# QnAs with Mikhail D. Lukin

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A professor of physics at Harvard University, Mikhail D. Lukin was elected to the National Academy of Sciences in 2018 for his work in quantum optics and quantum information science. Lukin has explored a variety of topics during his career, from quantum manipulation of atomic and nanoscale systems to nanophotonics and quantum metrology. He has developed several techniques, with applications including the realization of quantum computers and quantum networks and quantum sensors that can be used in materials science research and biological imaging. In his Inaugural Article (1), Lukin and colleagues used quantum temperature sensors and local laser heating to manipulate cell cycle timing in embryos of the nematode worm *Caenorhabditis elegans*, a model organism for cell and molecular biology research. Lukin recently spoke to PNAS about his findings.

Image credit: Mikhail Lukin.

**PNAS:** How did you become interested in using quantum sensors to study biological systems?

**Lukin:** I'm a quantum physicist, and my "day job" involves building quantum machines, such as quantum computers, quantum simulators, and quantum communication systems. Over the past two decades our community has developed very sophisticated and unique tools to study and control quantum systems. We have learned how to look at atoms one at a time and how to control electrons one at a time. Several years ago, we realized that some of the tools that we were developing to advance this quantum frontier can also be very useful to create a new generation of sensing and imaging instruments for areas like biology and medicine.

**PNAS:** What kind of tools did you develop to study *C. elegans* embryogenesis?

**Lukin:** A few years ago, we realized that we could use quantum systems for applications in nanoscale sensing. The key idea is to use small atom-like impurities in a diamond crystal. Diamonds are normally transparent and colorless, and what makes them colorful are defects or impurities. If you use special types of impurities in diamonds and control them at the single-atom level, these individual impurities can behave quantum mechanically even under ambient conditions. It turns out one can use them to make exquisite sensors. They can measure things like magnetic fields, temperature, and many other parameters of a system. This is the primary tool that we have been using to look at small objects, for applications such as magnetic resonance imaging at the level of an individual molecule.

About six or so years ago we did a proof-of-principle experiment where we introduced small diamond particles into living cells and used these particles to measure the temperature locally inside the cells. We used local heating with a laser to control the temperature very carefully, to the point where we could control whether a cell was dead or alive by varying the temperature. These experiments were



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very much proof-of-concepts, but we started thinking about whether we could use these tools for real-world biological applications. That's why this new paper (1) is special.

**PNAS:** What did you find?

**Lukin:** We looked at the cell division process in worm eggs. By using a combination of laser heating and very precise temperature measurement via small diamond particles, we can selectively accelerate the development of different cells. We can speed up the development of certain cells relative to each other and actually break the normal sequence of cell division. And then we could look at how cells develop after the sequence is broken. It was not clear whether this process would kill the cell, or [if] the cell would be able to somehow restore its normal development order. It turns out it's the latter. Cells seem to have a built-in mechanism where after a certain number of cell divisions there is some kind of checkpoint that restores the original development order. The result is that you get healthy worms despite the broken cell division sequence. I think that's the key result, and what's very special is that we used these tools from the field of quantum science to really monitor and control these biological processes.

**PNAS:** What kind of experiments could these tools be used for?

**Lukin:** This experiment proves that the tools that we developed could be extremely useful to look at many unique features of biological processes that people were not able to look at previously. I think this opens up many opportunities to study how a cell develops and to understand processes inside the cell, such as energy and heat generation. For example, there are many open questions about how much heat is generated by mitochondria in the cell, which scientists are struggling to understand. I think these new tools will be very helpful to answer some of these questions.

**PNAS:** What were some of the challenges of using quantum sensors to study biological systems?

**Lukin:** If you want to use quantum sensors, generally, what you need to do is to completely isolate a system from the environment to preserve [a] so-called quantum superposition state. For example, usually if you want to build a quantum computer, you need to have your system isolated using high vacuum and very low temperatures. Here, we actually used quantum sensors in a living biological system, and needed to manipulate this quantum object and measure it within a real biological environment. For example, these small diamond particles need to be delivered into the worm egg, positioned properly, and it should all happen without disturbing the normal process of development. It required a multiyear collaboration with colleagues from several leading groups with complementary expertise in completely different fields of science to realize these ideas. In a way, it's amazing that it really works. If someone had asked me 10 years ago if anything like this was possible, I would have said "absolutely not." It's a remarkable example of how techniques from the field of quantum science and engineering can really have an impact across a broad array of subjects.

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**1** J. Choi *et al.*, Probing and manipulating embryogenesis via nanoscale thermometry and temperature control. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 14636–14641 (2020).