Graduate student Amber Post, professor William Happer and research associate Nick Kuzma of the Princeton University Physics Department.

[Photo credit: Denise Applewhite.]
Since the end of World War II, the Department of Defense (DoD) and the scientific and technical managers who oversee the DoD programs in basic research have played a key role in maintaining the excellence of U.S. science and technology. One of the strengths of scientific research in the United States has been the existence of a plurality of sources of federal funding: for the non-biological sciences, the most important are the National Science Foundation (NSF), the Department of Energy (DoE), the National Aeronautics and Space Administration (NASA) and DoD. At the request of the Optics & Photonics News Editorial Advisory Committee, I have written an account of how my own career has been affected by DoD research funding. Many of my contemporaries would have very similar stories to tell.

After graduating from Princeton University with a doctoral degree in physics, I began my research career in 1964 with a post-doctoral position at Columbia University. I was fortunate to work for professor Bob Novick in the Columbia Radiation Laboratory, which had been founded by professor I. I. Rabi to develop short-wave radar during World War II. I had done my doctoral research on radioactive atomic beams at Princeton University for one of Rabi’s first students, professor Donald Hamilton. When I arrived at Columbia, I felt I was entering the promised land: working with quite modest means and facilities, Rabi and the team of bright people he had assembled had made immense contributions to physics.

I soon discovered that my post-doctoral salary was being paid by the DoD Joint Services Electronics Program (JSEP), which helped generations of young people get their start in science and engineering. At Columbia, JSEP had supported Willis Lamb’s fundamental work on the fine structure of the hydrogen atom as well as the first measurements of $g - 2$ for the electron by Polycarp Kusch and Henry Foley. Both experimental results helped to convince the world of science that quantum electrodynamics was on a firm footing. JSEP had also supported professor Charles Townes’ work on the maser and the laser. All three of these groundbreaking DoD-supported experiments ultimately led to Nobel Prizes.

At least once a year, there was a formal review of the JSEP program by DoD scientists and managers from the Army, Navy and Air Force. It was stressful but exciting to spend several days telling about our research work, arguing with knowledgeable DoD reviewers and learning how hard it was, even then, to defend the budget for basic research, which is known as 6.1 in the Pentagon. At the time, one of the fiercest defenders of the JSEP program in the yearly DoD funding cycle was Arnold Shostak of the Navy. Participants in the JSEP program, both in DoD and in universities, affectionately referred to Arnold as the program’s “Daddy Rabbit.”

My first research assignment at the Columbia Radiation Laboratory was to work on the physics related to Paul Davidovitz’s optically pumped rubidium maser. Having spent several years in graduate school recording the counts of radioactive atoms made in cyclotrons or nuclear reactors, I was thrilled to be working on experiments in which the signal was carried by visible, ultraviolet or infrared photons. The signals were so large that most experiments were carried out with lock-in amplifiers and other analog detectors rather than by photon counting. Neither accelerators nor nuclear reactors were essential.

I was very impressed by the methods of optical pumping, which produced spin-polarized alkali-metal atoms much more conveniently than the atomic beam machines with which I had done my doctoral experiments. Like many of my friends, I also loved the beautiful colors of the resonance lamps that were commonly used at that time, since tunable lasers were not yet available. Soon I was irreversibly captured by the elegance of the field of atomic, molecular and optical physics. Though my training in nuclear physics stood me in good stead throughout my career, I never seriously considered going back to the world of accelerators and “big physics.”

