

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

T. Kraemer et al., Nature 440, 315-318 (2006).

reported by A. Tamii

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

T. Kraemer¹, M. Mark¹, P. Waldburger¹, J. G. Dardt¹, C. Chin^{1,2}, B. Engesser¹, A. D. Lange², K. Pilch², A. Jaakkola², H.-C. Nägerl¹ & R. Gröner^{1,2}

systems of two interacting particles are necessary for this complex physical behaviour. A landmark theoretical result in low-dimensional quantum physics is the existence of a bound state in two dimensions (Efimov 1971). This discovery is associated with a resonant two-body scattering length. Contrastingly, there is no bound state in three dimensions. This is a direct consequence of the fact that the formalisation of Efimov's problem in the context of another physics 30 years ago, in an abstract grand unified theory of elementary particles, was not solved (Efimov 1976). This question thus has remained an elusive goal. Here we report the observation of an Efimov resonance in an ultracold gas of neutral atoms. We observe a resonance in the negative two-body scattering length, arising from the coupling of two-body and three-body scattering lengths. This is the first signature of a resonance in three-body recombination loss, where the strength of the two-body interaction is varied. We also detect a resonance in the three-body scattering length, which is a consequence of the coupling of two-body and three-body scattering lengths, indicating dramatic interferences of their partners. This results confirm recent theoretical predictions of Efimov (1971) and have implications for the understanding of universal properties of nonrelativistic interacting few-body systems. While Efimov's conjecture (1971) has provided the key to two-body scattering cross-sections, our results indicate that the Efimov resonance cannot always manifest in the world of low-energy

of these identical $^2S_{1/2}$ states is doubly linked to the concept of entanglement in systems with a minimum two-body interaction, where the wavefunction has a nontrivial length: a characteristic two-body physics length, which is the characteristic range r of the two-body interaction potential, details of the characteristic two-body physics are encoded in the wavefunction. Unfortunately that leads to a generic behavior in these two-body physics, reflected in the energy spectrum of weakly bound states, which is universal. The importance of these states could not be observed experimentally. An important feature of the nuclei is that, as typically prepared, they are in a state of minimum energy, which is the ground state. Only two neutrons have come with a spinless core (likely to be ^4He) and the two neutrons have formed a pair, which is the deuteron. The deuteron has an excited state with $E_{\text{exc}} = 2.224\text{ MeV}$. The existence of this state could not be understood: a different approach by experimentally measuring the $^2S_{1/2}$ state of the deuteron, which is the $^2S_{1/2}$ state of off-shell nucleon-nucleon quantum gases, had not been possible at approximately that level of detail, enabling the investigations of interesting aspects of the two-body physics. The two-body physics is the basis of the many-body quantum limit. Moreover, two-body interactions can be precisely noted as the basis of field-theoretic interactions^{20,21}.

Elmer's mass $m_{\text{Elmer}}^{(i)}$ can be obtained by the energy conservation of the three-body system as a function of the incoming scattering length l_1 (Fig. 11). Let us first consider the well-known weakly bound state (Fig. 11), which only exists for large positive l_1 in the momentum region $0 < k < k_{\text{th}} = \sqrt{2\mu V_0}$. In this region, the energy of the three-body system is $E = E_{\text{Elmer}}^{(i)}$, where $E_{\text{Elmer}}^{(i)}$ is the atomic mass and E is Planck's constant divided by 2μ . In Fig. 11, where the momentum limit corresponds to $l_1 \rightarrow \infty$, the Elmer energy $E_{\text{Elmer}}^{(i)}$ is represented by a parabola for $l_1 > 0$. If we now consider the bound state with zero energy, a threshold state, the scattering length for the bound state is the threshold length l_{th} (Fig. 11) given by the three-atom threshold E_{th} (Fig. 10) for negative l_1 and by the dimer-atom threshold $l_{\text{th}}^{\text{da}}$ for positive l_1 . Energy states below the dimer-atom threshold are unphysical. The threshold state is the state with the lowest energy. From the negative l_1 side, a first Elmer trimer state appears to be near a weakly bound two-body state that does not exist. When passing through the resonance the state connects to the $l_{\text{th}}^{\text{da}}$ state, where a three-body state exists. The threshold state is a bound state of each Elmer trimer as discussed when scattering lengths are increased and binding energies are obtained in powers of universal scales.

