The research supported by this grant was focused on applications of laser-polarized 3He and 129Xe in magnetic resonance imaging and on the basic physics that makes this possible. During the past few years, magnetic resonance imaging of human lungs with laser-polarized 3He and 129Xe is being done with increasing frequency at a growing number of sites throughout the world. The resulting lung images are of unprecedented resolution and they clearly show pathologies that are more poorly diagnosed, if at all, by currently available modalities like x-rays or gamma-ray scintillography. A very important consideration in the use of laser-polarized 3He and 129Xe is that the nuclear spins of these gases do not relax at the surface of the container in which they are pumped or stored. This research has shown that in the case of 129Xe in cells with polymer wall coatings, much of the relaxation is due to unusually long trapping of the 129Xe atoms at sites surrounded by protons in the polymer.
FINAL TECHNICAL REPORT
For the Research Period
July 1, 1994 through September 30, 1997
for work performed under
Grant AFOSR F49620-94-1-0466.P00001
THE PHYSICS OF SPIN POLARIZED ATOMIC VAPORS.
Submitted March 4, 1998
by
W. Happer, Co-Principal Investigator

1. Overview

The research supported by this grant was focused on applications of laser-polarized $^3$He and $^{129}$Xe in magnetic resonance imaging and on the basic physics that makes this possible. Formal clinical trials on human patients are about to begin at hospitals located at Duke University in Durham, NC and at the University of Virginia, in Chalottesville, VA. This exciting new diagnostic capability will have medical applications both in the Air Force, and also in the civilian sector. The new medical application could not have been developed without far-sighted support by AFOSR over many years.

Although the medical application of spin-polarized gases has has received great publicity during the past few years, the work supported by this AFOSR grant has and will continue to have applications to other technologies of the Unites States Air Force. For example, the Rb clocks used in the GPS satellite system are based on optical pumped gas cells. The basic physical processes operating in these clocks is closely related to that of the cells used to polarize $^3$He and $^{129}$Xe gas for medical imaging. Surprising new developments continue to show up in the basic physics of these and other closely related systems.

Much of the work supported by this grant has already been published in peer-reviewed journals, as listed below, but we will give a brief summary of some of the more important accomplishments in the next section.

2. Major Accomplishments

Lung Imaging. During the past few years, magnetic resonance imaging of human lungs with laser-polarized $^3$He and $^{129}$Xe is being done with increasing frequency at a growing number of sites throughout the world. The resulting lung images are of unprecedented resolution and they clearly show pathologies that are more poorly diagnosed, if at all, by currently available modalities like x-rays or gamma-ray scintillography.

Surface relaxation. A very important consideration in the use of laser-polarized $^3$He and $^{129}$Xe is that the nuclear spins of these gases not relax at the surface of the container in which they are pumped or stored. In work led by Dr. Bastiaan Drichiys, we have shown that in the case of $^{129}$Xe in cells with polymer wall coatings, much of the relaxation is due to unusually long trapping of the $^{129}$Xe atoms at sites surrounded by protons in the polymer.

Relaxation of $^{129}$Xe in Oxygen. For imaging studies of humans with laser polarized $^{129}$Xe, some oxygen will be present in the inhaled xenon, either intentionally administered
for safety, or mixed with air left in the lungs from the previous breath. In work led by Dr. Brian Saam we have shown that an admixture of 20% oxygen to xenon gas at atmospheric pressure shortens the nuclear spin relaxation time to about 10 seconds, not too short a time for excellent lung images to be acquired.

High-Volume Production of Laser-Polarized $^{129}$Xe. In work led by Bastiaan Driehuys we have shown that large amounts (liters) of laser-polarized $^{129}$Xe can be produced by continuous flow of a lean mixture of xenon in a helium-nitrogen carrier gas through a cell, pumped by a broad-band diode laser array. The nuclear spin polarized $^{129}$Xe that results is accumulated by freezing it out of the gas stream in a cold trap at liquid nitrogen temperatures.

Edge Enhancement. In work led by Dr. Brian Saam, we have shown that the hindered diffusion of spin-polarized gases at depolarizing walls leads to sharp peaks at the edges of the image. This image distortion is in good quantitative agreement with a theory of edge enhancement developed in our group. The natural functions for describing edge enhancement are Airy functions.

