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Sensing Disturbances in the Force

It will be a feat of engineering and physics at the smallest scales, but it could open the biggest doors — to new science and more advanced technologies. UC Santa Barbara physicists Ania Jayich and David Weld, and materials scientist Kunal Mukherjee, are teaming up to build an atom-defect hybrid quantum system — a sensor technology that would use the power of quantum science to unlock the mysteries of the atomic and subatomic world.

“We’re at this tipping point where we know there’s a lot of impactful and fundamentally exciting things we can do,” said Jayich, whose research investigates quantum effects at the nanoscale. The $1.5 million grant from the Department of Energy’s Office of Basic Sciences will kickstart the development of a system that will allow researchers an unusually high level of control over atoms while simultaneously leaving their “quantumness” untouched.

“In this whole field of quantum technology, that has been the big challenge,” Jayich said. In the quirky and highly unintuitive world of quantum mechanics, she explained, objects can exist in a superposition of many places at once, and entangled elements separated by thousands of miles can be inextricably linked — phenomena which, in turn, have opened up new and powerful possibilities for areas such as sensing, computing and the deepest investigations of nature.

However, the coherence that is the signature of these quantum behaviors — a state of information that is the foundation of quantum technology — is exceedingly fragile and fleeting.

“Quantum coherence is such a delicate phenomenon,” Jayich said. “Any uncontrolled interaction with the environment will kill it. And that’s the whole challenge behind advancing this field — how do we preserve the very delicate quantumness of an atom or defect, or anything?” To study a quantum element such as an atom, one would have to interrogate it, she explained, but the act of measuring can also destroy its quantum nature.

To Hold Without Touching

Fortunately, Jayich and colleagues see a way around this conundrum.

“It’s a hybrid atomic- and solid-state system,” Jayich said. Key to this technology is the nitrogen-vacancy (NV) center in diamond, an extensively studied point defect in diamond’s carbon atom lattice. The NV center is comprised of a vacancy created by a missing carbon atom next to another vacancy that is substituted with a nitrogen atom. With its several unpaired electrons, it is highly sensitive to and interactive with external perturbations, such as the minute magnetic or electric fields that would occur in the presence of individual atoms of interest.

“In the proposed experiment, we would have an atom on the diamond surface that couples to a shallow, subsurface NV center inside the material, in a highly controlled, cryogenic and ultra-high vacuum environment,” Jayich explained. The diamond surface provides a natural trapping that allows researchers to more easily hold the atom in place — a challenge for many quantum scientists who want to trap individual atoms. Further, upon reading the state of the defect, one could understand the quantum properties of the atom under interrogation — without touching the atom itself and destroying its coherence.

Previous methods aimed at interrogating individual adatoms (adsorbed atoms) relied on passing current through the atoms and necessitated metal surfaces, both of which, according to Jayich, reduce quantum coherence times.

“The past several decades of work in atomic physics have resulted in tools that allow exquisite quantum control of all degrees of freedom of atomic ensembles, but typically only when the atoms are gently held in a vacuum far away from all other matter,” added Weld. “This experiment seeks to extend this level of control into a much messier but also much more technologically relevant regime, by manipulating and sensing individual atoms that are chemically bonded to a solid surface.”

With the hybrid system, Jayich said, it would be “very easy to talk to the NV center defect with light, and the atoms have the benefit of retaining quantum information for very long periods of time. So we have a system where we leverage the best of both worlds — the best of the atom and the best of the defect — and put them together in a way that’s functional.”

A Foundation for Future Quantum Tech

Looking forward, the state-of-the-art spatial resolution and sensitivity of this atom-defect hybrid quantum system could offer researchers the deepest look at the workings of individual atoms, or structures of molecules at nanometer- and Angstrom scales.

“If you can see things on smaller scales with better sensitivity than anybody else, you’re going to find new physics,” Jayich said. The connections of microscopic structure to macroscopic behavior in materials synthesis could be elucidated. Quantum phenomena in condensed matter systems could be probed. Proteins that have evaded structural determination — such as membrane proteins — could be studied.

This project is a “natural fit” for UC Santa Barbara, say the researchers, due to the campus’s strengths in both physics and materials sciences. The technique is reminiscent of molecular beam epitaxy (MBE), a method of “growing” a material atom-by-atom on a substrate.

“There is a strong tradition of materials deposition at UCSB, ranging from metals, semiconductors to novel electronic materials,” Mukherjee said of the campus’s long record of materials growth and world-class MBE facilities. Among the first few atoms they intend to study are rare-earth types such as holmium or dysprosium “as they have unpaired electrons which are protected from environmental interactions by the atomic structure,” noted Mukherjee, adding that he is “particularly excited” about the challenge of removing the atoms from and resetting the diamond surface without breaking vacuum.

Additionally, the physical and materials knowledge gained by mastering the interface of such a hybrid system would contribute to the development of quantum computing systems. According to Jayich, future practicable quantum computers would likely be a hybrid of several elements, similar to how conventional computers are a mix of magnetic, electronic and solid-state components.

About UC Santa Barbara

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