Soon after I arrived at Columbia, Polycarp Kusch became provost of the university. Kusch decided he no longer
had time to carry out the research he had been conducting with the Air Force Office of Scientific Research (AFOSR) and he graciously allowed me to take over as the principal investigator of his research program. At that time, I had the pleasure of meeting Ralph Kelley, a young program manager at the AFOSR with whom I was to interact for many years. He also put together one of the finest programs in Atomic, Molecular and Optical (AMO) physics in the United States and maintained it, through many vicissitudes, until his retirement a few years ago. Inspired by the physics I had learned from my mentors—Bob Novick, Allen Lurio and Kusch—I and my young colleague, Rajendra Gupta, began to develop ways to measure hyperfine interactions in systems with only a few atoms. Keeping in mind the “golden rule” (he who has the gold makes the rules) I began to look for research that could be more easily interpreted as mission-relevant and that involved experimental systems that had lots of atoms in them.

In the 1970s there were several DoD programs aimed at finding alternatives to the expensive mechanical gyroscopes that were used at that time for inertial navigation. One promising approach was the use of optically pumped nuclear magnetic resonance (nmr) gyroscopes. If nuclear or electronic spins are free of external torques, they will continue pointing in the same direction in space. You can measure the orientation of optically pumped atoms with great precision by observing the way the atoms attenuate and scatter the pumping light. If the inertial platform rotates forward, the spins will appear to rotate backward. But there is a catch: it is difficult to keep the spins free of external torques. All spins have magnetic moments and external magnetic fields acting on these moments cause the spins of a single type to rotate in a way that is indistinguishable from gyroscope rotations. In addition to the rotations caused by the applied magnetic field and platform rotation, there are small but important rotations produced by scattering of the pumping light (“light shifts”) and by collisions with other atoms (“collisional shifts”). It is almost impossible to eliminate stray magnetic fields to the level needed for gyroscopes, so the practical solution is to simultaneously measure both the rotation of the gyroscope platform and the stray magnetic field. You can do this by using two different species of spin, say the spins of two different mercury isotopes, such as $^{201}\text{Hg}$ and $^{199}\text{Hg}$, as was being done at that time by Jim Simpson and his team at the Singer Company.

I believed that nmr gyroscopes had the right combination of relevance to satisfy the requirements of the Mansfield Amendment was interpreted very broadly. There were, however, limits: I remember receiving a stern lecture from a grizzled AFOSR program manager about the irrelevance of excited-state hyperfine structure and exotic interactions in systems with only a few atoms. Keeping in mind the “golden rule” (he who has the gold makes the rules) I began to look for research that could be more easily interpreted as mission-relevant and that involved experimental systems that had lots of atoms in them.

To our surprise, the signs of the hyperfine coupling coefficients of the D states were “wrong.” The peculiar sign reversal was caused by contributions to the hyperfine interaction from core electrons polarized by their exchange interaction with the valence electron. At that time, DoD was willing to support this rather esoteric research, which taught me and my students a great deal about physics and helped me to contribute in later years to much more relevant work. The Duke of Wellington has been quoted as saying, “The Battle of Waterloo was won on the playing fields of Eton.” In this same way, many important advances in U.S. science and technology originated on the playing fields of basic research supported by DoD.

With the 1970 passage of the Mansfield Amendment, it became much harder to work with DoD support. Under the amendment, DoD was instructed to support only “research with a direct and apparent relationship to a specific military function or operation.” Thanks to the wisdom of 6.1 program managers, and much to the benefit of DoD and the

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**Figure 1.** Measurement of hyperfine interactions in optically inaccessible states. This is an example of very basic research funded by DoD even within the constraints of the Mansfield Amendment.
Amendment and interesting physics to make them appropriate for academic research. A group at Litton Industries was developing an nmr gyroscope based on spin-polarized noble gases. This work appealed to me since it was based on experiments by my Princeton professor, Tom Carver. With Marie Anne Bouchiat, and a graduate student, Clark Varnum, Carver had shown that it is possible to polarize the nuclear spins of 3He by mixing the 3He gas with optically pumped alkali-metal vapors like Rb. Collisions between the spin-polarized alkali-metal atoms can transfer large amounts of angular momentum to the spins of the 3He atoms. At Litton Industries, Bruce Grover had shown that the same spin-exchange optical-pumping methods developed by Carver for He worked even better for other noble gases such as 21Ne, 81Kr, 129Xe and 131Xe.

