Quantum Sensing with Cold Atoms and Matter Waves

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Light & Matter

Organization of the talk

The topic of my talk is quantum sensing with cold atoms and matter waves. It is based on experimental research projects that we are pursuing at the IFSC, USP. In order to put this area into context, I will start with a brief introduction into quantum mechanics and the ongoing quantum revolution nowadays called 2.0. Then, I will explain how sensing fits into this revolution and focus on the use of atoms interacting with cavities as sensors.

In the main part of the talk, I will present two examples, where atoms can be used for improved quantum sensing. One is based on a synchronization phenomenon of atomic dipoles in so-called bad cavities eventually leading to superradiant lasing and spin squeezing. The other is based on a synchronization phenomenon of the motion of matter waves in ring cavities, which can be harnessed for the realization of better gravimeters.

Let me begin with a few words on quantum mechanics 2.0.

Quantum mechanics everywhere

QM is not just for nerds, but one of the most influential achievements of history!

QM is universal and affects our everyday lives like no other theory in physics after the first quantum revolution, that led, among many other applications, to the invention of the transistor and the laser.

QM is correct and complete. At least, we know of no situation today where it would not apply or give false results. Thus it establishes, along with the theory of relativity, the framework within which all other theories of modern physics must fit.

It is estimated that one-third of the world's GDP today is generated by technologies emanating from the first quantum revolution. This revolution, which was triggered by discoveries by Planck, Bohr, Einstein, Heisenberg, Schrödinger and Einstein and other physicists in the first part of the last century, led to the invention of the transistor (fundamental constituent of any electronic circuit), the laser (fundamental constituent of communication technologies), and many other technologies.

While the foundations of QM are well understood and experimentally confirmed, this does not mean that we are understanding all aspects, implications and possibilities of QM. Indeed, we are currently at the forefront of a second quantum revolution. Based on discoveries made 50 years ago, but of extremely difficult technological realization, it will change all areas of high technology, such as sensing, communication and computation.

The most visible spearhead is the race for the first quantum computer launched by Google, IBM, Microsoft and Amazon. Here we see a Google quantum processor containing 100 qubits. It looks harmless here, but it needs a whole sophisticated infrastructure to protect quantum operations from environmental disturbances.

In my group of research, we focus on quantum sensing.

Private sector

The private sector is discovering the market opportunities. Although dominated by a few big players, smaller companies also want their part of the cake. It is clear that important sectors of QT are taken over by private companies, in particular in quantum computation (Google, Amazon, IBM, AT&T, Microsoft, Intel, D-Wave, Accenture, ...). 6 (counting Canada 8) of the TOP 10 quantum computer developing companies are US. Only exceptions are Alibaba Group and Baidu from China and Atos Quantum from Europe.

"Quantum sensing" is more tricky. Google finds only a few. Two gravimeters and some others offering products with questionable the quantumness.

AOSense Inc. (US) founded by Marc Kasevich, has business operations in atom sources, electronics, sensors, and laser systems. The company offers gravimeters. As I heard Kasevich has a lot of support from military, so that much information is classified.

GWR Instruments Inc. (US) offers a portable superconducting gravity meter specifically designed for geophysical applications that require much higher stability and precision than those provided by mechanical spring-type gravity meters.

ADVA Optical Networking SE (Europe): offers quantum sensors through its subsidiary Oscilloquartz SA (Oscilloquartz). The company offers a cesium clock for precise timing for both next-generation networks and legacy infrastructures.

Apogee Instruments Inc. (US) offers quantum sensors and meters for PAR (Photo-synthetically Active Radiation) measurement, specifically in research and agricultural projects for characterizing light sources used to grow plants and corals.

Kipp & Zonen BV (Dutch) offers solar instruments, atmospheric science instruments, soiling monitoring system and PAR quantum sensors for indoor and outdoor installation for studies of crop growth in greenhouses.

Technavio has segmented the quantum sensors market based on the product and region.

The National Quantum Initiative Act

Governments concerned in not loosing sovereignty due to technological backwardness recognize the importance of quantum technologies, in particular, quantum communication and sensing, for national security and wealth. For example, the US passed a law called "National QT Initiative Act" 2 years ago after only 2 years of intense lobbying by interested parties.

1. This is a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.
It allocates responsibilities, budgets, and funding of research at universities and institutes.
2. An initiative in AI similar to the QT initiative is pending for legislation, interestingly asking for twice the QT budget.
3. Budget: Not known how much defense invests in these areas. And also civil projects co-sponsored by defense.

