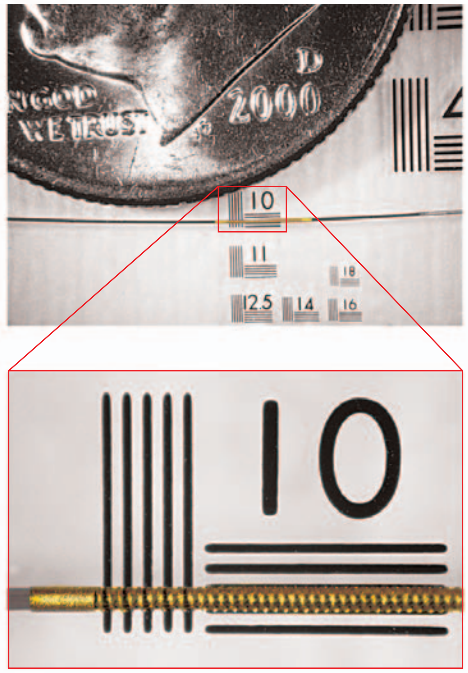
A 1-Ton Device in a Briefcase

NUCLEAR magnetic resonance (NMR) spectrometry is known for its ability to rapidly identify chemicals. Because this technique does not compromise the sample, the sample's properties remain intact for additional testing. A typical NMR spectrometer, however, weighs a ton and occupies an entire laboratory. A research team from Livermore's Physical and Life Sciences Directorate has revamped the technology so that it weighs a mere 9 kilograms (20 pounds) and fits inside a briefcase. The new device can be transported into the field for on-the-spot analysis of potential chemical warfare agents or other hazardous chemicals.

NMR spectrometry measures how nuclei move in a magnetic field. Electromagnetic pulses generated by the spectrometer move through a sample, and the material's nuclei are "excited," absorbing energy from the pulse and subsequently radiating energy back out. Changes in the resonant frequency of each nucleus due to the surrounding electrons provide a fingerprint that distinguishes different molecular structures, making NMR spectrometry a

A portable nuclear magnetic resonance (NMR) device developed at Livermore fits inside a briefcase. Members of the development team (from left) Lee Evans, Joana Diekman, Kristl Adams, and team lead Julie Herberg display the new device next to a laboratory-scale NMR spectrometer.

powerful tool that is used extensively for chemical, material, biological, and medical applications. Separation techniques such as liquid chromatography and capillary electrophoresis are routinely coupled with an NMR analysis to supply additional information about a sample. Together, these tools can separate, unambiguously identify, and provide structural information about samples in small volumes.



Microcoils for the portable NMR chemical sensor are made using a programmable laser lithographic method called LaserLathe, which was developed at Livermore. Microcoils made with this technique can be as small as 100 micrometers in diameter.

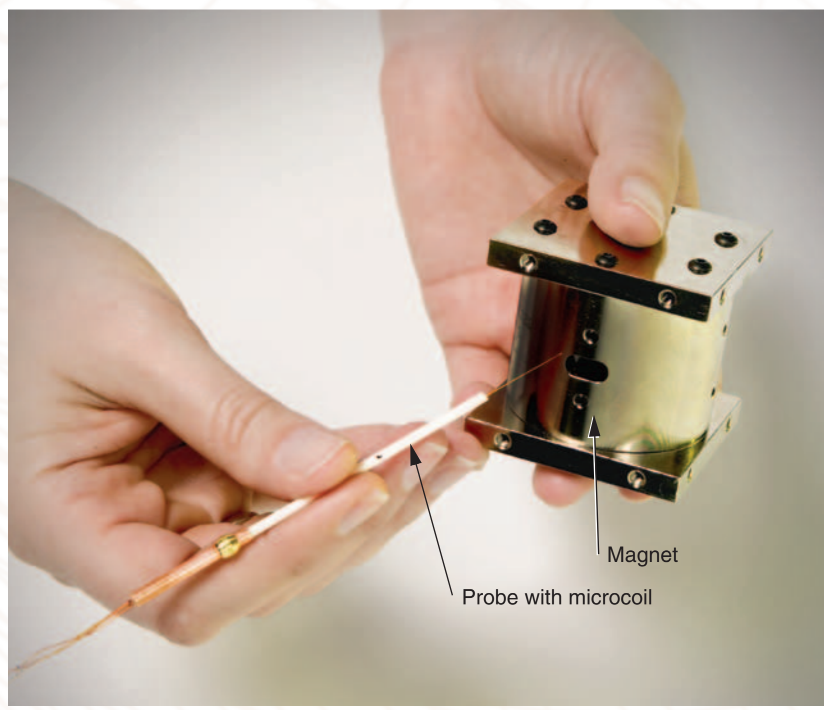
When Time Is of the Essence

The portable NMR device, which was developed with funding from the National Nuclear Security Administration's Office of Nonproliferation Research and Development, can identify the signatures of chemical and biological weapons, narcotics, explosives, toxins, and poisons. "At the moment, we are focusing on chemical agents, typically in very small quantities," says Livermore physicist Julie Herberg, who leads the portable NMR development team. "These agents are usually oils that decompose in a short time, so responders need a tool in the field that can evaluate substances quickly." She notes that mass spectrometry, which measures the mass of individual ions, can identify chemical agents more quickly but with less specificity than NMR.