Figure 9. Schematic diagram of the waveguide geometry. A central "2nd fiber" is surrounded by a "1st fiber" layer, which is further enclosed by a "Non-fiber cladding". The total width is labeled as "Waveguide width, w_0 ". Dimensions are given as " $x = 0$ " at the left edge and " $x = w_0$ " at the right edge.

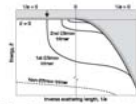


Figure 1. Effects of the size of the interaction. Approximation of an infinite series of weekly effects of 150-mm rain events for movement from study interaction. The location energy is plotted as a function of the distance two-hourly walking length (x). The shaded region indicates the scattering continuum for these areas ($x = 0$) and for the sea zone and a distance ($x = 95$). The arrow marks the intersection of the first 150-mm rain with the 150-mm zone threshold. The 150-mm rain series of 150-mm rain, we have actually reduced the movement walking factor from 22.7 to 2. The comparison, the dashed line indicates a slightly biased non-150-mm rain, which does not interact with the scattering continuum.

abstract:

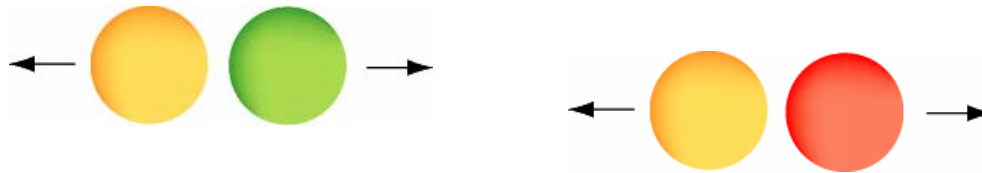
Systems of three interacting particles are notorious for their complex physical behaviour. A landmark theoretical result in few-body quantum physics is [Efimov's prediction](#) of a [universal](#) set of (infinite number of) [bound trimer states](#) appearing for three identical bosons with a resonant two-body interaction. Counterintuitively, these states even exist in the absence of a corresponding two-body bound state. Since the formulation of Efimov's problem in the context of nuclear physics 35 years ago, it has attracted great interest in many areas of physics. However, the observation of Efimov quantum states has remained an elusive goal. Here we report [the observation of an Efimov resonance in an ultracold gas of caesium atoms](#). The resonance [occurs in the range of large negative two-body scattering lengths](#), arising from the coupling of three free atoms to an Efimov trimer. Experimentally, we observe its signature as a [giant three-body recombination loss](#) when the strength of the two-body interaction (scattering length 'a') is varied. We also detect a [minimum in the recombination loss for positive scattering lengths](#), indicating destructive interference of decay pathways. Our results confirm central theoretical predictions of Efimov physics and represent a starting point with which to explore the universal properties of resonantly interacting few-body systems. While [Feshbach resonances](#) have provided the key to control quantum-mechanical interactions on the two-body level, Efimov resonances connect ultracold matter to the world of few-body quantum phenomena.

Introduction:

Efimov States

[1] V. Efimov, PLB33,563(1970), 他[2,16]

3粒子のいずれの2つのペアも束縛状態を持たない場合



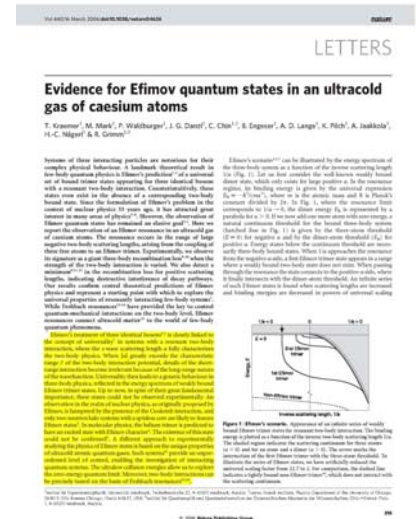
3粒子状態は束縛状態を持つか？



(低Energy、 $|a| \gg r_0$ の極限で考察)

答え: 束縛状態を無限に持つ。

また、束縛状態のシリーズは、特徴的な定数で記述される。



Introduction:

‘Universality’

“properties of the many-body system that are determined (only) by the scattering length are called *universal*”

[7] E. Braaten and H.-W. Hammer, arXiv:cond-mat/0410417.

