Observation of Hybrid Soliton Vortex-Ring Structures in Bose-Einstein Condensates

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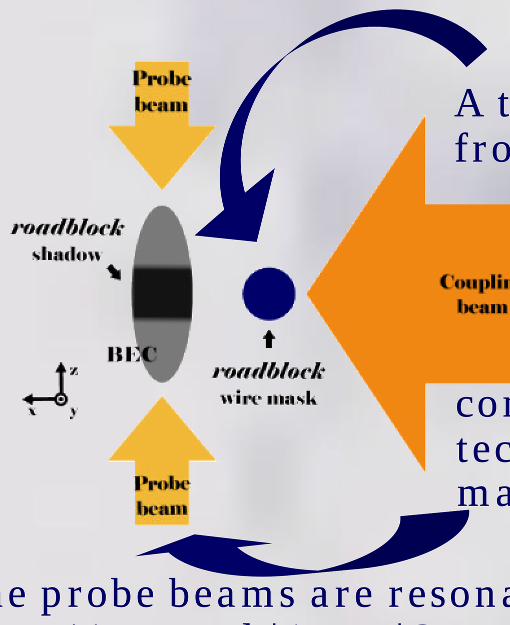
A New Class of Nonlinear Excitations

- We report the first observation of complex hybrid structures comprising solitons and vortex rings in a BEC
- Solitons and vortex rings initially collide to form the hybrid structures that evolve in their own right
- We show how the dynamics of the structures diverge from those of non-interacting nonlinear excitations

Making Hybrid Structures

- In previous work [Ref. 1], we studied grey solitons and vortices generated from quantum shock waves by creating a single, narrow density defect in a BEC
- We presently optimize the likelihood of collisions between these excitations by creating ***two*** defects symmetrically placed about the center of the BEC

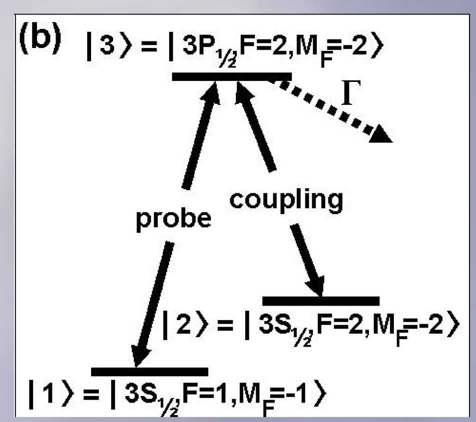
Double-Light Roadblock



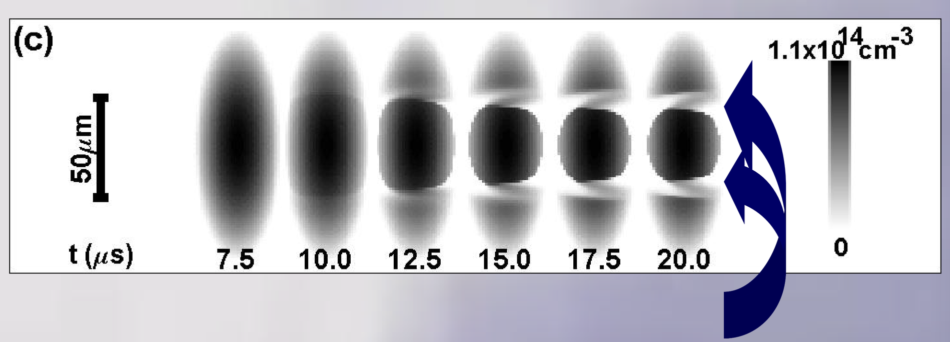
A thin wire blocks the 'coupling' beam from illuminating the center of a magnetically trapped BEC.

We then inject two counter-propagating 'probe' pulses, which compress spatially via our slow-light technique [Ref. 2] by several orders of magnitude to fit within the BEC.

The probe beams are resonant with the atoms' internal |1> to |3> transition while the coupling beam is resonant with the |2> to |3> transition, as shown to the right.



