Alexander Sushkov's group is using magnetic resonance to search for dark matter and build nano-sized imaging machines

By Tess Joosse

How do you detect a force that is thought to be everywhere, but has never been identified? How do you build a machine capable of looking into the smallest parts of a living organism? In Alexander Sushkov's laboratory, questions like these – and the thrill of the challenge – power the group's quantum physics research.

"The main theme of our lab is precision," Sushkov says. "We do precision experiments that explore some unexplored space or unexplored territory of fundamental physics, searching for something that no one has ever seen before."

But the group isn't just focused on discovery; they're also interested in using that fundamental knowledge to build new quantum tools for precision measurements. "Can we use some of these tools and techniques to actually develop new technologies?" says Sushkov, a Boston University Photonics Center faculty member. He was recently awarded tenure and promoted to associate professor in the BU College of Arts & Sciences department of physics.

One area of research his team drills down on is magnetic resonance, the phenomenon of atomic spin that powers the MRI (or magnetic resonance imaging) machine you might encounter when receiving a diagnosis for an injury or illness. Atoms have an inherent spin like the needle of a compass, and the lab's magnetic resonance experiments seek to measure and manipulate these spins, Sushkov explains.

"We try to control the evolution of these compass needles. Controlling their dynamics can be done by applying currents and voltages, creating electric and magnetic fields, or with lasers and various tools that we have in the lab," he says.

Their goal is to push the limits in terms of how precisely they can measure and control magnetic resonance. "Our task is to take magnetic resonance to its very fundamental limits of precision, [which are governed] by quantum mechanics. So, what we want to do is take magnetic resonance to its fundamental quantum limits of sensitivity, and maybe even try to answer the question, 'Can we actually beat some of these quantum limits and do better?'"

The team's research could help solve one of the most puzzling and pressing pursuits in the field of physics: the hunt for dark matter.

"No one knows what dark matter is," Sushkov says. "We suspect that it's there – there's lots of evidence that it is." Scientists first caught signs of it when they noticed that stars were moving faster around their galaxies than they should be based on their mass, and other observations since have hinted that dark matter exists and is ubiquitous.

Dark matter is thought to make up a huge fraction of the universe as non-visible matter. But its exact identity and composition is a mystery, Sushkov explains. Physicists have suggested several possibilities, including black holes and hypothetical particles including Weakly Interacting Massive Particles (or WIMPs) or the axion, which is Sushkov's focus.

"It wasn't originally invented as a dark matter candidate," he says of the axion. "It was [first described] in the 1970's to reconcile some problems with the Standard Model." But this theoretical particle, so light it almost behaves like a wave, has qualities that make it a possible component of dark matter. Sushkov is now searching for it in his lab. "Let's run some experiments that push the boundary and ask the question: If an axion was dark matter, how can we detect it?" he says of the experiments.

Sushkov and his colleagues have devised a benchtop detector called the Cosmic Axion Spin Precession Experiment, or CASPEr. "This setup looks similar to MRI," he explains. "It's a fairly large superconducting magnet that's sitting inside a refrigerator at temperature just above absolute zero." The researchers place a small amount of solid matter inside the magnet and use sensors to measure how the many atomic compass needles in the solid are spinning.

If axion dark matter were to exist, it would torque the compass needles of these atoms, Sushkov explains. "You can think of it as a tiny little magnetic field that tilts the needles a little bit. And that's what we're searching for in our machine. We very precisely measure the evolution of these spins, search[ing] for a tiny little tilt that we can then attribute to an interaction with axion dark matter."

Suskhov compares the group's search for the axion to the quest of an explorer setting sail for a faraway land that might exist… or might not. "We're exploring. We think that maybe it's there, but we have to go and discover it," he says.

In addition to their dark matter investigations, the Sushkov lab uses magnetic resonance experiments to create new measurement tools from a much more well-known material – diamonds. Specifically, they are interested in exploiting a feature of lab-grown diamonds called a nitrogen vacancy center, which "acts as an isolated atom trapped inside the diamond crystal," Sushkov explains.

The nitrogen vacancy center has a compass needle spin, too. "We can manipulate what this spin does using a green laser, and then we can read out the dynamics of this atomic spin using just a microscope," he says. The researchers are probing how to fashion these spinning centers into a nanoscale MRI machine that could be trained on single cells or even smaller subjects, potentially a huge boon to biomedicine and life sciences research.

"If your sample is a single molecule or a virus or a cell, this approach makes sense because now your sensor itself is also of the same size or smaller than the feature you're trying to measure," Sushkov says.

The team uses Photonics Center cleanroom facilities to fabricate devices used in these diamond experiments and in their dark matter searches, and Sushkov says he values regular interaction and collaboration with other Photonics Center faculty members. He also works closely with researchers in the physics department's condensed matter theory group. "They are very good at coming up with approaches for controlling these atomic spin systems in a way that will let us run our precision measurements with better sensitivity," he says.

Within the lab, Sushkov enjoys being at the bench with the postdoctoral scholars and graduate, undergraduate, and high school students that make up his group. "Putting together the experiment, taking measurements, and analyzing data side by side, that's the most rewarding thing," he says. "There's certain knowledge and skills that can be transferred remotely. But for the most important things, you really need to watch someone work."

Beyond training them in specific experimental techniques, Sushkov also relishes watching his students grow into scientific thinkers. "I think the most important skill students get to learn in physics is problem solving," he says. These intellectual and technical obstacles are what attracted Sushkov to experimental physics early on in his own studies, after initially thinking his career might take a different direction.

"I wanted to be a theorist when I got into grad school," he says. "I talk to my undergraduate students about this all the time – you have to try a bunch of stuff. I tried doing some experimental research, and it gradually became clear that I was more suited to and interested in [it]."

The challenges of experimental research are what drew him in most.

"These kinds of precision measurements – they're hard to do. It takes a long time, one has to think very carefully about what they're doing, and one has to persist," Sushkov says. "It's high risk, one has to invest a lot of time and energy and effort into the work, but the payoff is that we could measure something more precisely and more accurately than anyone has ever done before."

Sushkov says he is always motivated by how his team's research could be applied in the real world, in addition to being added to physics textbooks someday.

"The reward in the short term is finding a solution and getting stuff to work," he says. "But in the long term, it's also ensuring that this problem I'm working on is not something that's completely abstract, but may ultimately lead to new knowledge or some new technologies that will hopefully improve our day-to-day lives."