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COVID-19 pandemic for up to half of that cost overrun. Slippage in the project's completion date was caused by contractor performance and the contractor's failure to notify the NNSA of cost overruns in a timely enough manner to inform the budget process, it said in the FY 2025 budget request.

Spaulding sees another factor responsible for the burgeoning costs for maintaining and modernizing the weapons complex: the "pyramid of contractors" that manage the work. The weapons labs are now operated by partnerships that include contractors such as Battell, Bechtel, Honeywell, and BWX Technologies, he notes.

David Kramer

New center for quantum sensing focuses on medical applications

The techniques promise earlier disease detection that can lead to better outcomes.

Clogged arteries. Osteoporosis. Malnutrition. Brain disease. With quantum sensing, those and other ailments could be detected earlier than is currently possible. The emerging field got a boost in late February: a six-year grant totaling about $22 million from the Novo Nordisk Foundation to form the Copenhagen Center for Biomedical Quantum Sensing.

The new center is a collaboration among three university physics groups—two in Denmark and one in the US. The researchers plan to use squeezed light, entangled atomic spins, and purified stable isotopes to develop and implement detection methods that push sensitivity limits in disease diagnostics.

Medical diagnostics is a relative newcomer to the burgeoning field of quantum sensing, which has applications in communications, imaging, seismology, and other areas. A growing number of research groups, perhaps as many as 50 worldwide, are doing work related to what will be done in the new center, notes Eugene Polzik of the Niels Bohr Institute at the University of Copenhagen and the center's director. "Our strength is in collaboration and in our strong focus on applying novel quantum measurement principles toward goals in biomedical applications. We are also working closely with life scientists and medical doctors."

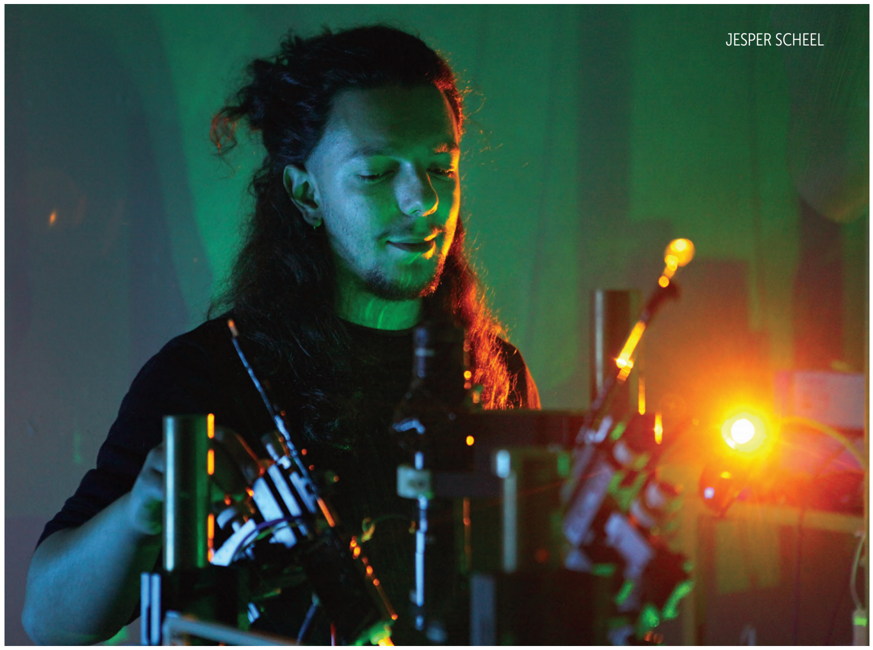
The center fits into a broader quantum strategy that the Novo Nordisk Foundation adopted a few years ago, says Lene Oddershede, the foundation's senior vice president for natural and technical sciences. It had already been funding quantum computing for a while, with the long-term goal of solving problems in the life sciences, she says. "Now we are supporting quantum sensing with the aim of harvesting nearer-term applications in biology and medicine. I believe quantum technology can have an enormous impact on sustainability and health." (See the interview with Oddershede, who left a position as a tenured physics professor to join the foundation, at http://physicstoday.org/oddershede.)