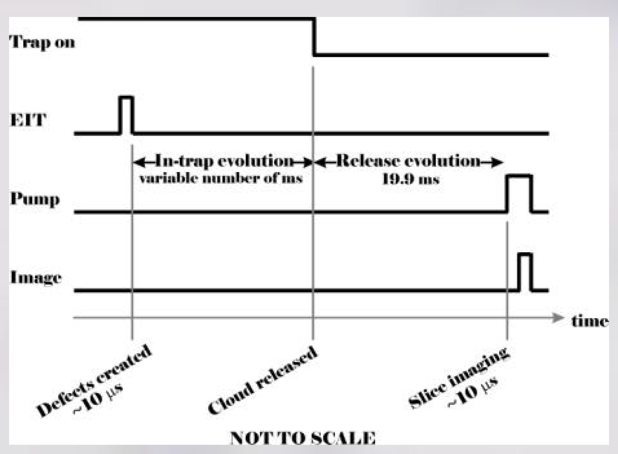
When the pulses arrive at the wire's shadow, their propagation is effectively arrested and they are further compressed.



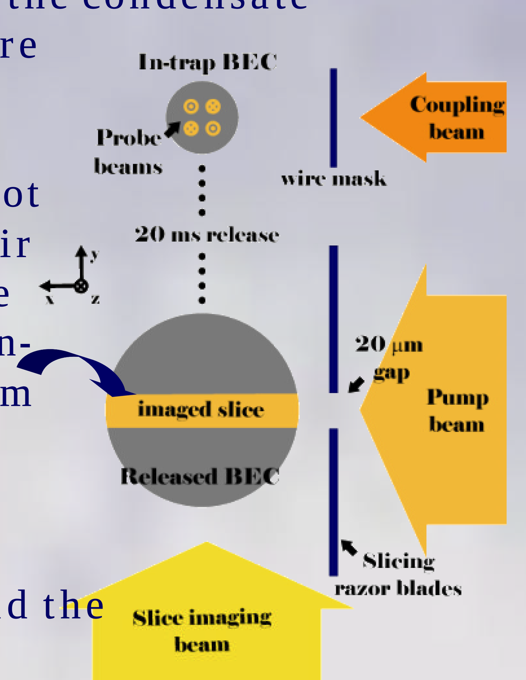
This results in two deep, narrow density defects symmetric about the BEC's center. Atoms at the halted pulses' locations are ejected, having first been transferred from initial state, |1>, to the untrapped |2> via a slow-light induced dark state. This is shown is the adjacent simulation.

Evolving and Imaging the BEC

After creating the defects, we vary the duration of BEC evolution in the trap and then release the BEC and let it expand for a fixed duration.



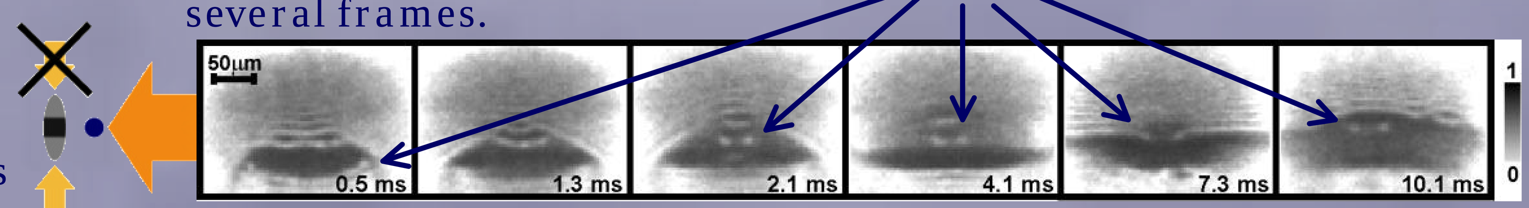
At this point the condensate excitations are highly three-dimensional. In order to not wash out their structure, we image the central 20-30 mm slab of the expanded cloud by first pumping only those atoms to a second internal state.



