Formation of bright matter-wave solitons during the collapse of attractive Bose-Einstein condensates.

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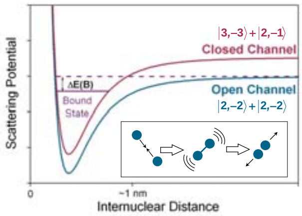
We observe bright matter-wave solitons form during the collapse of ^{85}Rb condensates in a three-dimensional (3D) magnetic trap[1]. The collapse is induced by using a Feshbach resonance to suddenly switch the atomic interactions from repulsive to attractive[2]. Our previous observations of the collapse process[3] revealed that remnant condensates containing several times the critical number of atoms for the onset of instability survive the collapse. It was not understood why such condensates did not undergo further collapse until the number of atoms remaining was below the critical number. In the work presented here, we explain this result by showing that the remnant condensate forms a highly robust configuration of 3D solitons, such that each soliton satisfies the condition for stability. The solitons are observed to oscillate along the (weaker) axial direction of the trap, colliding repeatedly in the trap centre. The stability of this motion out to long observation times indicates that neighbouring solitons have a relative phase that ensures that they interact repulsively even though the atomic interactions are attractive[4].

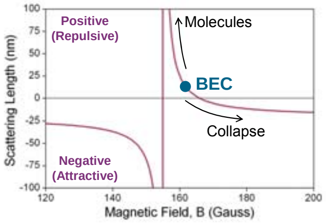
Introduction: the ^{85}Rb Feshbach resonance

A broad magnetic-field-induced Feshbach resonance exists in collisions between ^{85}Rb atoms in the $F = 2$, $m_F = -2$ hyperfine ground state at a magnetic field, B ~ 155 Gauss.

$$a_{eff}(B) = a_{bg}\left(1 - \frac{\Delta B}{B - B_0}\right)$$

where[5]: $B_0 = 155.041(18)\,G$, $\Delta B = 10.71(2)\,G$, $a_{bg} = -443(3)a_0$





Stable Bose-Einstein condensates can be created at a magnetic field, B~162.3 Gauss[2]. The broad resonance can then be exploited to trigger the collapse of condensates with attractive interactions[3,6] and to produce ultracold diatomic molecules[7].

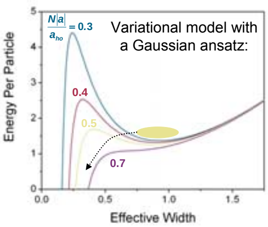
BEC with attractive interactions

In a 3D harmonic trap, the zero point kinetic energy can stabilise the condensate provided the number of atoms in the BEC (N_0) is less than a critical value:

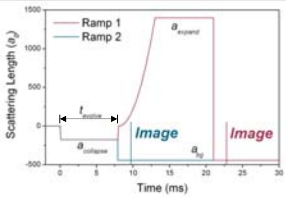
$$N_0 < N_{critical} = k\frac{a_{ho}}{|a|}$$

where a_{ho} is the harmonic oscillator length, a is the s-wave scattering length and the stability coefficient, k = 0.55(6) for the trap used in this work[5,6].

In 1D, ***bright solitons*** can form, where dispersion is balanced by the attractive nonlinearity[8].



Experimental ramps

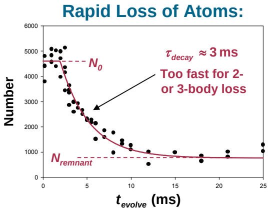


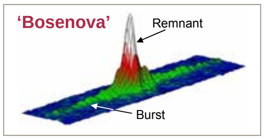
1. **Number Measurement**
   - BEC expanded above resolution limit using large repulsive interaction.
   - Number can be measured reliably, but spatial information is lost in expansion.
2. **Spatial Size Measurement**
   - In-trap dimensions probed with no expansion.
   - Size of BEC is comparable or below the resolution limit (7μm FWHM).