As our first contribution to nmr gyroscope physics, we thought we would determine the relative contributions of binary and three-body collisions in the spin transfer. For the heavier noble gases, work by Bouchiat led us to expect that much of the spin-exchange would take place in the loosely bound van der Waals molecules like RbXe which are formed in three-body collisions. Binary and three-body spin-exchange mechanisms are summarized in Fig. 2.

We also decided to determine the relative merits of the different alkali-metal atoms—Li, Na, K, Rb and Cs—for polarizing noble gas nuclei by spin-exchange optical pumping. When we began our work in the late 1970s, the theoretical models predicted that the spin losses occurred mainly because of spin-orbit interactions of the valence electron near the nucleus of the alkali-metal atom. Low-Z alkali-metal atoms like Na or Li should have worked better than the high-Z atom Rb that had been used almost exclusively until that time.

In 1980, I moved with my research group from Columbia University to Princeton. At Princeton, Nat Bhaskar and my student Mei Yin Hou continued work we had started at Columbia on spin-exchange optical pumping of 129Xe with Na. After much experimental frustration, we learned that Na is actually one of the worst choices we could have made for

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**Figure 2.** Spin exchange by (a) three-body and (b) binary collisions. DoD supported basic research in this area because of its relevance to nuclear magnetic resonance gyroscopes. Later, closely related physics became very important for magnetic resonance imaging and studies of how quarks and gluons contribute to the spin of the neutron.

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**Figure 3.** The original sodium guide star came about because of DoD support of basic research in atomic physics, which permitted researchers to learn about the layer of sodium atoms at 90 to 100 km above Earth’s surface.
spin polarizing Xe nuclei. My students Zhen Wu and Thad Walker found that the original theoretical models had greatly underestimated the spin-orbit interactions in the core of the noble gas atom and we were able to develop a simple and effective theory that took these interactions into account.

Especially with the powerful computers that are now widely available, there is a temptation to put too much trust in theoretical models without subjecting the predictions to incisive experimental tests. On a fireplace mantle in Princeton University is Einstein’s famous quote, “Raffiniert ist der Herrgott, aber boshaff ist er nicht,” (The Lord God is subtle, but he is not malicious). I like to think of this as an admonition not to underestimate how many surprises there are in the natural world, but to recognize that there really is a grand design which you can understand with the right combination of theory and experiment. Most DoD program managers recognize this truth.

Affronted by the tactics of the Weathermen and other extreme groups during the Viet Nam War, in 1976 I joined the consulting group known as JASON. The JASON group was formed by physicist Murph Goldberger and his academic colleagues in the 1960s to bring the resources of academic science to bear on highly technical DoD problems like reentry physics for ballistic missiles and nuclear weapons. The group was managed by the Institute for Defense Analysis (IDA), which proposed to call the undertaking “Project Sunrise.” Murph told his wife Mildred about “Project Sunrise” and showed her a copy of the IDA description, a booklet with a picture of Greek columns on the cover. Mildred, who had majored in classical Greek in college, said “Sunrise” was a terrible name and suggested JASON: the mythical Jason had in fact had many adventures with his crew mates as they sailed off in search of truth.

Each summer I spent about six weeks at a JASON summer study program working on classified problems of national defense. I found that many things I had learned from my DoD-supported academic research were immensely useful in this new, classified world. One example is the development of the sodium guide star by JASON during the 1980s. The high-energy laser program of the strategic defense initiative was just beginning to recognize how severely atmospheric turbulence could degrade the intensity a ground-based laser could deposit on a target in space. Astronomers had already learned about the advantages of adaptive optics, and the first “rubber mirrors” had been developed to compensate for atmospheric turbulence. But it was not at all clear how to measure the atmospheric turbulence in the direction of the target.