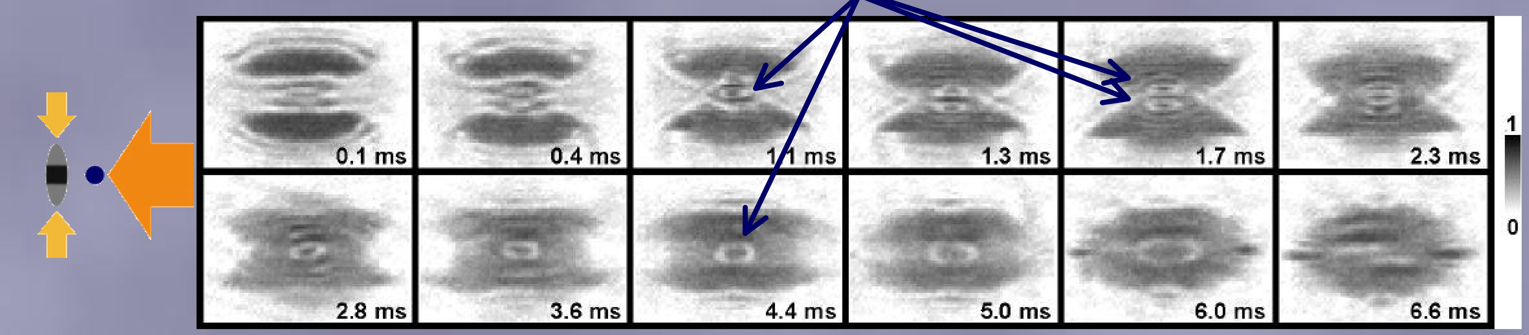
By varying this 'slice' position, we also found the general structure of the excited BEC to be cylindrically symmetric.

Experimental Data

- We took resonant transmission images of the excitations created at both single-, and double-roadblocks.
- The single-defect case generates solitons (pale stripes) that ultimately decay into vortex rings via the 'snake' instability: the soliton fronts are unstable in dimensions higher than 1D and kink until they break apart into vortex rings, as we first saw in [Ref. 1].
- In the 'slices' shown, one can see the cores of such vortex rings in several frames.



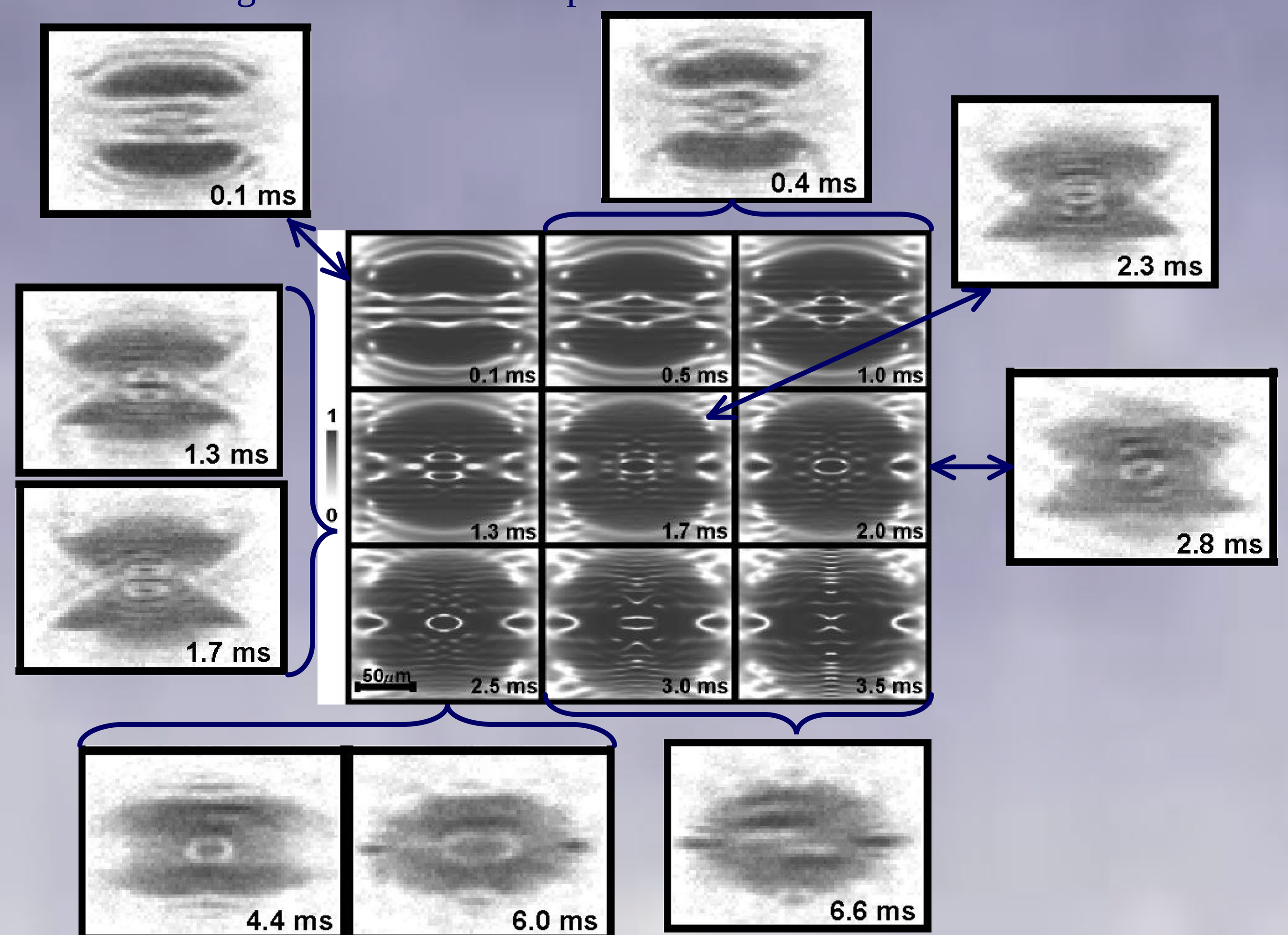
- However, in the double-defect case, the white loops in the 'slices' represent roughly ellipsoidal *shells* of low density within the BEC.



