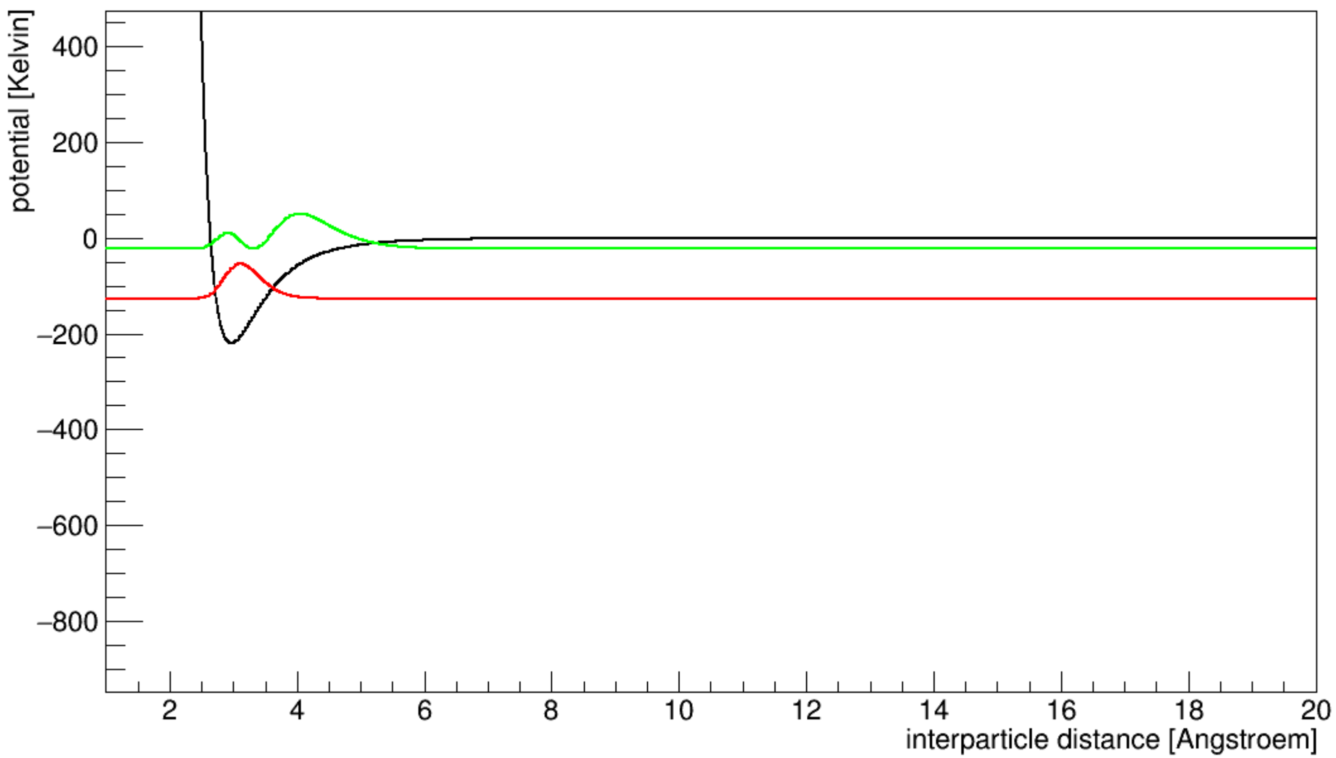
Two body system

Potential scale 40



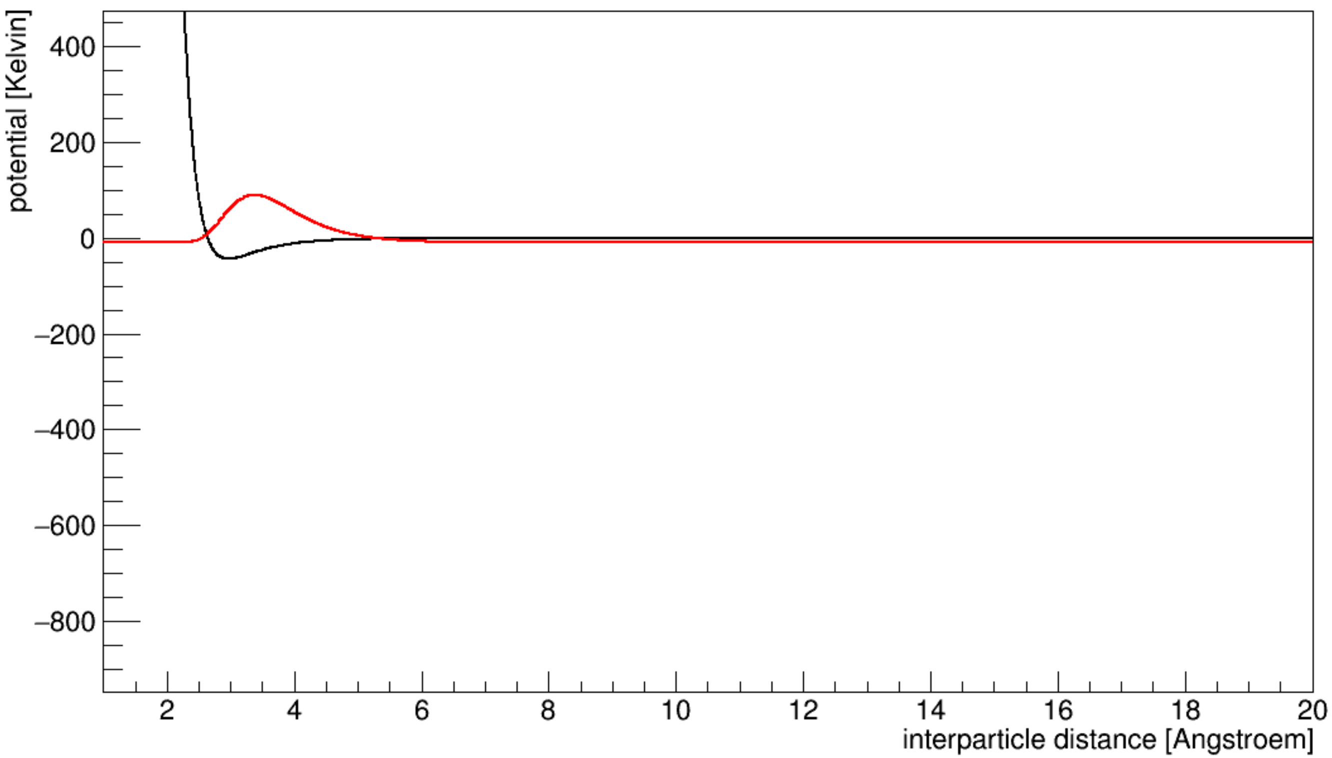
Two body system

Potential scale 20



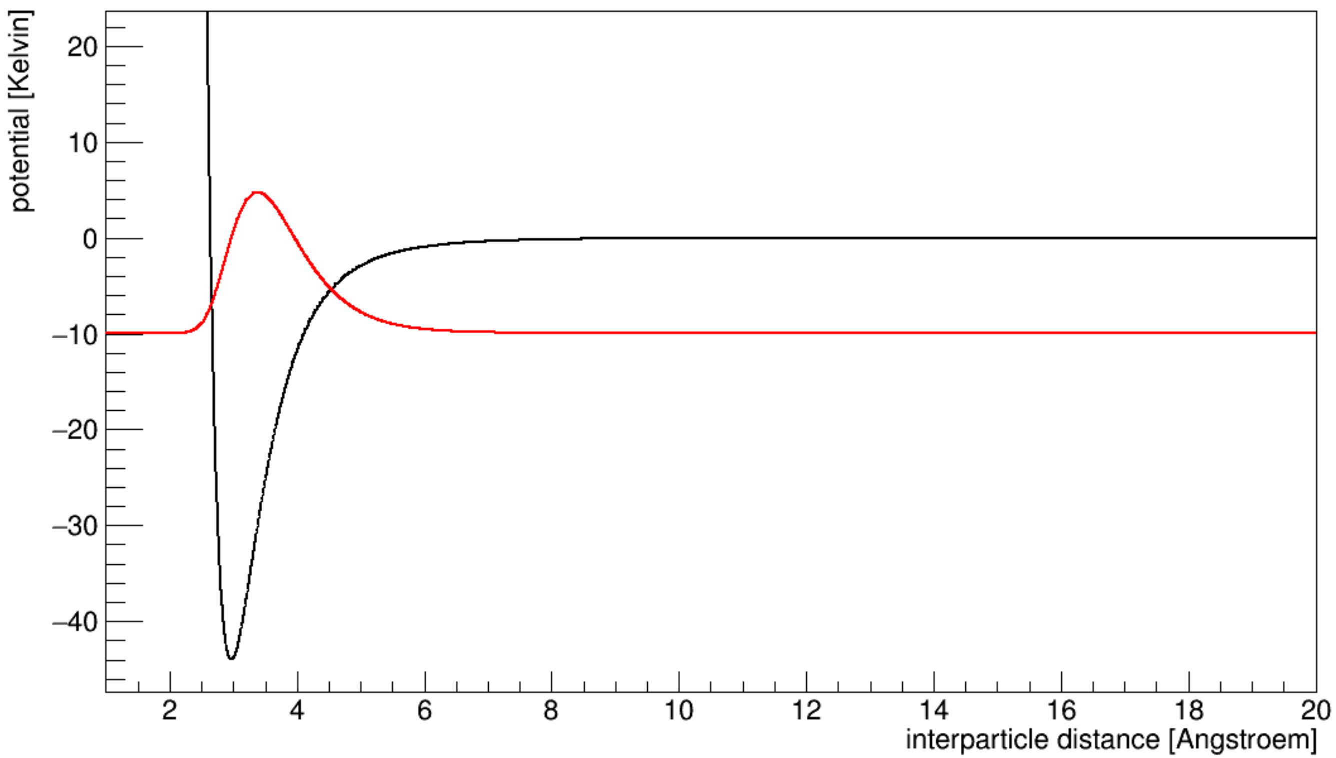
Two body system

Potential scale 4



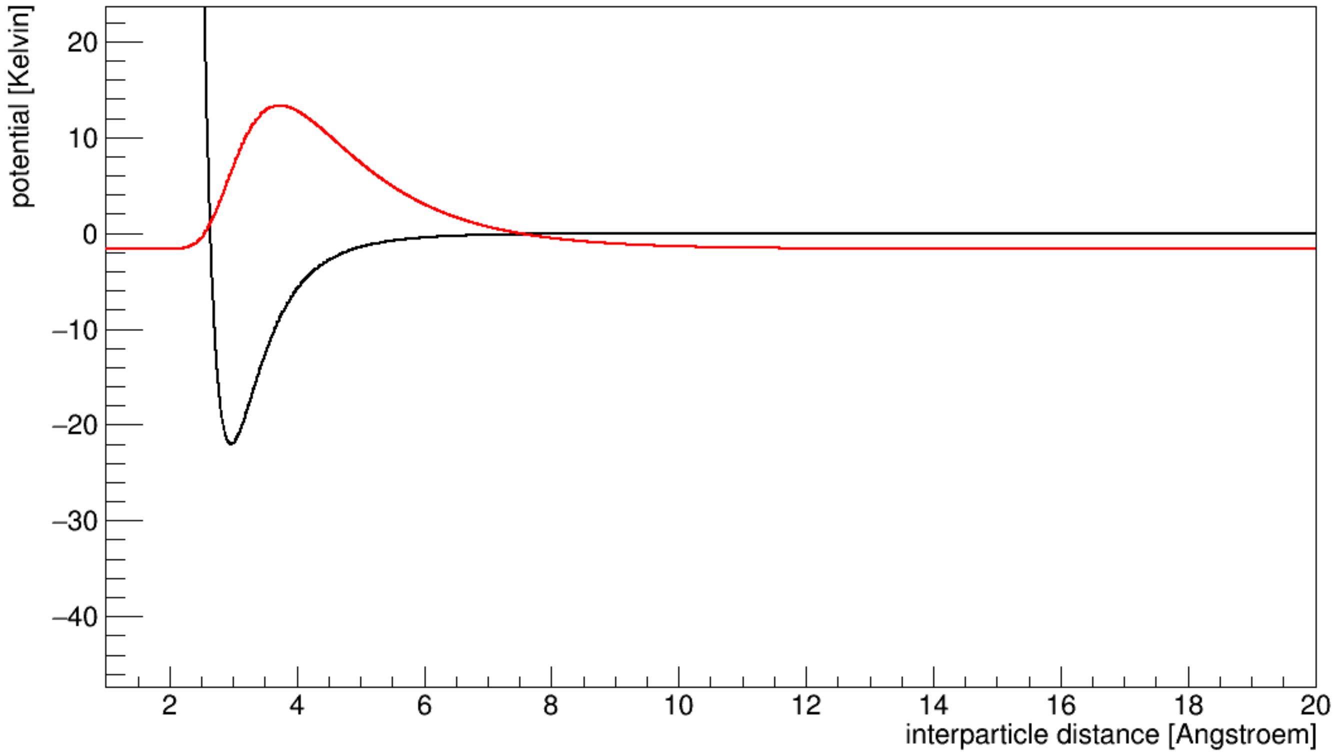
Two body system

Potential scale 4



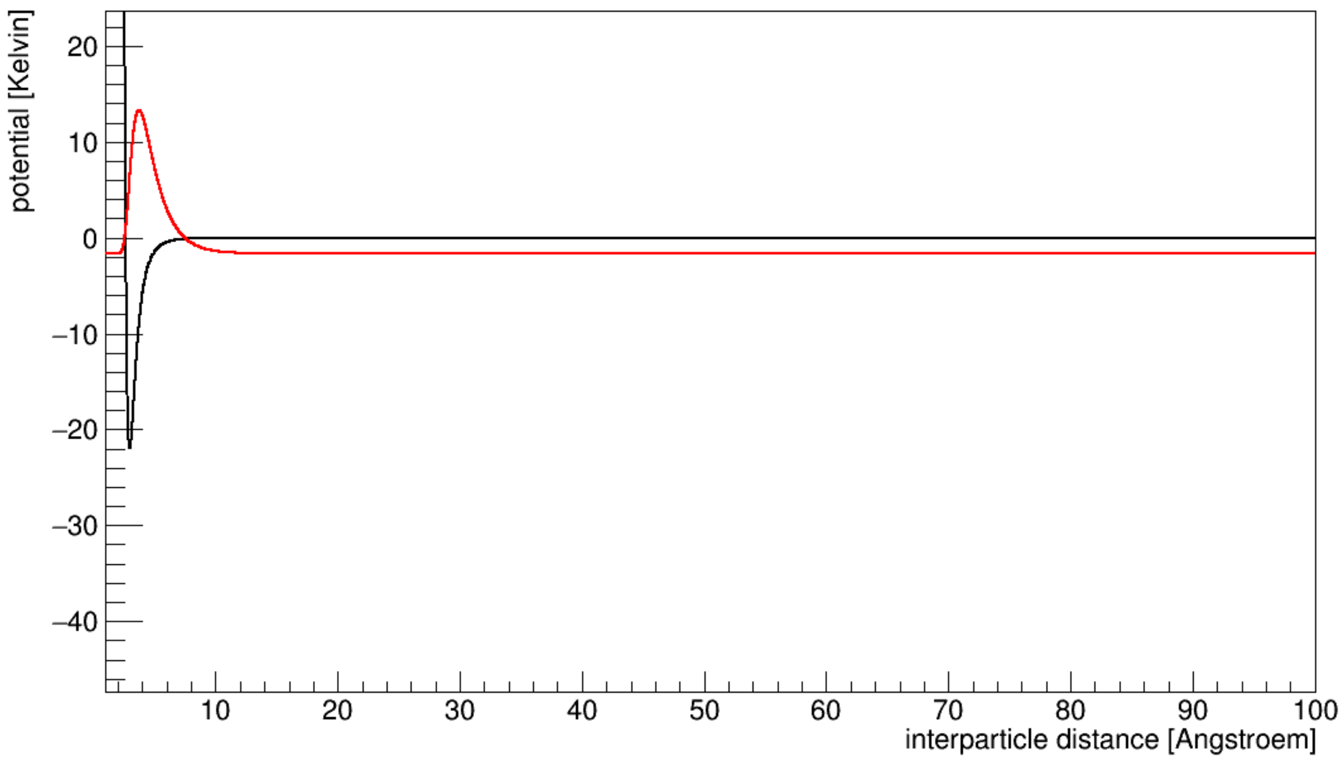
Two body system

Potential scale 2



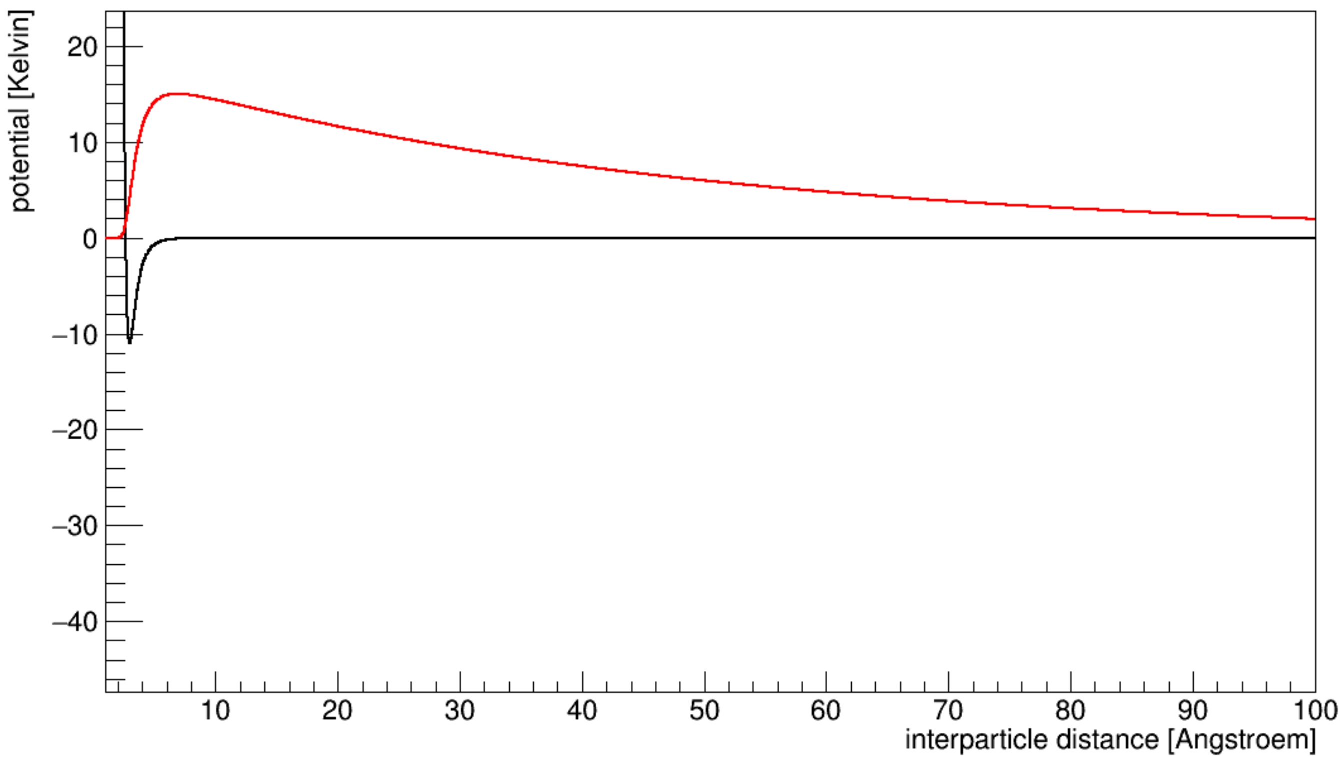
Two body system

Potential scale 2



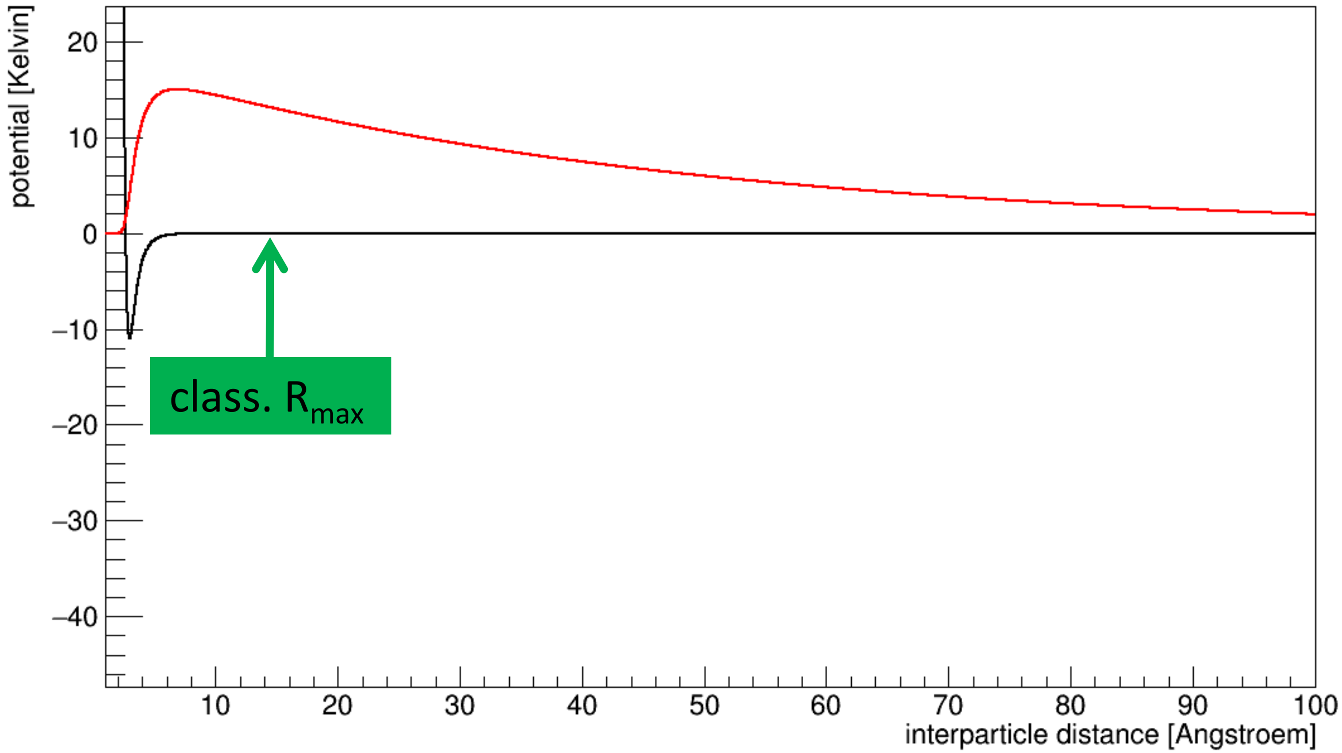
Two body system

Potential scale 1



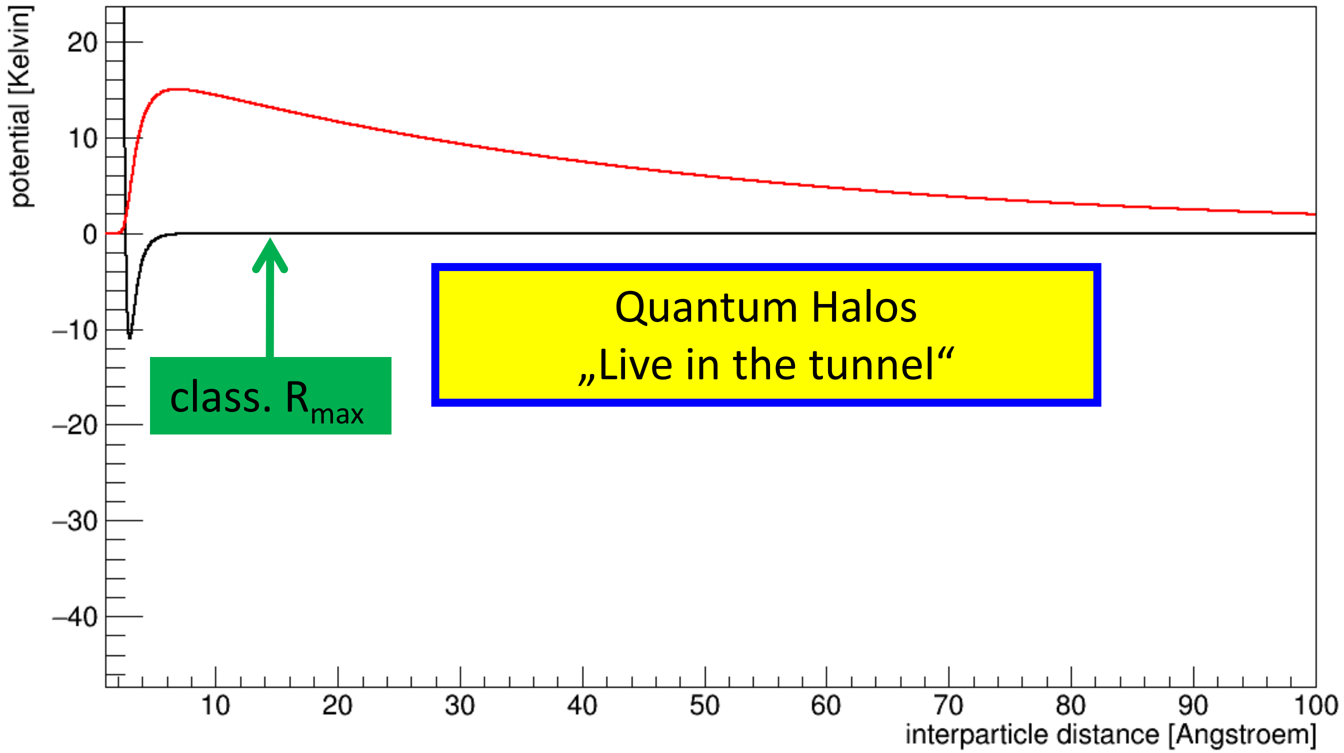
Two body system

Potential scale 1



Two body system