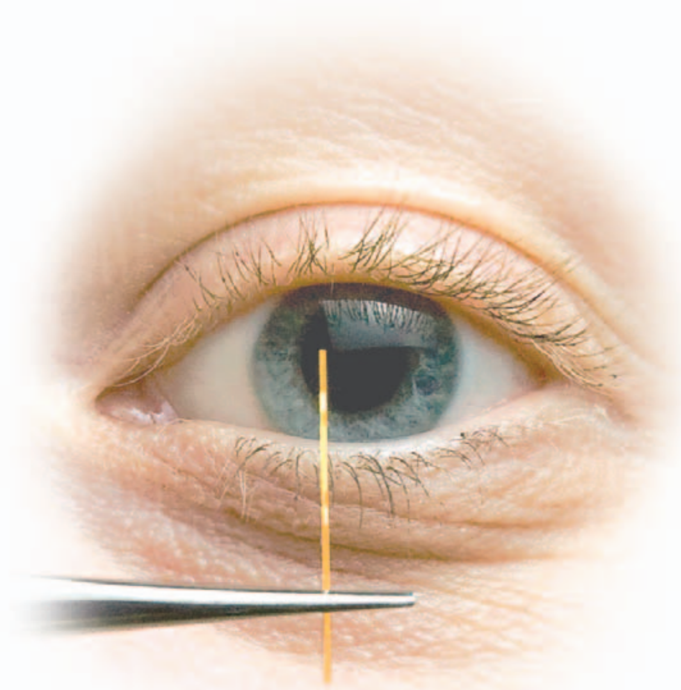
A typical NMR spectrometer requires huge superconducting magnets that are cooled with liquid nitrogen. Livermore's briefcase-size device operates on the same principles as the laboratory-scale machine, but it has a small permanent magnet that does not require cooling.

In the portable NMR briefcase, samples are introduced to the system through tiny capillaries. Three-dimensional lithographic and laser-cutting techniques combine to etch micrometer-scale coils on the capillary wall. "Other research groups are developing small NMR instruments," says Herberg, "but the coils on those machines are typically hand-wound, which limits the coil size, configuration, and reproducibility." In contrast, a Livermore-designed technique called LaserLathe can be programmed to repeatedly produce the miniature helical radio-frequency coils that are at the heart of any magnetic resonance system. The LaserLathe can fabricate radio-frequency coils with adjustable widths and line spacings on tiny capillary tubes ranging from 0.1 to 1.3 millimeters in diameter. A lithography-on-cylinder technology, LaserLathe is also used to produce heating wires around hohlraums for fusion experiments at the National Ignition Facility and coils for guide catheters in magnetic resonance imaging procedures.

With the microcoil, the smaller device is as accurate as the laboratory-scale spectrometer with its huge superconducting magnet and can analyze concentrated samples in volumes as small as a microliter or even a nanoliter (10^{-6} or 10^{-9} liters). To improve the portable device even more, the Livermore team is coupling it with capillary electrophoresis to provide concentrated samples that are separated for analysis. In the combined technique, the miniscule sample is added to a 360-micrometer capillary filled with a buffer



Livermore physicist Kristl Adams holds the completed probe assembly for the portable NMR sensor. The probe, which contains the sample capillary inside a larger microcoil-wrapped capillary, is inserted into the permanent magnet for sample analysis.



Livermore physicist Julie Herberg holds a microcoil through which a chemical passes for NMR analysis. The miniaturized coil makes the portable NMR system feasible.

solution. The capillary ends are placed in the buffer, and a voltage is applied. Electrophoresis then separates the chemical species based on the different molecules' size and charge.

"We use a capillary within a capillary," says Herberg. "This setup allows a responder in the field to easily replace the inner capillary should it clog or break. The design also provides continuous current across the capillary for good electrophoresis separations."

Conundrums to Solve

Although the system is transportable and functioning, the team is still working to improve the device. One concern is that the electrophoresis current distorts the NMR signal. The team's solution is to stop the voltage during NMR acquisitions, in other words, to apply voltage only between scans.

Another issue is balancing NMR sensitivity and electrophoresis resolution. For optimal NMR, the higher the sample concentration is, the higher the spectrometer's sensitivity will be. But capillary electrophoresis requires very small samples and lower concentrations, in the parts-per-million range. Using a capillary with a large inner diameter allows more sample into the coil volume, which will increase NMR sensitivity but can result in less homogeneity from the magnetic field and the coil itself. A capillary with a smaller internal diameter combined with high voltage and small sample size results in the best electrophoresis resolution but decreases the NMR detection limit.

Yet another challenge is that the field strength of the device's permanent magnet fluctuates with temperature. "If samples are of low concentration, we want to scan for a long time to increase the nuclear resonance signal-to-noise ratio," says Herberg. But in an environment with changing temperature, scans extended over a long period will produce smeared images that are difficult to interpret. "We are evaluating materials that are more temperature stable for our portable magnets," says Herberg. In addition, the team is applying a predictive model to increase detection capabilities by taking shorter scans, limiting temperature shifts, and combining scanned images to reveal spectra that were not clear before.

Even with these challenges remaining, the team has made considerable progress. And the briefcase-size NMR device offers many advantages. "Our portable system is inexpensive and robust," says Herberg, "important factors that will make it available to more users and improve its reliability in the field."

—Katie Walter

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