MEASURE FOR MEASURE

Berkeley atomic physics group finds the symmetry in basic and applied research

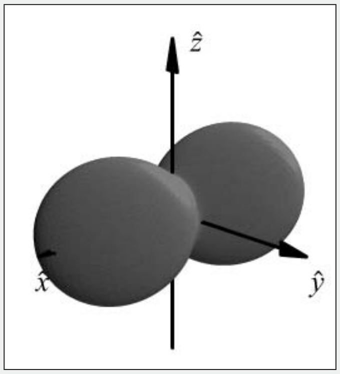
The difference between basic and applied research can all too easily get boiled down to time and money. The knowledge gained from basic research is priceless. But it can take decades to find the answers to fundamental questions, and the difficulty of fitting basic research into typical funding cycles is well known. Applied research, on the other hand, has a more rapid and predictable payback and so attracts support more easily. Any scientist would hurry to point out that, one way or another, all applied research projects owe their existence to fundamental research that came before.

That truth certainly hasn't eluded Berkeley physics professor Dmitry Budker. He leads an experimental atomic physics group that has reached a productive balance of basic and applied research. The work Budker and his colleagues are engaged in not only encompasses fundamental investigations of the atom but also has grown to include applied atomic spectroscopy and the development of sophisticated measurement technologies. The breadth and depth of the group's activities, and its collaborations with physicists around the world, provides Budker's students with experience in an enormous range of research techniques.

A Magic Moment

Budker is a former graduate student of Berkeley emeritus physics professor Eugene Commins. A pioneer in atomic physics, Commins conducted a 15-year experimental quest for the electric dipole moment (EDM) of the electron. Faithful to Commins' tradition of commitment to long-term research, Budker and his colleagues are engaged in an ambitious multiyear effort to measure the electric dipole moment of the neutron. The Neutron EDM project is a large collaborative experiment with the Los Alamos Neutron Science Center (LANSCE), Oak Ridge National Laboratory, and researchers from a dozen other organizations. The experiment employs an innovative and unique method for measuring the neutron EDM to an accuracy that's one to two orders of magnitude better than the current best measurement.

Measuring the neutron EDM with greater precision opens fresh opportunities to probe the fundamental symmetries postulated by the Standard Model of particle physics—the theory that describes interactions among the fundamental particles that make up all matter. In particular, neutron EDM research can improve our understanding of the physics of both weak and strong interactions of subatomic particles.



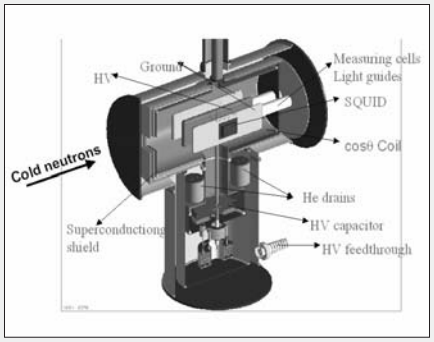
A representation of a polarized atomic state using the so-called Angular-Momentum Probability Surface as described in a paper by S. M. Rochester and D. Budker, Am. Journ. Phys. 69(3), (2001). Animated examples of temporal evolution of atomic polarization can be found at http://socrates.berkeley.edu/~budker/APVis/APVisHome.html .

A measurement of the neutron EDM is a test of the combined charge-reversal and spatial-inversion invariance (CP), once considered inviolable, as well as time reversal invariance (T)—the assertion that subatomic processes behave the same whether the direction of time runs forward or backward. "A non-zero value for the neutron EDM would indicate a violation of both T and CP," Budker explains. "The invariance with respect to a combination of all three reversals, CPT, is still holding up as a true symmetry of nature, although it also is subject to ever more rigorous experimental tests by several other research groups."

Matter vs. Antimatter

A better understanding of T invariance and CP violation could be the key that unlocks one of the central mysteries of physical cosmology: why our universe contains more matter than antimatter—or why we exist at all. According to prevailing theory, the Big Bang created both matter and antimatter, whose subsequent interaction should have resulted in their mutual annihilation, leaving behind a universe empty but for photons. Yet matter somehow prevailed and antimatter now exists only in scarce amounts in laboratories. Why? The Standard Model suggests that CP violation tilted the balance in favor of matter, but the model's prediction of CP violation is insufficient to explain the matter-antimatter asymmetry. The Neutron EDM experiment has the potential to reveal new sources of both T and CP violation and to uncover new physics beyond the Standard Model.

The Neutron EDM experiment is using an approach based on extending the technique of magnetic resonance: the rotation of a magnetic dipole moment in a magnetic field. The novel technique involves trapping ultracold neutrons and studying their precession frequency under the influence of a high-voltage electric field parallel to the magnetic field. The neutron trap is placed in superfluid helium maintained at a temperature of 300 millikelvin. Inside the trap with the neutrons is a dilute mixture of ^{3}He atoms that are polarized in the same plane as the neutrons. The EDM measurement comes from the difference in the variation of the precession frequencies of the neutrons and 3He atoms under the reversal of the strong electric field. "The trick," says Budker, "is that for a given size of the neutron EDM, the EDM of the ^{3}He atom should be orders of magnitude smaller. On the other hand, ^{3}He is sensitive to a magnetic field in about the same way a neutron is, so by comparing the two, it is possible to separate the EDM from possibly much larger spurious effects—for example, those due to unavoidable imperfections of the magnetic field."