→ expansion in ak

c.f.

有効距離の理論

到達距離の短い中心力相互作用によるS波の弾性散乱の振る舞いは、低エネルギーの極限では、2つの定数(a, r_0)により特徴づけられる。

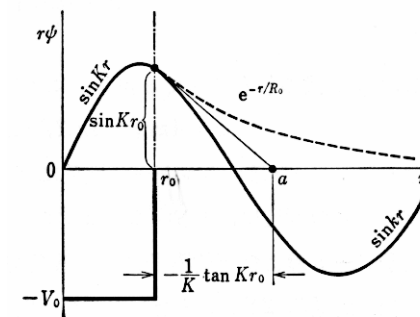
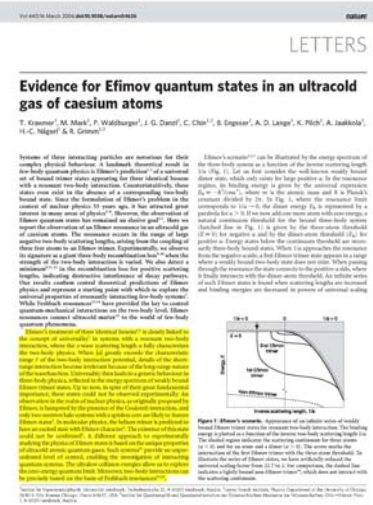
$$k \cot \delta = -\frac{1}{a} + \frac{r_0}{2} k^2$$

k : 波数、 δ : 位相のずれ

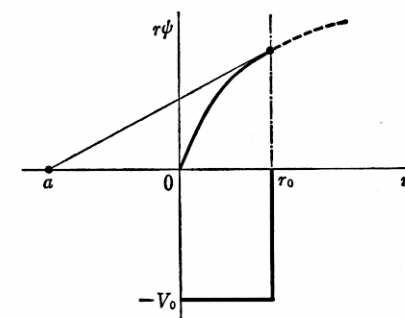
a : scattering length (散乱長、散乱半径)

r_0 : effective length (有効距離)

※ r_0 は論文の中では ℓ と記載されている。



(a) 束縛状態 $a > 0$



(b) 非束縛状態 $a < 0$

図 32 散乱半径 a とポテンシャル内部の波動関数との関係

原子核物理学 by 八木

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Introduction:

Efimov States

Low energy limit

Universality in the case of $|a| \gg r_0$

$a \rightarrow \infty, r_0 \rightarrow 0$ の極限では、3粒子間のポテンシャルを特徴付けるスケールはどう表されるか？

$\rightarrow -\frac{1}{mR^2}$ の形でなければならない。

R: hyperradius (3核子の各ペア距離のrms)