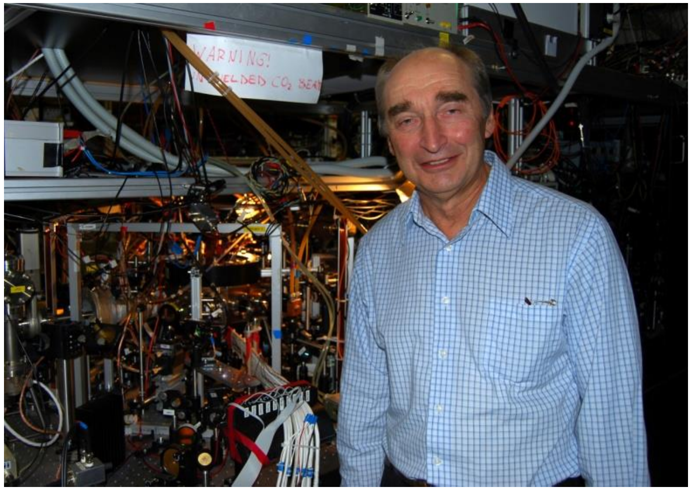
Potential scale 1



Two body system

What happens to a 3 body system under this condition?

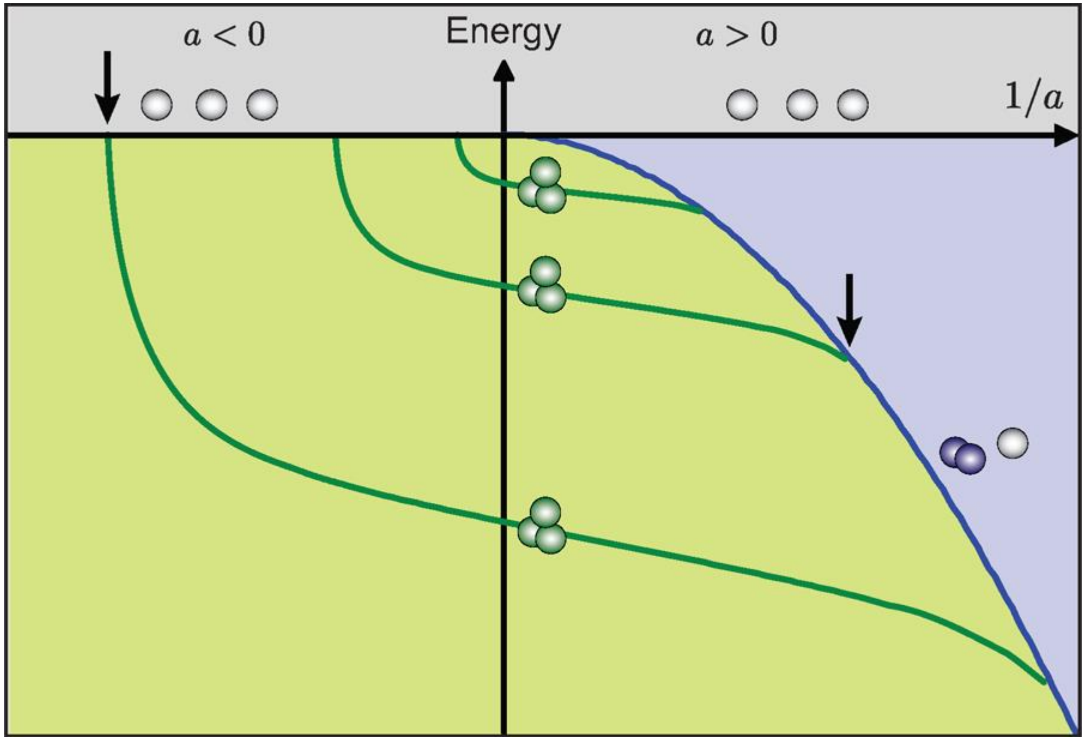
Efimov effect (prediction 1970)



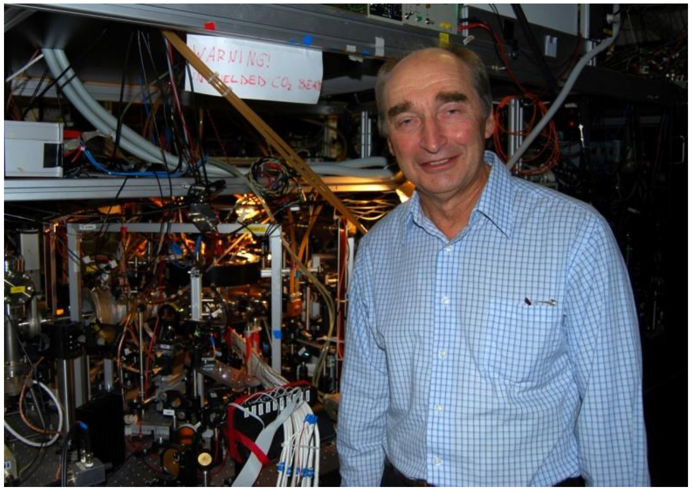
2005

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

potential depth



Efimov effect (prediction 1970)



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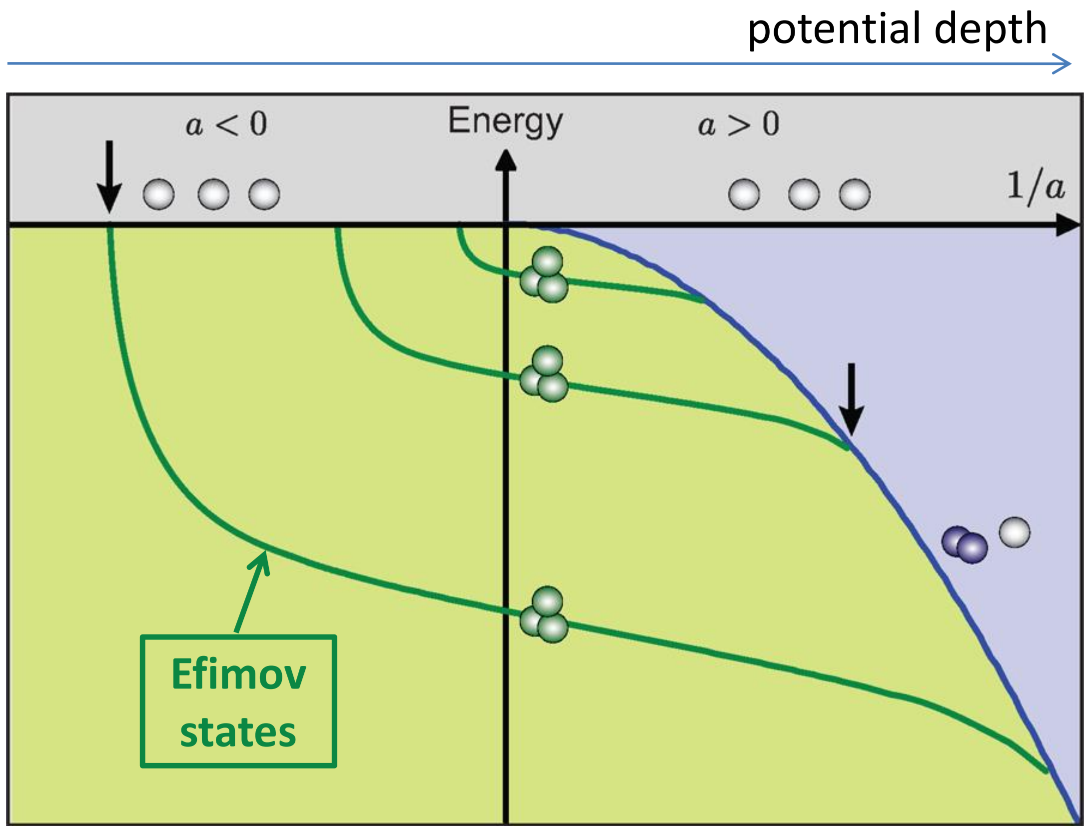

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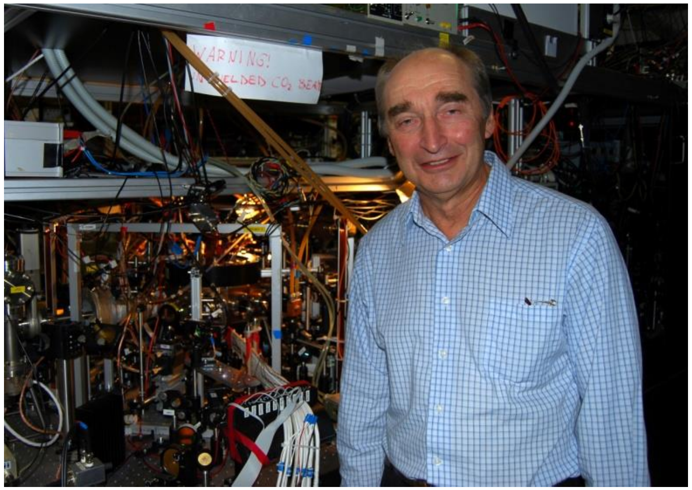

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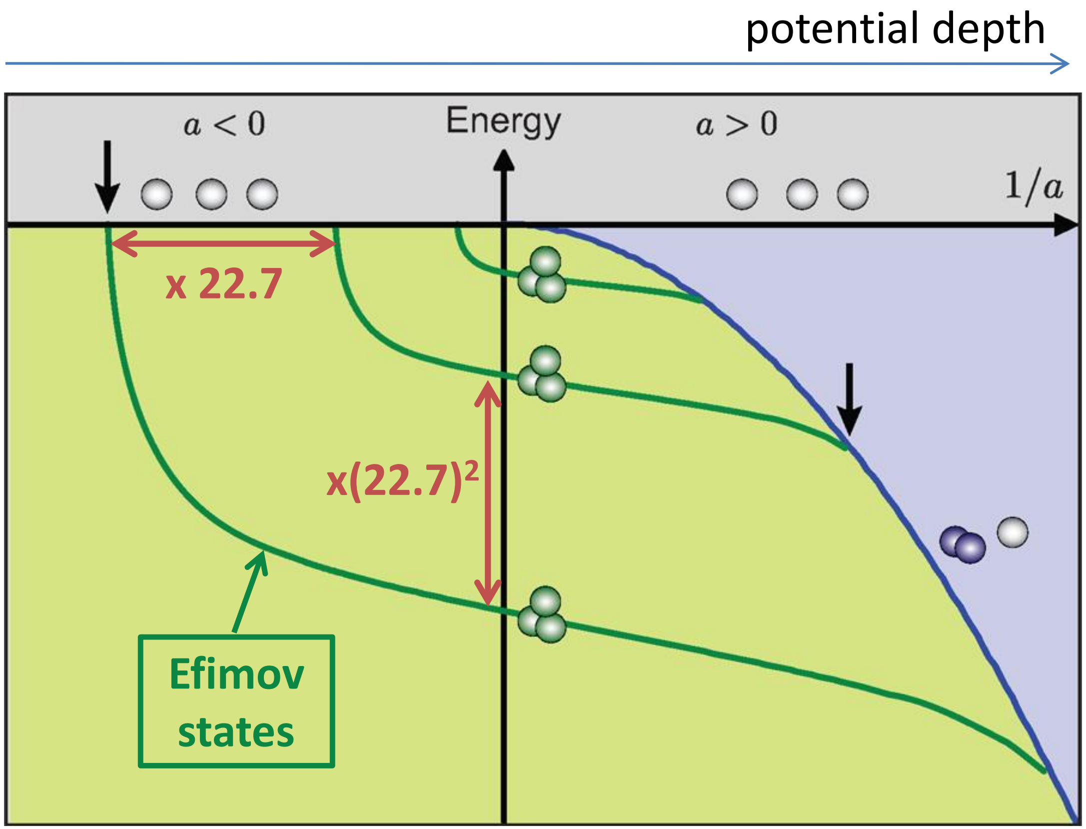