- A careful comparison of the single- and double-defect cases allows us to determine that the shells in the latter comprise vortex rings and soliton fragments.
- These are created due to combinations of soliton kinking, soliton-soliton collisions, and soliton-vortex ring collisions.
- The interaction of these excitations and the decreasing density of the BEC, as it expands, act to restabilize the solitons and preserve their fragments.
- The dynamics of the compound structures are primarily determined by the velocity flow fields of their constituent vortex rings.
- The single shell depicted along the bottom row of the data series is shown to be stable but eventually shears and comes apart at the sides. This is a result of a vortex ring collision and annihilation.
- The entire dynamical series is extremely robust and highly reproducible.

Simulation Data

- We have performed simulations of our experiment based on a generalized Gross-Pitaevskii equation, beginning with the double-light roadblock, from which we confirm the nature of the hybrid excitations.
- Each image shown depicts the transmission through a 'slice' of a BEC that has evolved for the indicated amount of time in the trap before being released and expanded for 14 ms.

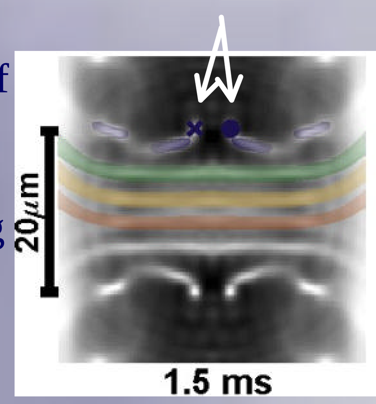


- The similarity of the theoretical results with the experimental data is remarkable. As an aid, the experimental images corresponding to the theoretical ones are indicated with arrows and braces.
- The last stage of the simulation is performed in cylindrical symmetry, therefore the low density shell is restricted to a symmetrical break-up, unlike in the experiment.

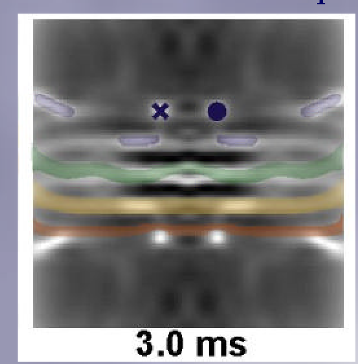
Simulation of Expansion Evolution

- The simulations provide us with the history of observed structures that must be expanded to be optically resolved.
- As an example, the simulated release dynamics for a BEC that has evolved in the trap 3.0 ms after double-defect creation is shown on the plots below. Duration of expansion is indicated on the images.

A. Already after 1.5 ms of expansion, a number of solitons have formed. The solitons propagating in the –z direction (downward) have been tinted in order to more easily track them from frame to frame. There are also mirror images of these propagating in the opposite direction that have not been tinted. The solitons have been shed from a quantum shock wave traveling in the same direction, therefore the order of soliton creation (and depth) is blue, green, yellow, and red.

