ULTRACOLD UB

Ultracold gases and Bose-Einstein Condensates

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INTRODUCTION

The present report aims to gather all the work done during the Physics Degree subject *Pràctiques en empresa* during the autumn semester of 2016-2017, and being supervised by Bruno Juliá and Antonio Muñoz. Its theoretical background lays on Bose-Einstein condensates and ultracold gases, mostly focused on the study of solitons. The practical part, which involved most of the time of the work, consisted in the creation and development of an application aimed at the scientific divulgation of solitons and their behaviour under some given external potentials. The work is based on the previous studies carried out by a group of both teachers and students from the *Universitat de Barcelona* during the summer of 2016.

Through the months, different work has been done. It could all be summarized in three separated parts:

(i) Introduction and understanding of the project's background

(ii) Creation and development of the interface

(iii) Documentation

In this report we will be focusing on those three large blocks, explaining all the needed background for further sections in the first chapter and then showing how the project evolved from the beginnig to its current state. It all began being a program run from a terminal and it has ended up being an attractive tool to be used for science popularization, which includes multiple games for the users to understand better the underlying physics. To end with, it will include a chapter dedicated to the documentation done for the project and its future readers and/or users.

My participation in this project, Ultracold UB, is not the only one. Some students, both graduated and undergraduated students have worked on it previously, and hopefully someone will still continue with this project as this one is a first version of a project that can become even more complex with time.

Even being a cooperative and opened work as previously said, it has been mostly based on an autonomous work carried out every day at home and with a certain regularity and then once per week presenting our results or progress in a meeting with the supervisors. It all led to an overall work of 310 hours.

1 Theoretical Introduction

We will be focusing here on the physical background of the project Ultracold UB. Starting from the Bose Einstein codensates and then introducing the Schrödinger equation from which we will evolve to the Gross-Pitaevskii equation, showing the changes introduced and the differences between both of them. Finally, we will dedicate a part to introduce a particular and exact solution of the Gross-Pitaevskii equation: the bright solitons, being those the main point of study of the work developed.

1.1 Bose-Einstein condensate

A Bose-Einstein condensate (BEC from now on) is a state of matter that can be achieved by a dilute gas of bosons when they are cooled to very low temperatures, i.e. really close to the absolute zero. At such temperature and given that the bosons are confined in a region (by means of an external field) the particles try to occupy a state of minimum energy and most of them occupy the lowest-energy state, also named ground state. In such conditions, the atoms become indistinguishable and they can also be represented by a wave. When cooling even more we will find that the atoms are almost at rest and the wavelength of those atoms gets larger, and at a given point, the waves of the different atoms overlap one each other, and they end up behaving as a huge and single particle, instead of a group of atoms.

We must emphasize that this phenomenon only happens in bosons, that is particles with integer spin. Remember that there are two kind of particles: fermions and bosons. The first ones, fermions, are particles having half-integer spin, and they are ruled by Pauli's exclusion principle, that states that two fermions cannot occupy a same quantum state. Nevertheless, we do also have bosons, that as we previously said, are particles with integer spin; in contrast to fermions, those particles have no restrains about occupying a same quantum state, and so as we said that the BEC occurs when a lot of particles occupy the same state at very low temperatures, we can see now that it can only be possible with bosons.

1.2 Schrödinger equation

As well as in classical mechanics we have Newton's laws to describe the dynamics of particles, in quantum mechanics we do have also an important equation that tells us about the evolution of a given system, such equation is the Schrödinger equation.

We should first start by remembering that any particle in the quantum world can be well-described by a wave, represented by a wavefunction Ψ. Thus we can study the evolution of a system in time as follows:

$$i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi(\vec{r},t) + V(x)\Psi(\vec{r},t) \tag{1}$$

where on the lefthand side we find the partial derivative of the wavefunction respect to time, whereas on the righthand side we find a general Hamiltonian operator acting over the wavefunction.

1.3 Gross-Pitaevskii equation

When considering a BEC, the particles interact between them by means of a contact interaction potential, as follows:

$$V(\vec{r}-\vec{r}') = gN\delta(\vec{r}-\vec{r}') = \frac{4\pi\hbar^2}{m} a_s N\delta(\vec{r}-\vec{r}') \tag{2}$$

where a_s is the s-wave scattering length. This potential is a two-body interaction; as in many-body we would have a sum of all the interactions between the particles, the expression becomes more complex. To simplify the many-body problem we can start with a meanfield description. We consider that all the atoms populate the same single particle state and derive an averaged effect of the two-body interaction. The resulting equation governing the dynamics is the time dependent Gros-Pitaevskii equation:

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t} = \left(-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}x^2} + V(x) + gN|\Psi(x,t)|^2\right)\Psi(x,t) \tag{3}$$

where μ is the chemical potential; and expressed in units of harmonic oscillator. We can see here that this equation differs from the Schrödinger one due to the non-linear term arising from the interaction between particles.

Several approximations can be taken at this point. One of them is the Thomas-Fermi approach, which neglects the contribution of the kinetic energy. Nevertheless, we will be working with the whole expression to study the particular cases, the bright solitons.

1.4 Bright Solitons

The introduction of the non-linear term in the Schrödinger equation, obtaining the Gross-Pitaevskii (GP) equation, leads to the appearance of a wavepacket that is localized in space and that does not change its shape throughout its motion. Depending on the interaction between the atoms on the BEC, recall the g factor in the interaction term of GP equation, different solutions for the equation can be found. If the interaction between the atoms is repulsive the solutions that we will find are dark solitons; but if we consider attractive interaction, the solution we arrive to are the bright solitons.

2 Development

We will explain briefly here how the work began and how we developed the current interface. In fact, the most relevant part of the project was to know how to address it to a public which is not that much familiar with this field, mainly to 16-18 years old students. The approach we took to make them being interested and have a better understanding, as we will see in this section, was to create some simulations or analogies in the classical world, so they could compare both behaviours and see differences or similarities between them.

