Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 35 (2005) 78–81
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Tunable interactions in ultracold Bose gases

K.E. Strecker [a], G.B. Partridge [a], A.G. Truscott [b], R.G. Hulet [a,*]

[a] Department of Physics and Astronomy, Rice Quantum Institute, Rice University, Houston, TX 77251, USA
[b] Research School of Physical Sciences and Engineering, Australian National University, ACT 0200, Australia

Received 4 August 2003; accepted 10 September 2003

Abstract

We have created bright matter wave solitons by using a Feshbach resonance to tune the interactions in a Bose–Einstein condensate of ^{7}Li. The solitons are made to propagate in a one-dimensional potential formed by a focused laser beam. We observed dispersive wave-like properties for repulsive interactions and soliton-like behavior for attractive interactions. Adjacent solitons are observed to interact repulsively.
© 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: One-dimensional ultracold Bose gases; Bose–Einstein condensation; Matter–wave solitons; Feshbach resonance

At temperatures near absolute zero, confined bosons condense into the lowest quantum state of their confining potential, or trap. In this regime, they lose their individual identities and behave collectively as a Bose–Einstein condensate (BEC). Many properties of the condensate are determined by the interactions between atoms. If the interactions are repulsive, the condensate is stable and its size and number have no fundamental limit. However, if the interactions are attractive, only a limited number of atoms can form a condensate (Bradley et al., 1997), which is stabilized against collapse by the confining potential. Beyond this critical number of atoms, the condensate will collapse (Sackett et al., 1999; Gerton et al., 2000). Further, if the confining potential is made asymmetric, such that the atoms can only undergo one-dimensional motion, they are predicted to form a stable, self-focusing BEC or matter–wave soliton (Reinhardt and Clark, 1997; Pérez-García et al., 1998).

Solitons arise as a general solution to the nonlinear wave equation. They occur in all types of wave phenomena, such as water waves, sound waves, and light waves. Solitons are formed when the nonlinear term in the wave equation exactly compensates for wave packet dispersion. A condensate can be described by the nonlinear Schrödinger equation, where the nonlinear term arises from the inter-atomic interactions (Dalfovo et al., 1999). In this case, the self-focusing term is a cubic nonlinearity, known as a Kerr nonlinearity in optics. For a condensate, the sign and magnitude of the nonlinearity are determined by the inter-atomic interactions, given by the scattering length a. The interactions are repulsive for $a > 0$ and attractive for $a < 0$. A phenomena known as a Feshbach resonance enables a to be continuously tuned from positive to negative values. A Feshbach resonance is a scattering resonance in which pairs of free atoms are tuned into resonance with a, vibrational state of the diatomic molecule (Tiesinga et al., 1993). A typical resonance is shown in Fig. 1. An experimental signature of such a resonance is an enhanced loss of trapped atoms (Inouye et al., 1998) due to an increased rate of inelastic collisions, such as molecule formation. A mea-

* Corresponding author. Tel.: +1-713-348-6087; fax: +1-713-348-5492.
E-mail address: randy@rice.edu (R.G. Hulet).

0273-1177/$30 © 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2003.09.058

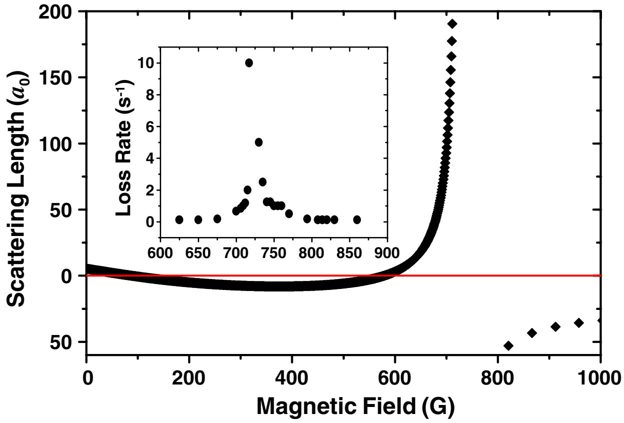

Fig. 1. Calculation on the Feshbach resonance for the (F, m_F)=(1, 1) state of ^{7}Li. The calculation shows a resonance near 725 G, and a zero crossing near 550 G. The inset shows the measured loss of atoms as a function of magnetic field. We observe a sharp peak in the loss rate near the peak of the Feshbach resonance.

surement of the losses is shown in the inset of Fig. 1. The Feshbach resonance provides a continuous knob to adjust the atom-atom interaction from repulsive to attractive, and from weak to strong.

