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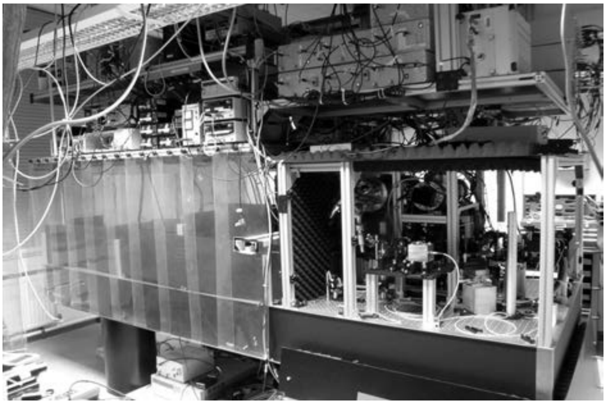
Simulating Patterns, Measuring Fringes: Simulating Matter with Matter

Mira Maiwöger

I’m working in the group of Jörg Schmiedmayer at the *Atominstitut* of the Technical University in Vienna. Like Lukas Mairhofer I am experimenting with matter waves in a lab. In this talk I focus on the aspect of simulation and show you some experiments where we simulate interference patterns in order to explain what’s going on in our experiment or to reproduce the experimental observations. In my lab we work with ultra-cold atoms. We’re basically doing the opposite of what Lukas does: we’re cooling atoms down to almost zero temperature, where strange things happen.

At high temperatures, individual atoms will behave like billiard balls. The lower the temperature gets the lower the velocity of the atom becomes. At the same time the wavelength of the matter waves associated with the atoms increases up to a certain critical point where the interparticle spacing is the same as their de Broglie wavelength and the matter waves start to overlap, until at zero temperature all these atoms form a giant matter wave that can be described by a single wave function. This is called a Bose–Einstein condensate (BEC). So in my lab we’re working with rubidium atoms and we are developing new tools to manipulate them, to create BECs, and to perform different experiments with them.

In many other groups ultra-cold atoms, especially in optical lattices, are used as analog quantum simulators, and I thought I should mention that in this symposium. Ultra-cold atoms in such lattices are used as model systems, as analog model systems. The idea is that they behave like certain other systems, for example as if they were a superfluid or a magnetic material. So that behavior is simulated instead of calculating what a magnetic material would do. These cold atoms are observed in order to get the answer to a very different problem. This was first proposed by Feynman in 1982, when he said let the computer itself be built of quantum mechanical elements that obey quantum mechanical laws. Once you're having those giant matter waves, those ultra-cold atoms that you can manipulate really precisely and that you can read out really precisely, you basically have an intrinsically quantum mechanical system that you can interrogate instead of the solid state that you want to know some answers about.



[Fig. 1] (Courtesy of the author).

However, in our lab we are doing something different with BECs. Fig. 1 shows our experiment. It basically looks like any other cold atom experiment. We have a single vacuum chamber where we prepare the BEC and do all the stuff we want to do with it, and then perform measurements just by taking photographs of these atomic clouds. On one side, hidden behind the shield, is all the optics we need to manipulate and prepare the atoms in the right state in order to be magnetically trapped. In contrast to the type of traps that only work with laser light, we trap our atoms in magnetic fields, and these fields are produced by wires on an atom chip. One of the main advantages of this atom chip is that it's a really stable and versatile device to prepare, control, and manipulate our BECs.

In our group there is more than one BEC experiment, but I will focus on my experiment. There are many things that we do with this setup and the one I'm going to talk about today is the so-called optimal control of the motional state of a quantum system. Here we are using optimal control theories, so we're calculating what we should do with this cloud of ultra-cold atoms in order for it to behave in a certain way, and I will tell you how this works in a minute.

Another thing that we've been studying recently is a phenomenon called population inversion, which we can simulate with our atoms. That mechanism is required for optical lasers. In our system the wave function is initially sitting in the ground state of the magnetic potential, but we can manage to get all the atoms—or at least a huge fraction of atoms—up to the first excited state of this potential. In this case collisions between the atoms will occur that produce correlated pairs of atoms with opposite momentum. This is in some way analogous to down-conversion in a nonlinear optical medium.