3粒子状態のポテンシャル形は、electric dipole field 中の電荷のポテンシャルと同じ

Schrodinger方程式の解は、無限に存在し、次の定数でスケールする。

$$E_{n+1} = \exp(-\frac{2\pi}{s_0})E_n = \frac{1}{515.03}E_n$$

$$a_{n+1} = \exp(+\frac{\pi}{s_0})a_n = 22.7a_n$$

ここで

$$s_0 \approx 1.00624$$

は

$$s_0 \cosh \frac{\pi s_0}{2} = \frac{8}{\sqrt{3}} \sinh \frac{\pi s_0}{6}$$

の解

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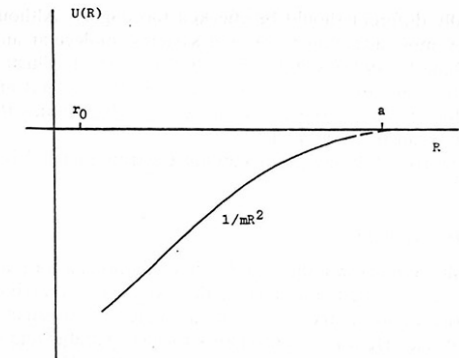
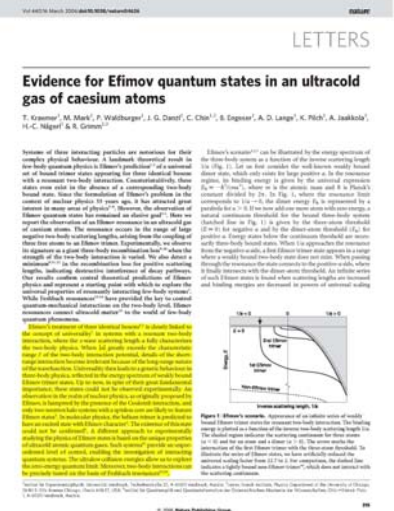


FIGURE 1 An effective three-body long-range interaction.

V. Efimov, CNPR19,271(1990)

Efimov States

dimerのBinding Energy は、

$$E_b = \frac{\hbar^2}{ma^2}$$

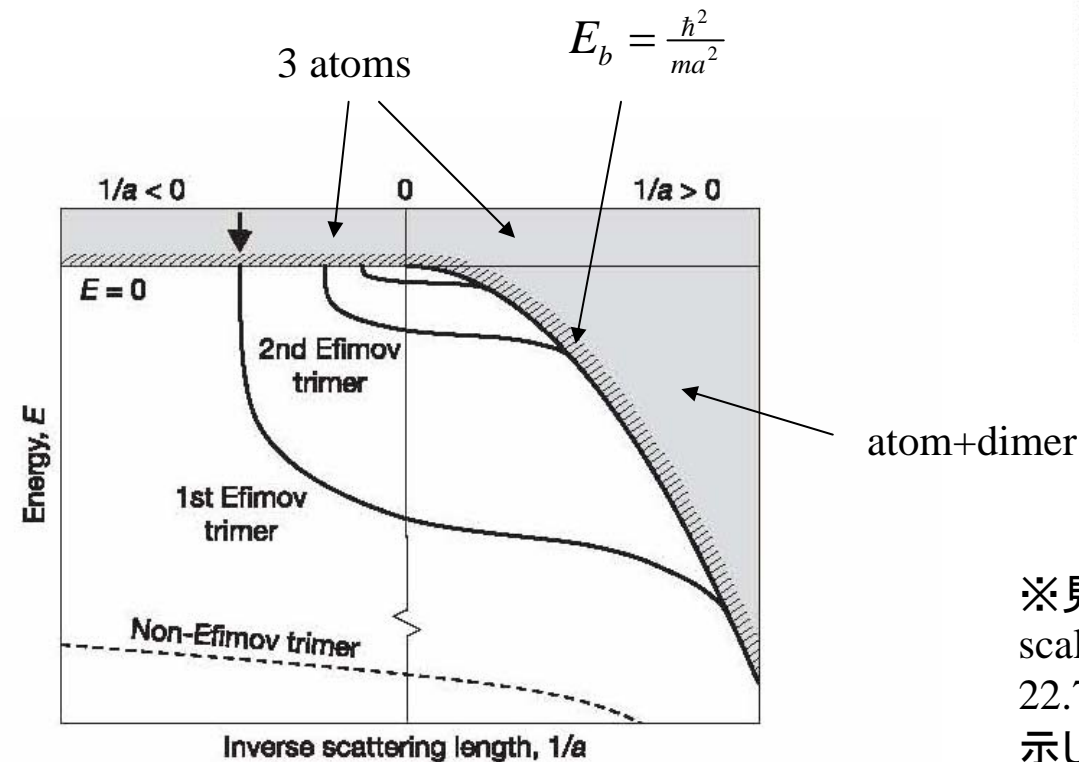


Figure 1 | Efimov's scenario. Appearance of an infinite series of weakly bound Efimov trimer states for resonant two-body interaction. The binding energy is plotted as a function of the inverse two-body scattering length $1/a$. The shaded region indicates the scattering continuum for three atoms ($a < 0$) and for an atom and a dimer ($a > 0$). The arrow marks the intersection of the first Efimov trimer with the three-atom threshold. To illustrate the series of Efimov states, we have artificially reduced the universal scaling factor from 22.7 to 2. For comparison, the dashed line indicates a tightly bound non-Efimov trimer³⁰, which does not interact with the scattering continuum.