The apparatus and technical details have been previously described (Truscott et al., 2001; Strecker et al., 2002), but the general experimental detail will be restated. The first step in the experiment is to form a large stable BEC. To produce a condensate of ^{7}Li, atoms are evaporatively cooled in a magnetic trap to near 1 μK. The atoms are then transferred to an optical trap consisting of a focused infrared Nd:YAG laser (1064 nm) for radial confinement, and two cylindrically focused doubled Nd:YAG beams (532 nm) 250 μm apart, providing "endcaps" for axial confinement. A bias field is then ramped to 700 G, where the atoms are transferred from the $F = 2$, $m_F = 2$ spin state to the $F = 1$, $m_F = 1$ state by an adiabatic microwave sweep. When the applied magnetic field is increased to this value the scattering length changes from $a \sim 5a_0$ to $a \sim 200a_0$ (McAlexander, 2000). The intensity of the infrared laser beam is then reduced by a factor of two. The gas cools as the hotter atoms escape, and the remaining atoms rethermalize to form a large stable BEC. The magnetic field is then reduced to a value near 545 G, where $a \sim -3a_0$. The atoms are detected by near resonance imaging.

The atoms must be set in motion in order to show soliton behavior. This is achieved by repeating the experiment as described above, but with the infrared laser focus displaced axially from the endcaps. In this way, the BEC is initially formed on the side of the weak axial potential provided by the infrared laser beam. Once the solitons are formed, the endcaps are removed, and the atoms are allowed to oscillate in the axial potential for a varying length of time before being imaged. This process is repeated for different values of magnetic field and release time. Fig. 2 shows the results. The images on the left hand side are taken at a field of 630 G, corresponding to $a \sim +10a_0$, while the images on the right hand side are taken at a field of 545 G, corresponding to $a \sim -3a_0$. We see the condensate with positive a disperses as it propagates, while a condensate with negative a propagates without spreading, as expected for a soliton.

A defining quality of solitons are their interactions. The images of solitons in Fig. 2 reveal something the nonlinear Schrödinger equation did not predict: soliton trains. More detailed images of the soliton train are shown in Fig. 3, where it can be seen that the solitons bunch at the turning points and spread out in the middle. From this we infer repulsive interactions between adjacent solitons.

Theoretical modeling using the nonlinear Schrödinger equation shows that two solitons with a π phase difference will interact repulsively (Khawaja et al., 2002; Salasnich et al., 2002). This repulsion is a manifestation of the wave nature of the solitons rather than the interatomic interactions, which are attractive in this case. A model was developed to simulate two solitons with a π phase difference in a harmonic well. The relative motion

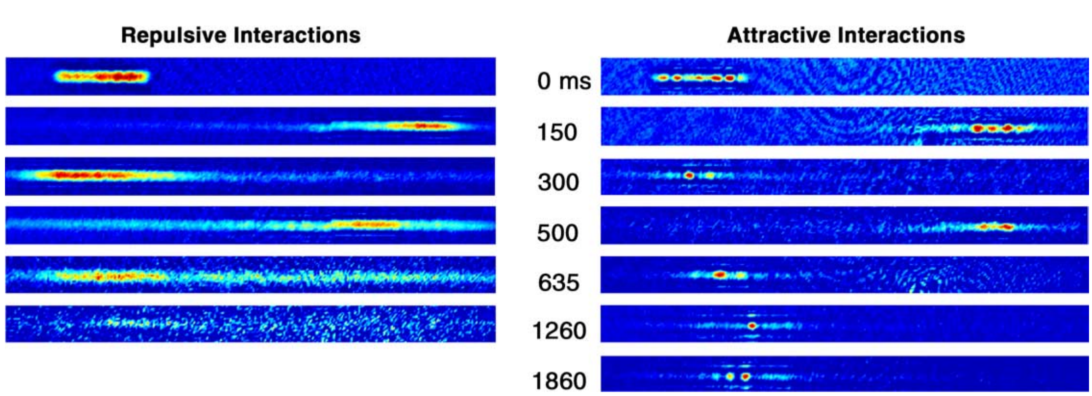

Fig. 2. A comparison of the motion of a Bose–Einstein condensate with repulsive and attractive interactions under the influence of the harmonic axial potential. The axial frequency is approximately 3 Hz. The length of each frame corresponds to 1.28 mm in the plane of the atoms.