In this sense we can also analogously simulate the effects that take place in a very different medium with our cold atoms systems. We usually work with quasi one-dimensional BECs.

In my experiment I generate cigar-shaped BECs. Cigar-shaped means they are 100 times longer than they are wide. Therefore in many situations we can describe the behavior that we're seeing with one-dimensional theories, which makes it easier for theoretical physicists to explain what is going on. It also adds some other phenomena that you don't see in three-dimensional physics. It's really about playing around with a system that is artificially abstractified in some sense. With the complexity of this experimental apparatus we actually eliminate a lot of the effects that could mess up the nice theory we have for it. So we have a tool to probe rather simple models. Furthermore, we recently learned how to split one BEC, one of those cigar-shaped condensates, in a double-well potential. Then we can also do interferometry with it. In 2013, a Mach-Zehnder interferometer was implemented with such BECs. We have a lot of little projects around the development of new tools; it is basically a playground with toys for ultracold atoms. Now I want to get back to this optimal control story, which has mainly been done by my colleague Sandrine van Frank during her PhD, and about which she taught me a lot last year.

What we want to do is to move a fraction of the atoms really precisely out of the ground state into which we are cooling down the atoms, where we are condensing them. So in our initial state all the atoms are in the ground state of the harmonic potential, and we want to transfer a portion of the atoms to this first excited state with a high fidelity. This could be 10% of the atoms, this could be 50%, this could be 90%. We came up with a scheme for that, together with theoreticians who modeled and who simulated how to do this. We achieve this by displacing the condensate transversely, that is along the tightly confined axis. This is achieved by really special pulses and those pulses were optimized by our colleagues in Ulm. You need to do a model of your system, the simplest way to describe the BEC; in this case it is a formula we call the nonlinear Gross–Pitaevskii equation. It is a variant of the Schrödinger equation in the mean-field description.

This approach treats the entire wave packet consisting of many atoms as a single wave. Atomic interactions are ignored; they only appear in a density term. We also ignore the longitudinal axis of our elongated BEC, which is also the axis where finite temperatures play a role—so we consider our condensate to have zero temperature. Then we need some handle to manipulate our system, which in our project is the transverse displacement of the BEC. This allows us to transfer a portion of the atoms from the ground state into the excited state. What the theoreticians do is that they minimize some sort of cost function, which in this case is the fidelity or the infidelity. So you want to minimize the error you make when transferring a fraction of the atoms to this first excited state. You want to be as precise as possible. The theoreticians have developed an algorithm that takes the technical limitations of our experiment into account. We went to our collaborators and said we can do up to 20 kilohertz. That's what the device can do, we cannot do more. We cannot shake it any faster. They came up with the sort of pulses that are very close to the quantum speed limit, the fastest you could do according to quantum theory.

I will tell you in a second how they work and what you can learn from that. Let me come back to the experimental tools. As I mentioned before we use an atom chip. We have to slow down the atoms a lot, to velocities that would correspond to a temperature of a thousandth part of a degree above absolute zero. Only then can we actually trap them in those magnetic fields produced by the chip, but in principle you use a really small, really thin trapping wire. When we run a current through this wire, it produces a magnetic field that, together with an additional external magnetic field, creates the harmonic potential where atoms are trapped and finally condense into the ground state. I think I never mentioned that we use rubidium 87, so one of the most well-behaved species that there is for doing BECs. That's a common quote of my professor Jörg Schmiedmayer: he always says rubidium is so well behaved, it's easy. So these well-behaved atoms we trap usually in those cigar-shaped potentials as I told you before, so that they are one-dimensional, or quasi one-dimensional.