Efimov states

- **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

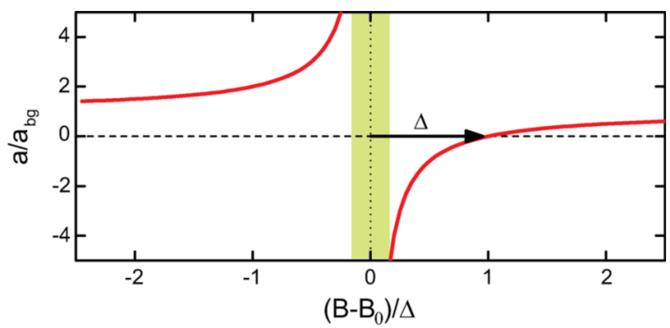
Experimental evidence for Efimov states, 2005

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

NATURE|Vol 440|16 March 2006

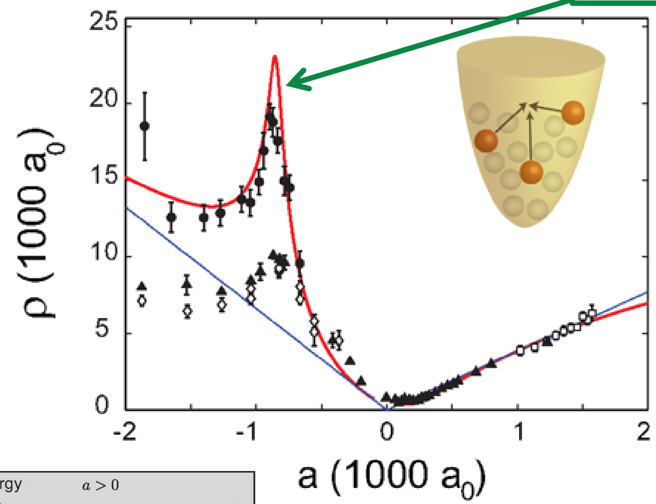
T. Kraemer[1], M. Mark[1], P. Waldburger[1], J. G. Danzl[1], C. Chin[1,2], B. Engeser[1], A. D. Lange[1], K. Pilch[1], A. Jaakkola[1]
H.-C. Nägerl[1] & R. Grimm[1,3]

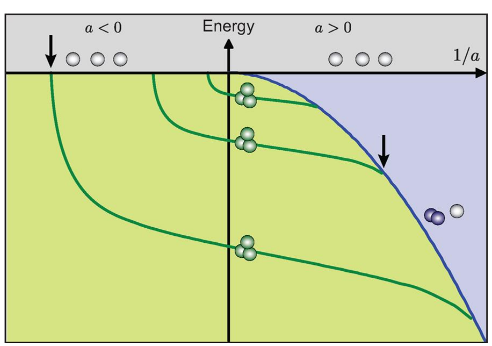
Feshbach resonance



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

Efimov resonances





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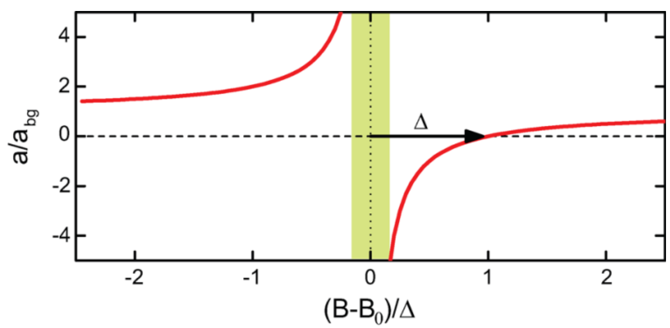
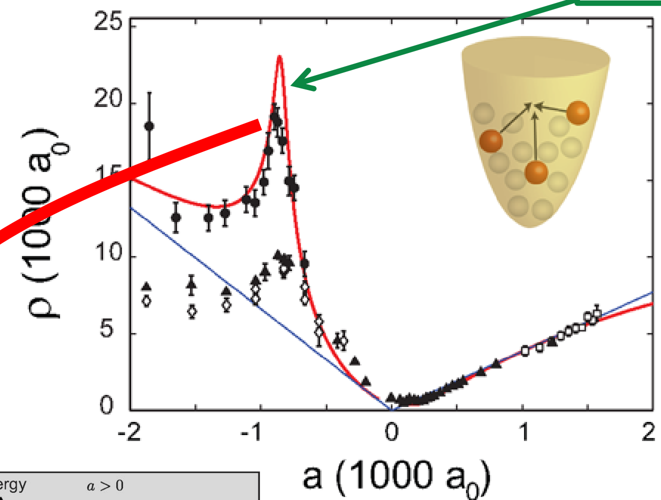
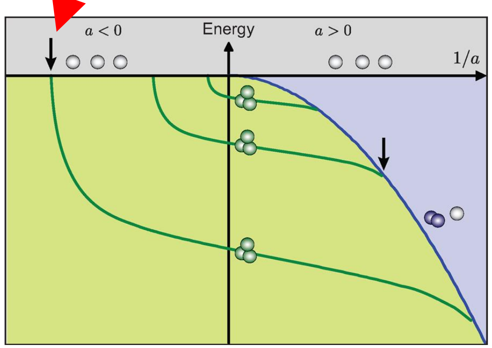


Tuning scattering length **a** with magnetic field **B**

Efimov resonances





Efimov effect & He trimer

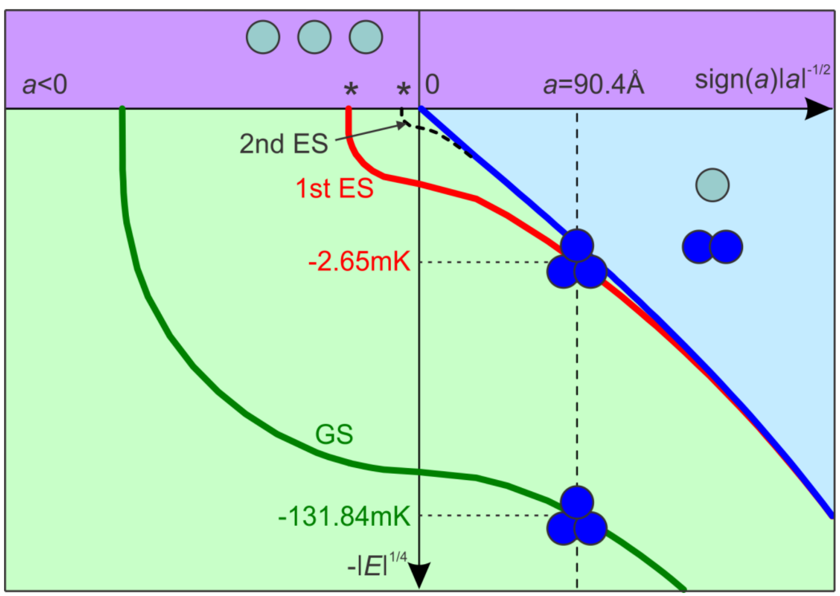
VOLUME 38, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 1977

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 $^4He_3$. 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

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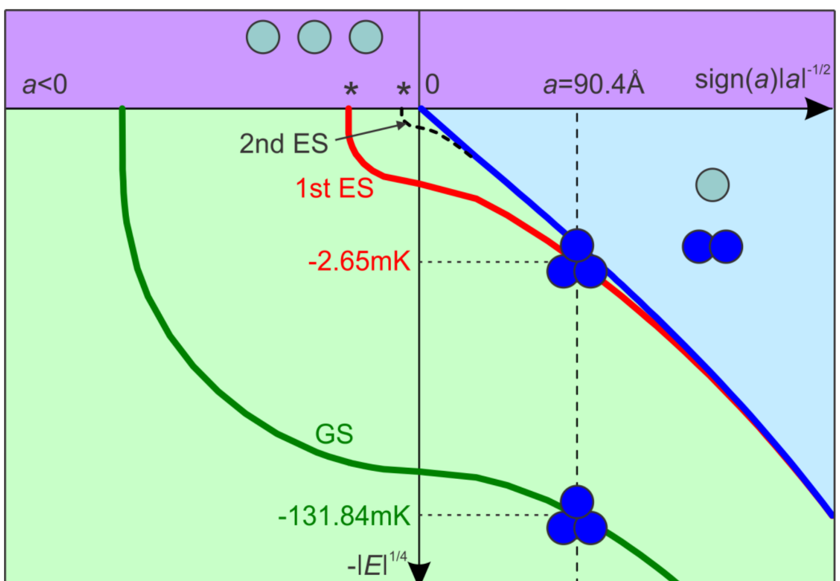


8 times larger than the ground state

Predicted in >50 theory papers

^{4}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

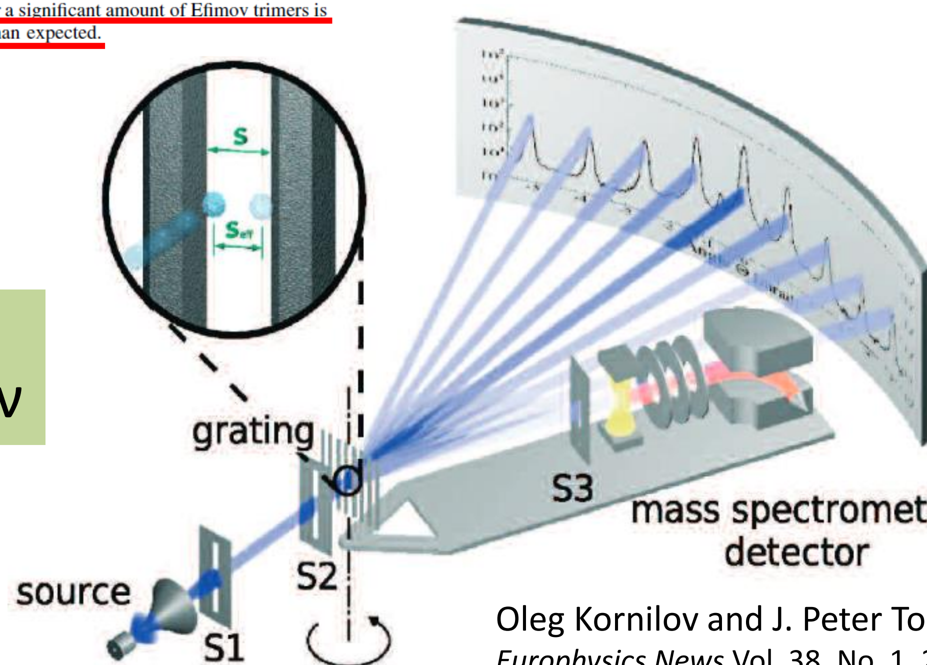
PRL 95, 063002 (2005) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2005

Matter Wave Diffraction from an Inclined Transmission Grating: Searching for the Elusive ^{4}He Trimer Efimov State

R. Brühl,[1] A. Kalinin,[1] O. Kornilov,[1] J. P. Toennies,[1] G. C. Hegerfeldt,[2] and M. Stoll[2]
[1]*Max-Planck-Institut für Dynamik und Selbstorganisation, Bunsenstraße 10, 37073 Göttingen, Germany*
[2]*Institut für Theoretische Physik, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany*
(Received 3 December 2004; published 2 August 2005)

The size of the helium trimer is determined by diffracting a beam of ^{4}He clusters from a 100 nm period grating inclined by 21°. Because of the bar thickness the projected slit width is roughly halved to 27 nm, increasing the sensitivity to the trimer size. The peak intensities measured out to the eighth order are evaluated via a few-body scattering theory. The trimer pair distance is found to be $\langle r \rangle = 1.1^{+0.4}_{-0.5}$ nm in agreement with predictions for the ground state. No evidence for a significant amount of Efimov trimers is found. Their concentration is estimated to be under 6%, less than expected.

de-Broglie wavelength:
$\lambda_{db} = h/mv = h/Nm_{He}v$



Oleg Kornilov and J. Peter Toennies
Europhysics News Vol. 38, No. 1, 2007, pp. 22-27

Outline

1. Efimov effect & He trimer
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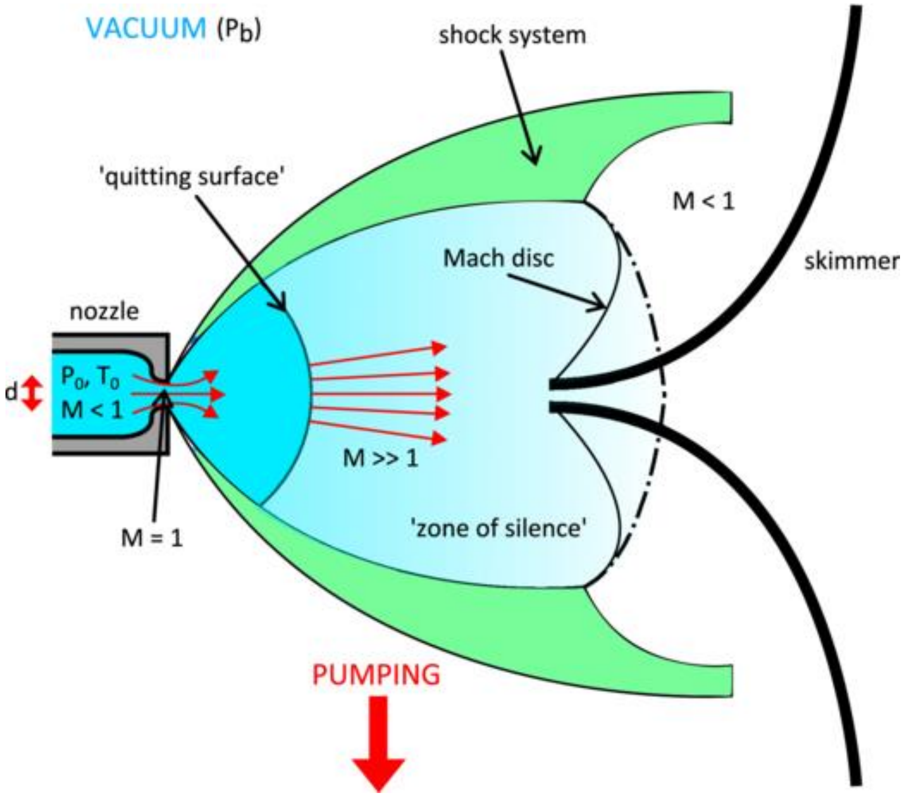
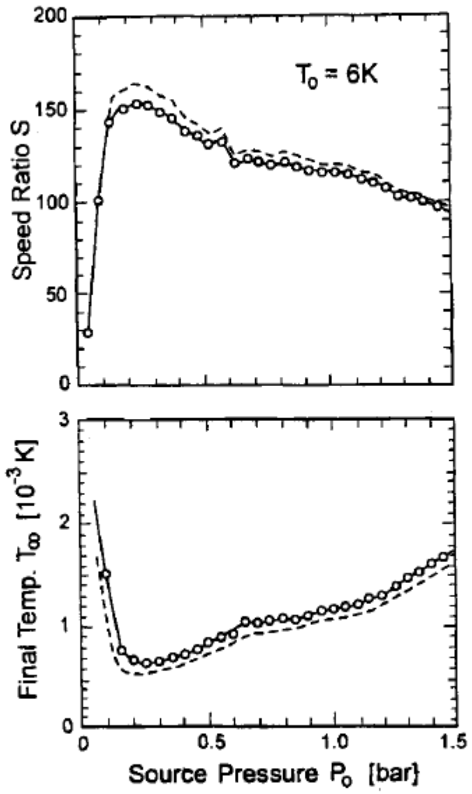
3. Results on the Efimov state of He_3:
   - size
   - binding energy
   - structure