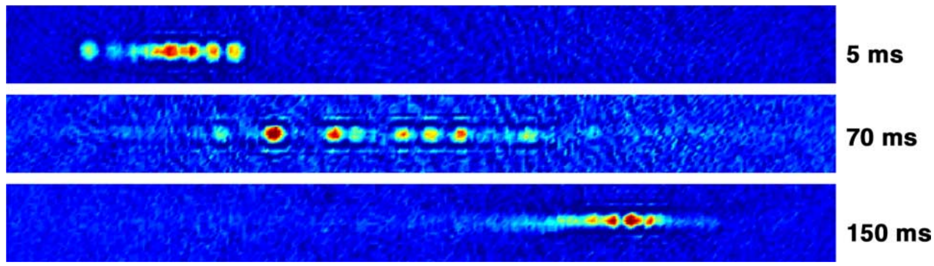

Fig. 3. Soliton trains undergoing an oscillation in the axial potential. The solitons are seen to bunch at the turning points and spread out in the middle of the oscillation, suggesting repulsive soliton–soliton interactions. The number of observed solitons varies shot to shot due to fluctuations in the initial number of atoms and a slow loss of signal with time.

decouples from the center of mass motion, and the solitons are left to evolve in time. Fig. 4 shows the theoretical results with a solid line, while the data are shown by solid circles. The experiment and the theory are in good agreement. An explanation of the information of soliton trains is suggested by the presence of the alternating phase structure. Upon changing the scattering length from positive to negative, the condensate becomes unstable to the growth of perturbations at a particular wavelength. The only length scale is the "healing length", $\xi = (1/8\pi n|a|)^{\frac{1}{2}}$, where n is the atomic density. The healing length is the characteristic length scale of a vortex in a superfluid. Initially the phase is constant across the condensate, but as the sign of the scattering length is switched, a mode with wavelength ξ becomes unstable, perhaps initiated by quantum mechanical fluctuations, and imprints the condensate with the alternating phase structure (Khawaja et al., 2002).

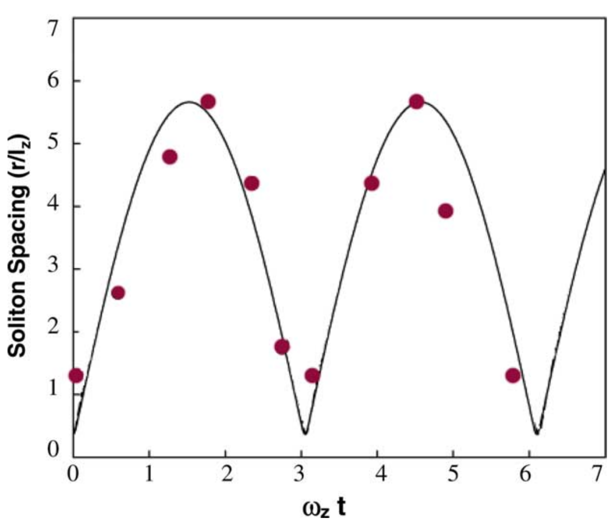

Fig. 4. The relative spacing between solitons in the trap. The solid line is a calculation of the equations of motion for two solitons in the trap using the nonlinear Schrödinger equation and assuming a π phase difference between solitons (Khawaja et al., 2002). The vertical axis is soliton separation (r) in units of the axial trap length, and the horizontal axis is time in units of the axial harmonic frequency times 2π. The solid points are data chosen by looking at the separation of the brightest two adjacent solitons.

A numerical simulation was able to produce up to seven solitons with alternating phases. Although simplified, the simulation is successful in reproducing the observed phase structure. The model suggests that the number of solitons produced should vary with the initial size on the condensate. To further test this theory, we attempted to change the initial size of the condensate before changing the sign of the scattering length. The same experimental procedure as above was followed except that the removal of the endcaps was delayed a time Δt before the sign of the scattering length was changed. This allows the condensate some time. Δt, to expand before the solitons are formed. Fig. 5 shows the number of solitons formed increases linearly with Δt.

A similar experiment was preformed in Paris (Khaykovich et al., 2002). In that experiment only single solitons, rather than trains, were observed. This difference in observation may be explained by two primary differences in the experiments: (1) the axial potential was anti-trapping and (2) the numbers of atoms in the initial condensate was an order of magnitude fewer.