2.1 Understanding of the project's background

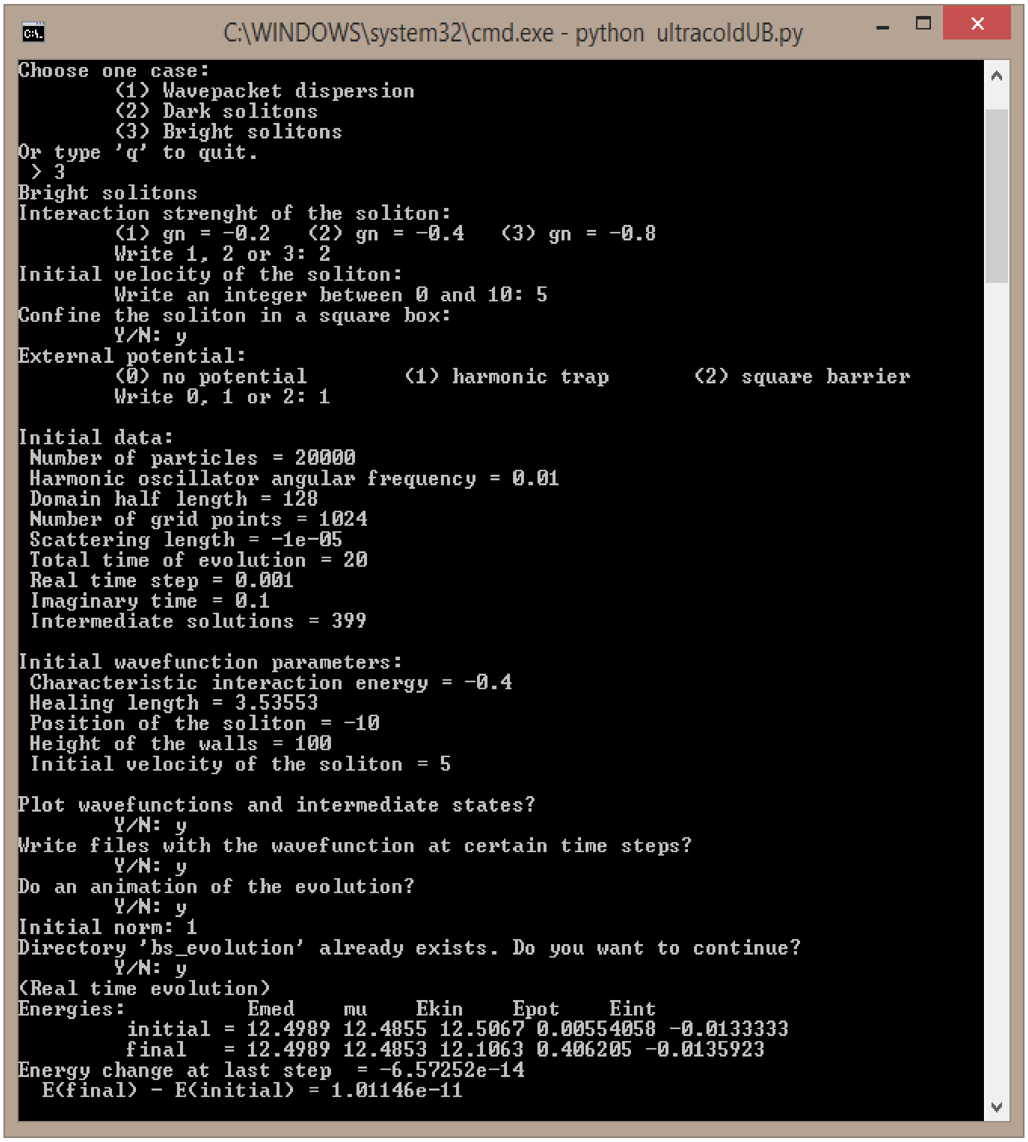
The first weeks were aimed to understand all the work done up to the moment. There was a previous work done during that summer by Maria Arazo, Alejandro Romero and Ivan Morera, which has been the base of all the work done later on. Its aim was to solve the Gross-Pitaevskii equation for different cases of interaction and under different external potentials. I was focusing on the bright solitons part, and so the first step was to understand how the model was implemented and solved. By reading bibliography about BEC and bright solitons in particular, I got to know the parameters used in the characterization of such solitons as well as what they were, as I had not heard about them until that moment. For what concerns the methods used for solving the equations, it has been used the Fast Fourier Transform (FFT) solver and basically the Split-Step Method, in order to solve the non-linear Schrödinger equation, i.e. GP equation.

2.2 Creation of the interface

At the begining of the project, the UltracoldUB program was basically a command prompt where the user had to introduce the desired parameters (see Figure 1).

From here, several figures opened up in separate windows, enabling us to see how the soliton evolved in time under the conditions we preovioulsy introduced. So, the base of the program was already made, but the problem was its appereance. If we wanted it to be a good tool for scientific divulgation among other students, and even more, among younger students, it had to be much more visually attractive, otherwise its physical background might not get people's interest or it could be not well-understood due to the lack of information on the graphics (no text to explain what they could see there at all). So our objective then was to create a graphical user interface (GUI) in order to gather there all what we had, and include more things that we would develop during our project.

The first we had to do was to learn how to create a GUI. With the help of tutorials, we got to know that PyQt, a tool of Python to create interfaces, was exactly what we wanted. PyQt is a powerful tool for what concerns creating GUIs and it is not difficult to use. Moreover, it enables the creator of the GUI to see almost instantly the work done and how it will be seen once it is run by an external user. So from here, the point was to start by creating the three separate modules in which consisted the previous program. For the bright solitons module, at first it only contained the basis of the original program, and even more, none of the output graphics. We first created the structure of the module: include the different options that the user could chose (e.g. external potential, initial conditions, etc), and then we uploaded and linked each action with the corresponding code to create the output graphics.



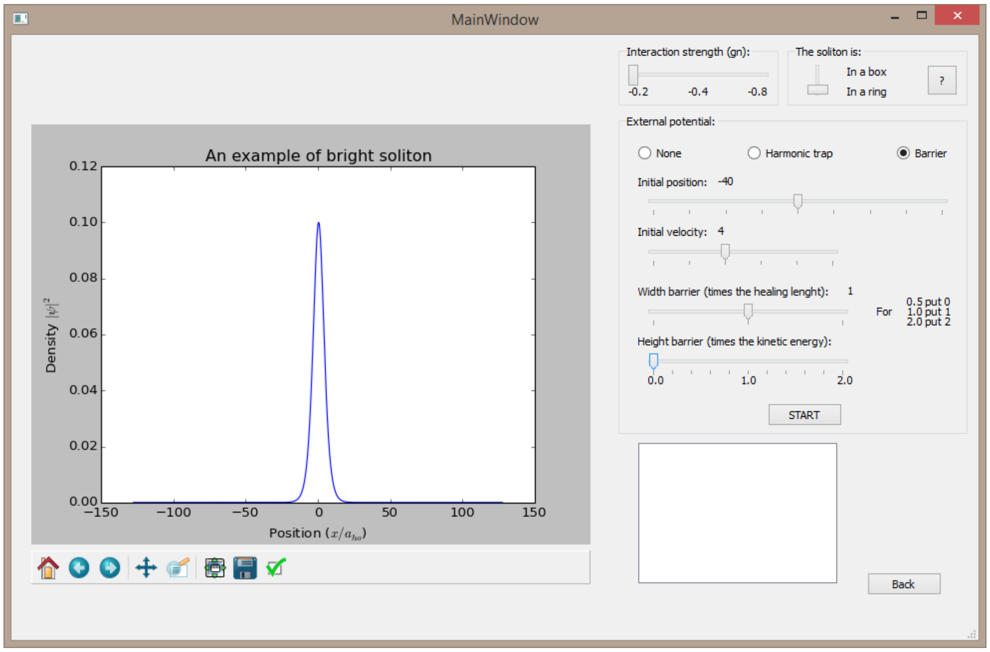
```
Choose one case:
        (1) Wavepacket dispersion
        (2) Dark solitons
        (3) Bright solitons
Or type 'q' to quit.
 > 3
Bright solitons
Interaction strenght of the soliton:
        (1) gn = -0.2   (2) gn = -0.4   (3) gn = -0.8
        Write 1, 2 or 3: 2
Initial velocity of the soliton:
        Write an integer between 0 and 10: 5
Confine the soliton in a square box:
        Y/N: y
External potential:
        (0) no potential        (1) harmonic trap       (2) square barrier
        Write 0, 1 or 2: 1

Initial data:
 Number of particles = 20000
 Harmonic oscillator angular frequency = 0.01
 Domain half length = 128
 Number of grid points = 1024
 Scattering length = -1e-05
 Total time of evolution = 20
 Real time step = 0.001
 Imaginary time = 0.1
 Intermediate solutions = 399

Initial wavefunction parameters:
 Characteristic interaction energy = -0.4
 Healing length = 3.53553
 Position of the soliton = -10
 Height of the walls = 100
 Initial velocity of the soliton = 5

Plot wavefunctions and intermediate states?
        Y/N: y
Write files with the wavefunction at certain time steps?
        Y/N: y
Do an animation of the evolution?
        Y/N: y
Initial norm: 1
Directory 'bs_evolution' already exists. Do you want to continue?
        Y/N: y
(Real time evolution)
Energies:          Emed     mu     Ekin     Epot     Eint
         initial = 12.4989 12.4855 12.5067 0.00554058 -0.0133333
         final   = 12.4989 12.4853 12.1063 0.406205 -0.0135923
Energy change at last step  = -6.57252e-14
  E(final) - E(initial) = 1.01146e-11
```