Experimental method: Preparation in a supersonic jet



M. Barr et al.,
Meas. Sci. Technol. **23**,
105901 (2012)



L. W. Bruch et al.,
J. Chem. Phys. **117**,
1544–1566 (2002)

d = 5μm

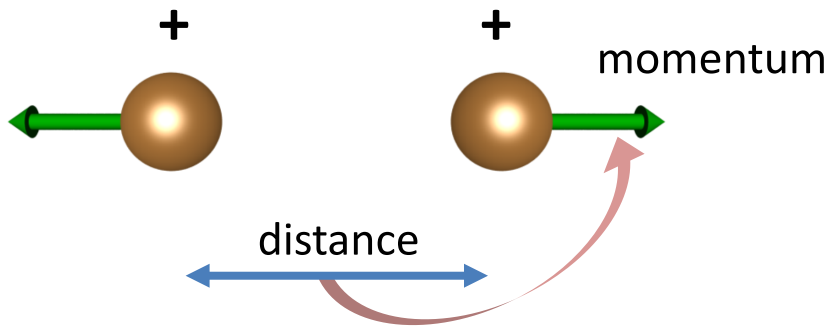
T_0 = 8K

P_0 = 0.2-4bar

speed ratio > 100

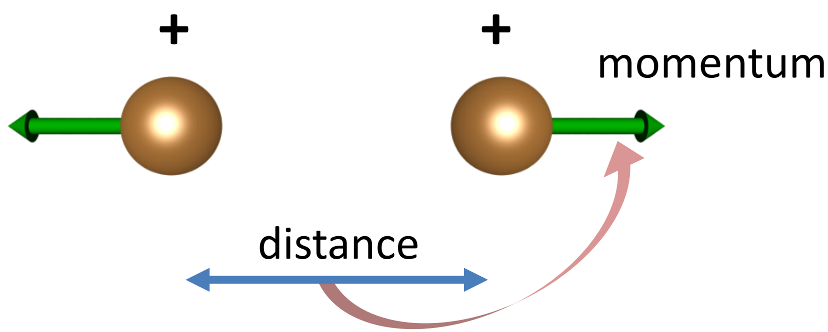
T_∞ < 1 mK

Experimental method: Detection by Coulomb Explosion Imaging



acquired momenta (or KER) ➡ structural information

Experimental method: Detection by Coulomb Explosion Imaging



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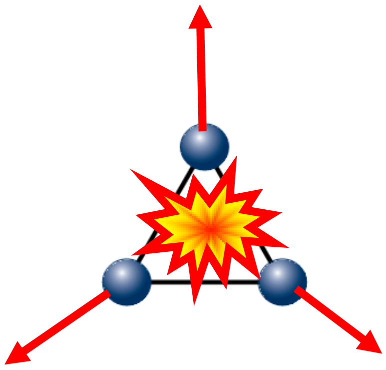
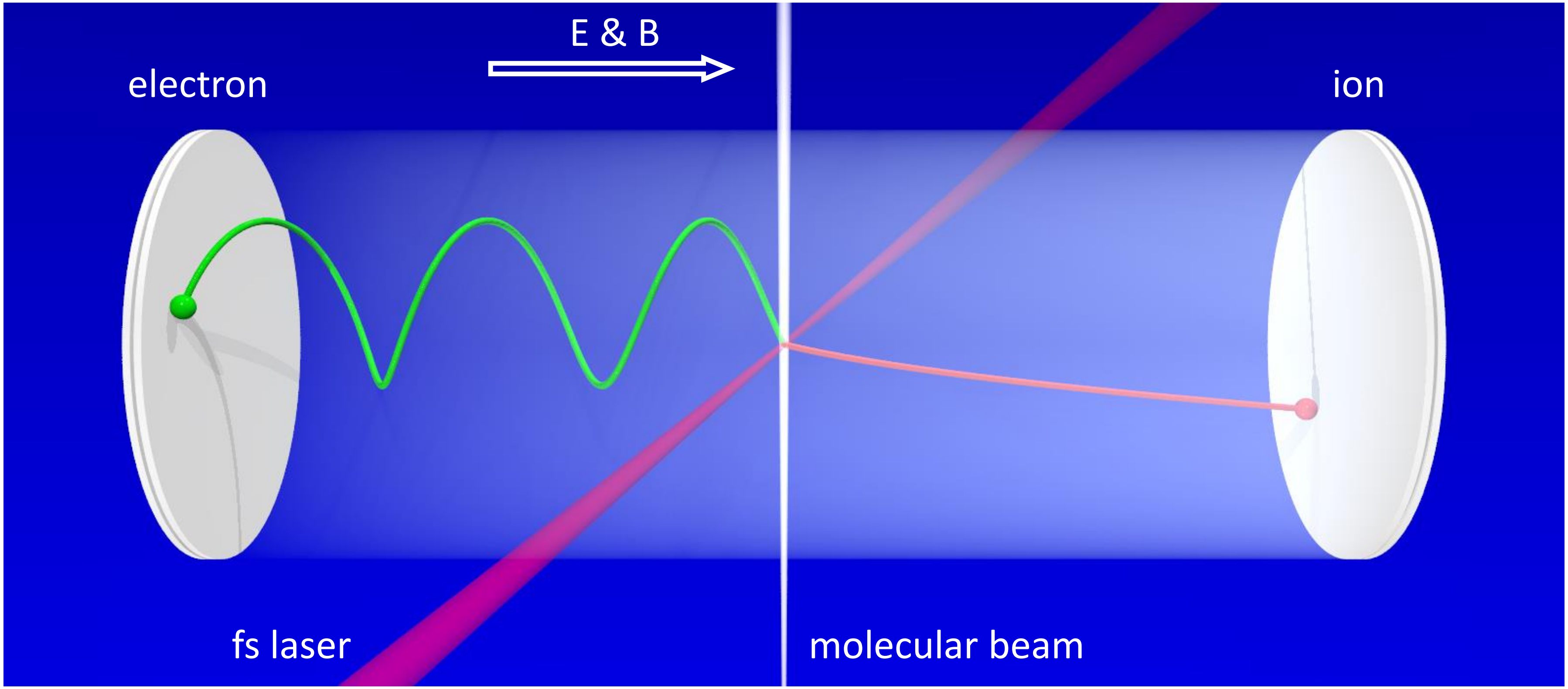


Kinetic Energy Release (KER) ≡ $E_1 + E_2 + E_3$ =

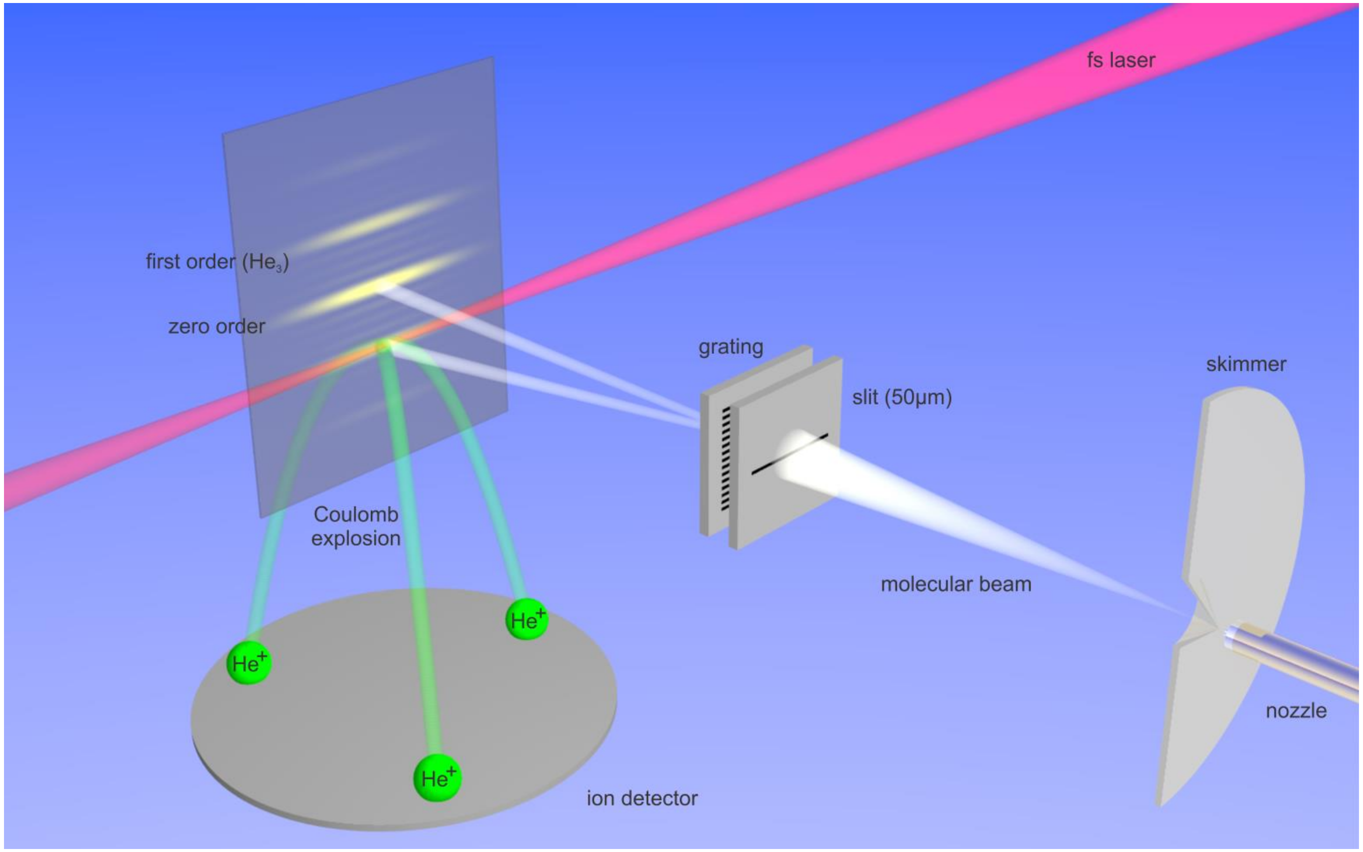
= $1/R_{12} + 1/R_{13} + 1/R_{23}$

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

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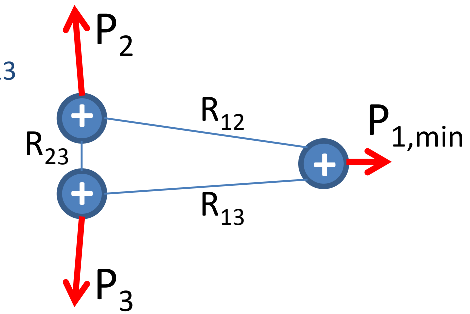
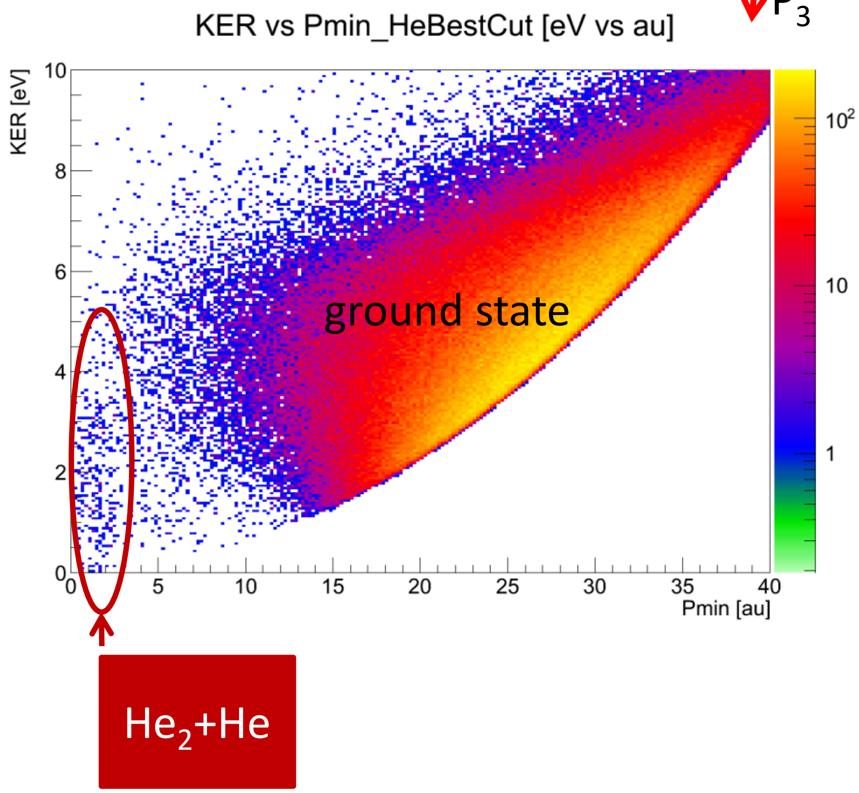
   - size
   - binding energy
   - structure

Results: nozzle temperature T_0=8K

KER ≡ $E_1 + E_2 + E_3 = 1/R_{12} + 1/R_{13} + 1/R_{23}$



P_0 = 1.39 bar



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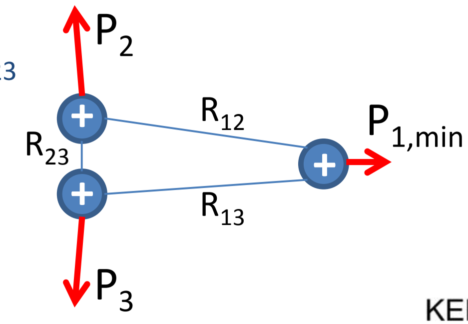

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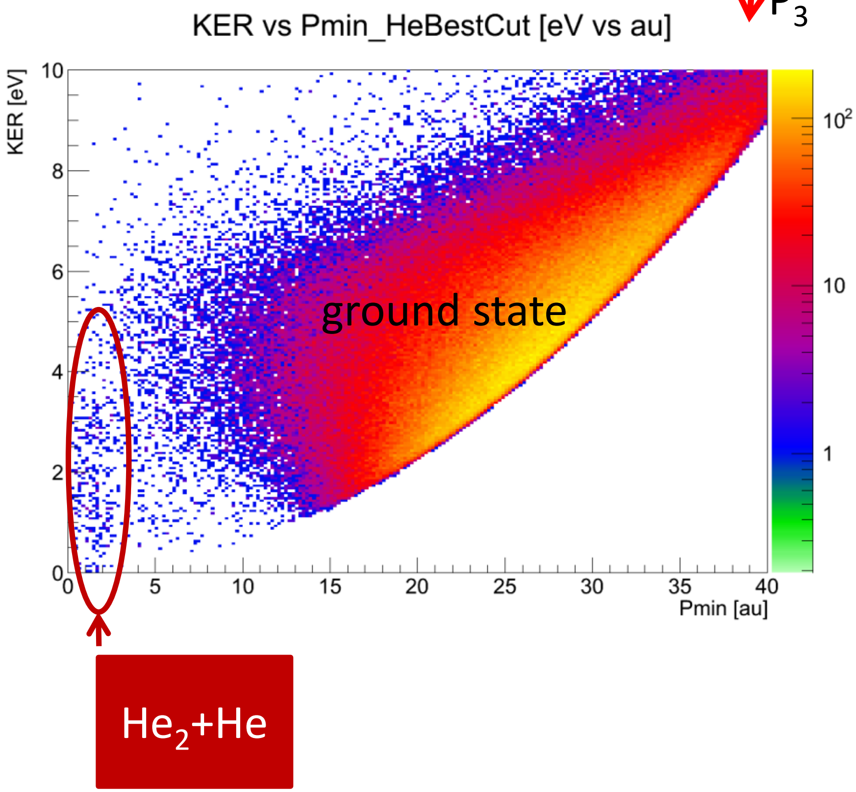

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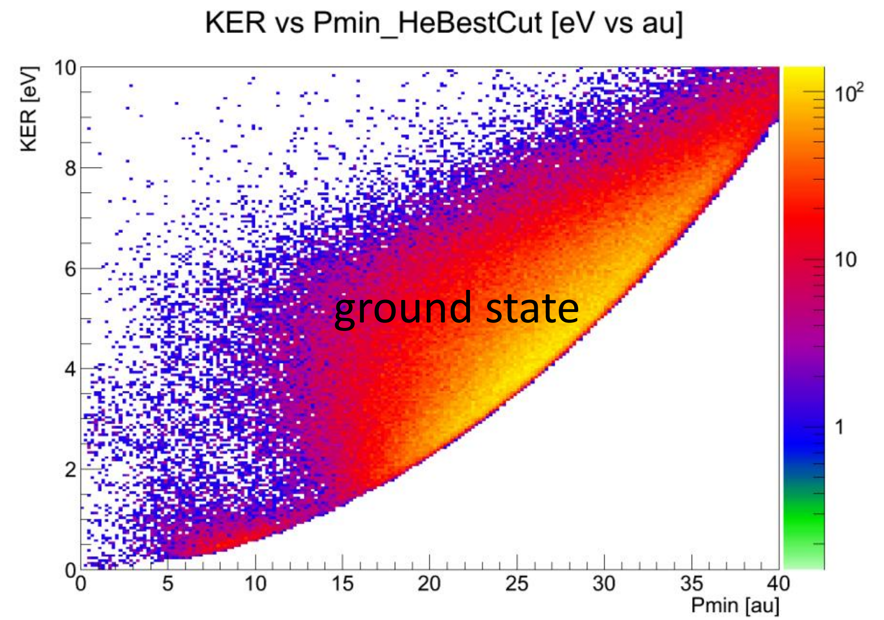

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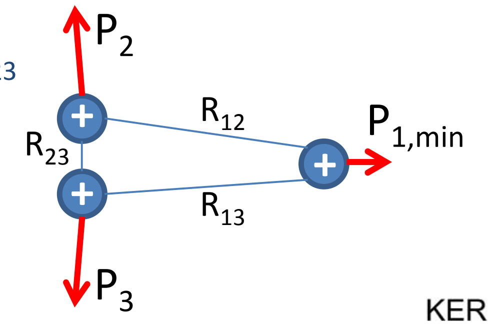