※見やすくするため、
scaling factor の
22.7 を 2 として図
示している。

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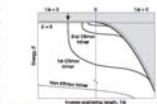
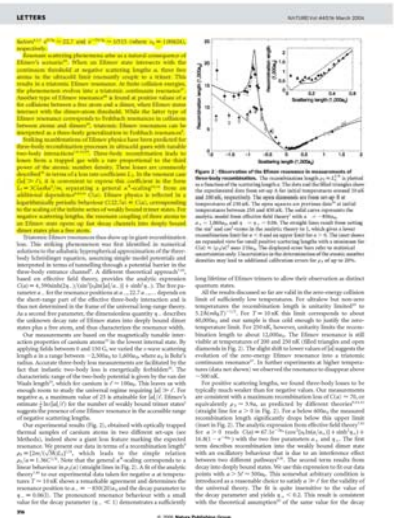
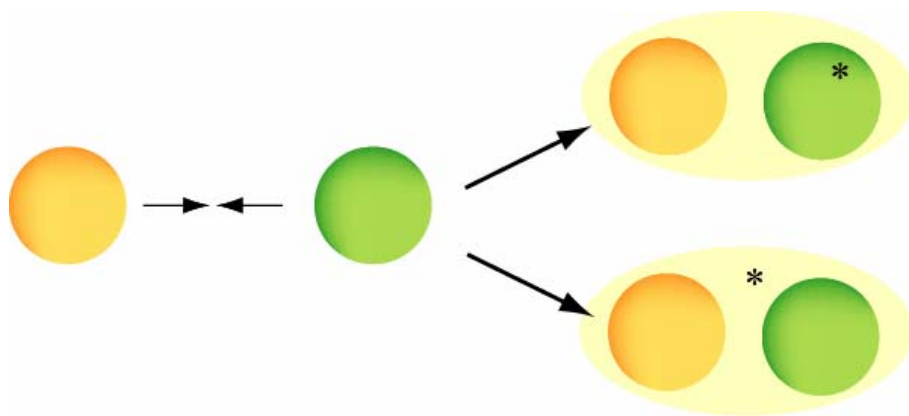
[illegible]

Figure 1 *Illnesses' scenario*. Approximation of an infinite series of weekly waves of influenza A virus activity for a constant low-level endemicity. The relative intensity is plotted as a function of the average two-weekly averaging length Δt . The shaded region indicates the averaging uncertainty for three waves: $\Delta t = 10$ and for six waves and a disease $\Delta t = 20$. The arrow marks the intersection of the first Illnesses wave with the three waves threshold. The Illnesses for seven of Illnesses states, as have artificially induced the outbreak of influenza A virus activity. The dashed line indicates the threshold for a 'high' based on the Illnesses Δt , which does not intersect with the averaging uncertainty.



Experiment: Feshbach Resonance

2粒子の低エネルギーでの衝突で、一方の粒子が励起状態になる、もしくは分子としての励起状態に入ることによってエネルギーを失い、2粒子が束縛した状態になる反応。特に初期運動と励起の自由度のカップリングが小さい場合を想定する。終状態は元に戻るため、寿命がある。



Csの2原子($F=3, m_F=3$ に偏極してくる)は、衝突によりd,g状態などの分子励起状態に入るFeshbach Resonanceを起こす。励起状態のスピンは初期状態のスピンの一般には異なるため、外部磁場を加えることで励起状態とのエネルギー差を変えることができる。これにより、散乱長を(弾性散乱の散乱断面積 $\sim 4\pi a^2$)を制御することができる。