Interesting points (for me):
1. USA is rather known for capitalism, the market rules everything! Governmental intervention rather known from countries like China ...
For comparison, I read in the report by Fedorov (IOP Publishing special issue in Quant.Sci.Techn.) that the Russian initiative was mainly lobbied by banks, he lists 6 of them explicitly.
2. Why not for QT? Obvious response is that the Defense and Security Agencies identified the field as relevant (data security against code-cracking, geo-localization, ...)
3. Historical analogy to development of internet funded by US Defense Agencies and NSF prior to being adopted by industry.

The law text is well-written (unlike in other countries).

Now, let me focus on one of the key technologies, quantum sensing.

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What is a sensor?

A sensor is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor.

Sensors are everywhere, they facilitate or control our everyday life. In fundamental science we need sensors to measure weak forces with high sensitivity and strong forces with great accuracy.

What is a quantum sensor?

A quantum sensor is a measurement device exploiting quantum correlations in order to improve sensitivity and resolution. They have lots of advantages, they are precise, fast, robust, and can be integrated in electronic circuits.

What is an atomic quantum sensor?

Atoms are particularly interesting sensors, because they are intrinsically 'quantum', and some of them have ultra-narrow transitions. They are at the heart of atomic clocks and gravimeters with incredible precisions.

What is a quantum sensor 2.0?

Most current quantum sensors use single-atom quantum superpositions. Although nowadays individual atoms can be observed, most sensors use ensembles of many atoms in order to enhance the signal-to-noise ratio of error signals. Atomic clocks and gravity sensors are examples for this. In such sensors, the achievable precision is limited to the Standard Quantum Limit or shot noise.

However, quantum information technologies 2.0, in principle, allow to overcome this noise by entanglement, and to approach (and even overcome) the so-called Heisenberg limit by correlating the noise of all atoms. Squeezing is an example of such techniques.

Quantum sensing using cavities?

In order to sense a force with atoms, it is not sufficient that the atoms feel the force, one also has to read out the result. Fortunately, this can be done very conveniently sending light to the atoms. Indeed, light having interacted with the atom and carries information on the atomic state from the vacuum chamber to the detector and hence to the user, where it can be analyzed and treated.

Here, a nice trick to collect all the information and not loose photons by spontaneous emission of the atom, consists in placing the atom inside an optical cavity which is sufficiently 'bad' that it dominates dissipation. The cavity isolates a single coherent light mode, guarantees a collective coupling between the atoms, which is a precondition for their quantum correlation.

1. Principle of frequency standards 2. Projection noise, what's that? 3. Measurement with a single trapped Yb^{+} 4. Spin squeezing in matter wave interferometry 5. Beyond the standard quantum limit

Classical projection noise

Jogue uma moeda e pegue-a. Um pão de geléia. A curva é muito plana.

Projection noise in a two-level system

Projection noise in a Rabi experiment

Dicke model

The starting point is illustrated in this scheme: We assume that we have trapped and cooled a cloud of atoms inside a ring cavity consisting of 3 mirrors and resonantly pumped by a laser. The atoms are subject to spontaneous emission at a rate Γ, the cavity is subject to transmission through the mirrors at a rate κ. The transmission is recorded by a detector.

Now, since our sensors is supposed to be quantum, we need to stress a quantum description. That is, we describe the light field by a photon annihilation operator and the atoms by two-level quantum systems, that is, spins.

In the absence of contact interactions these spins couple together following the rules of the angular momenta algebra, as we learn it in QM. This model is called the Dicke model. The spin vectors sum up to a collective spin vector denoted by a capital letter. Driven by a light field, a single spin (also called qu-bit) will (in the absence of spontaneous emission) always evolve on top of a so-called Bloch sphere.

When several such spins couple, they can do it in various ways, so that the total spin ends up on one of various concentric spheres. The important thing is now that, once the collective spin points to a specific Bloch sphere, coherent collective evolution cannot change this, since $\hat{H} = \hat{H}(\hat{\mathbf{S}})$ only depends on the collective spin and $[\hat{\mathbf{S}}^2, \hat{\mathbf{S}}] = 0$. Consequently, if all atoms are initially in the ground state, this corresponds to a fully stretched collective spin state, which will stay like this even being excited by a light field.