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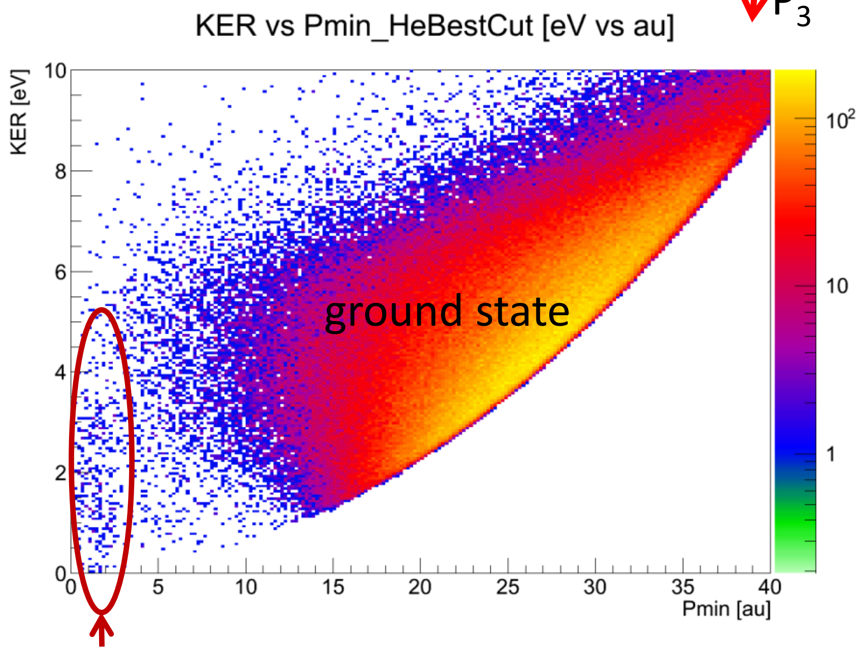
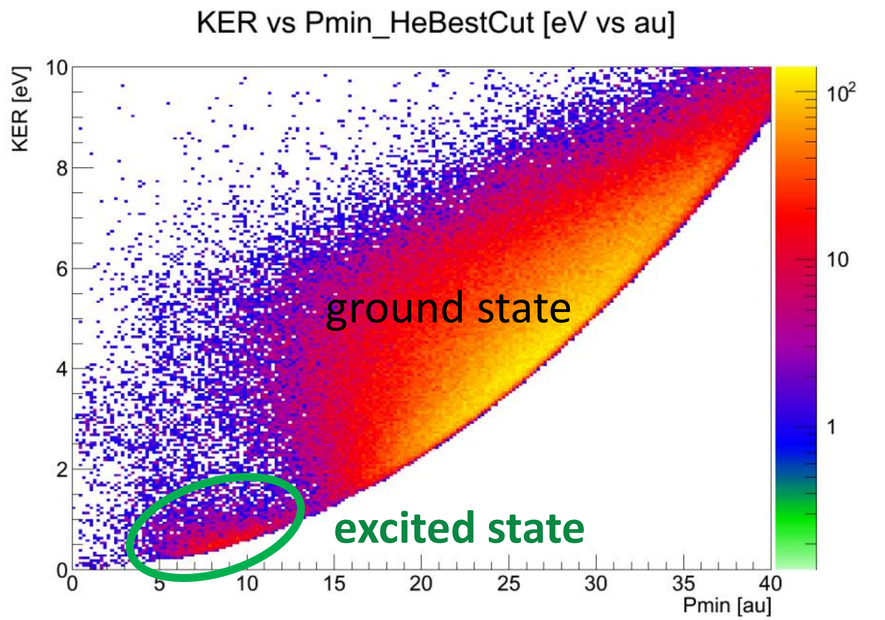


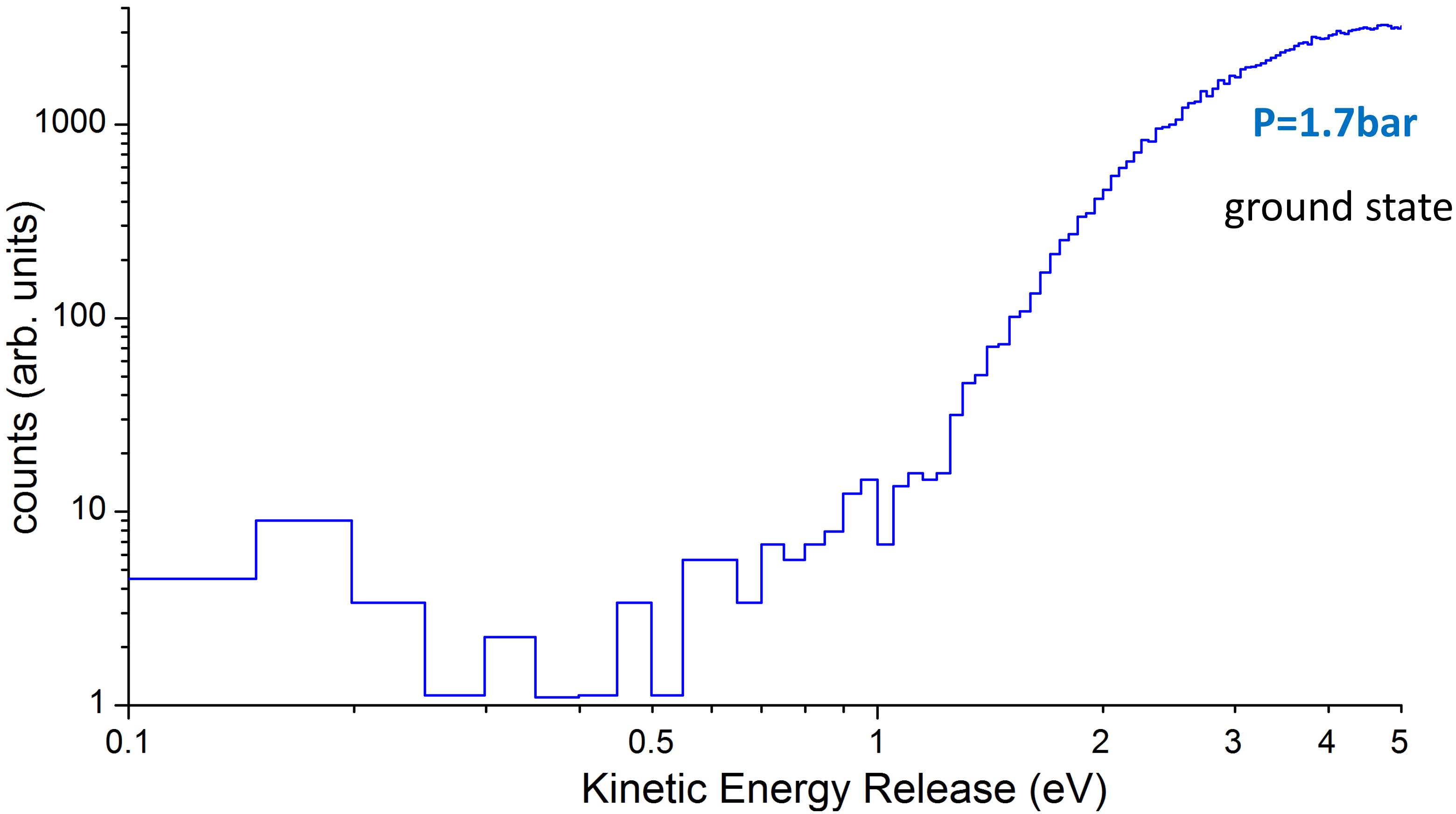
He_2+He

P_0 = 0.33 bar



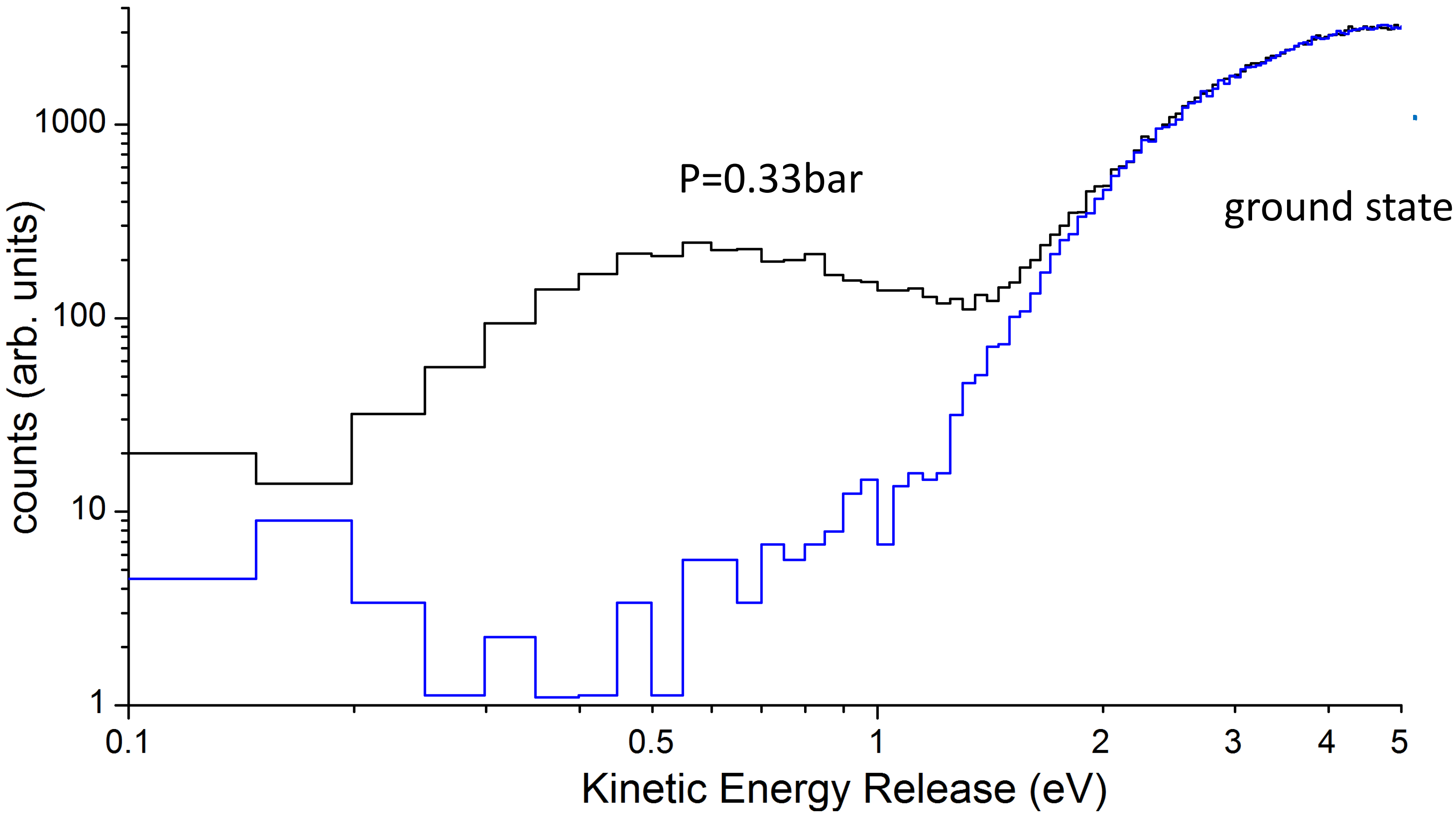
~50 events per hour, ~80 Å
1% with respect to the ground state

Results: T_0=8K, KER=E_1+E_2+E_3



Science, **348**, p.551, 2015

Results: T_0=8K, KER=$E_1+E_2+E_3$



Science, **348**, p.551, 2015

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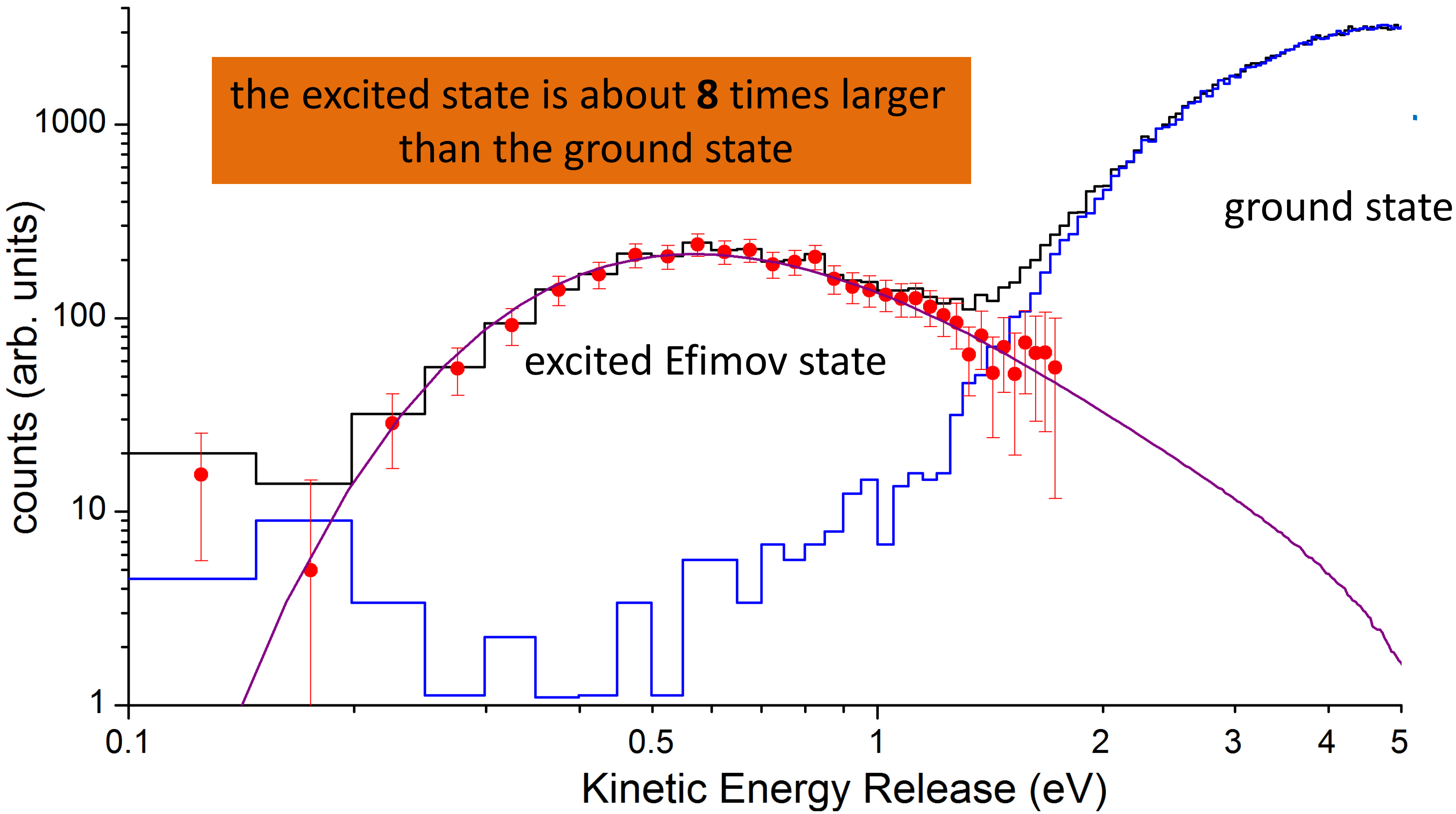
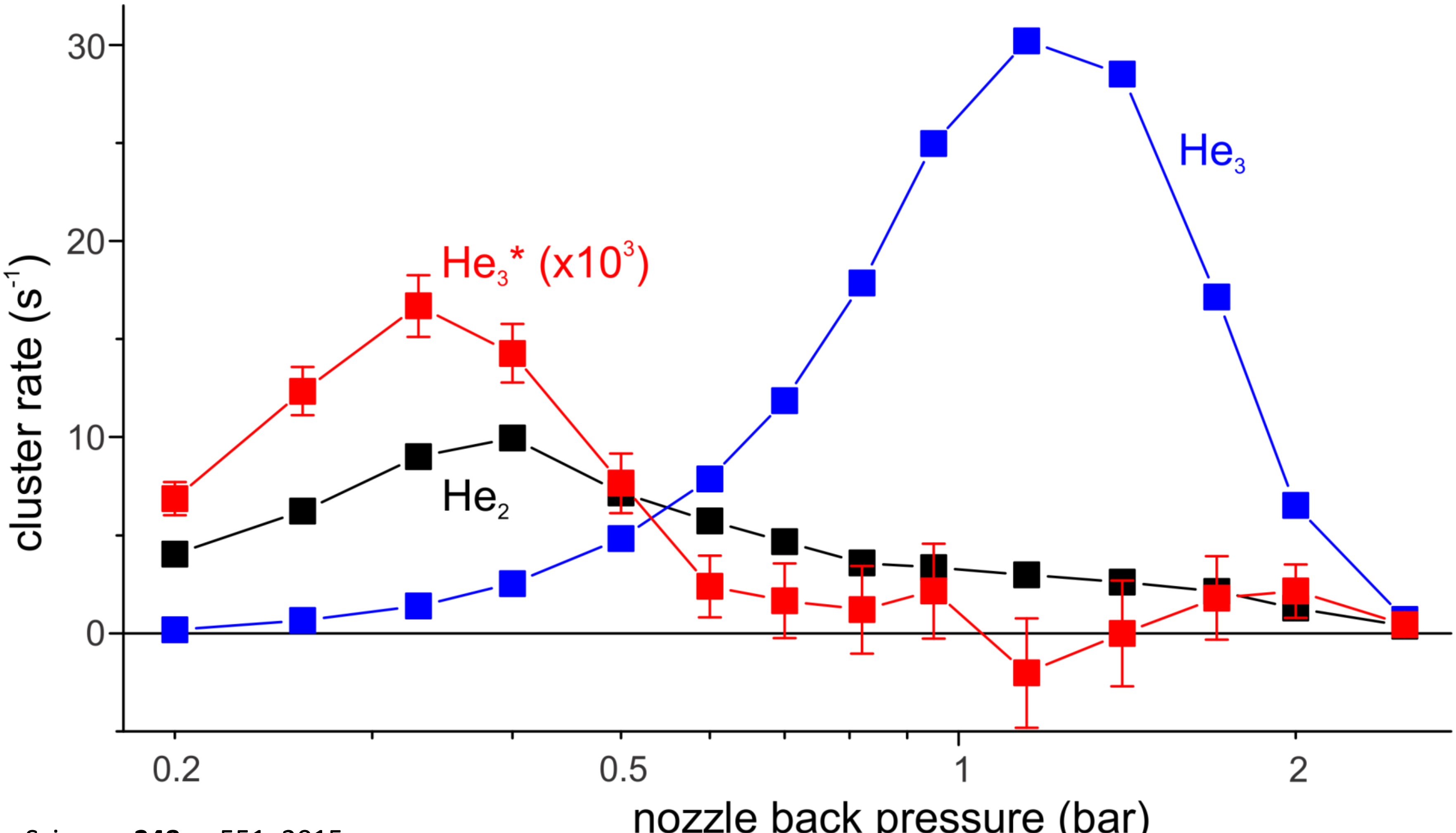