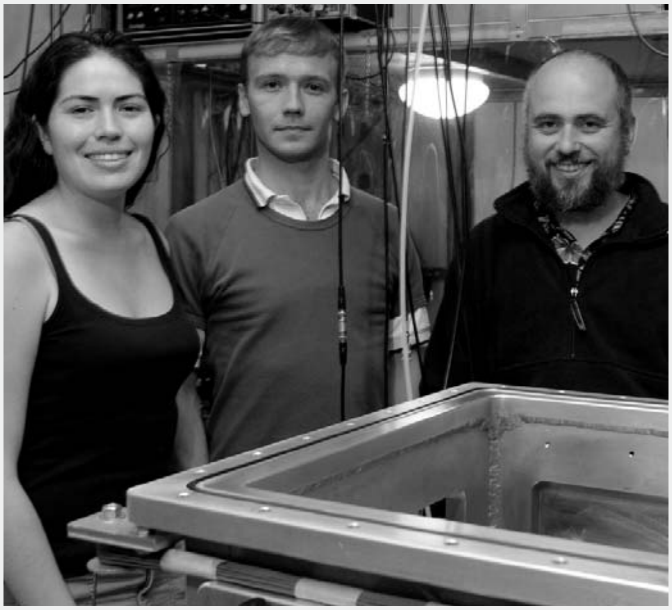
A proposed layout of the neutron EDM experiment. More information about the experiment can be found on the collaboration's web pag http://p25ext.lanl.gov/edm/edm.html .

Springboard for Applied Research

Experimental conditions of extremely low temperatures and extremely high voltages present technical challenges, says Budker. "We started by designing a fundamental experiment, but quickly encountered a rather technical problem—how to measure and monitor the electric field in these very exotic conditions."

Shifting gears into applied research, Budker worked with assistant researcher Valeriy Yashchuk and graduate student Alexander Sushkov to develop a novel method for measuring strong electric fields inside a bath of superfluid helium. The technique is based on the Kerr effect and uses the electro-optical properties of superfluid helium to measure the electric field.

"We're using the liquid helium itself as the probe for the electric field," says Budker. "In the absence of an electric field the superfluid is isotropic, so if you shine a laser beam through it, the refractive index will not depend on the polarization of the light. But with an electric field applied, the refractive index will depend on whether the light is polarized parallel or perpendicular to the direction of the field. The Kerr effect converts the linear polarization of the light into an elliptical polarization, and we measure the degree of ellipticity."



From left to right, graduate students Jennie Guzman and Alex Sushkov, with physics professor Dmitry Budker

Advanced Magnetometry

The group's tests of fundamental symmetries have also led to applied research in the development of advanced, highly sensitive atomic magnetometers based on nonlinear magneto-optical rotation (NMOR). Measuring extremely faint changes in magnetic fields has been the domain of superconducting quantum interference devices (SQUIDs), whose sensitivity depends on cryogenic cooling from liquid nitrogen or helium. The Budker group's NMOR magnetometers offer, in principle, a level of sensitivity that rivals that of SQUIDs, but at room temperature—with no need for cryogenics of any kind. Developments in this area are moving from demonstrations to applications.

In collaboration with the Berkeley College of Chemistry, for example, Budker and his group are applying their NMOR magnetometry techniques to the measurement of nuclear magnetic resonance and magnetic resonance imaging. Another project is developing new magnetometers for space research, with the help of the Berkeley Space Sciences Laboratory. The group is even talking to the Berkeley Center for Geochronology about possible applications for measuring the magnetic properties of rocks.

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Cross-Pollination

This combination of fundamental and applied research, multidisciplinary science, and collaboration makes for a rich and rewarding environment for researchers and students alike, notes Budker. "At first the branching into applied research was done out of necessity," he says, "but now I'm extremely happy, because we now have two intertwined parts of the group pursuing various symmetry tests and working on applied spectroscopy and magnetometers at the same time.

"It's extremely beneficial from a research perspective, because the ideas and techniques from these two aspects are feeding each other, and also from the perspective of student instruction, because it diversifies the students' exposure to different kinds of science. Having so much going on in the group makes life very, very interesting. I believe our people are really enthusiastic about coming to work every day, because they know there are going to be exciting discussions, ideas, and results."

On the Second Floor of Birge Hall

Physics professor Dmitry Budker has an unusually large and diverse research group that includes undergraduates as well as graduate students, postdoctoral fellows, and visiting researchers from all over the world. All five of the group's laboratories are housed on the second floor of Birge Hall. Here is a summary of what's going on.

Parity violation in atomic ytterbium. Ultimately, this work may lead to a precision comparison of parity nonconservation effects on different isotopic and hyperfine transitions. Last year, this lab was also host to an undergraduate thesis project by now-graduate student Jennie Guzman. Her work involved a study of spin relaxation processes in paraffin-coated vapor cells important for atomic clocks and magnetometers.

Atomic spectroscopy for tests of fundamental symmetry. This lab is set up with a system of lasers and an atomic beam apparatus that enables investigators to produce an excited state in any atom to determine atomic energy levels, and measure their lifetimes and polarizabilities.

Sensitive magnetometry based on nonlinear magneto-optical rotation. In applied research that sprouted from fundamental research on symmetry violation, the group is developing magnetometers with detection sensitivities that rival superconducting quantum interference devices (SQUIDs), without the need for cryogenic cooling.

Investigation of optical properties of liquid helium and the search for the electric dipole moment of the neutron. In applied research that supports the Neutron EDM experiment, the group is developing a laser-polarimetric technique for measuring 100 kV/cm sized electric fields in experimental volumes filled with liquid helium.

A new spectroscopic test of Bose-Einstein statistics for photons. This research is testing one of the cornerstones of our understanding of fundamental physical laws, the spin-statistics connection, which governs whether a particle is a boson or fermion.

Search for temporal variation in the fine-structure constant. This investigation, in collaboration with Physicists Steve Lamoreaux and J. Torgerson of Los Alamos, is a sensitive search for possible variation in one of the fundamental values in physics — the fine structure constant, or alpha. The experiment uses radio-frequency electric-dipole transitions in dysprosium.