Another tool we have, which I think our group was the first to apply, is using those radio frequency wires, where we send oscillating currents through, which allows us to deform a trap. If we turn on those RF wires and we send a current through them, we can dress the trap and deform it until double-well potentials evolve. The final shape depends on the power we are sending through the RF wires. This is basically our tool to create quite arbitrary trap shapes. In the optimal control case I want to have an anharmonic trap because I want to have the first-level spacing different from the second-level spacing so that I'm really able to target only this first excited state and not excite my atoms up to all the other states.

Another important tool in our experiment is the device to look at our atoms. We have an imaging system where we release the atoms from the trap, and then they fall through a thin sheet of focused laser light after 46 milliseconds' of free flight. We then collect the fluorescent photons emitted by the atoms on a camera. This means that we only see images that are integrated over the direction of gravity. So of course we can never image the entire cloud. We can image it in several shots, like resolving layer after layer, but every time we would need to make a new BEC. We just wait for a certain time and then switch our trapping fields off. The atoms will fall down and fall through the light sheet and we collect single images.

Then we integrate over this direction and just stack the images together, and then you actually see the pulse shaking the atoms as well, so it's not only after transferring the atoms to this first excited state but even during this transfer that we take images.

For the analysis, in order to know whether our shaking and bringing the atoms into a target state has worked, we apply a fitting procedure. Here we use again this Gross–Pitaevskii equation, idealized for zero temperature and the one-dimensional situation where we only take the transverse direction into account and ignore everything that happens along the extended axis. It turns out that in order for the equation to fit the result reasonably well we need to take at least three states into account, so more than we actually want to address in the experiment. We need to take at least the ground state, the first excited state, and the second excited state into account. We then compare the simulations on the basis of the Gross–Pitaevskii and compare this to our measurements.

So we've created a very artificial scenario that actually works quite well for a certain amount of time. Afterwards it gets fuzzy and starts to decay. But we can control our well-behaved atoms reasonably well with this technique.

So as I mentioned before, a simulation is about taming the future, which was the part I was talking about before. But simulation is also about explaining the past. Of course we wanted to know why the theory does not fit the results after a certain point. What are the reasons that after, I don't know, 10 milliseconds our model that we're using to fit our data is deviating so much from the data, where the agreement with the theory breaks down somewhere? In the meantime we started to look into different models or different ways of simulating our situation. We now use a Gross–Pitaevskii equation again, but we change it a bit. With the usual Gross–Pitaevskii equation for zero temperature this behavior would continue much, much longer: it would not decay after 20 milliseconds. Here we are trying to simulate the system for finite temperatures and we actually see that we can get there. So it's probably enough, at least for the first 20 milliseconds, just to add temperature to our model and we learn that this is the critical point that was missing before. So that is how I experience the interplay between theory and experiment.

Discussion with Mira Maiwöger

Anne Dippel: Thank you Mira for showing the opposite side of complex quantum systems, showing quantum behavior, and maybe there are some questions from the audience concerning that experiment? It's going in the opposite direction, it's another setup. Still, we have quantum mechanics proved.

Hans De Raedt: I have kind of a more general question. If I look at the sophistication of your experiment; it's really impressive by itself. To see what appears to be some quantum effect and then compare this to what people did in the 1800s looking at the spectra of simple atoms, which was of course the source for developing quantum theory. There is something strange. Originally to see quantum effects you had to do nothing: just look and it's really true. In the meantime in order to see something that even closely resembles a little bit quantum behavior you have to have extremely expensive equipment, very sophisticated things, tools—a lot of people working on it.

Mira Maiwöger: To be honest to me this is part of the fun, that my object of study is some piece of reality that to me feels so highly artificial. I mean it was predicted in 1925 and it took 70 years to produce it in a lab for the first time. I really enjoy that I'm actually studying this artificial thing that to some degree can be useful as well when trying to simulate other systems.

HDR: Yes, sure, I can definitely appreciate the fun, I see that too. My question goes a little bit further. The fact that you have to work so hard to see it also means something. It's not just fun.

MM: Of course it means something—we can create a very specific phenomenon that consists of 10,000 to 100,000 atoms. These atoms are a fact that lasts a few, 10, milliseconds—which is a rather long time scale for a fact describable by a single wave function.