The fact that the spins are fully stretched does not mean that the spins are correlated. In the figure I tried to illustrate this by arbitrary precession angles for the individual spins. And there is nothing, linear terms in the Hamiltonian can do about it: they only perform rotations of the collective spin. Correlation of the spins, that is, spin-squeezing, which is a weak form of entanglement, requires non-linear terms in the interaction Hamiltonian, f.ex. terms quadratic in the z-component of the collective spin.

Why bad cavities?

So, the question is how to engineer non-linear terms in the Hamiltonian.

The starting point is the Dicke Hamiltonian with the cavity detuning Δ_c, the pump rate η. Possible decay processes are described by jump operators, such as cavity transmission at a rate κ leading to photon annihilation or spontaneous emission at rate Γ leading to atomic deexcitation.

Now, let us suppose a bad cavity, where the losses are completely dominated by cavity transmission. Then, the cavity field will quickly adjust to any changes of the collective spin. It will not be an independent quantity anymore and may thus be eliminated from the equations of motion.

Introducing some abbreviations, it is possible to show the Hamiltonian can be approximated by this expression. You notice, that the interaction terms are linear in $\hat{S}_x$ and $\hat{S}_y$, but they are non-linear on $\hat{S}_z$.

And this is exactly what we need for spin-squeezing or superradiant lasing.

Storyboard for an experiment

Now, that we know what we want, 1) let us design our experiment with a bad cavity. When we tune the laser frequency across a resonance frequency of the cavity we observe a peak whose width corresponds to the loss rate via transmission of light through the cavity mirrors.

2) We take atoms with narrow transitions and cool them.

3) Now, when we insert a cloud of ultracold atoms into the ring cavity, we observe that the transmission peak is split in two. This normal mode splitting can be considered a smoking gun of the presence of atom-cavity interactions.

4) However, it is not a quantum effect. Indeed, if you replace the atoms by a beam splitter, you observe the same normal mode splitting. But there is a difference between atoms and beam splitters, which is that the atoms are saturable. This is a consequence of the fact that the atoms have discrete quantized energy levels. And the saturation entails a non-linear behavior.

5) I will not address, however, the question, how to harness the non-linearity in an experimental sequence leading to spin-squeezing.

The experiment

And this now is the experiment that we set up São Carlos with the goal of observing this quantum nonlinearity. The science chamber is hidden in between the optics needed to bring the light from various laser sources close to it. The lasers occupy the major part of the table and the electronics the racks.

The next picture shows a zoom on the vacuum chamber. In the third picture the three mirrors of the ring cavity are clearly visible. Light injected through left mirror circulates inside the ring cavity before being transmitted through one of mirrors, where it can be detected.

The atomic species that we use is strontium, and we excite it on a quite narrow transition of 7.5kHz linewidth. In comparison, the 3.4MHz decay width of the cavity is large, which puts us in the bad-cavity limit.

Experimental procedure & state of the art

Every experimental run goes through a sequence of steps needed to inject atoms into the science chamber, pre-cool and trap them, cool them further and transfer them into the mode volume of the cavity, and finally record cavity spectra and take picture of the atomic velocity distribution. During the sequence, dozens of optical elements have to be switched, tuned, ramped or modulated.

Here, you a picture of 1 million 5mK hot atoms suspended in free space. We measure their velocity distribution by suddenly switching off the trap and let the atom cloud expand ballistically for a few milliseconds. The spatial distribution of the cloud photographed after this time-of-flight tells us the temperature. In the first photograph the cloud was 5mK hot, in the second roughly 10uK and in the last one 1uK.

Then we still need to transfer the atoms to the cavity, where the atoms are then stored in the optical dipole potential of the light circulating in the cavity.

Normal mode splitting

Finally, we record the normal mode spectra. This is actually not that simple because, in order to scan a laser through a cavity resonance, you have to know where that resonance is. And this you can only find out injecting a laser measuring the cavity length. We do this with a second laser probing another cavity mode far from the atomic resonance not to perturb the atoms. This laser 2 actually serves to confine the atoms in the cavity mode. The laser 1 is phase-locked to laser 2 and scanned to a cavity resonance, which is close to the atomic transition. The cavity itself can be adjusted by means of a piezo.

Without atoms the cavity's transmission spectrum is simply an Airy function. If atoms are in the cavity, we observe the normal mode splitting which depends on the number of atoms interacting with the cavity.

Normal mode splitting $\equiv$ 1D photonic band gap

These spectra show the dependence of the normal mode splitting on the detunings of the cavity and the laser from the atomic resonance.