Quantum technologies

Polzik and his research team use atomic spins as magnetic sensors, expanding on techniques that his and other groups

JACKSON WILLIAMS/NOVO NORDISK FOUNDATION

IN THIS QUANTUM MAGNETIC SENSOR, cesium atoms are in a channel that preserves atomic spin state for many milliseconds—long enough for biomedical magnetic field measurements. The channel's cross section is 300 × 300 microns. The sensor, which records collective spin states, was made at the Niels Bohr Institute in Copenhagen by the group of Eugene Polzik, director of the new Copenhagen Center for Biomedical Quantum Sensing.



LUCA TROISE, a postdoc at the Technical University of Denmark, uses a quantum diamond sensor to measure neural activity in a slice of mouse brain. Magnetic fields from firing neurons affect spins in the sensor, which in turn govern the resulting fluorescence. The project is part of the new Copenhagen Center for Biomedical Quantum Sensing.

developed over the past decade or so. The sensitivity is not limited by "quantum mechanics taken naively," he says: Take two spins, orient them oppositely, and entangle them. If nothing happens, they remain antiparallel. But if one of the spins is subject to a magnetic perturbation, the two spins will not be exactly antiparallel. The relative orientation of spins can be determined, he says, "so you can measure the deviation from parallelism with sensitivity not constrained by the standard quantum limits that stem from the Heisenberg uncertainty principle for a single spin."

Polzik and his colleagues are keen to take their tricks of getting around standard quantum limits and apply them to "relevant measurements." Improving the spatial resolution of MRI is "the lowest hanging fruit," Polzik says. Small sensors—based on cesium atoms—placed around a patient's head monitor the local magnetic field extremely precisely, which improves the diagnostic potential. His team and his medical collaborators hope to deploy the approach in a couple of years.

A spin-entanglement approach can also detect conductivity in arteries and organs, Polzik says. Changes in local electrical conductivity can indicate changes in health. For example, if vessels become clogged from a heart attack or other heart problem, the conductivity decreases. Doctors currently insert wires to measure conductivity, says Polzik. "Our devices will aim to probe noninvasively."

By generating entanglement to get more precise measurements, Polzik says, "we may be able to get the spatial distribution of conductivity—and then tell you where in the heart or brain a problem is."

A few kilometers north at the Technical University of Denmark in Kongens Lyngby, Ulrik Andersen, a principal investigator with the new center, uses diamond crystals to detect weak magnetic fields in biomolecules, individual cells, and biological tissue. The technique involves creating so-called color centers by knocking out two neighboring carbon atoms from a crystal; one is replaced with nitrogen, which results in a pink tint (and the moniker), and the other remains vacant. Electrons are then trapped in the color centers. A change in the spin of the trapped electrons can be read optically to indicate, for example, a firing neuron. (See the article by Lilian Childress, Ronald Walsworth, and Mikhail Lukin, Physics Today, October 2014, page 38.)

"When a neuron fires, a magnetic field is generated, which can be sensed by the trapped electrons," says Andersen. His group collaborates with biologists who prepare samples of mouse brain tissue; the samples remain active for about 24 hours. The diamond sensors can image the magnetic field with high spatial and temporal resolution, he says.

Andersen also works on microscopy techniques that push sensitivity. "With squeezed light, we can manipulate the quantum fluctuations of the light field," he says. The Heisenberg uncertainty principle holds, he continues, but by redistributing the uncertainties among the amplitude and phase, "you can decrease the noise in the amplitude measurement and increase the sensitivity of your measurement." (See, for example, the Quick Study by Sheila Dwyer, Physics Today, November 2014, page 72.) "If we can use such light to image biological systems," he says, "we will be able to increase the imaging speed and quality significantly. That is the next step."

Mark Raizen at the University of Texas at Austin is the third principal investigator with the new center. He developed a method for separating stable isotopes, in which a collimated atomic beam is optically pumped with a laser to change the magnetic moment of a specific isotope, thereby allowing the desired isotope to be separated with an applied magnetic field (see Physics Today, September 2016, page 22). He's now focusing on putting separated isotopes to medical use in combination with squeezed-light sensing techniques. The most advanced application to date involves testing individuals' absorption of iron from food, a collaboration with Steven Abrams, a pediatrician and researcher at Dell Medical School, part of the University of Texas Medical Center in Austin.

