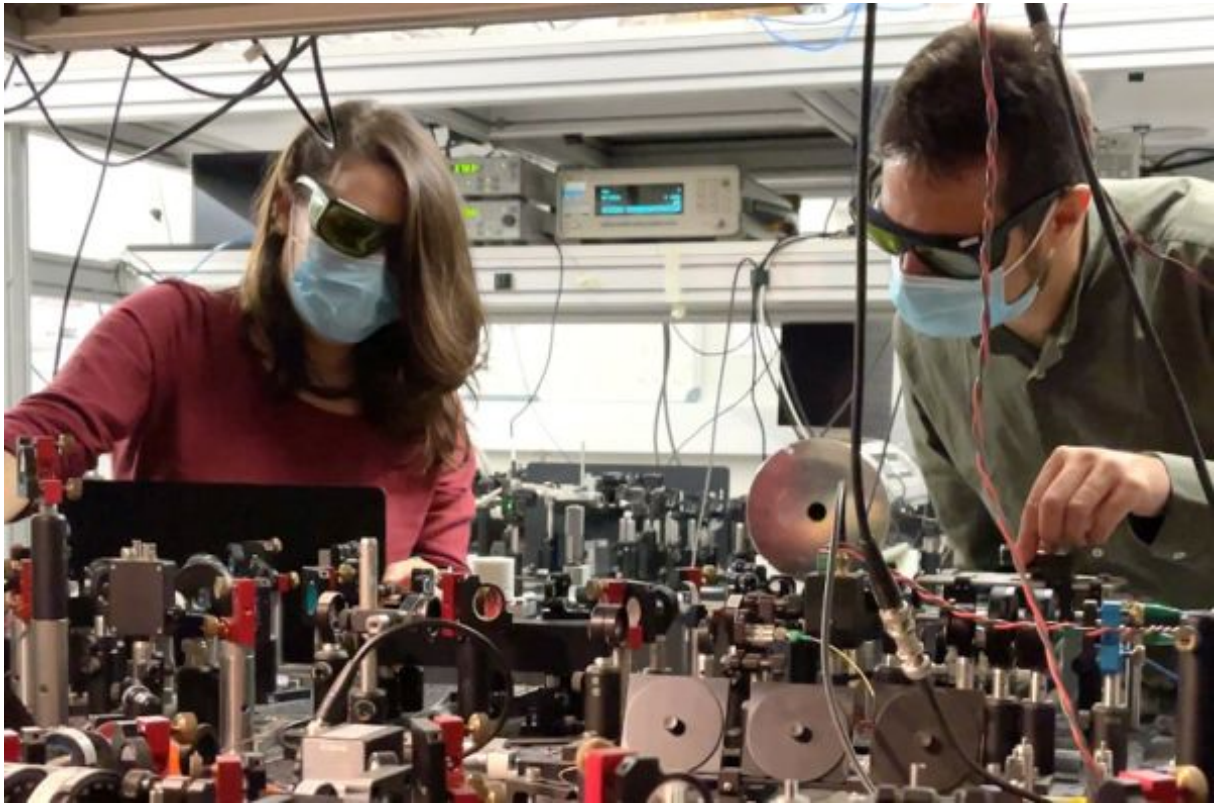




Ultra-precise magnetic field detection using squeezed light

Researchers from ICFO and Hangzhou Dianzi University show experimentally that extra-quiet light can make a sensitive magnetometer even more sensitive.

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Precise detection of magnetic fields is important for applications that range from magnetic brain imaging, to detection of sunken ships, to exploration of the solar system. For many of these applications, the most sensitive magnetic-field measuring instruments (magnetometers) are $\frac{1}{2}$ optically-pumped magnetometers, $\frac{1}{2}$ which use laser light to probe magnetically-sensitive atoms. In many cases, the sensitivity of these instruments is limited by random variations (noise) in the laser light used. If that noise can be reduced, the magnetometer becomes more sensitive, and tinier changes in the magnetic field can be detected.

Scientists work hard to make their lasers as noise-free as possible, but there are limits: light, even laser light, arrives as packets of energy (photons), and the random arrival of these

photons produces a noise known as shot noise. Even the quietest laser still has shot noise, and this often sets a limit on how precise a measurement can be.

Nevertheless, the shot-noise limit is not absolute. If one could organize the photons to arrive in a more regular stream, more like beer flowing out of a tap in a bar, than like raindrops falling randomly on a roof, the light stream would be quieter and the measurement more precise. While it is not easy to organize photons in this way, it is not impossible. The idea, known as squeezed light, was proposed by a theoretician in 1981 as a way to improve the sensitivity of gravitational wave detectors, which also use laser light. Four decades later, squeezed light is routinely used in gravitational wave detectors like LIGO and VIRGO to improve the sensitivity, and to understand more precisely events like the collisions of black holes.