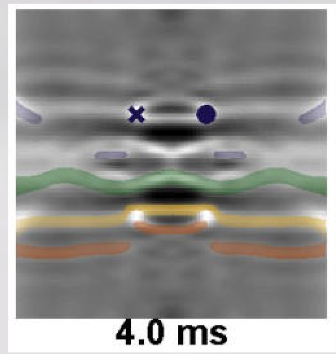


B. Since the blue soliton is the first created, deepest, and as a result the slowest traveling, its center decays into a vortex ring whose cores are labeled by a dot and cross.

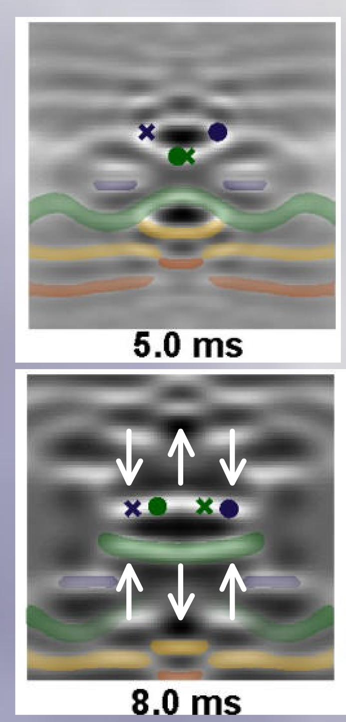


C. Both of the frames at 1.5 ms and 3.0 ms display solitons propagating across the center line of the BEC. Those with opposite propagation directions sometimes overlap.

D. At 4.0 ms, as the third and fourth created solitons (yellow and red) reach the newly formed vortex rings on the side opposite whence they originated, pairs of low density shells form. Since the secondly created solitons (green) are slower and deeper, they kink and their midpoints bend toward one another as they cross the center of the BEC.

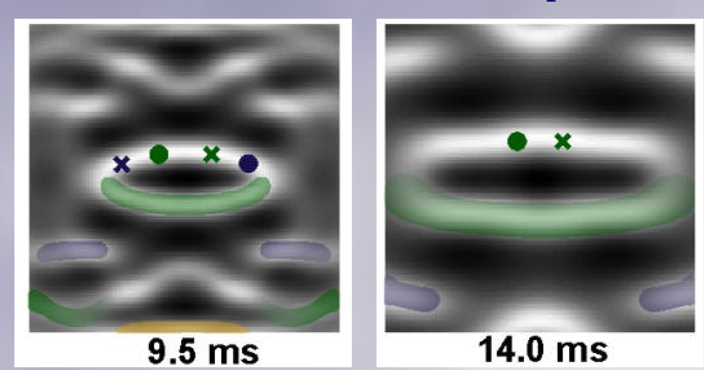


E. By 5.0 ms, these green fronts have reached the already-created vortex rings, forming, with the yellow solitons, pairs of low density shells. The central portions of the green solitons kink further, producing within themselves two smaller vortex rings (green dot and cross shown on top only) with opposite circulation from the larger ones. These vortex cores can be identified from the phase of the wavefunction.



F. These truly hybrid low density structures, consisting of parent soliton segments and vortex rings, 'dislocate' from the rest of the soliton fronts. They each comprise two concentric vortex rings embedded in a roughly hemispherical solitonic shell.

G. Like an umbrella turning inside-out, the curvature of these hybrid structures reverses through 8.0 ms, as the inner rings propel themselves away from one another and the outer rings propel toward the center line. C.f. the experiment at 2.3 ms in-trap evolution time.



H. As the outer vortex rings propagate toward each other, a stable closed shell forms from the two green hybrid segments (9.5 ms). It is an ellipsoidal solitonic shell incorporating four vortex rings of alternating circulation that encircle the structure like lines of constant latitude on a globe.

I. The outer rings eventually annihilate (circulation at blue cores disappears), and the two segments that formed the central shell lose their curvature and begin to break apart at the sides.

References

1. *Observation of Quantum Shock Waves Created with Ultra-Compressed Slow Light Pulses in a Bose-Einstein Condensate.* Zachary Dutton, Michael Budde, Christopher Slowe, and Lene Vestergaard Hau. *Science* **293**, 663 (2001), and Science Express, June 28 2001 (<zdoi;10.1126/science.1062527>).
2. *Light speed reduction to 17 metres per second in an ultracold atomic gas.* Lene Vestergaard Hau, S. E. Harris, Zachary Dutton and Cyrus H. Behroozi. *Nature* **397**, 594 (1999).