Science, **348**, p.551, 2015

Results: T_0=8K, pressure scan



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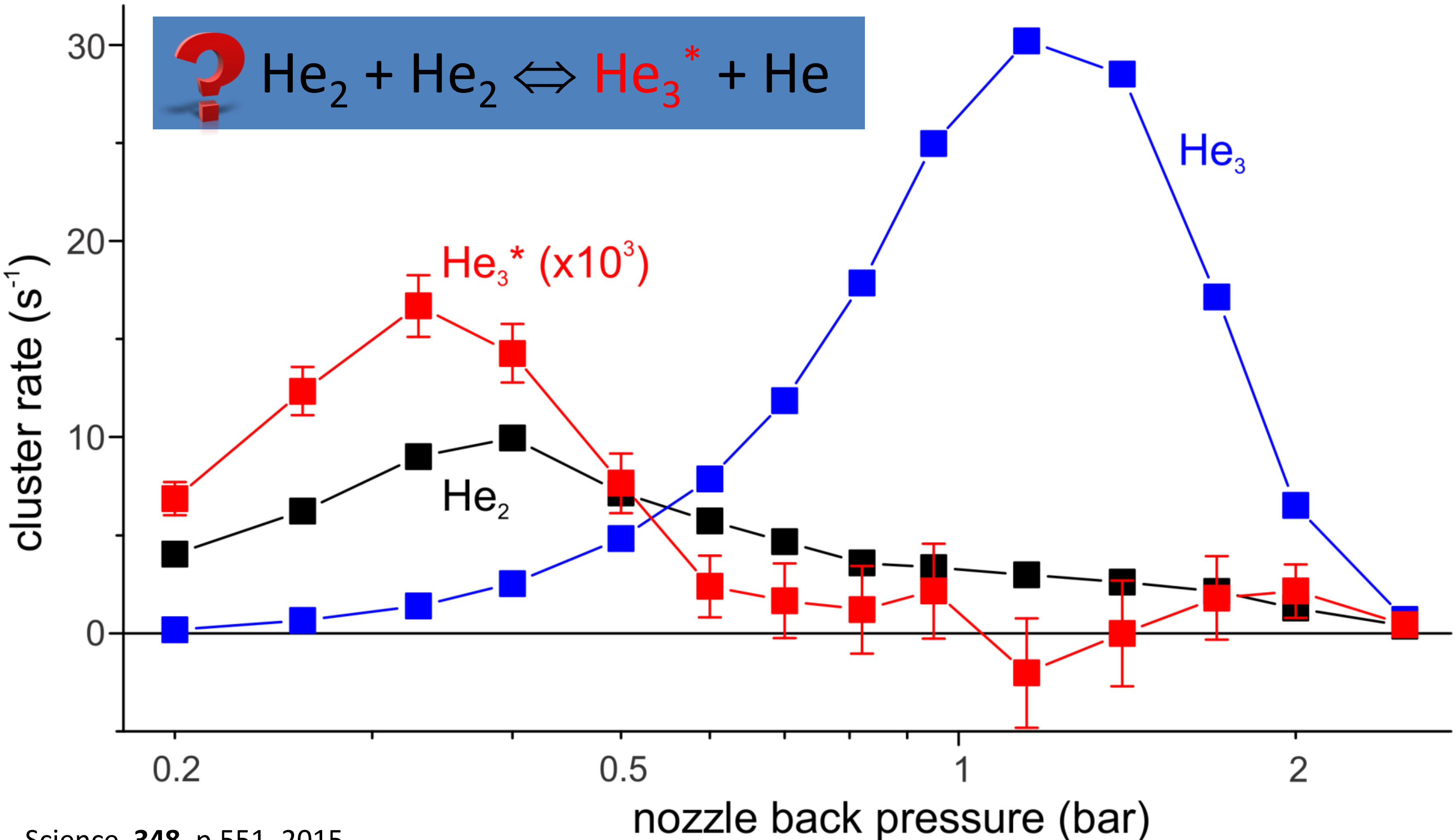
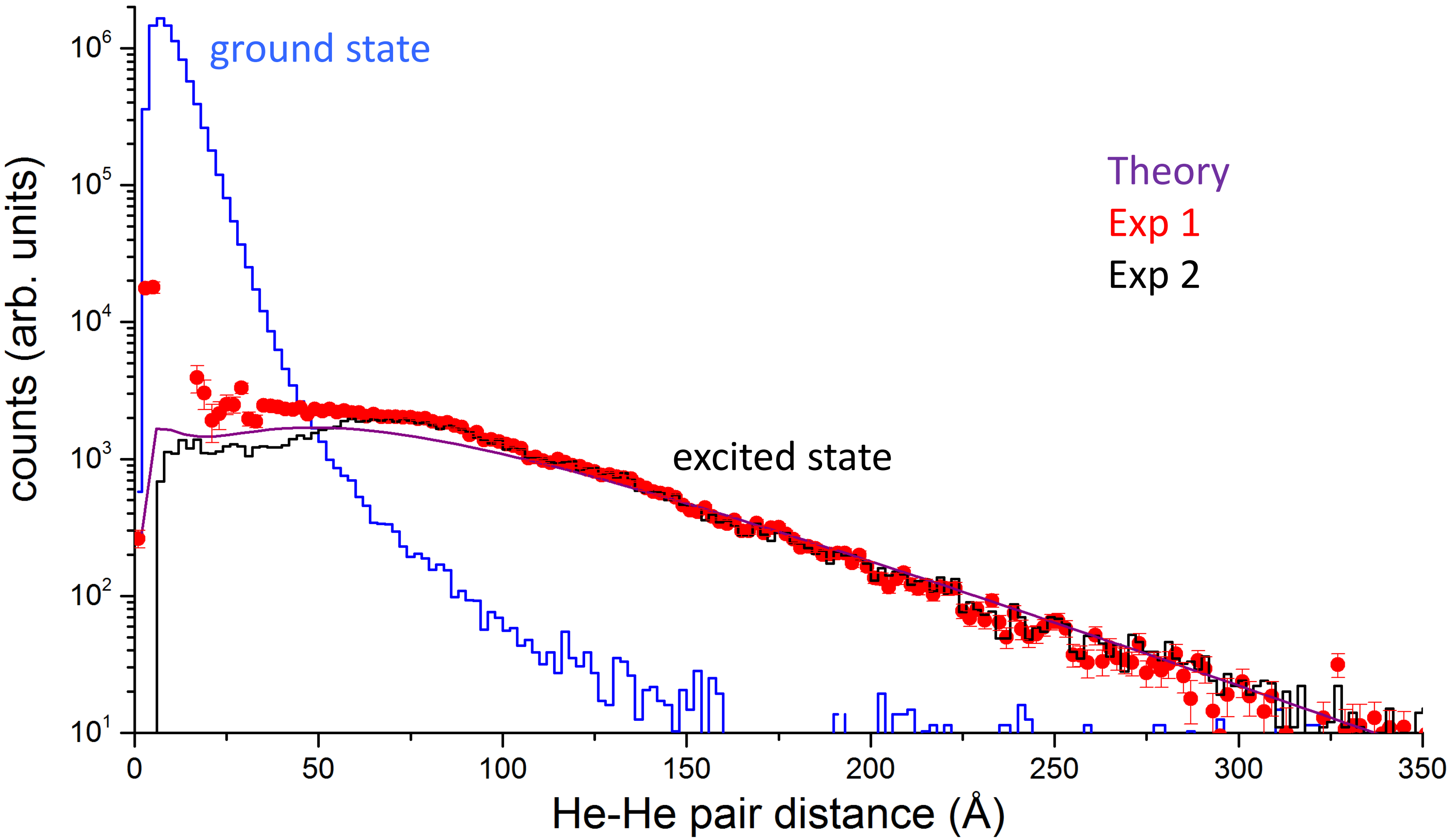


Science, **348**, p.551, 2015

He-He pair distance distribution



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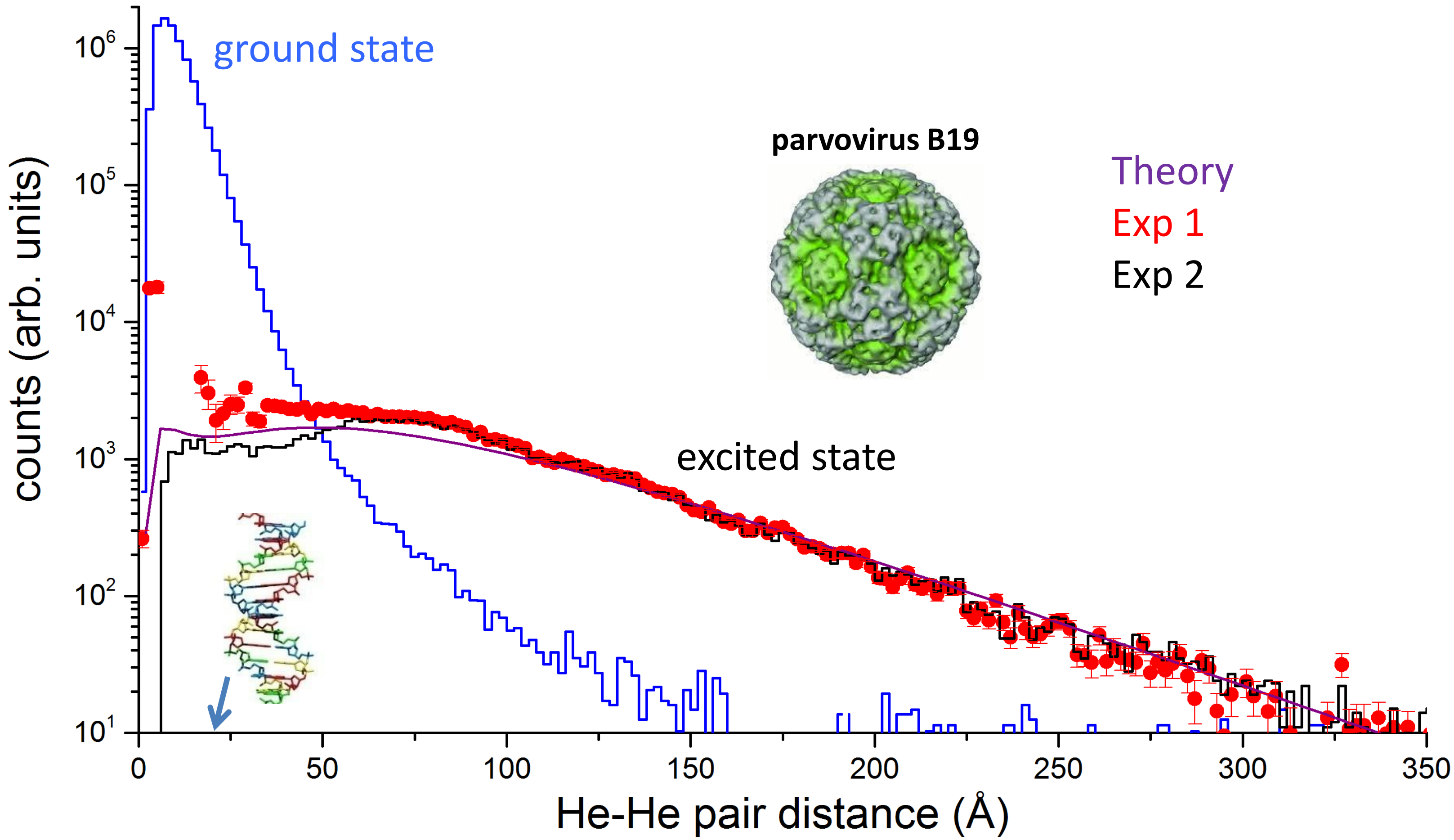


Science, **348**, p.551, 2015

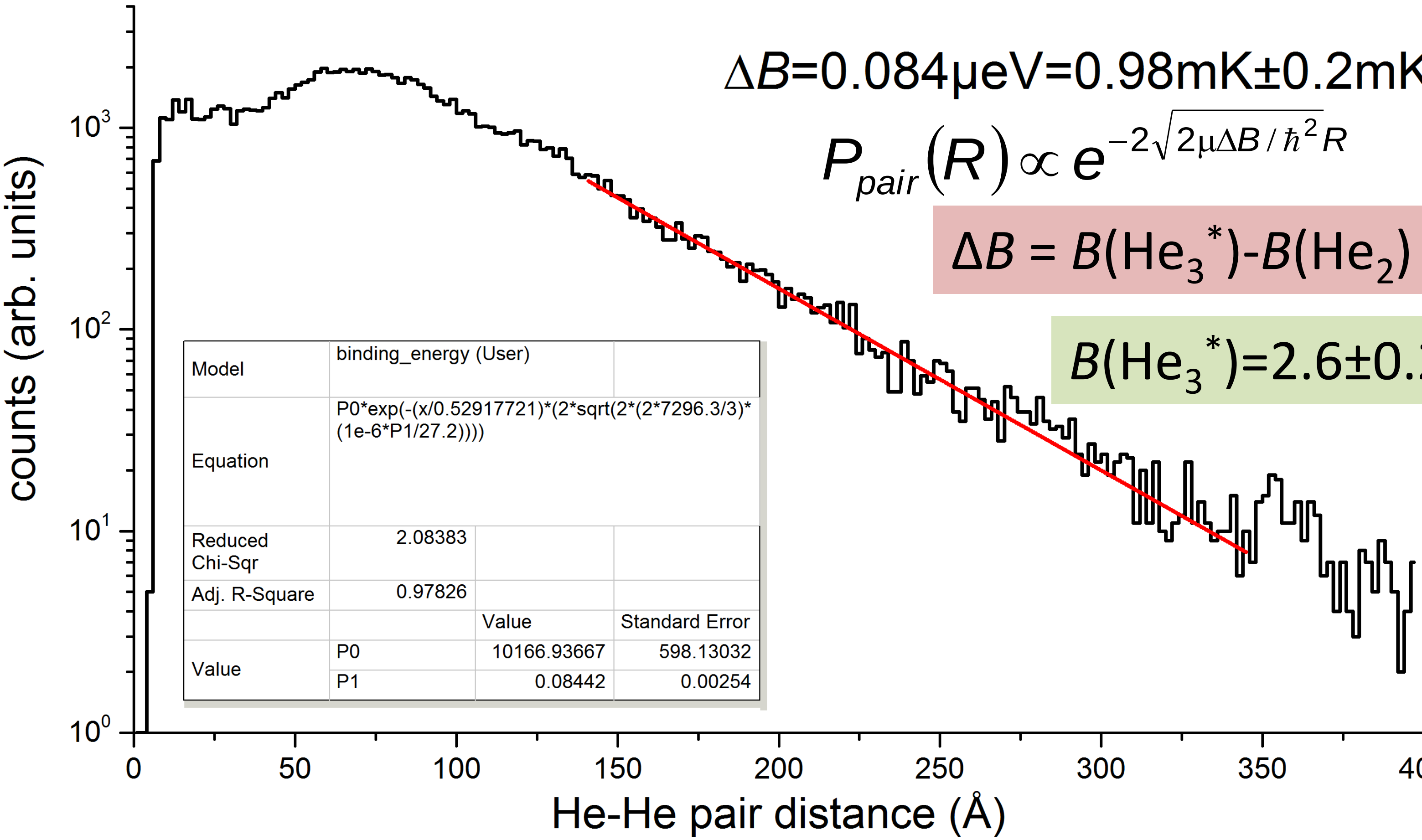
The binding energy of the excited state of He_3