Could this squeezed light technique also improve magnetometers? Until this article, the answer was unknown. The earliest experiment to apply squeezed light to a magnetometer (also performed at ICFO) had seen an improved sensitivity. But a later experiment, with a more sensitive magnetometer, then reported the opposite, that the squeezed light did not help. For nearly a decade, the question remained open, can squeezed light improve the sensitivity of a sensitive magnetometer?

In a recent study published in Physical Review Letters, ICFO researchers Charikleia Troullinou, Ricardo Jimenez-Martinez, Vito Giovanni Lucivero, led by ICREA Prof at ICFO Morgan Mitchell, and in collaboration with Jia Kong from Hangzhou Dianzi University in China, resolve this question. They show that the critical factor is the evasion of measurement back-action. That is, the light that probes the atoms must only disturb the atoms in ways that do not change their response to the magnetic field. They then constructed a back-action evading magnetometer, applied squeezed light, and saw that this improved the sensitivity.

In their experiment, the team built a Bell-Bloom (BB) optically pumped magnetometer (OPM) and used polarization squeezed light to observe the response of a dense, hot cloud of rubidium atoms (^{87}Rb) to a magnetic field. As Charikleia Troullinou comments, **"We used linearly polarized light to probe the magnetic properties of the hot dense atomic ensemble and implemented a very sensitive magnetometer limited mainly by quantum noise. On top of that, the generation of squeezed light and its use for probing instead allowed us to suppress the photon shot noise in the signal. We showed that this directly improves the magnetometer's performance, making it more sensitive and better in its response to fast signals."**

What is quantum measurement back-action? What is back-action evasion?

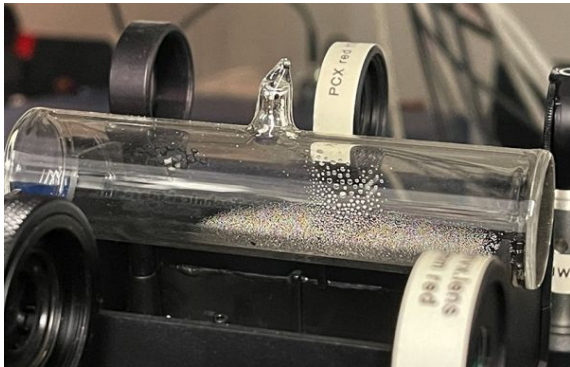
When you measure a microscopic system like an electron or an atom, the microscopic system influences the measuring instrument - it causes some change that we can detect. This influence is the *“action”* of the microscopic system on the instrument. The Heisenberg uncertainty principle says that the instrument must also cause a *“quantum measurement back-action”* (or simply *“back-action”*) on the microscopic system. For example, if you measure the position of an electron, the back-action disturbs its momentum. More complex measurements can be spoiled by this back action. For example, if you try to measure the electron's velocity by measuring position now, waiting a time, and then measuring position again, you will be disappointed to find out that your result is inaccurate: the back-action of the first position measurement disturbs the momentum, and thus the velocity before you can finish the measurement. A *“back-action evading measurement”* is one that does not have this problem - the microscopic system gets disturbed by the measurement, but in a way that does not spoil the measurement procedure.

Dr. Lucivero comments ***“We figured out that, in the context of atomic sensors, the Bell-Bloom measurement scheme is naturally backaction evading, since the backaction noise affects the spin component that is not measured. Then the effect of squeezed-light is beneficial over the entire frequency spectrum.”***

As ICREA Prof. at ICFO Morgan Mitchell comments ***“The important and surprising thing about this result is that squeezed light improves the sensitivity of a good magnetometer, used in a way that good magnetometers normally operate. This means the technique could be put into practice almost immediately, for example on magnetometers used in geotechnical applications. It also means that one can have all the advantages already identified for these magnetometers, plus the sensitivity boost from squeezed light. It really is a “free lunch” - something good with no negative side-effects.”***

FIGURE DESCRIPTIONS Figure 1 Description: Charikleia Troullinou and Dr. Vito Giovanni Lucivero working in the experimental setup in the lab at ICFO. Image credit: ©ICFO

Figure 2 Description: Glass cell containing the rubidium metal that are mixed with nitrogen gas and heated up to 105° Celsius. At that high temperature, the metal vaporizes, creating free rubidium atoms that diffuse around inside the cell. Image credit: © ICFO



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