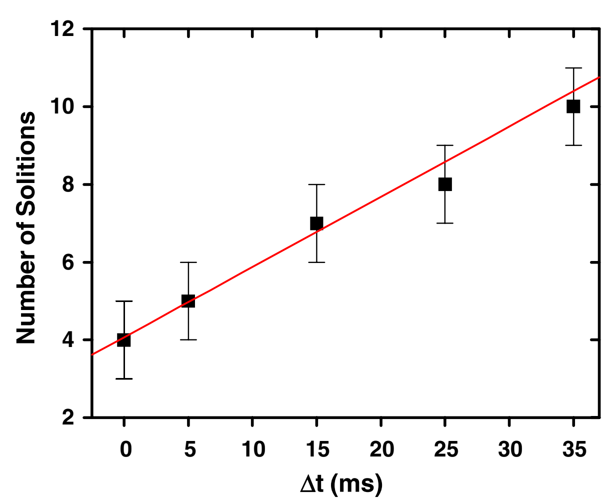

Fig. 5. Number of solitons produced as the release time, Δt, from the endcaps is varied. The data was recorded by varying Δt and waiting a fixed time before imaging the atoms. The error bars are due to uncertainty in identifying every soliton produced.

The key to these experiments is the ability to tune the atom–atom interactions smoothly from positive to negative. This interaction "knob" has opened a new door for studying BEC with attractive interactions. Not only can we now study solitons, and soliton interactions, but these solitons could be the basis for an atomic soliton laser, which may revolutionize precision measurements in devices such as inertial and rotational sensors based on atom interferometers.

References

Bradley, C.C., Sackett, C.A., Hulet, R.G. Bose–Einstein condensation of Lithium: observation of limited condensate number. Phys. Rev. Lett. 78, 985–989, 1997.

Dalfovo, F., Giorgini, S., Pitaevskii, L.P., Stringari, S. Theory of Bose–Einstein condensation in trapped gases. Rev. Mod. Phys. 71, 463–512, 1999.

Gerton, J.M., Strekalov, D., Prodan, I., Hulet, R.G. Direct observation of growth and collapse of a Bose–Einstein condensate with attractive interactions. Nature 408, 692–695, 2000.

Inouye, S. et al. Observation of Feshbach resonances in a Bose–Einstein condensate. Nature 392, 151–154, 1998.

Khawaja, U.A., Stoof, H.T.C., Hulet, R.G, Strecker, K.E., Partridge, G.B., Bright soliton trains of trapped Bose–Einstein condensates, Phys. Rev. Lett. 89, 200404-1–200404-4, 2002.

Khaykovich, L., Schreck, F., Ferrari, G., Bourdel, T., Cubizolles, J., Carr, L.D., Castin, Y., Salomon, C. Formation of a matter–wave bright soliton. Science 296, 1290–1293, 2002.

McAlexander, W.I., Collisional interactions in an ultracold lithium gas, PhD Thesis, Houston, Rice University, 2000.

Pérez-García, V., Michinel, H., Herrero, H. Bose–Einstein solitons in highly asymmetric traps. Phys. Rev. A 57, 3837–3842, 1998.

Reinhardt, W.P., Clark, C.W. Soliton dynamics in the collisions of Bose–Einstein condensates: an analog of the Josephson effect. J. Phys. B 30, L785–L789, 1997.

Sackett, C.A., Gerton, J.M., Welling, M., Hulet, R.G. Measurement of collective collapse in a Bose–Einstein condensate with attractive interactions. Phys. Rev. Lett. 82, 876–879, 1999.

Salasnich, L., Parola, A., Reatto, L., Condensate bright solitons under transverse confinement, Phys. Rev. A 66, 043603-1–043603-7, 2002.

Strecker, K.E., Partridge, G.B., Truscott, A.G., Hulet, R.G.. Nature 417, 150–153, 2002.

Tiesinga, E., Verhaar, B.J., Stoof, H.T.C. Threshhold and resonance phenomena in ultracold ground-state collisions. Phys. Rev. A 47, 4114–4122, 1993.

Truscott, A.G., Strecker, K.E., McAlexander, W.I., Partridge, G.B., Hulet, R.G. Observation of Fermi pressure in a gas of trapped atoms. Science 291, 2570–2571, 2001.