ΔB=0.084μeV=0.98mK±0.2mK

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

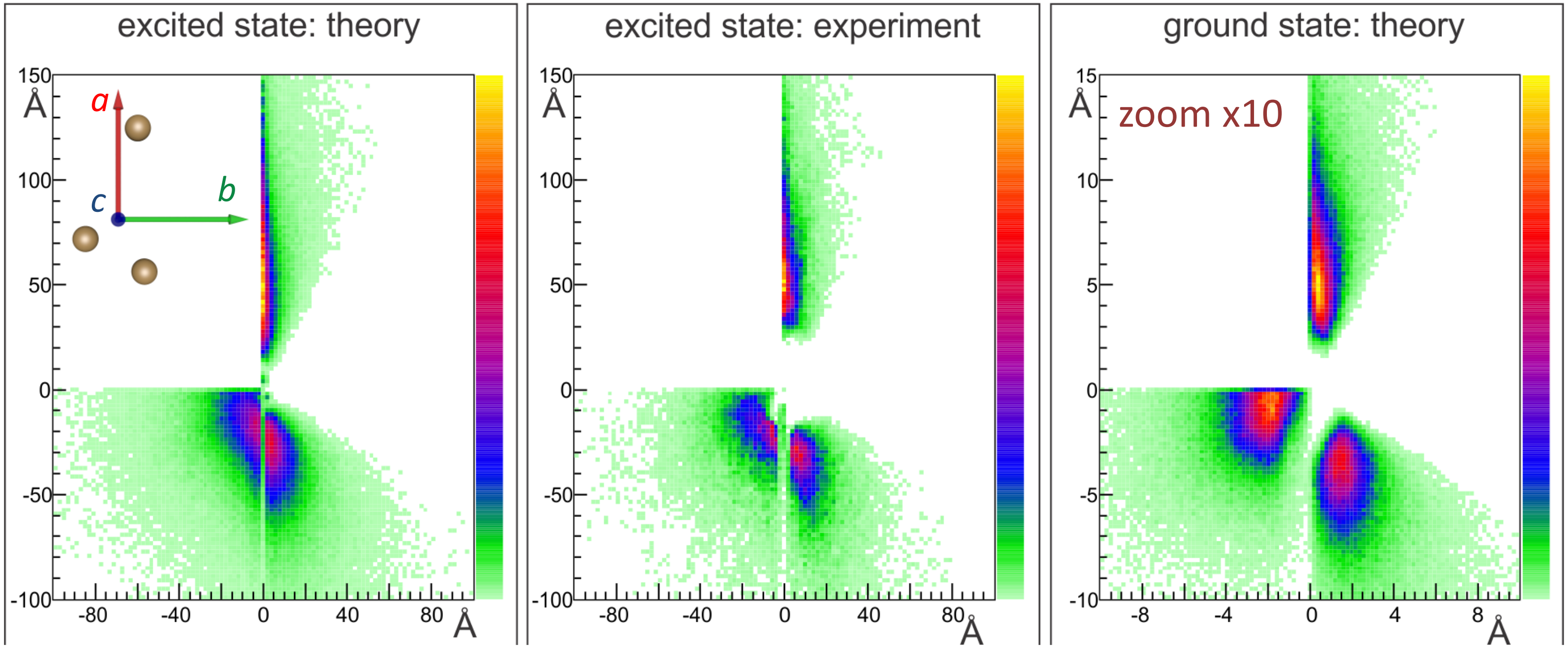
$\Delta B = B(He_3^*)\text{-}B(He_2)$

$B(He_3^*)$=2.6±0.2mK

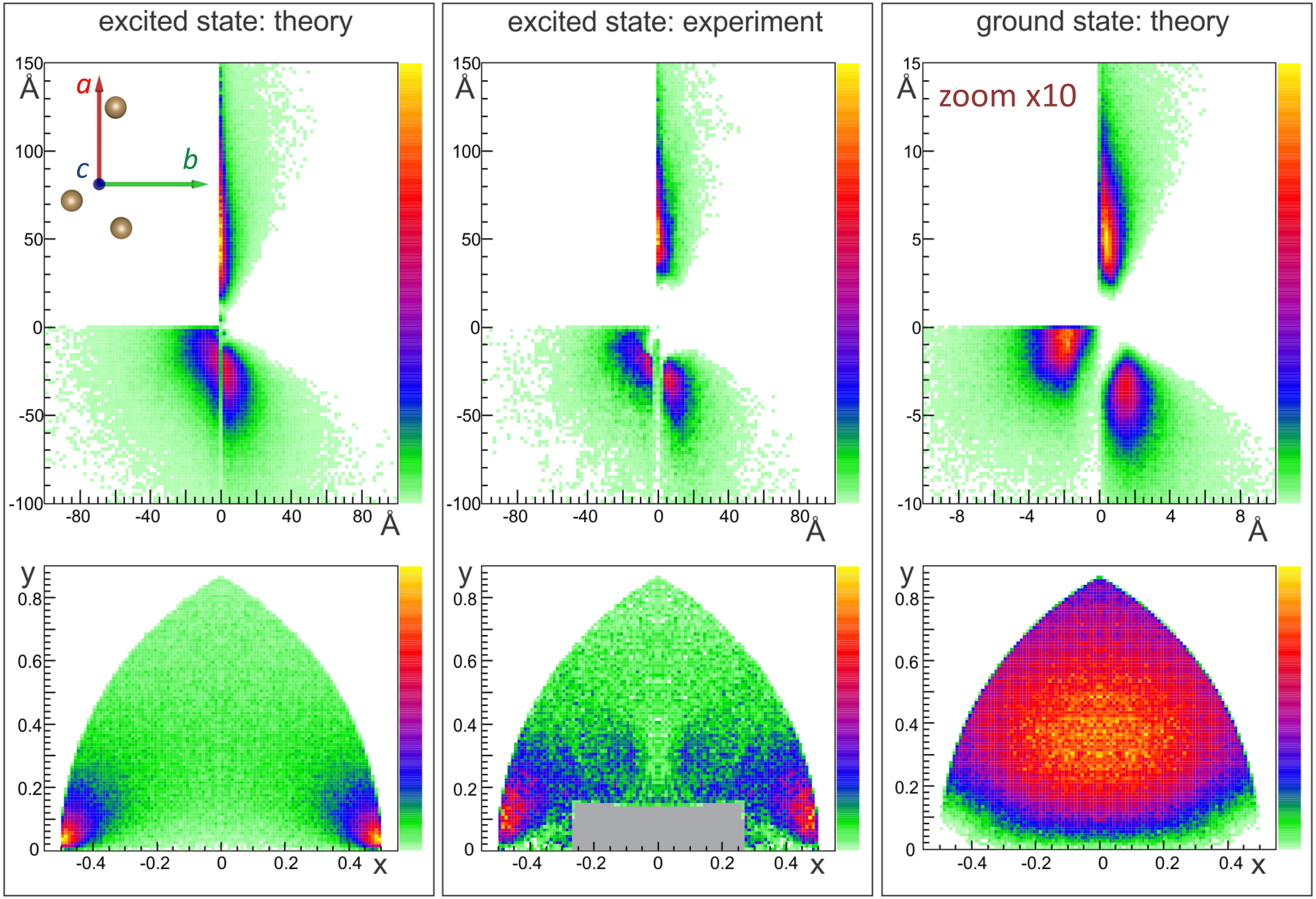


Model	binding_energy (User)		
Equation	P0*exp(-(x/0.52917721)*(2*sqrt(2*(2*7296.3/3)*(1e-6*P1/27.2))))		
Reduced Chi-Sqr	2.08383		
Adj. R-Square	0.97826		
		Value	Standard Error
Value	P0	10166.93667	598.13032
	P1	0.08442	0.00254

Structures


excited state: theory
excited state: experiment
ground state: theory
a
b
c
zoom x10
150
100
50
0
-50
-100
-80
-40
0
40
80
Å
15
10
5
-5
-10
-8
-4
4
8

Structures



excited state: theory
excited state: experiment
ground state: theory
a
b
c
zoom x10
Å
y
x
150
100
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0
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-100
-80
-40
40
80
15
10
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8
0.8
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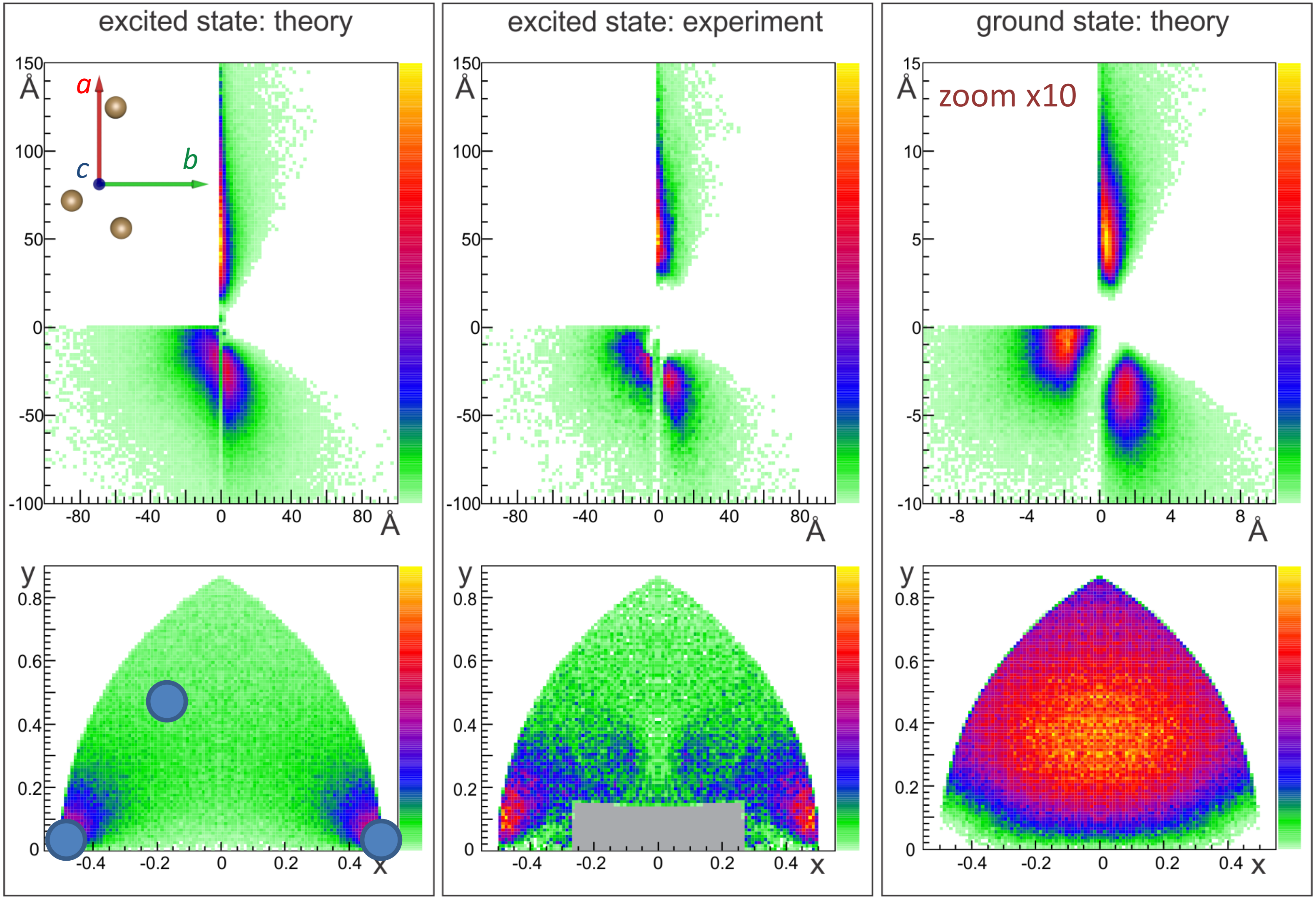
0.4
0.2
-0.4
-0.2

Structures



excited state: theory
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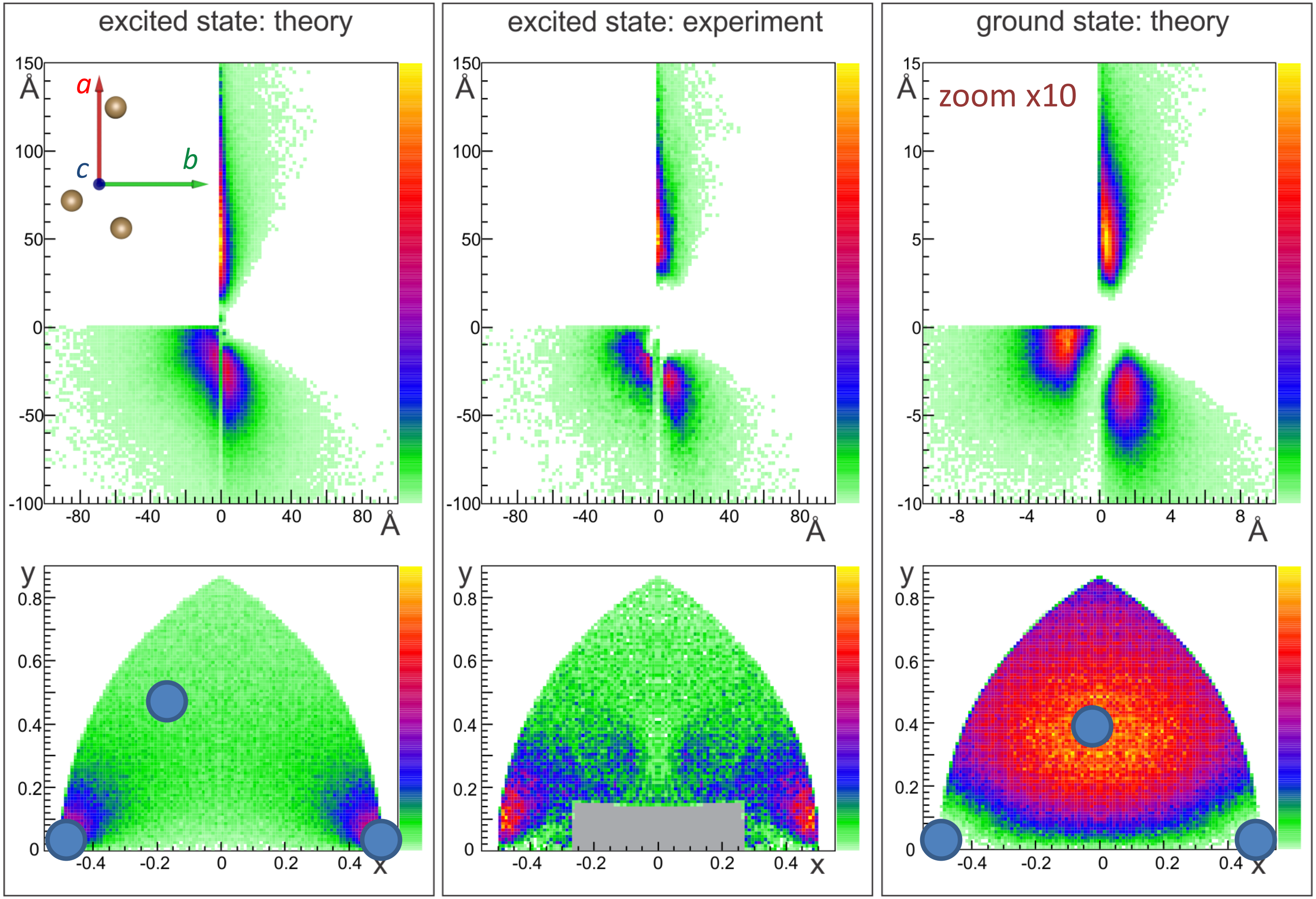
zoom x10
a
b
c
Å
x
y

Structures



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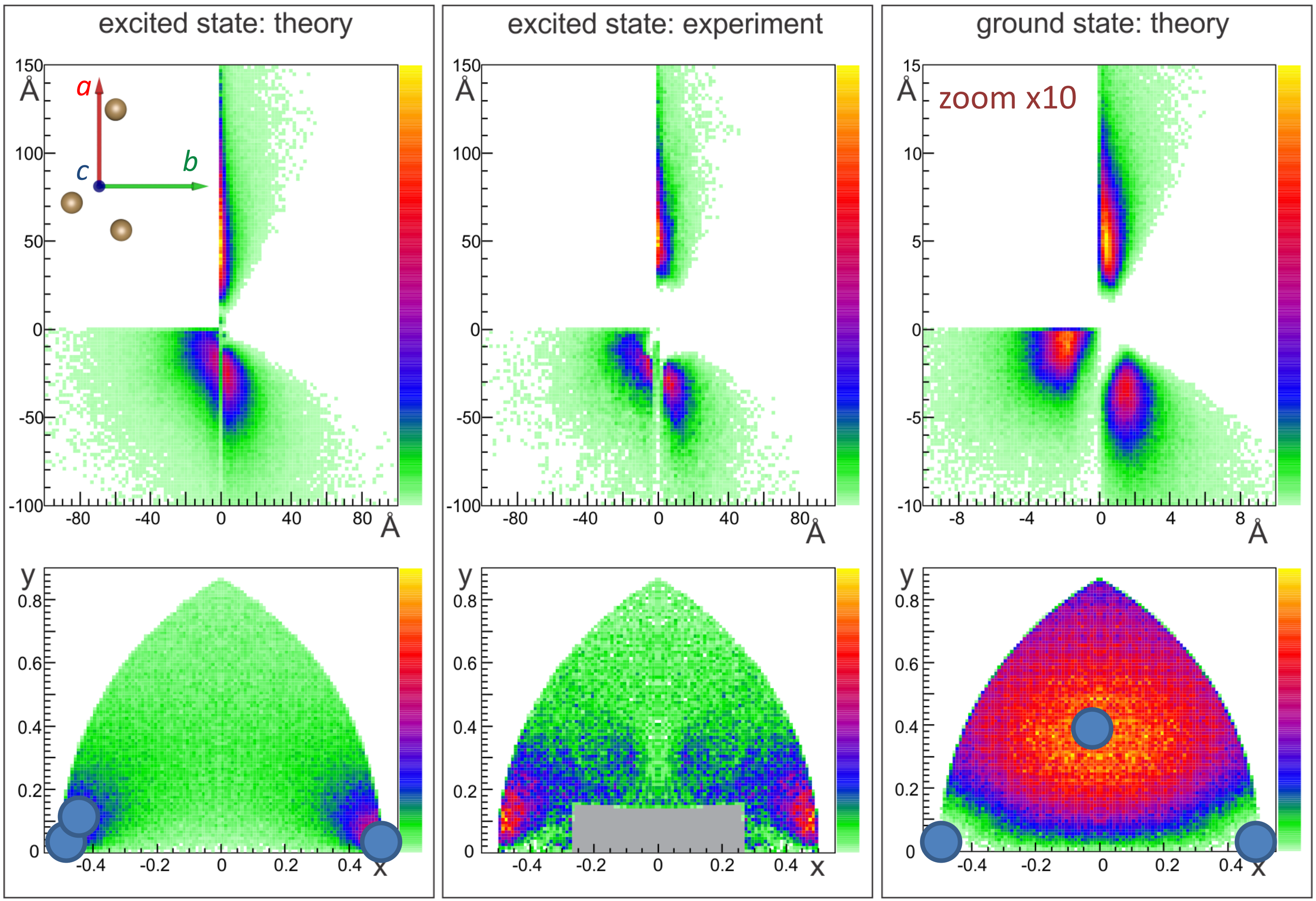
Å
y
x

Structures



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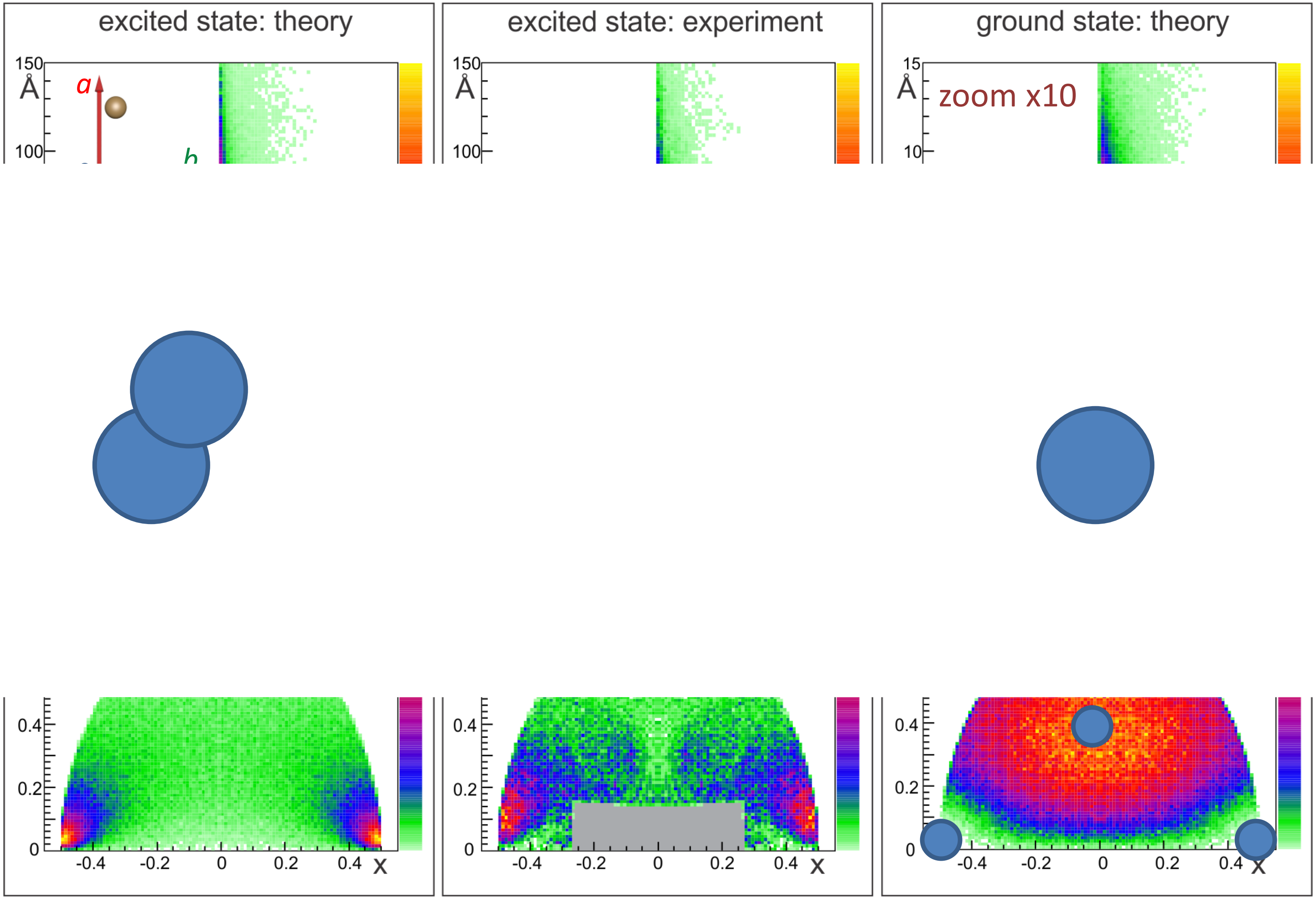
Structures