Figure 1: Screenshot of the original program ran for a bright soliton case.



○ None ○ Harmonic trap ● Barrier

Initial position: -40

Initial velocity: 4

Width barrier (times the healing lenght): 1

For 0.5 put 0
1.0 put 1
2.0 put 2

Height barrier (times the kinetic energy):

Figure 2: Screenshot of the first attempt of interface for a bright soliton case.

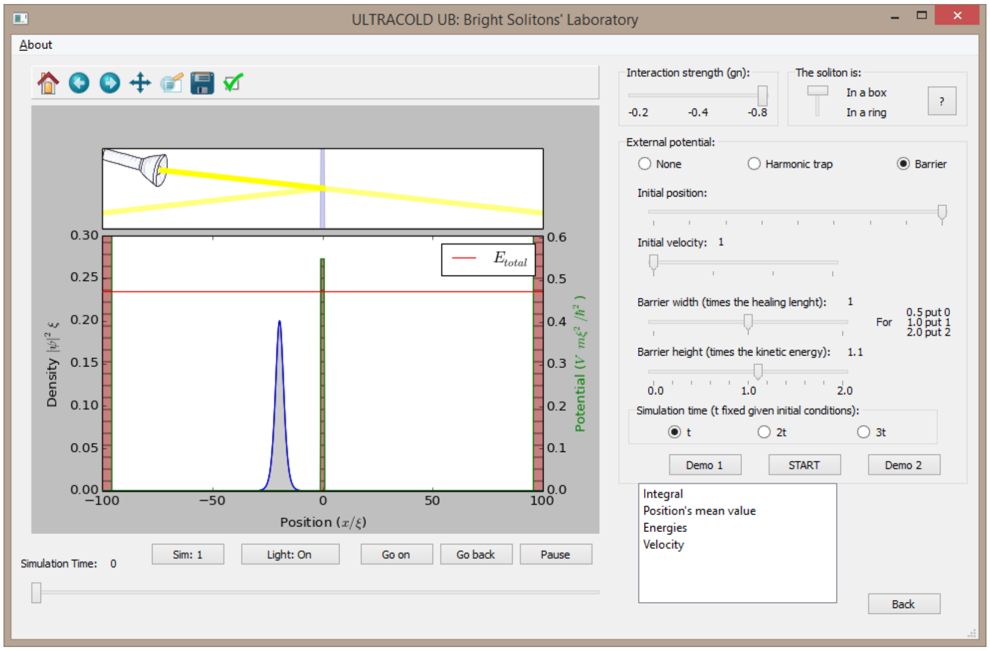
2.3 Further development of the interface

Once all the original program was moved into a graphical interface, we started creating tools for the divulgation and understanding of the subject underlying the project. PyQt was very versatile, for instance we could create animated simulations, so the user could see the evolution not only on the static plots (e.g. $x(t)$) but also the evolution as if it was a movie of the movement itself. Here, one could perfectly see the harmonic motion of a bright soliton due to the harmonic trap it was under, and compare how it was the same motion one could see when playing with a pendulum.

As we said in this section's brief introduction, we decided that this project would be a powerful tool to spread ultrcold gases and quantum mechanics. The point was to make it available to a public which has not heard about it that much, that is pre-university stages of learning - more orientated to 16-18 years old students, who see mostly the classical physics at school. But the problem was the following: how to make them understand some of the quantum concepts, that we were taught at university, and may be difficult to understand at school? Well, it was then when the idea of small games and analogies to classical physics came to us.

One of the firsts things we included was a "game" for the user to understand the harmonic oscillator motion, i.e. to simulate the motion of a bright soliton under an harmonic trap by means of adjusting the coefficients (amplitude and frequency) on the equation of motion and see their input result instantly. This has proved afterwards to be very useful when actual students played with it, because most of them were currently learning that at school and according to them, it made them understand better what they were learning, and not just thinking of it as a pure maths problem.

Then, we moved onto more complex things to explain such as the quantum tunneling effect. Recalling our surprise when we were first told about it, we had to think of examples in real life which, far from being the same, had a slight resemblance to it. For this particular case of the tunneling effect, we made use of the relfection and refraction of light through a (crystal here) surface.



Interaction strength (gn):

The solitón is: In a box / In a ring

External potential: ○ None ○ Harmonic trap ● Barrier

Initial position:

Initial velocity: 1

Barrier width (times the healing lenght): 1

For 0.5 put 0, 1.0 put 1, 2.0 put 2

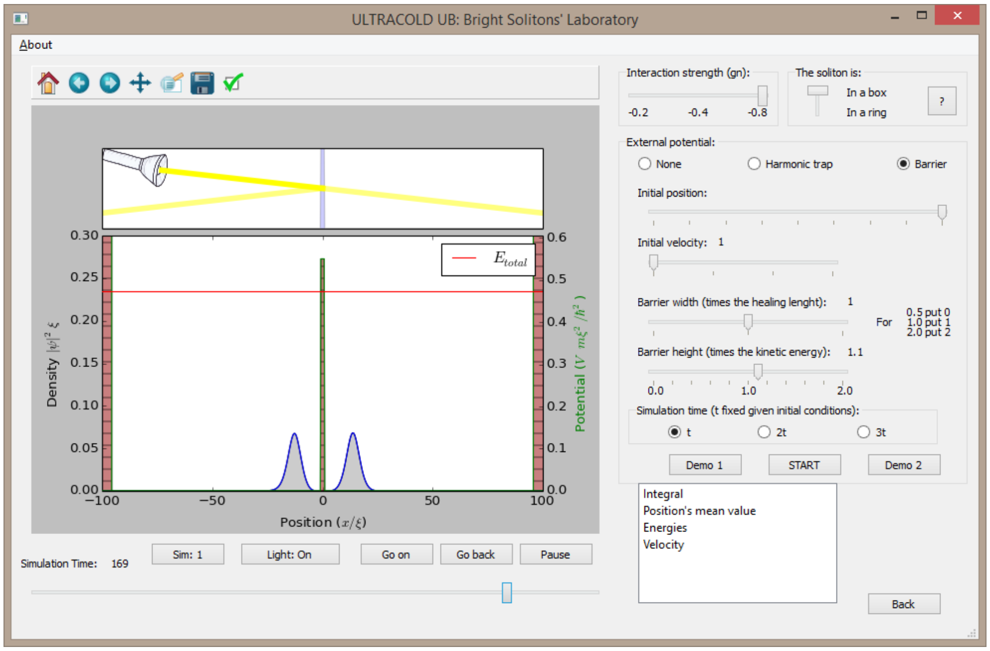
Barrier height (times the kinetic energy): 1.1

Simulation time (t fixed given initial conditions): ● t ○ 2t ○ 3t

Integral
Position's mean value
Energies
Velocity

Simulation Time: 0

Figure 3: Screenshot of the case of the tunneling effect for the bright soliton, at the initial time.