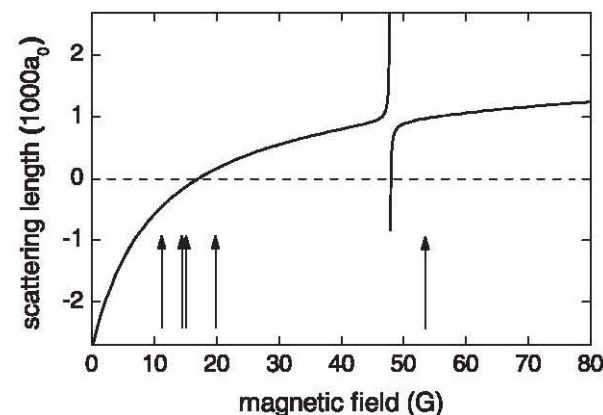


FIGURE 1 Scattering length as a function of magnetic field for the state $F=3, m_F=3$. There is a relatively broad Feshbach resonance at 48.0 G due to coupling to a d -wave molecular state. The arrows indicate several very narrow resonances at 11.0, 14.4, 15.0, 19.9 and 53.5 G, which result from coupling to g -wave molecular states. The data are taken from [13]



Experiment: Trap

T. Kraemer et al., Appl.Phys.B79, 1013(2004)

Zeeman slowed atomic beam 3×10^8 atoms/6sec



Magneto-Optical Trap
(MOT)

$\tau=200\text{s}$ at 1×10^{-11} mbar
high-power laser diode



Compression

rampup dB/dy 7-33 G/cm in 40ms
laser 10-30 MHz



Cooling

degenerate Raman-sideband cooling
injection locked slave laser
4 laser 65 mW
 4×10^7 atoms, $0.7 \mu\text{K}$, 1 mm
 $F=3, m_F=3 \rightarrow 90\%$
heated to $2 \mu\text{K}$

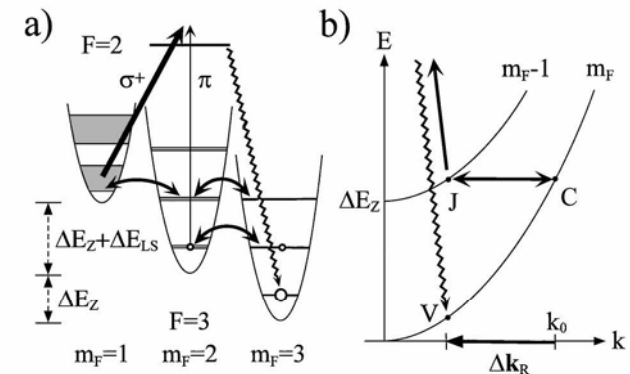
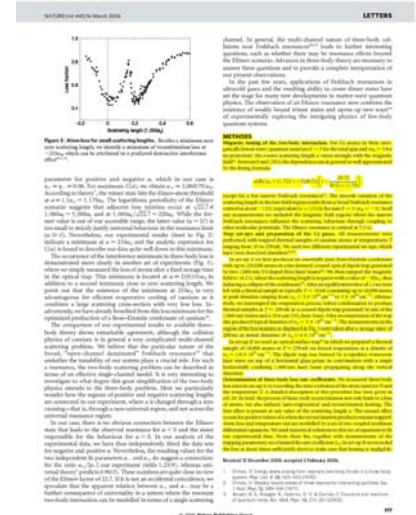


FIG. 1. (a) Vibrationally excited atoms are cooled quickly by degenerate Raman transitions (double-sided arrows) and fast σ^+ optical pumping, while the final cooling stage uses only weak π pumping. This scheme strongly suppresses reabsorption heating. (b) Initially unbound atoms are transferred from $m_F(C)$ to $m_F - 1(J)$ when a two-photon degenerate Raman transition satisfies energy and momentum conservation. Optical pumping back to $m_F(V)$ cools the atoms by one Zeeman energy splitting ΔE_Z .

A. Kerman et al., PRL84, 439 (2000).

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Experiment: Trap



Reservoir Trap



Plain Evaporation Cooling



Dimple Trap



Forced Evaporation Cooling

heated to $2\mu\text{K}$

anti-Helmholtz coil 31.3G/cm
(Magnetic levitation)
Helmholtz coil 0-200 G
 CO_2 -laser $\times 2$ 90+65W
potential depth $7\mu\text{K}$
 $605\mu\text{m}$ - $690\mu\text{m}$

