Journey of Solitary Waves in Quantum World

Gunjan Verma
Indian Institute of Science Education and Research, Pune
Email: 89gunjan@gmail.com

Most of us while playing with the sand, tend to make fascinating structures with it be it magnificent castles, caves or mountains. Despite knowing that these structures are not eternal and bound to collapse either by the sea waves rolling over the shores or by the slight touch of our mischievous friend, most of us would still desire to see our creation sustain forever. In 1834, John Scott Russell, an engineer and naval architect was the first man to witness such a fantastic piece of nature (a special kind of water waves), now called solitary waves which try to sustain themselves indefinitely. Solitary waves are way different and unique in their properties than the waves we encounter in our day to day life. Once generated, unlike ordinary waves, these waves try to maintain their shape being unperturbed by any disturbances in the surrounding. When two of such waves collide, each one of them passes through each other without feeling the presence of one another, keeping their identity intact.

You must be thinking what makes these waves magically so robust? To answer this, let's imagine the moment when we drop a pebble in a still pond. It generates a wave which travels as an expanding circular ring on the water and fades as it moves away from the source and eventually dies out. This water wave can be thought of as it is made up of many small waves where each of this wave tends to travel with different speed. Thus, some of these tiny waves would move fast, and some would move slow making the overall shape of the wave (initially generated) to change and continuously spread over the larger area while propagating. This phenomenon is called dispersion.

---

* Ms. Gunjan Verma, Ph.D. Scholar from Indian Institute of Science Education and Research, Pune, is pursuing her research on "Dynamics of Bose-Einstein Condensate in Linear and Nonlinear Regime." Her popular science story entitled "Journey of Solitary Waves in Quantum World" has been selected for AWSAR Award.

Spreading of the wave eventually causes it to die and disappear. Now if somehow the speed of these small waves can be adjusted appropriately such that the waves which tend to move slow and lag behind are pushed forward while the waves which tend to travel faster are slowed down, the overall shape of the initial wave can be preserved forever. When water (medium) acquire such powers to modify the speed of small waves in it, it is called as a nonlinear system. Thus when nonlinearity balances the dispersive behaviour, robust solitary waves are formed.

These waves not only exist in water but found to exists in a variety of systems starting from tiny cells of living beings to optical fibers (cables used to transfer light signal from one place to another) to massive and huge rotating neutron stars etc. These waves proved to be of enormous importance in our today's multi-billionaire telecommunications industry where the information through the optical fibers is sent as light pulses in the form of a solitary wave which helps to keep the information intact. On the other side, these solitary waves bear the understanding of much-feared tidal waves (Tsunamis) in oceans, signal propagation in neurons and formation of majestic phenomena such as Morning Glory Cloud (hundreds of km long cloud wave) etc. As these structures were found to exist in various domains and proved to be of great worth, scientist wondered about there existence in the quantum world too. Indeed, these solitary waves were found to exists in the much fascinating quantum world, and I joined the excitement of the scientific field and conducted my PhD research to understand their behaviour in the quantum world. You must be thinking what a quantum world is? Is it different than the world we live in?

We know that everything in this universe is made up of atoms and atoms are so tiny that we can't see them individually with our naked eyes. Whatever entity we see all around us is generally made up of a vast number of atoms. We call this as the classical world, but when we observe thing close to the level of individual atoms, we approach the quantum world, and these two worlds are very different from each other! To give an example, in a classical world if we throw some balls on a wall, the balls are supposed to bounce back. Also, if we can measure the ball's initial position, speed and at what angle we are throwing the ball, using the rules of classical mechanics we can very well predict the complete fate of the ball such as where it is going to land finally. But for the same case, in the quantum world, we can never precisely tell where the ball is going to land beforehand and can only tell what is the probability of it in landing at a certain place. Also, in the quantum world, there will always be a finite probability that some of the balls would tunnel or pass through the wall to the other side which is entirely counter-intuitive to the behaviour seen in the classical world.

Truly speaking quantum world is weird and very non-intuitive but today it is a well-established fact that the strange rules of quantum mechanics govern the movement and behaviour of every single particle in our universe. The question arises why don't we see these effects in our day to day life? According to the laws of quantum mechanics, every particle possesses both wave and particle-like properties. This is called wave-particle duality. One cannot determine the particle's position and its momentum (velocity) at the same time. The better we know the precise location of the particle, the less we know about its momentum (velocity) and vice versa. This is called uncertainty principle. Individually every particle in this universe is bound to show these quantum mechanical properties, however when a large no. of particles come together in a system; they tend to behave incoherently, suppressing their unusual quantum features and leading to the reality of our classical world.

As it is challenging to isolate a single particle and observe the quantum world and this raises the question of whether we create a quantum world with a large number of particles or not? Yes! Indeed we can. If we can make the large number of particles in a system to behave coherently such that every particle mimics the behaviour of every other particle in the system, allowing it to look like a single giant atom, it can result in a quantum world. In fact, as a part of my PhD work, we regularly created such a quantum world in our lab which is called Bose-Einstein Condensate (BEC). We form Bose-Einstein condensate by cooling a gas of few thousand atoms (bosons) to a temperature of about 100 billion times lower than the temperature of ice in your fridge. Einstein predicted the idea of this quantum world or quantum system in 1925, based on the calculation of our very own Indian scientist Satyendra Nath Bose. We build our own cooling machine with the help of Lasers and Magnetic fields. It took almost 75 years for scientists to first demonstrate such a working cooling machine since the prediction of BEC which later also fetched two Nobel Prize in 1997 and 2001.

Once we generate the quantum world which is about 100,000 times larger than the biggest atoms in the universe in our lab, we look at the behaviour of solitary waves in it. Solitary waves are of many different types, and we study one of its kind in the condensate, called dark solitary waves. Usually, waves in water are seen as a bump or heap on water, but dark solitary waves are peculiar as they look like a depression (absence of particles) in the medium (water or condensate). In my numerical calculations, I found dark solitary waves sustain only if the quantum world (BEC) is shaped like a thread and if we shape the quantum world like a sheet or a ball, the waves become unstable. Once the waves become unstable, they start to bend like a snake and finally break into a chain of vortices (like hollow cores). We notice, these hollow cores wander in the quantum world and collide with each other where they burst into ordinary waves finally disappearing in time. This behaviour is not observed in classical systems. While studying these waves, we also figured out a new way to generate these waves in the condensate. Our findings contribute towards the understanding of solitons in the less known quantum world. We expect in the long run such contribution will help us to build the complete picture of solitary waves which in turn would allow us to harness their full potential. In future, we would implement these theoretical findings in our experimentally created quantum world!

This article is based on my published research papers as mentioned below.

Title: Generation of dark solitons and their instability dynamics in two-dimensional condensates (Physical Review A, Vol 95, Issue 4, Page 043618)

Title: Bose-Einstein condensation in an electro-pneumatically transformed quadrupole-Ioffe magnetic trap (New Journal of Physics, Vol 17, Page 023062)

Title: A compact atomic beam based system for Doppler-free laser spectroscopy of strontium atoms (Review of Scientific Instruments, vol 88, page 033103)