Interaction strength (gn):

The solitón is: In a box / In a ring

External potential: ○ None ○ Harmonic trap ● Barrier

Initial position:

Initial velocity: 1

Barrier width (times the healing lenght): 1

For 0.5 put 0, 1.0 put 1, 2.0 put 2

Barrier height (times the kinetic energy): 1.1

Simulation time (t fixed given initial conditions): ● t ○ 2t ○ 3t

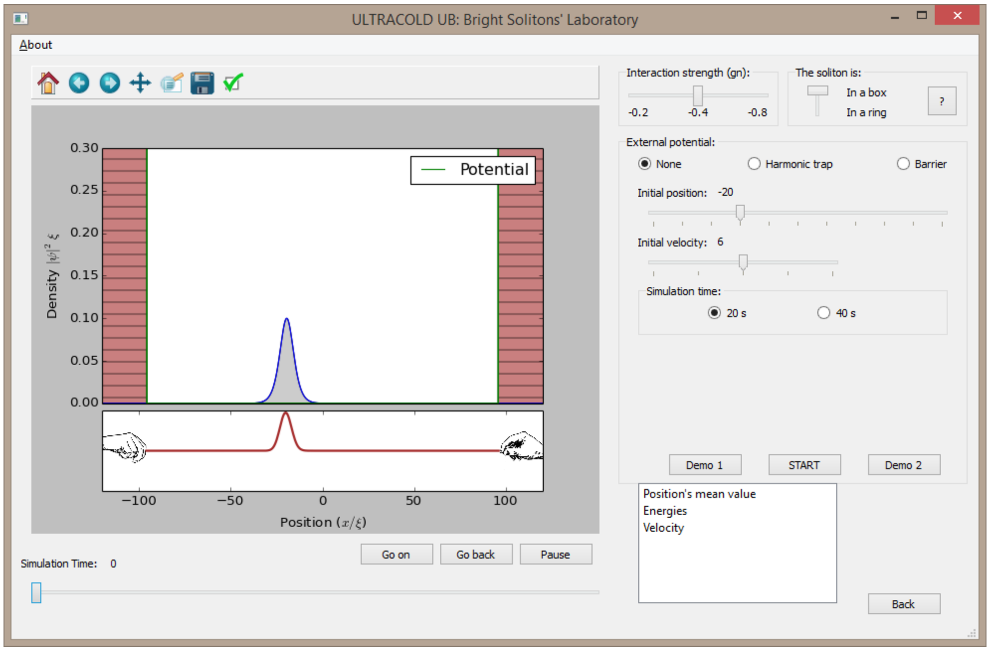
Integral
Position's mean value
Energies
Velocity

Simulation Time: 169

Figure 4: Screenshot of the case of the tunneling effect for the bright soliton, after crossing the barrier and splitting into two equal parts.

In this example the point was to divide the soliton into two equal parts; this could be achieved by studying the transmission and reflextion coefficients, T and R respectively, by computing the total probability of finding the soliton on each side of the barrier. With such coefficients, we could then draw the plot above the evolution plot, in order to see the amount of light that passed through the crystal surface and the one relfected by means of the opacity of the beam. The result for such simulation is shown in Figures 3 and 4.

Other analogies were aimed to understand a bright soliton moving freely on a box with fixed boundary conditions. In this case, we could see that the bright soliton moved as a pulse would do in a string. So we created a pulse on a string evolving in time so that the motion of the bright soliton and the pulse coincided at each moment. Despite being decribed by different wave-functions, one was a gaussian wavepacket and the other was a bright soliton, their resemblance was so accurate that it was a good analogy. In this case we had something like Figure 5.



External potential: ● None ○ Harmonic trap ○ Barrier

Initial position: -20

Initial velocity: 6

Simulation time: ● 20 s ○ 40 s

Position's mean value
Energies
Velocity

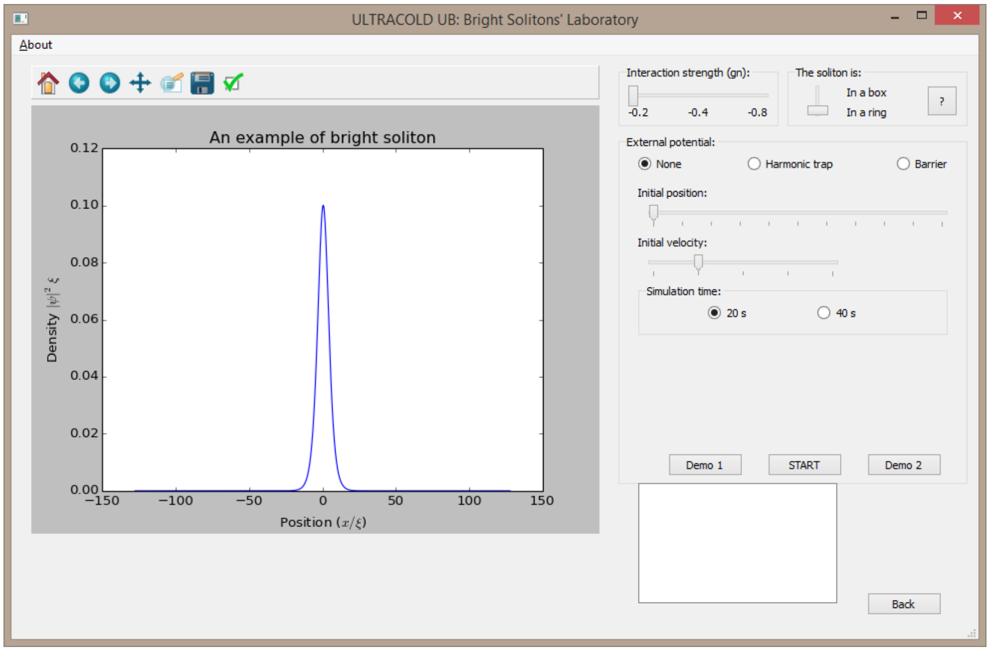
Simulation Time: 0

Figure 5: Screenshot of the case of the bright soliton moving freely in a box.

2.4 Detailed descrption of the bright soliton's module

In this section we will see in detail the module of bright solitons and what it includes. It must be said, though, that there are other two modules apart from the bright solitons one (wavepacket dispersion and dark solitons) and the first to be run by an external user should be the wavepacket dispersion, which includes an introduction to some basic concepts in quantum mechanics, such as the treatment of an entity by means of its wave-function. After this previous introdution, the user is free to choose which module to run, and we will here only focus on the bright solitons.