73.5 G
1215 a_0
 4×10^6 atoms, $1\mu\text{K}$, 10sec

7.8×10^6 atoms, 2sec

broadband fiber laser 1064nm
rampup 70mW-270mW/1.5sec
 $34\mu\text{m}$ - $260\mu\text{m}$
300 a_0 to reduce 3-body recombination loss
 1.7×10^6 atoms, 2sec

rampdown laser beams
A2 \rightarrow off
A1 \rightarrow 0, B1 \rightarrow 5mW, B2 \rightarrow 220mW/5.5sec

21G, 210 a_0
 5×10^5 atoms at 200nK
 1.1×10^5 atoms at 10nK

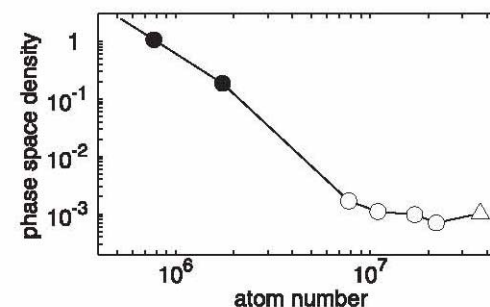


FIGURE 3 Peak phase space density as function of atom number. The path of evaporation proceeds from right to left. The triangle shows the atomic ensemble immediately after lattice cooling. The open circles show the ensemble in the reservoir trap after 0.08, 0.22, 0.64, and 2.0 s. The filled circles correspond to the sample in dimple trap right after loading and after 1.5 s of evaporation. The phase transition occurs after 2 s of forced evaporation with $\sim 5 \times 10^5$ atoms left in the dimple trap

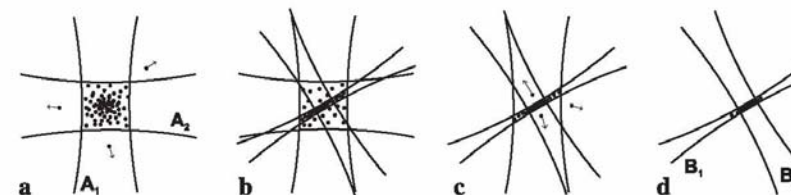
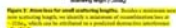


FIGURE 2 Illustration of the various stages of trap loading and evaporative cooling as seen from above. (a) Plain evaporation in a crossed CO_2 -laser trap generated by beams A_1 and A_2 at a scattering length of $a = 1215a_0$. (b) 1.5 s of ramping and collisional loading into a crossed 1064-nm fiber laser trap generated by beams B_1 and B_2 with a final scattering length $a = 210a_0$. (c) Forced evaporative cooling after switching off CO_2 -laser beam A_2 . The power of all remaining lasers is ramped down, and the power in CO_2 -laser beam A_1 is reduced to zero. (d) Final configuration of the crossed 1064-nm trap. Imaging is done in the horizontal plane at an angle of 30° with respect to the long axis of the cigar-shaped atomic cloud



the positive and negative α , which in our case is $\alpha = 0.05$ (two-tailed test). The null hypothesis is rejected if the test statistic is greater than $\alpha/2$ or less than $-\alpha/2$. The rejection region is $\alpha/2$ or less than $-\alpha/2$. The rejection region is $\alpha/2$ or less than $-\alpha/2$.

incumbency length approximately drops below the upper bound of 100 years (see Fig. 2). The analysis is performed for different fixed values of α , β and γ (Table 1). The results are plotted in Fig. 3. The results show that the optimal incumbency length is a function of the parameters α , β and γ . The optimal incumbency length is a function of the parameters α , β and γ . The optimal incumbency length is a function of the parameters α , β and γ . The optimal incumbency length is a function of the parameters α , β and γ .

In our case, there is no obvious connection between the El Niño state that leads to the observed increase for $\alpha < 0$ and the atmosphere responsible for the behaviour for $\alpha > 0$. In our analysis of the experimental data, we have thus independently fitted the data sets for negative and positive α . Nevertheless, the resulting values for the two independent fit parameters α and β do suggest a connection for the ratio α/β . In our experiment yields 1.28% , versus our simulation results 1.25% . These numbers are quite close to the value of the El Niño factor of 12.7% . It is not an accidental coincidence, we speculate that the apparent relation between α and β , may be a further consequence of universality in a system where the resonant triad-like interaction can be modelled in terms of a single scattering

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