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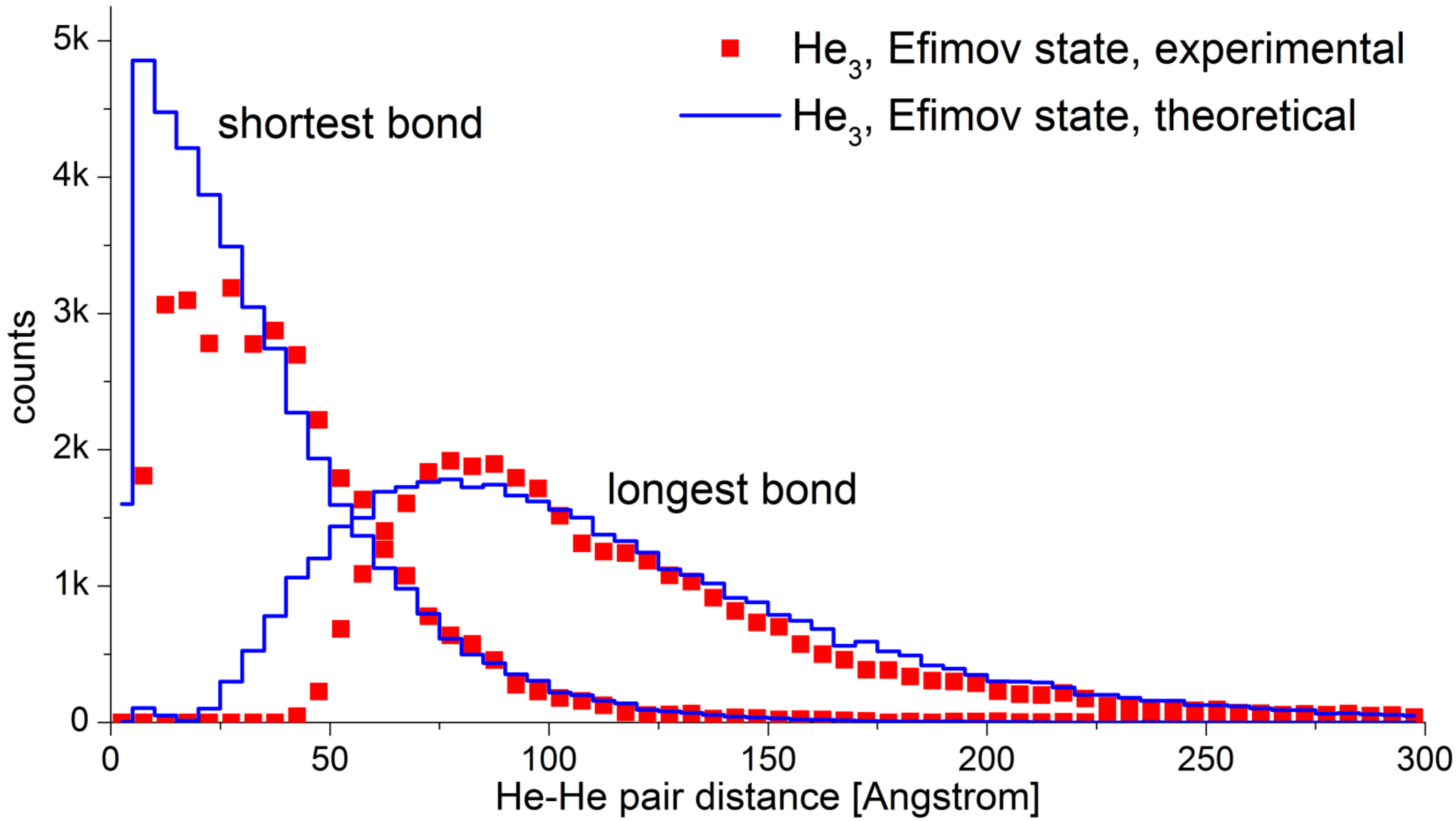
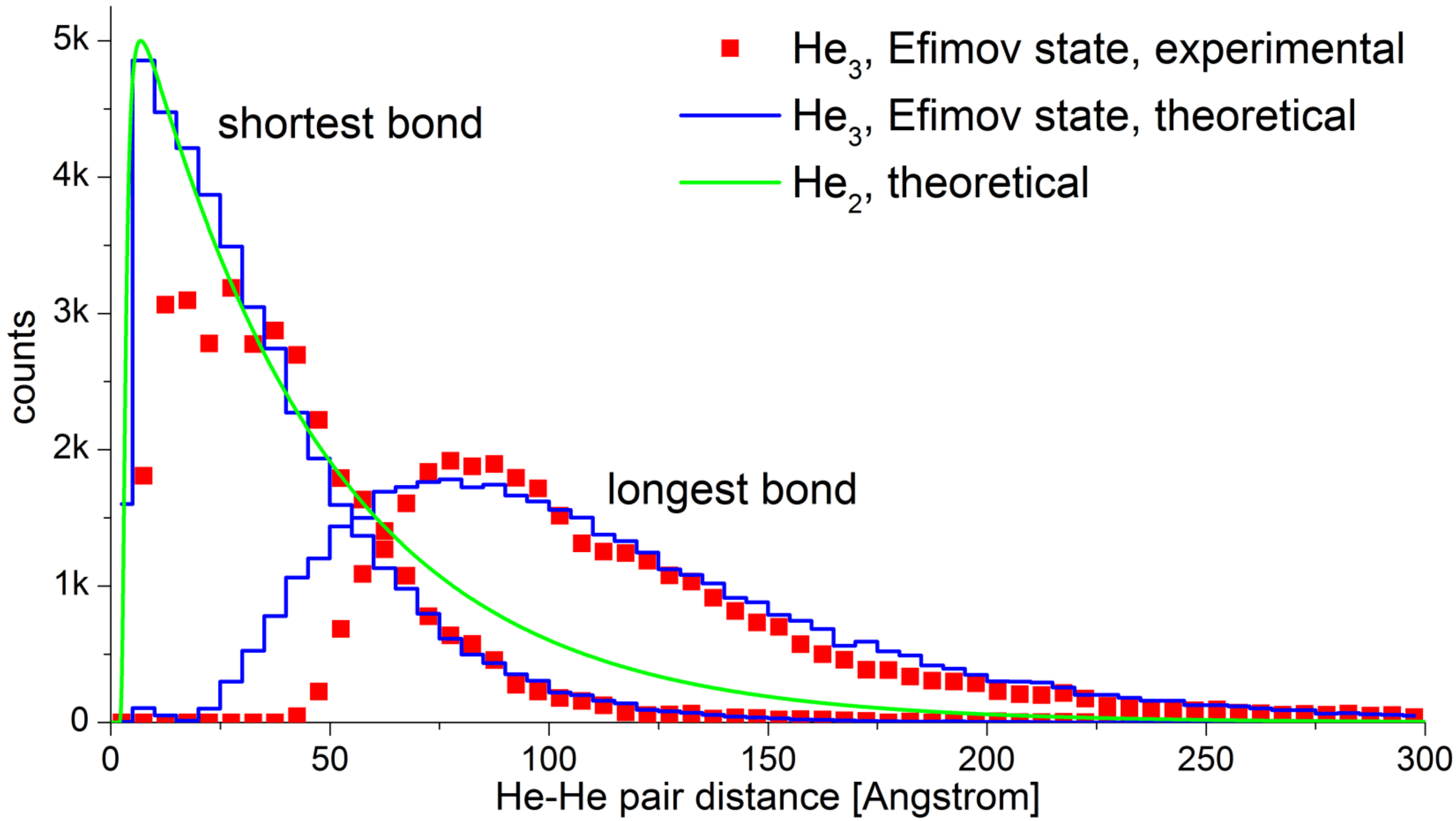
0.2
0
-0.4
-0.2
0
0.2
0.4
x
a
b
15
10
zoom x10

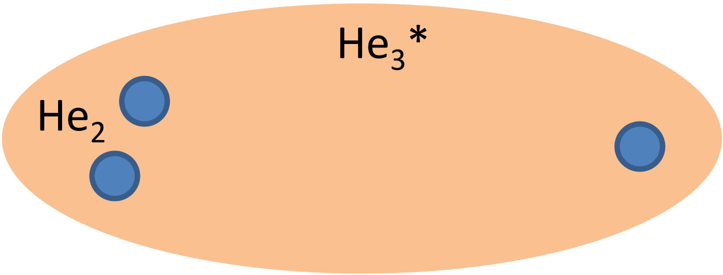
Structure of He_3*: shortest & longest bonds



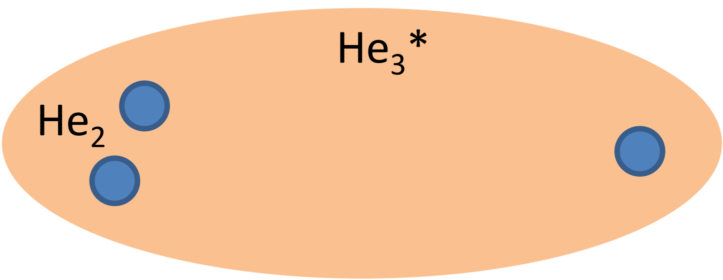
Structure of He_3*: shortest & longest bonds

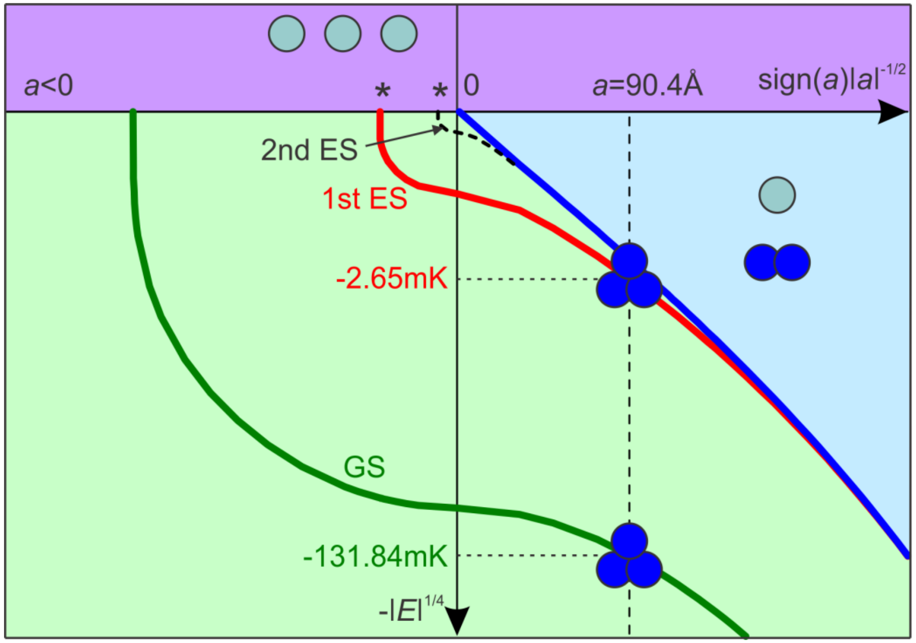


Structure of an Efimov state

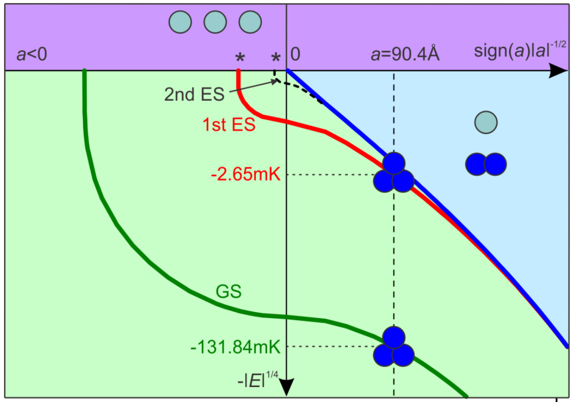


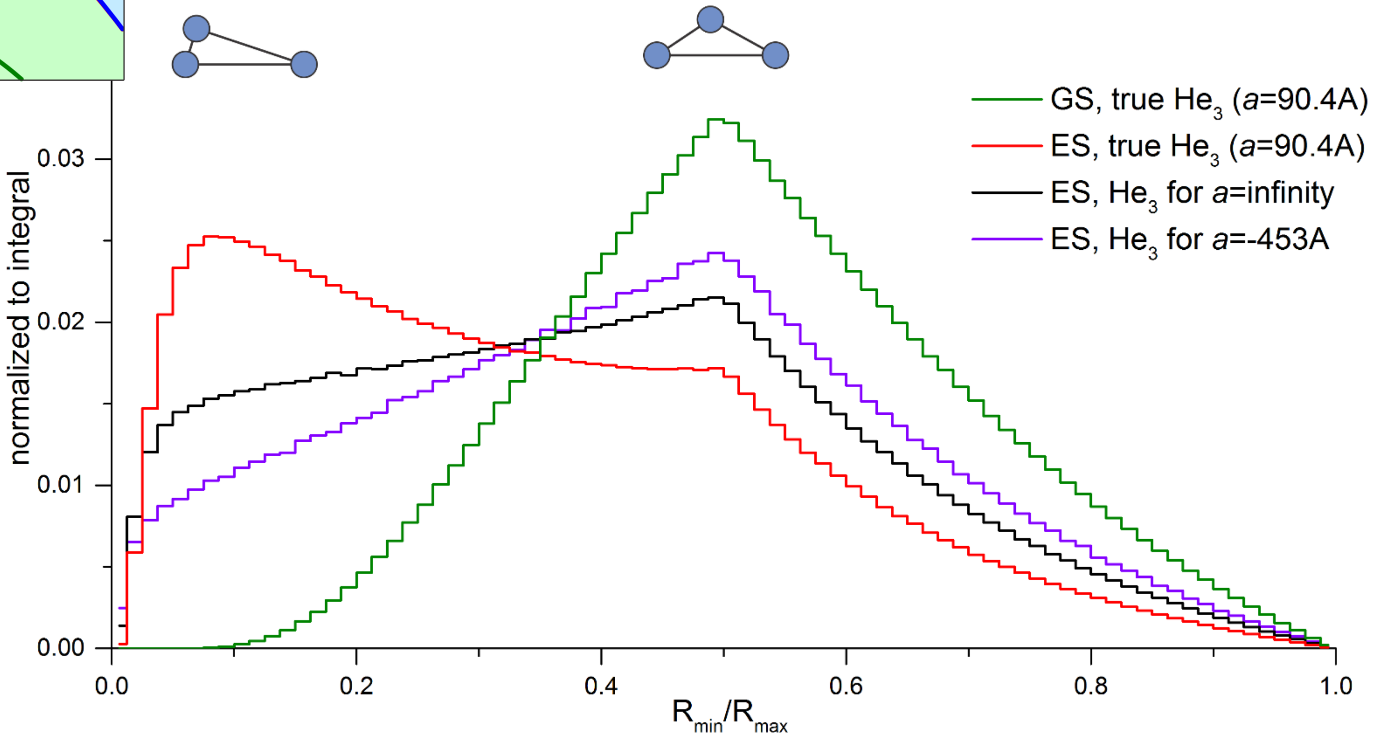
Structure of an Efimov state





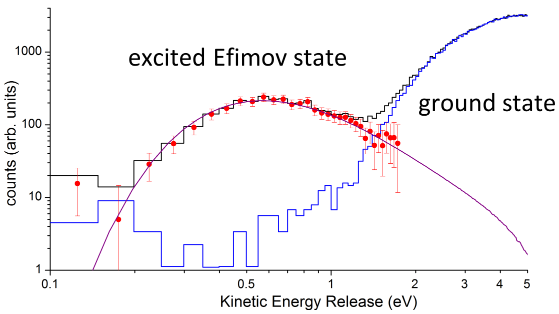
R_{min}/R_{max} distribution of He_3

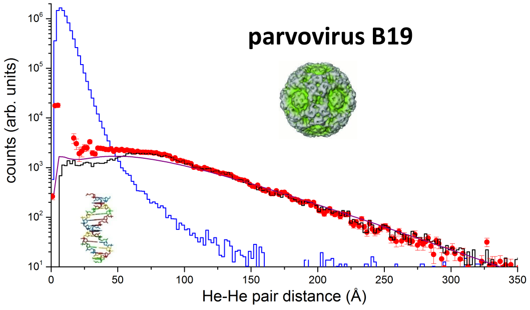


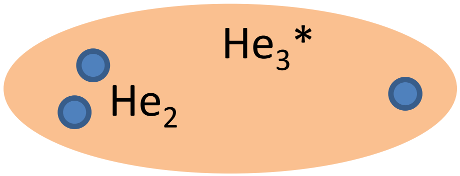


Conlcusions

- The Efimov state of the helium trimer has been observed
- The structure of the Efimov state spread out over 300A
- The binding energy of the Efimov state of He_3 is determined to be 2.6±0.2mK
- The typical shape of the Efimov state of He_3 is the He_2 with the third He atom attached farther away







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Thank you for your attention!