Once selecting this module, the user sees a screen like Figure 6. On the left of the screen there is a plot showing an example of a bright solitons. There it is represented the density against the position; recall that the bright soliton is represented by its wave-function $\psi(x)$, whose associated probability to be found at a point x is the normalized density $|\psi(x)|^2$. On the right there are the input parameters to be introduced by the user. First we see the interaction strength (g_n), which is negative as we are working with bright solitons and those are characterized by attractive interactions; if the interaction is small (-0.2) the soliton will look wider and smaller than the one in the example, but if the interaction increases on module (-0.8), the shape of the density function will be sharper and compacter.


External potential: ● None ○ Harmonic trap ○ Barrier

Simulation time: ● 20 s ○ 40 s

Figure 6: Screenshot of the main window of the bright soliton module.

On the right of the g_n box, the user can decide wether the soliton is moving inside a box or if it moves in the free space with periodic boundary conditions. The first option would imply fixed boundary conditions (the soliton would run against the box walls and then change the direction of its motion). The second one is like to let the soliton in a ring: if the soliton moves to the right, at some point when arriving to the right border, it would reappear on the left border but still moving to the right. In case those two conditions are not clear enough for the user, an external help (see "?" button) clarifies it.

Then, the external potential is selected by chosing one of the three possibilities, which will be seen in detail afterwards:

1. None: in this case, the soliton moves freely in space with no external perturbation.
2. Harmonic trap: the soliton will have an harmonic oscillator motion.
3. Barrier: the soliton collides against a barrier and depending on its energy, it may go through the barrier.

2.4.1 No external potential

As it has been said, in this case the soliton moves withouth the effect of any potential. Suppose that the soliton is left in a ring (periodic boundary conditions): the position will always increase linearly with time, and the velocity will be the slope of it. The slope will remain constant except for a sharp change when the soliton crosses the right border and appears on the left side again, and then it will continue with the same slope. Also, the velocity and the energy here will remain constant, as there are no external forces.

When considering though the case of the soliton in a box, some of these properties change. The position may present a peak during its evolution if the soliton hits the wal: suppose the soliton is first moving to its right so the position increases with time; then it hits the wall and starts moving to its left (which will be seen as a decreasing of position on time), so we will have a peak at the time the soliton is hitting against the wall. By chosing different times of simulation, the user could achieve several hits against both the right and left side of the box. In this case, as the walls are simulated with by a potential, when the soliton hits it, there is a change of the potential energy during this short period of time, and so the kinetic energy does also change. This is translated into a small perturbation on the energies during the hitting of the wall, and then the energies remain constant as they had been before. The most characteristic change here is the one of the velocity: as the soliton completely changes its direction of motion, the velocity changes too, so while hitting the wall there is a moment when it has null velocity and then it retakes its motion with -v_0, being v_0 its original velocity.

For this last case, the simulation of a pulse in a string was introduced for a better understanding. In this case, it has been considered fixed boundary conditions for the string, so the pulse would travel above at first and then would change its direction (and so velocity) and start moving below. In fact, the soliton would do the same when plotting not the density $|\psi|^2$ but the real part of the wave-function; so there is a clear analogy between those two cases.

As it can be seen, the only free parameters needed here were the initial position of the solitons and its initial velocity, and so those both are the ones that the user can enter by means of the sliders in Figure 6.

2.4.2 Harmonic trap

In the case of the harmonic trap, the option of the boundary conditions is not considered, because the soliton will be trapped in an harmonic motion and will always oscillate around zero, so the problem of the soliton crossing the borders is not relevant here. As input parameters, the user can choose the intial position of the soliton - which will also be the maximum position the soliton will reach during its motion - and the number of oscillations that it will make.

During the simulation one can see that the shape of the soliton changes. This is due to the effect of the harmonic potential. When it is on the borders of its motion, the shape of the soliton is wider and not so high, but when it comes to the center of the motion, its shape becomes more compact.

In the output plots, the users are able to see the properties of the harmonic oscillator motion, as well as they get to understand the sinusoidal movement by looking at the evolution of position and velocity with time. They can also check that the conservation of energy holds in this case. There is an extra plot available for this potential which it the $v(x)$ plot. In this case, they can check that when the position is zero, the velocity presents its maximum (or minimum) value, and when the soliton's mean position is on the borders of the motion (which is the same as $\pm x_0$, being x_0 the initial position) the velocity is zero.

One of the demos included (see buttons on both sides of ”Start” button in Figure 6), computes a specific case of the harmonic trap in order to see clearer results of the harmonic oscillator motion. In such demo, the soliton starts its motion at the position most separated from the origin, because it has been seen that results are more exact than when the soliton starts its motion really close to the origin, maybe due to some computation limitations or fluctuations when solving anallitically the equations of motion. The results obtained and the plots show the same behaviour (somehow clearer as said) as any other case.

2.4.3 Barrier potential

The last option available for users as external potential is the barrier potential. In this case, the user is able to simulate how a soliton behaves when crashing against a barrier - though as a wall in our wall - and if given some conditions, the soliton will be able to pass partially through it or not. It is here too that the user gets to know the quantum tunneling effect, which can also be achieved by means of some particular inputs in the simulations.

Before starting computing any simulation, the user must introduce some input parameters as the initial position and the initial velocity. Some other relevant, and new, parameters in this module are the width of the barrier, which is expressed as a function of the healing lenght (ξ), or the height of the barrier, expressed as a function of the kinetic energy. Finally, the user is free to choose how long the simulation will last, so they can see more evolution. In this case, the boundary conditions retake its role and they determine if the soliton is put inside a box or it moves under periodic boundary conditions.

As output, the user is able to see plots of the evolution of the velocity, energies and position with time. The new plot intrpduced for this module shows the probability density for the soliton to be found at each time t on the left side of the barrier, inside the barrier or in the right side of it. This way, the user is able to see where is more probable to find the soliton.

As said in previous sections, this module includes some analogies to light reflection and refraction, as well as an animated simulation: a beam of stars ($\equiv$ light) going against a crystal surface with some incident angle. Depending on the width of the barrier and its height, the reflection and transmission cofficients - R and T - have different values. Therefore, the fraction of the beam that passes through the crystal surface is more (or less) than the one reflected. This is translated in the simulation as a probability of passing through the barrier (in the first simulation) and as a different size of the stars of the beam after hitting the surface (here there are both relfected and transmitted beam) in the second simulation.

To end with, this external potential has associated a demo too, in which the soliton is divided into two almost equal parts. This case is also an example of the tunneling effect, and several magnitudes can be studied by looking at the plots. In fact, in the case computed for this demo, the probability density of finding the soliton in the left side of the barrier is slightly smaller than the probability density of finding it on the right side, but this was the most accurate case that we could reproduce with the options for the input parameters.

3 Documentation

Once the program was almost finished, we needed to create a kind of manual for external users to know how to use it and, for instance, to see the most particular cases, which were included as demos in the program itself.

Given that the whole project has been developed as open source and can be found in GitHub[1] there was the need to write some explanations of how was the program written and how could it be used. To help other users to have a better understanding, we added comments on the code where some difficult steps, or steps not so easy to see, were computed. Also, some comments about the creation and design of the interface were included when they first appeared, to make it easy for the user to read the rest of the code.