I learned about these problems in a classified seminar organized by a fine DoD program manager, Rhett Benedict. I pointed out that it would be possible to get a good return signal for adjusting a rubber mirror by shining a laser on the layer of sodium atoms that is always present at an altitude of 90 to 100 km above Earth’s surface. I knew a lot about the sodium layer because it played an important role in Alfred Kastler’s invention of optical pumping, and DoD had allowed me to do basic research work in this field. The “sodium guide star” was highly classified for a number of years, but it was eventually reinvented by astronomers when my JASON colleague Claire Max, who had worked on the concept, managed to persuade DoD to declassify the old JASON work. A sketch from the original JASON report is shown in Fig. 3.

At Princeton I had the pleasure of working with professor Frank Calaprice’s nuclear physics group. We used spin-exchange optical pumping to polarize radioactive isotopes of xenon and radon and to measure their spin polarizations.

Figure 4. Early lung image made with hyperpolarized 3He gas produced by spin-exchange optical pumping. The original work in this area was supported by DoD in connection with programs on nuclear magnetic resonance gyroscopes for fighter planes.
and magnetic moments by observing the asymmetries of their gamma rays. I also had the good fortune to meet professor Art McDonald, who was interested in using large amounts of spin-polarized \( ^3 \)He as a target for experiments in high energy physics.

Two very talented, young post-docs joined this effort: Tim Chupp, now a professor of physics at the University of Michigan, and Gordon Cates, who was recruited away from Princeton by the University of Virginia a few years ago. Along with Princeton graduate students, Chupp and Cates soon perfected ways to produce dense, highly polarized targets of \( ^3 \)He gas by spin-exchange optical pumping.

Thanks to long years of DoD support, we now had the capability of producing large quantities of highly spin-polarized noble gases of noble gas isotopes ranging from helium to xenon. In keeping with the wish expressed by the critical AFOSR program manager of my youth, we were now working with lots of atoms. In fact, we had so much highly polarized gas that we began to think of other applications besides gyroscopes and basic physics.

In 1990 I left Princeton for several years to work at the U.S. Department of Energy (DoE). Cates remained at Princeton and continued to work on spin-exchange optical pumping. While I was at DoE, I received a call from Arnold Wishnia of New York State University at Stony Brook. Wishnia and his graduate student Mitchell Albert had been doing magnetic resonance imaging work with \(^{129}\)Xe to learn more about brain physiology. Xenon dissolves readily in brain tissue. By using the \(^{129}\)Xe that had been polarized by spin-exchange optical pumping, it would be possible to get much larger signals and complete the experiments much more rapidly.

I called Cates and in his usual vigorous way, he and his Princeton graduate students, Bastiaan Driehuys and Brian Saam, polarized some \(^{129}\)Xe at Princeton, drove it through metropolitan traffic to Stony Brook on Long Island and produced the first nmr image with laser-polarized gas.

Within a year or so, we had produced human lung images with \(^3\)He. One of the first images is shown in Fig. 4.

Like the comment in the musical Oklahoma, one might be tempted to think “they’ve gone about as far as they can go” in spin-exchange optical pumping. In fact, there are still many fascinating mysteries that I hope will be solved in my lifetime.

Recently, professors Thad Walker and Wilmer Anderson at the University of Wisconsin showed that the observed spin relaxation caused by collisions between pairs of alkali-metal atoms at buffer-gas pressures on the order of an atmosphere or more does not fit the paradigm illustrated in Fig. 2. Following up on this experimental observation, a joint Princeton–Wisconsin research team showed there is a surprisingly large contribution to spin relaxation from the spin-axis interaction in triplet dimers like Rb\(^2\)(\(^3\Sigma\)).

One consequence of the spin-axis interaction is a peculiar resonance change in the relaxation rate at magnetic fields where multiple level crossings occur in the spin sublevels of the Rb\(^2\)(\(^3\Sigma\)) molecule. The resonances are shown in Fig. 5.

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References