The outer ridges show the typical behavior of an avoided crossing expected for a linear atom-cavity interaction. However, there is an additional feature in the center, which can only be explained by a non-linearity. The sharp edges delimiting the center ridge point to a bistability.

Deriving the equations of motion from the complete Hamiltonian, we are able to reproduce the spectra theoretically. However, the conditions for an adiabatic elimination of the cavity are only fulfilled in the center of the spectra at zero detunings. Therefore, we will now concentrate on spectra taken when the cavity and the atomic resonance coincide, that is, vertical cuts through the center of the 2D spectra.

Phase diagram

The fact that we have at hand a good theoretical model encourages us to calculate normal-mode splitting spectra in other parameter regimes, in particular, for good cavities and as a function of pump power and for various spontaneous decay widths. We find that the spectra can adopt very different line shapes and develop bistabilities in various regions of the spectra. However, only in the bad cavity regime (right panel) we observe bistability exactly on resonance, which is the necessary condition for performing the adiabatic elimination.

Quintessence

The quintessence of these observations is: 1) We observed bistability on a (very narrow) resonance in the bad-cavity limit, which means that there is a nonlinearity at work. 2) We achieve strong atomic saturation corresponding to 50% excited state population, which implies that the dynamics is intrinsically 'quantum'. Taking both together, it means that non-classical correlations should, in principle, be feasible.

Next steps could be to implement spin-squeezing sequences in Ramsey interferometry. Also interesting would be to find a way (e.g. via optical pumping) to generate real inversion on the narrow transition, because this could lead to light amplification by the coupled atom-cavity system in a regime ruled by quantum-nonlinear effects.

In the last part of my talk, I would like to give you a brief glimpse of our future project, which is the construction of a gravimeter exploiting the atom-ring cavity interaction.

Gravimetry with Bose-Einstein condensates

Nowadays best gravimeters are based on atom interferometry. The basic idea is the following: Take a matter wave and let it fall in the Earth's gravitational field. But before that, apply a laser pulse separating the matter wave into two parts taking different paths. Thus, the Broglie waves of the two parts will accumulate different phases, which results in an interference pattern when the waves are superimposed again.

One smart way to realize this interferometer is to explore Bloch oscillations performed by atoms in an optical lattice. Now, what are Bloch oscillations? The phenomenon is known from solid state physics. It is the oscillation of a particle (e.g., an electron) confined to a periodic potential (e.g., a crystal), when a constant force acts on it. Although this phenomenon is very difficult to observe in real crystals due to the scattering of electrons by crystal defects, it was observed in semiconductor surfaces, in Josephson ultrasonic junctions and with cold atoms in optical lattices.

Imagine an atom with zero velocity inside a quasi-resonant stationary light wave. Its de Broglie wavelength is infinite, but when it is accelerated, for example by gravitation, its wavelength decreases. At some point, the de Broglie wavelength becomes proportional to that of the standing light wave. At this instant, the matter wave is able to interact with the standing light wave and undergoes a Bragg reflection, after which the atom has the same velocity, but now flies upward until, decelerated by gravity, it interacts again with the standing wave.

The atom therefore performs very regular Bloch oscillations with a frequency, which depends only on the gravitational acceleration. That is, we can convert a force measurement into a frequency measurement, which can be done with very high accuracy.

Brazilian gravimeter

We deposited the basic idea as a Brazilian patent: https://patents.google.com/patent/WO2005076042A1/en, https://patents.google.com/patent/BR102015007944A2/en

Continuous monitoring Bloch oscillations in a cavity

The self-stabilization of the oscillations is demonstrated in these figures. Since, the momentum transfer can only happen in units of $2\hbar k$, the matter wave is always in a superposition of discrete momentum states. The oscillations coded by different colors along the time axis are populations of subsequent momentum states. The upper figure shows the case of overwhelming CARL. The CARL acceleration forces the atoms into higher momentum states, but when the matter wave reaches a certain velocity, the acceleration weakens, and it takes more time to accelerate the matter wave to a higher velocity. This is seen in the bottom figure exhibiting the time evolution of the center-of-mass momentum. The matter wave is accelerated in the lab frame. Consequently, the oscillations are unstable.

Quintessence

So far we have not yet seen signatures of Bloch oscillations, but we are working on it.

The team

Acknowledging the people who did all the work. This is my group in its actual composition.

We have strong connections to research groups in Tübingen, Nice, Milano, Birmingham, and Glasgow.