Apart from the code comments, we wrote a manual (available in GitHub too) that could be used as a guide through the program. It does also include challenging questions about what they could see in the program. This guide leads the user throught the different modules (there are two separated documents: one for Wavepacket dispersion and dark solitons and the other for bright solitons) and talks about the physics underneath what the user sees and some examples or references to other cases. It must be taken as a complementary tool for the program, and for a whole understanding, necessary to be used, as the program itself does not contain so much information due to a lack of space - otherwise it would look too much stuffed.

3.1 Material for popular

For the exhibitions we were going to participate in, we decided to create some special material that could be helpful even being for the people who was testing the program, as well as for the people who was passing by our stand and just asking what were we doing.

As a way of spreading quantum mechanics and, in particular, ultracold gases and solitons, we made some posters. I contributed in two of them: the first was an introduction to quantum mechanics and bright-dark solitons, while the second of them was about some comparisons between the quantum world and the classical one, containing analogies between them so the reader could see some of the resemblances.

The posters are shown in figures 7 and 8.

As we said above, the user could find in the manuals in GitHub some exercices or challenges proposed through the program's different modules. Those exercices were aimed to high school students, of the same age of the students that were coming to the events for divulgation of the project. Therefore, we decided to gather all the challenges in a single sheet of paper, that would be left next to the computers at the events, so the users would be free to use them and play with the program a bit more if they wanted.

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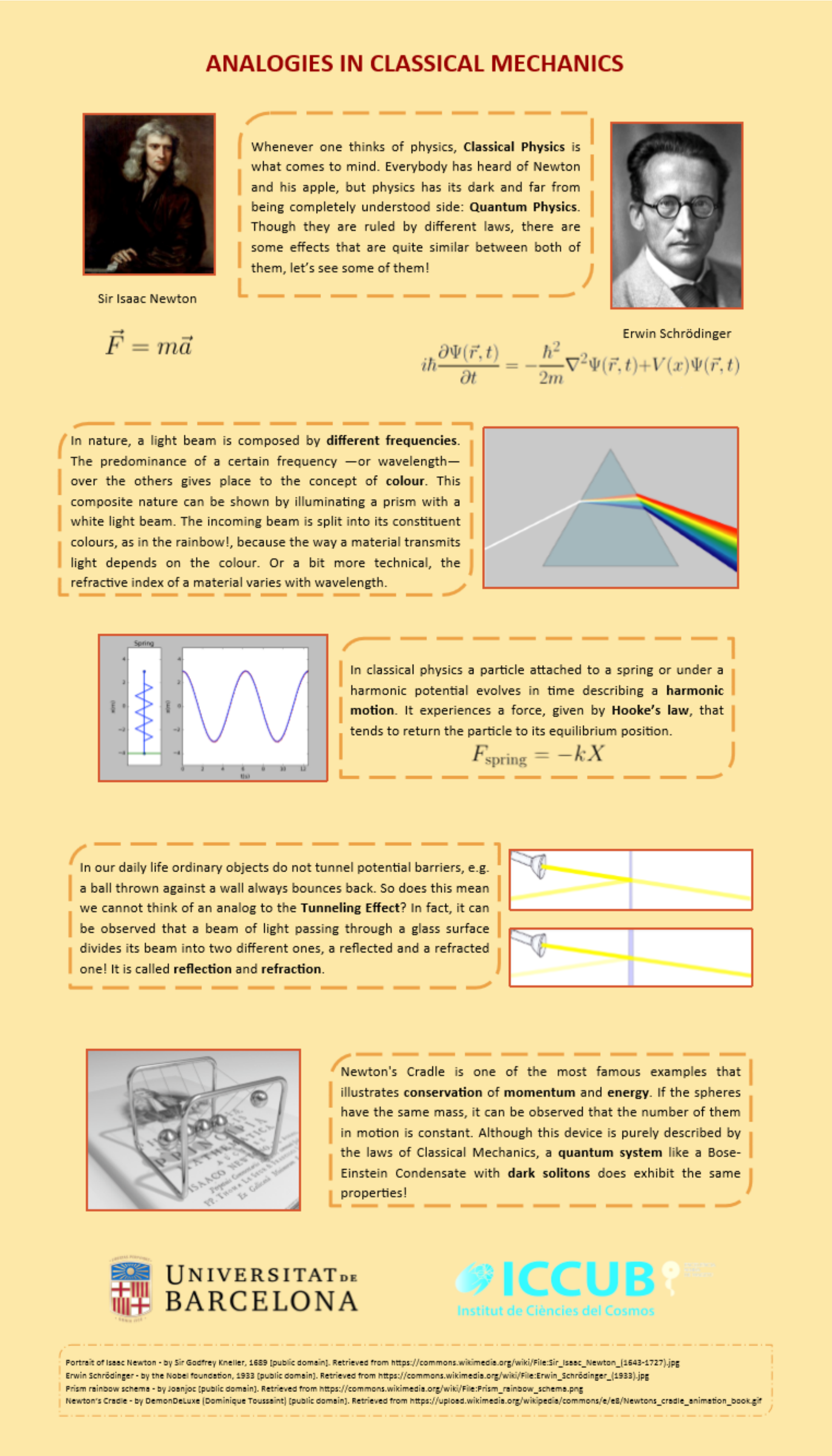
[1] https://github.com/brunojulia/ultracoldUB



ANALOGIES IN CLASSICAL MECHANICS

Whenever one thinks of physics, **Classical Physics** is what comes to mind. Everybody has heard of Newton and his apple, but physics has its dark and far from being completely understood side: **Quantum Physics**. Though they are ruled by different laws, there are some effects that are quite similar between both of them, let's see some of them!

Sir Isaac Newton

$$\vec{F} = m\vec{a}$$

Erwin Schrödinger

$$i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi(\vec{r},t)+V(x)\Psi(\vec{r},t)$$

In nature, a light beam is composed by **different frequencies**. The predominance of a certain frequency —or wavelength— over the others gives place to the concept of **colour**. This composite nature can be shown by illuminating a prism with a white light beam. The incoming beam is split into its constituent colours, as in the rainbow!, because the way a material transmits light depends on the colour. Or a bit more technical, the refractive index of a material varies with wavelength.

In classical physics a particle attached to a spring or under a harmonic potential evolves in time describing a **harmonic motion**. It experiences a force, given by **Hooke's law**, that tends to return the particle to its equilibrium position.

$$F_{\text{spring}} = -kX$$

In our daily life ordinary objects do not tunnel potential barriers, e.g. a ball thrown against a wall always bounces back. So does this mean we cannot think of an analog to the **Tunneling Effect**? In fact, it can be observed that a beam of light passing through a glass surface divides its beam into two different ones, a reflected and a refracted one! It is called **reflection** and **refraction**.

Newton's Cradle is one of the most famous examples that illustrates **conservation** of **momentum** and **energy**. If the spheres have the same mass, it can be observed that the number of them in motion is constant. Although this device is purely described by the laws of Classical Mechanics, a **quantum system** like a Bose-Einstein Condensate with **dark solitons** does exhibit the same properties!