"Iron deficiency exceeds all other forms of malnutrition," says Abrams, noting that it can cause developmental delays and brain damage. Half of the world's children and women in low- and middle-income countries are iron deficient, he says. In the US and other industrialized countries, that number is about 20%. Iron is plentiful, but adding it to food such that the taste is tolerable and the iron is absorbable can be challenging.

Abrams screens for iron absorption by adding iron to a food typical to a given test population. He uses the rare iron-58 enriched to more than 90%; the abundance of that isotope relative to the natural presence in later blood tests provides evidence of absorption. The plan to use squeezed-light spectroscopy for the analysis will both simplify the measurement—the method is cheaper and more portable than traditional mass spectrometers—and reduce the amount of blood needed. Raizen has been championing the use of atomic-physics methods for blood tests. "We could detect tiny amounts of iron from a single drop of blood. That's important for infants. A heel prick is sufficient."

For now, Abrams has stocks of iron isotopes from Russia, but the plan is for Raizen to produce those and other isotopes with the separation method he pioneered. They would be produced at his nonprofit Pointsman Foundation.

Tracing isotopes with quantum spectroscopic methods has promise for other health issues too: Calcium isotope ratios can be used to diagnose early-stage osteoporosis and kidney disease; zinc isotope ratios can indicate pancreatic cancer; copper isotope ratios can detect liver and ovarian cancers. By testing early and noninvasively, says Raizen, the treatment options are improved.

Raizen notes that the new center's longer-term plans include setting up satellite isotope-preparation sites to widen the availability of isotopes that can be used in combination with quantum sensors for medical diagnostics. The Novo Nordisk Foundation is looking at possibilities to team up with the Pointsman Foundation on a site in Copenhagen, says Oddershede. "Isotopes will be essential for the applications we envision."

"An important trend"

Martin Plenio is a theoretical physicist and the founding director of the four-year-old Center for Quantum Bio-Sciences at Ulm University in Germany. One of that center's projects, which has spawned a startup company, involves monitoring cell metabolism in tumors: By tagging molecules with carbon-13 and using quantum techniques to polarize and control the isotopes' spins, researchers enhance MRI signals by a factor of as much as 10 000, enabling temporal and spatial measurement of low concentrations of metabolites. The resolution makes it possible to see whether chemotherapy is effective, and if it's not, to change the drugs, says Plenio. "It's much faster than waiting to see if a tumor shrinks in response to treatment." Other studies of cell metabolism at the center use nanodiamonds to measure radical formation in ensembles of cells.

When he first became interested in applying quantum technologies to living systems, Plenio says, "people were skeptical. Now there is a growing recognition that gaining even one order of magnitude in sensitivity can make a huge difference."

Not directly involved in the new Denmark–US center, Plenio sees it as "a significant step in an important trend," because life sciences is an area for which quantum sensing can have a real impact. "I think we will see results fastest in this area of quantum technology."

Toni Feder

The many lives of an 11th-century astrolabe

An art historian uncovers an astronomical device that exposes centuries of cross-cultural exchange.

It started, as internet diversions often do, with a Google search. Art historian Federica Gigante was preparing a lecture last year when a search for one 17th-century art collector, Ludovico Moscardo, happened to return an image of Moscardo's collection. Looking closely, Gigante spotted "something that looked like an astrolabe," an astronomical device often used for timekeeping that was developed in antiquity but is associated primarily with the medieval Islamic world.

The find piqued the interest of Gigante, whose work at the University of Cambridge focuses in part on astrolabes and other Islamic astronomical instruments. After receiving photos of the device from the curator of a museum in Verona, Italy, Gigante went to examine the astrolabe in person (in part, she confesses, because she wanted an excuse to visit her parents).

FEDERICA GIGANTE examines the 11th-century astrolabe. She is holding the *mater*, or base disk. Visible on the table are the two removable plates and the mesh-like *rete*.

FEDERICA CANDELATO