Imaging of Spin Polarization of Laser-Pumped Alkali-Metal Vapors. The nuclear spin polarization $^3$He and $^{129}$Xe, produced by spin exchange with optically pumped alkali-metal vapors, cannot exceed the volume averaged electronic spin polarization of the alkali-metal vapor. In work led by Dr. Stephan Appelt and Dr. Andrei Baranga, we have developed an effective imaging method, similar in spirit to magnetic resonance imaging of nuclear polarization, which has allowed us for the first time to determine the three-dimensional spin polarization of optically-pumped alkali-metal vapor.

Theory of Spin Rotation Interactions. One of the major spin loss mechanisms for optically pumped alkali-metal vapors is the spin-rotation interaction between the electron-spin of the alkali-metal atom and the rotational angular momentum of a collision partner or second atom in a van der Waals molecule. In work led by Dr. Happer, simple and effective theory of the spin rotation interaction for alkali-metal atoms in both high-Z buffer gases like xenon or low-Z buffer gases like helium has been developed. One prediction of the theory, that potassium should be a much better partner for spin-exchange polarization of $^3$He than Rb or Cs has recently been confirmed by experiments of our group. The experimental findings will be published shortly in Physical Review Letters.

Hyperpolarized Liquid Xenon. In work led by Dr. Rich Fitzgerald and Ms. Karen Sauer, we have shown that laser polarized xenon, accumulated by freezing as described above, can be liquefied with little loss in polarization. The nuclear spin relaxation time of $^{129}$Xe in the liquid is 15 to 20 minutes, depending on the temperature. The relaxation rate is about the same in the earth's field as in fields of several tesla. So the polarized liquid xenon is very convenient for transporting about the laboratory, since no magnetic holding fields are needed. We have also shown that many polar substances dissolve readily in hyperpolarized liquid xenon, and polarizations of protons or $^{13}$C nuclei in the dissolved molecules can be enhanced by factors of 10 to 100 compared to thermal equilibrium values.

3. Patents

A fundamental patent "Magnetic Resonance Imaging Using Hyperpolarized Gases," Patent Number 5,545,396 was issued to Princeton University and the State University of New York on August 13, 1996 for work supported in part by AFOSR. Three additional
Princeton patents on wall coatings for hyperpolarized gases, on the $^{129}$Xe accumulator mentioned above, and on a system to polarize $^3$He have been licensed to MITI. All of these patents were based on work supported by this AFOSR grant and its predecessor grants.

4. Technology Transfer

Much of the technology developed under this grant is being transferred to the startup company Magnetic Imaging Technologies, Inc. (MITI), located in the Research Triangle area of North Carolina through a licensing agreement with Princeton University. MITI has also benefitted from an STTR award from the United States Air Force to help develop gas imaging. Two of the key technical people at MITI, Dr. Bastiaan Driehuys, Director of Research and Dr. Paul Bogorad participated in AFOSR sponsored research while they were students and post doctoral research associates at Princeton. MITI aims to make magnetic resonance imaging with $^3$He and $^{129}$Xe a commonplace medical diagnostic procedure as soon as possible. In 1997, MITI was awarded a Tibbetts Award from the Technology Office of the U.S. Small Business Administration as an outstanding, high-technology startup company.

5. Publications

Activities receiving full or partial support from Grant AFOSR F49620-94-1-0466 have already resulted in the 15 refereed publication listed below, and several more are accepted and awaiting publication.


6. Personnel

The following personnel received full or partial support from Grant AFOSR F49620-94-1-0466:

Dr. William Happer, Co-Principal Investigator
Dr. Gordon Cates, Co-Principal Investigator
Dr. Eli Miron, Visiting Research Scientist
Dr. Andrei Baranga, Visiting Research Scientist
Dr. Bastiaan Drieuys, Research Associate
Dr. Brian Saam, Research Associate
Dr. Hunter Middleton, Research Associate
Dr. Paul Bogorad, Research Associate
Dr. Stephan Appelt, Research Associate
Dr. Richard Fitzgerald, Research Associate
Ms. Karen Sauer, Graduate Student, PhD candidate
Mr. Christopher Erickson, Graduate Student, PhD candidate
Mr. Dan Walter, Graduate Student, PhD candidate
Mr. Benjamin Lev, Undergraduate Work/Study Student