HDR: Under the right conditions.

MM: Under the right conditions, yes.

HDR: So the only thing you're doing actually is…

MM: Creating the right conditions. Yes, yes.

HDR: But if quantum theory or quantum mechanics is supposed to be all around, it should not be necessary to wait for the correct conditions to be realized to see it. In the case of atoms, there's no doubt about it. That's clear. You don't have to produce spectral conditions, you'd see them right away. That there are lines are in the spectra and so on. But the more sophisticated we get, the more complicated the conditions are.

MM: Yes, what is reality?

Wolfgang Hagen: What is reality and what is the phenomenon and what is the difference in your experiment?

MM: I cannot separate. In my experiment I would say I cannot separate my phenomenon Bose–Einstein condensate (BEC) or this entity BEC from this huge apparatus.

WH: Does that mean that there is no difference between reality and phenomenon?

MM: No, because I make a cut between apparatus and object in describing it. By the way physicists deal with this phenomenon BEC we make this cut. We choose to decide that this tiny, tiny cloud of atoms out of this huge apparatus here is the object. We decide to describe only those 10,000 or 1,000 atoms that are prepared in such a way that they're consistently described by this theory. This is a cut I'm making. Of course I cannot separate my BEC from this huge apparatus that produces it. But in our way of thinking about it we can. Or we choose to do so. Or play with it and try to extend it and so on.

Arianna Borrelli: Thanks, yes, I'm working on the same issue. But more on the theoretical side. Because you speak of Bose–Einstein condensation, BEC, and then you referred of course to Einstein's paper, and of course in the Einstein paper the theory is half formal. What exactly he was writing there, it's a bit what we interpret from it. My question would be, your phenomenon—is it Bose–Einstein condensation and if so how is it primarily defined? Is it that equation for example? Of course the term Bose–Einstein condensation is something that you could apply to many, many other phenomena, to photons and so on. Is there for example some bridge through some theory or experiment between all those phenomena and your condensate? I'm trying to clarify how universal the idea of Bose-Einstein condensate is, because you talk about it as though it were universal and refer back to the Einstein paper, and of course I understand there is a problem with the experiment, but at the theoretical level is there universality?

MM: It really depends on the dimensionality of the condensate. I mentioned before that we were working with one-dimensional or quasi one-dimensional BECs, and if you treat the phenomenon of Bose–Einstein condensation theoretically in a stringent way then there is condensation only in three dimensions or in two dimensions. So in one dimension we always only can say condensed in a sense that we can claim that all the atoms are sitting in the ground state only in the transverse direction. Along the long axis of the BEC there are always phase fluctuations going on. Having a single wave function describing the condensate with a single phase does not work for the 1D case. We can, however, develop theories that can model how many phases we would need to describe the whole condensate and so on. I don't know—did this answer your question? No, it's not universal. Depending on the number of dimensions you have different scenarios, but you can describe them reasonably well to some degree until you get to a problem that you cannot describe anymore.

Lukas Mairhofer: I just wanted to come back to the discussion before. When I listen to Mira, I sometimes tell her you're not doing, you're not… well it's hard to say in English. You're looking at art, not at nature. You're looking at a piece of art. But in that way we can separate the artifacts, the drawing or whatever from the tools with which we made it. In that way I think we can make the cut, or we are allowed to make a cut, between Van Gogh's drawings and the palette that he used to make them.

AD: There is no difference between art and nature.

MM: Donna Haraway's slogan, "querying what counts as nature," is my categorical imperative.

AD: Not exactly, creating our own reality and the reflections about it that we discussed. This was the reason why I invited you and I'm very happy that this became very clear here, how artificial the experiment itself is.

MM: The nature of the experiment.

AD: The nature that is made within those experiments, compared to 200 years ago. Are there more questions?

Frank Pasemann: A last remark, that nature can be very strange.

AD: Yes, nature can be very strange, absolutely.