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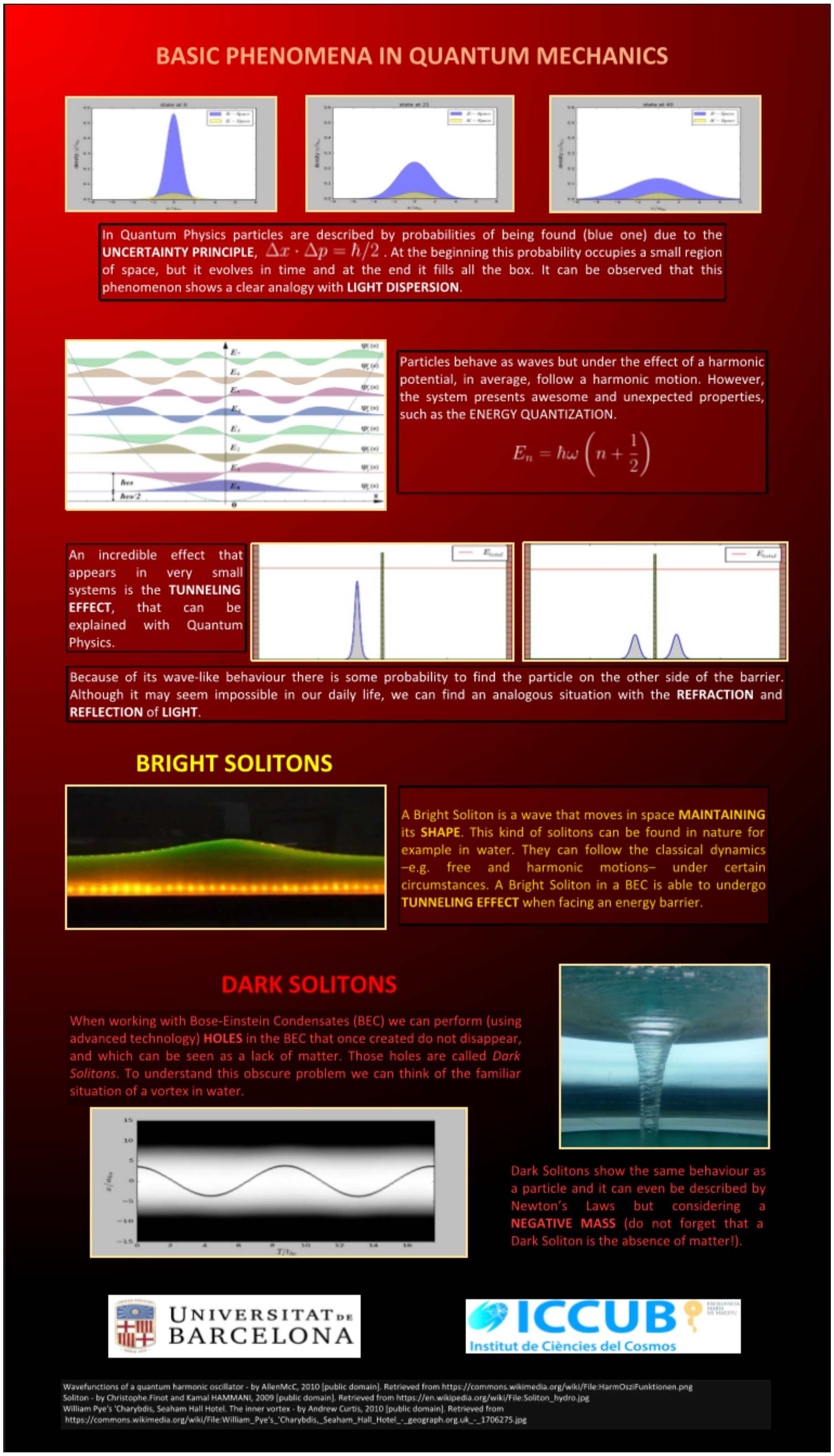
Portrait of Isaac Newton - by Sir Godfrey Kneller, 1689 [public domain]. Retrieved from https://commons.wikimedia.org/wiki/File:Sir_Isaac_Newton_(1643-1727).jpg
Erwin Schrödinger - by the Nobel foundation, 1933 [public domain]. Retrieved from https://commons.wikimedia.org/wiki/File:Erwin_Schrödinger_(1933).jpg
Prism rainbow schema - by Joanjoc [public domain]. Retrieved from https://commons.wikimedia.org/wiki/File:Prism_rainbow_schema.png
Newton's Cradle - by DemonDeLuxe (Dominique Toussaint) [public domain]. Retrieved from https://upload.wikimedia.org/wikipedia/commons/e/e8/Newtons_cradle_animation_book.gif

Figure 7: Poster made for the divulgation events: introduction to quantum mechanics and solitons.



BASIC PHENOMENA IN QUANTUM MECHANICS

In Quantum Physics particles are described by probabilities of being found (blue one) due to the **UNCERTAINTY PRINCIPLE**, $\Delta x \cdot \Delta p = \hbar/2$. At the beginning this probability occupies a small region of space, but it evolves in time and at the end it fills all the box. It can be observed that this phenomenon shows a clear analogy with **LIGHT DISPERSION**.

Particles behave as waves but under the effect of a harmonic potential, in average, follow a harmonic motion. However, the system presents awesome and unexpected properties, such as the ENERGY QUANTIZATION.

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

An incredible effect that appears in very small systems is the **TUNNELING EFFECT**, that can be explained with Quantum Physics.

Because of its wave-like behaviour there is some probability to find the particle on the other side of the barrier. Although it may seem impossible in our daily life, we can find an analogous situation with the **REFRACTION** and **REFLECTION** of **LIGHT**.

BRIGHT SOLITONS

A Bright Soliton is a wave that moves in space **MAINTAINING** its **SHAPE**. This kind of solitons can be found in nature for example in water. They can follow the classical dynamics –e.g. free and harmonic motions– under certain circumstances. A Bright Soliton in a BEC is able to undergo **TUNNELING EFFECT** when facing an energy barrier.

DARK SOLITONS

When working with Bose-Einstein Condensates (BEC) we can perform (using advanced technology) **HOLES** in the BEC that once created do not disappear, and which can be seen as a lack of matter. Those holes are called *Dark Solitons*. To understand this obscure problem we can think of the familiar situation of a vortex in water.

Dark Solitons show the same behaviour as a particle and it can even be described by Newton's Laws but considering a **NEGATIVE MASS** (do not forget that a Dark Soliton is the absence of matter!).

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Wavefunctions of a quantum harmonic oscillator - by AllenMcC, 2010 [public domain]. Retrieved from https://commons.wikimedia.org/wiki/File:HarmOsziFunktionen.png
Soliton - by Christophe.Finot and Kamal HAMMANI, 2009 [public domain]. Retrieved from https://en.wikipedia.org/wiki/File:Soliton_hydro.jpg
William Pye's 'Charybdis, Seaham Hall Hotel. The inner vortex - by Andrew Curtis, 2010 [public domain]. Retrieved from https://commons.wikimedia.org/wiki/File:William_Pye's_'Charybdis,_Seaham_Hall_Hotel_-_geograph.org.uk_-_1706275.jpg

Figure 8: Poster made for the divulgation events: analogies between classical and quantum mechanics.

4 Divulgation

With the end of our project during this autumn semester, we had the opportunity to spread this project to the younger public through different exhibitions, such as YoMo or Saló de l'Ensenyament. There we could see the interest of different people in this field, and give them the chance to know this field a bit deeper. They also had the opportunity to become somehow researchers themselves, as we shall remember that this project is based on an open-source code, and anyone willing to participate can, with the final supervision of changes by Bruno Juliá.