Trap frequencies remain constant throughout ramps: $\nu_r = 17.3\,\text{Hz}$, $\nu_z = 6.8\,\text{Hz}$

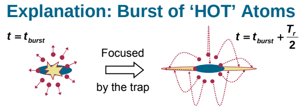
Dynamics of collapsing condensates[3]

Rapid Loss of Atoms:

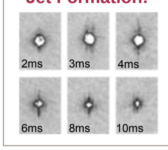




Explanation: Burst of 'HOT' Atoms



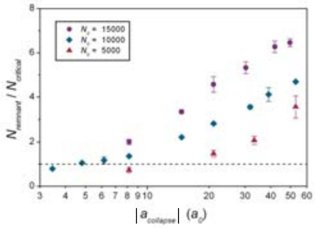
Jet Formation:



- Observed when the collapse is interrupted.
- Manifestation of local 'spikes' in the density.

Images 150 x 255 μm

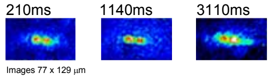
Remnant number violates stability condition?

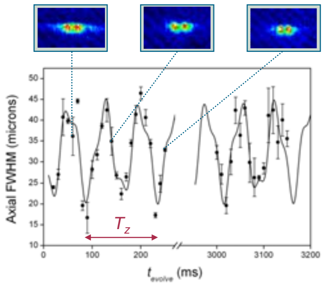


- $N_{remnant} > N_{critical}$ (~10x for $a_{collapse}$= -100a_0)
- Observations for t_{evolve} = 50 ms.
- But, remnant lifetime is several seconds.
- Gross-Pitaevskii Eq. (GPE) predicts onset of collapse, but NOT remnant number?

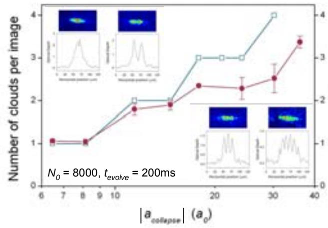
Remnant is highly excited

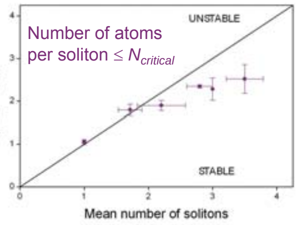
- Single Gaussian fit to images reveals large amplitude oscillation in axial width. Fitted frequencies consistent with the two lowest collective modes ($\nu_1 = 2\nu_z$ and $\nu_2 = 2\nu_r$).
- But, the images reveal the remnant BEC to separate into two distinct clouds: **solitons** oscillating along weak direction of trap.
- Solitons persist for over 3s (= 40 collisions).





Formation of multiple stable solitons[1]

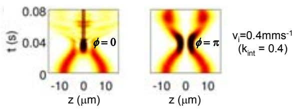


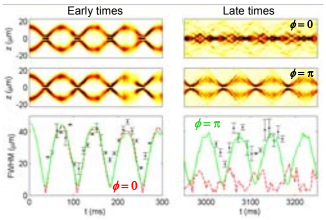


- Each soliton is stable against collapse.
- Explains puzzle of $N_{remnant} > N_{critical}$

Relative phase of neighbouring solitons[4,9]

Numerical solution of the 3D Gross-Pitaevskii equation reveals the solitons to be stable only for a π relative phase[4,9]. The solitons interact repulsively[10,11] and never fully overlap; so the critical density for collapse is never exceeded.





Discussion and Outlook

The existence and origin of the relative phase that ensures the remarkable stability of multiple solitons within the GPE framework remains an open question. New theoretical work suggests that the inclusion of quantum fluctuations causes the soliton dynamics to be predominantly repulsive in 1D independent of their initial relative phase[12]. Further experiments are underway in Durham to probe the relative phase directly through the study of controlled binary soliton collisions. Here the GPE model predicts a well defined population transfer between the solitons as the relative phase is varied[4].

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