4.1 YoMo 2017

We had the incredible oportunity to participate in the Youth Mobile Festival (YoMo) 2017 with our project: it was a great moment to show our project to the public. Given that it was the first time it would be run by a large public that had not participated into the creation of the project, different doubts came across our mind: would it be understandable? Would the physics behind it reach them? At first, we had not a clear idea of the ages of the participants, and so our fears increased. Nevertheless, the day went better than expected, and a lot of young students came to the stand and played a bit with the program.

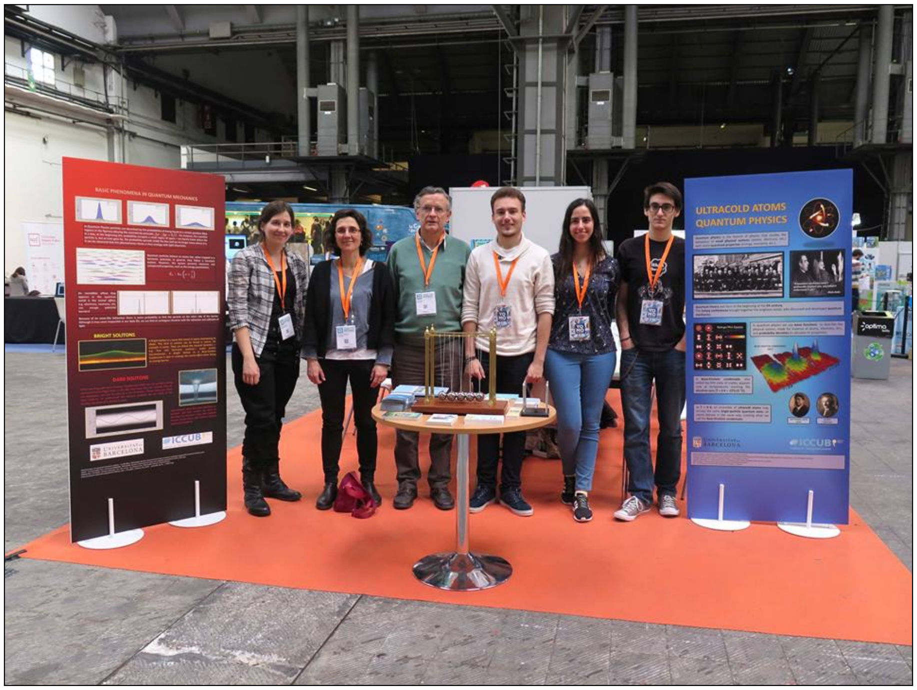

Figure 9: Participants on YoMo 2017. From left to right: Maria Arazo, Muntsa Guilleumas, Artur Polls, Iván Morera, Laura Moreno, Alejandro Romero.

From my own point of view, the public in such occasion was probably a bit younger than the one the project was aimed to, but the different activities and analogies during the program, enabled them to have an overall vision of the project without getting very deep in each part.

Nevertheless, a lot of students came to our stand during all day, and this was a great way for them to know about ultracold gases and to see some of the most important quantum effects.

From this experience, we could think that a further development of this project could include different modules depending on the age of the participants, so it took different approaches to explain the behaviours depending on the public at which it is aimed. But overall, it was a great experience to see the reaction of the public to the project, which was really good.

4.2 Espai Ciència 2017

During the morning of Saturday 25th of March, we went to Saló de l'Ensenyament to show our project in the UB stand in Espai Ciència, a space dedicated to the divulgation of projects of science in this annual exhibition for students to help them decide their future.

During that morning, a lot of students, most of them 18-years old, came to our stand because they were interested in physics. Some of them came already knowing that they wanted to do the Physics Degree, or some because they were just interested on knowing a bit more about this not-so-known-at-school field. Despite their different reasons, they seemed all very amused during our explanations and they had a lot of questions after we showed them a bit the program and how it worked. It is true that it was somehow better than YoMo because the public was in general older and they had a clearer idea of what they were looking for: that is, in YoMo most of the public ran into our stand without knowing what was going on there. But in Espai Ciència, they were aware of our stand and wanted to have a deeper knowledgement on that field, so it was partly more challenging for us and also more interesting.

I particularly remember a girl who came to the stand saying that she hated physics, but her mother told her to try to hear to us and see about quantum mechanics. During my explanation, we started talking about the things on the UltracoldUB program that she could associate to what she had previously learnt, or was learning at that moment at school, such as the harmonic oscillator. After playing a bit with the small games and simulations prepared through the explanation, she was able to understand better the physics underlying the project, and she even had fun with the harmonic oscillator motion, which made her even happier and, as she said, it was not that bad as it seems at first. Maybe it is not the best example of someone really interested in physics, but the fact is that her vision made me aware that this project was really helping people understand basic things in physics, and letting them know a world still unknown by them and that it seemed to be really attractive during that morning.

4.3 Festa de la Ciència UB 2017

In may 2017 we went to Festa de la Ciència de la UB with our project and spent there the whole morning. As in previous events, most of the students that came found the project to be interesting, but from my personal point of view, I found that some of the explanations were not aimed to the ages of the participants. This leads me to think again that the program is more oriented to Batxillerat students or undergraduate students, but maybe it becomes a bit difficult when considering ESO students, as there, the harmonic motion has not been explained yet, and it is a recurrent motion we see in the program. Nevertheless, the student were gladly surprised.

5 Conclusions

The program developed during the autumn semester 2016-2017, consists in introducing the concepts of quantum mechanics and ultacold gases, explaining and showing by means of simulations its main properties. In this project, the main objective was to develop a graphical user interface (GUI) in order to include there all the information and making it more attractive to the public. The idea is to make out of it a powerful tool for divulgation on this field. My work through this months was focused on the bright solitons module, which includes 3 different potentials, whose parameters can be modified in order to see different effects.

Taking part in the development of this project has given me the opportunity to learn about a part of the physics not so learnt at the degree, which is the ultracold gases and the solitons. Not only has it helped me learning more about physics, but to get more practice in a computing language that offers a lot of possibilities such as Python. I have learnt how to create interfaces and personalise them, which has been helpful in other subjects where I made use of them.

Moreover, as it was a collective project, I was able to get used to working in group, sharing doubts when we were stacked and having weekly meeting where we had to present our results or progress that week, so we got used to presentations, which in my opinion can be very useful to prepare the Treball de Fi de Grau presentation.

Finally, I would like to make a summary of the events we took part in and my personal evaluation about them. The first place we went to was YoMo and though we expected that the age of the participants would be much higher than it then really was, everything went better than as we expected. It was our first "test" to people who had not heard about the project before and most of the people were interested during our explanations and had a lot of questions after. True is that maybe the program should include different versions depending on the age of the participants, as a suggestion for further development of the project. Then, for Espai Ciència at Saló de l'Ensenyament, was in my opinion better than YoMo. It did not last as long as the first, but the public we were working with was older and had a clear interest for physics: they came because they saw the activity and wanted to do it , and they knew it beforehand. From my point of view, almost nothing could be improved that day, maybe there was a lack of visual material to catch other peoples attention or to use when the computers were occupied by other students, but I think it was more a lack of space of the stand and of time to prepare everything well.

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