Cesium, Optical Pumping, and Parity Non-Conservation

Samuel M. Arons
Williams College

UW REU 2002
Advisor: Prof. E. N. Fortson
Colleagues: R. Wynar, A. Andalkar, R. Lyman

August 27, 2002

Abstract

The concept of parity non-conservation (PNC)—that physical systems can display unique and irreversible handedness—has been around for quite some time; indeed, it was first measured in the ^{60}Co atom in 1957 by Wu et al. [1] and is predicted by the Standard Model. My work this summer as an REU student in the Fortson atomic physics laboratory at the University of Washington has been in the study of parity non-conserving effects in the ^{133}Cs atom; specifically, I have been working to characterize a particular RF absorption line in optically pumped cesium atoms. Once initial results are obtained, we will have the necessary background information to measure the anapole moment of the ^{133}Cs nucleus in an extension of this preliminary experiment. The results of the extended experiment will allow us to check the measurement of the anapole moment of ^{133}Cs made in Colorado by Wieman et al. [2] in 1997. Such a check is important because the Colorado experiment not only measured the anapole moment—which is due to nuclear spin PNC and suggests problems with current nuclear theory—but also measured effects of electron spin PNC that hints at new physics beyond the Standard Model. If we are able to duplicate their anapole moment measurements, it will be probable that their electron spin measurements are also correct. In that case, extensions of nuclear theory and/or the Standard Model will likely be needed. This paper will describe my work this summer as well as some of the ideas behind PNC and optical pumping.

1 Parity Non-Conservation in Atomic Cesium

One way to observe PNC in atoms is by the method of optical rotation. Imagine a small glass vial (or 'cell'), filled with some liquid or gas, that has been placed in a beam of

linearly polarized light. Now, if this cell contains a solution of a molecule like dextrose, then the angle of polarization of the beam of light will be rotated by some number of degrees in, say, the clockwise direction once the beam has exited the cell. This happens because molecules like dextrose are *chiral*, meaning that they are intrinsically right- or left-handed. Now, if one were to replace the dextrose solution with a solution of its chiral opposite—called levulose—then the angle of polarization of the beam of light would be rotated by the same amount but in the *opposite* (counterclockwise) direction. It is important to note here that dextrose and levulose have exactly the same molecular formula.[1] They are essentially the same molecule, but with the subtle difference that one twists to the right while the other twists to the left—and no matter how much you turn them or move them, you can never get them to coincide, like your right and left hands. What is perhaps even more important, though, is that nature allows both of them to exist; that is, the handedness is reversible.

What happens, though, if we replace the sugar solution with a cell containing gaseous cesium atoms? Again, we will see the angle of polarization of the light change by some small amount and in a particular direction. But the fundamental difference between the cesium and the dextrose is that *there is no chiral opposite of cesium.* There is no way to go out and find a 'left-handed' cesium atom that will make the angle of polarization rotate in the opposite direction; nature simply forbids it. That is why optical rotation by cesium is a parity-violating effect; the handedness is *ir*reversible.

Optical rotation can be used to measure two kinds of parity-violating effects: electron spin PNC and nuclear spin PNC. In our experiment, we measure the cesium nucleus' anapole moment, which is a manifestation of nuclear spin PNC.[2] The anapole moment of an atomic nucleus is a little less easy to visualize than optical rotation. Try, though, to imagine a nucleus (with its anapole moment 'turned off', for the time being) sitting in space with its magnetic dipole moment field around it. The magnetic field lines are all nice and straight, running from the north to the south pole of the nucleus. Now, imagine 'turning on' the anapole moment. Suddenly, the magnetic field lines of magnetic dipole get twisted into a screw-like shape. This twisting is caused by the anapole moment. Since this is a parity non-conserving effect, the direction of twisting can only be in one direction; 'right-handed' threads are the only kind allowed in cesium's nuclear magnetic field.[3]

The first measurement of ^{133}Cs's anapole moment (although they also simultaneously measured electron spin PNC) was made in 1997 by Wieman, et al. at the University of Colorado, Boulder [2]. Although the anapole moment is predicted by the Standard Model, the magnitude of cesium's anapole moment—roughly speaking, the number of 'threads per cm' of twisting of the nuclear magnetic field lines—was found to be different from what nuclear calculations predict. The goal of our experiment is to make a separate measurement of the anapole moment by using a different technique. If

[1] The formula is $C_6H_{12}O_6$. Perhaps surprisingly, this is the same molecular formula as that of glucose—it turns out that dextrose is just another name for glucose.

[2] Electron spin PNC, which we do not measure, has to do with the electroweak interactions between the electrons and the nucleons in the cesium atom; more specifically, the exchange of Z^0 bosons between the two kinds of particles has a particular handedness. It is electron spin PNC that hints at new physics beyond the Standard Model. Unfortunately, I am afraid I do not have the technical knowledge to give any further details.

[3] The anapole moment arises from inter-nucleon forces. Again, I am afraid I do not have the expertise to give any more information.

we can duplicate the anapole moment results, then there are two ramifications. First, there is evidence that corrections are needed to the nuclear theory that predicts the anapole moment, and second, it becomes more likely that the Colorado experiment's electron spin PNC measurements are correct. That in turn would suggest the existence of new physics beyond the Standard Model.

2 Optical Pumping

2.1 Motivation

While the ultimate goal of our experiment is to measure cesium's anapole moment, the work done this summer involved a preliminary study that will lay the groundwork for the final experiment. Specifically, we use the technique of optical pumping to manipulate cesium atoms contained in a weak ($\sim$1 gauss) magnetic field into a very particular state. Next, we characterize a radio frequency (RF) transition in the optically pumped sample. Once we measure the intrinsic linewidth and -strength, we will be able to put the sample in a much larger 5–10 Tesla (50–100 kG) field and reverse some parameter, such as magnetic field direction, to see if there are any differences in the RF absorption line. Those differences will tell us about the anapole moment.

2.2 Two Kinds of Pumping

As mentioned above, the technique of optical pumping involves manipulating atoms into a particular state. In our case, we have *two* lasers doing *two* kinds of optical pumping: magnetic sublevel- and hyperfine pumping. I shall briefly explain each of them.

Magnetic sublevel pumping can only take place when the atoms in question are placed in a magnetic field; the B-field causes Zeeman sublevel splitting and thus differentiates the normally degenerate magnetic sublevels from each other. If the incoming laser light is circularly polarized, quantum-mechanical selection rules require that transitions must satisfy $\Delta m_l = \pm 1$, depending on the circularity of the light (σ^+ for +1 and σ^- for -1). In either case, light will be excited to a sublevel in a higher hyperfine state with a different value of m_l and can decay back down into a variety of lower sublevels with known probabilities. Eventually, the atoms will decay into a sublevel from which they *cannot* be excited since, for that sublevel, there is *no* sublevel in the upper state that can satisfy $\Delta m_l = \pm 1$. When this happens, the atoms get 'stuck' in that particular sublevel and are said to be in a 'dark state' since they can no longer absorb the circularly polarized laser light. When this happens, the sample has been successfully optically pumped.

Hyperfine pumping works in much the same way as magnetic sublevel pumping, except that the there is no restriction on Δm_l since hyperfine pumping is done with linearly (π) polarized light. Thus the Zeeman sublevels can effectively be ignored. The incoming laser light gets absorbed by atoms in the target hyperfine level and get excited into a more energetic state, where, again, they can decay with known probabilities back down to several different lower hyperfine levels. If they decay into a level that is lower than the one at which they initially started, then they effectively

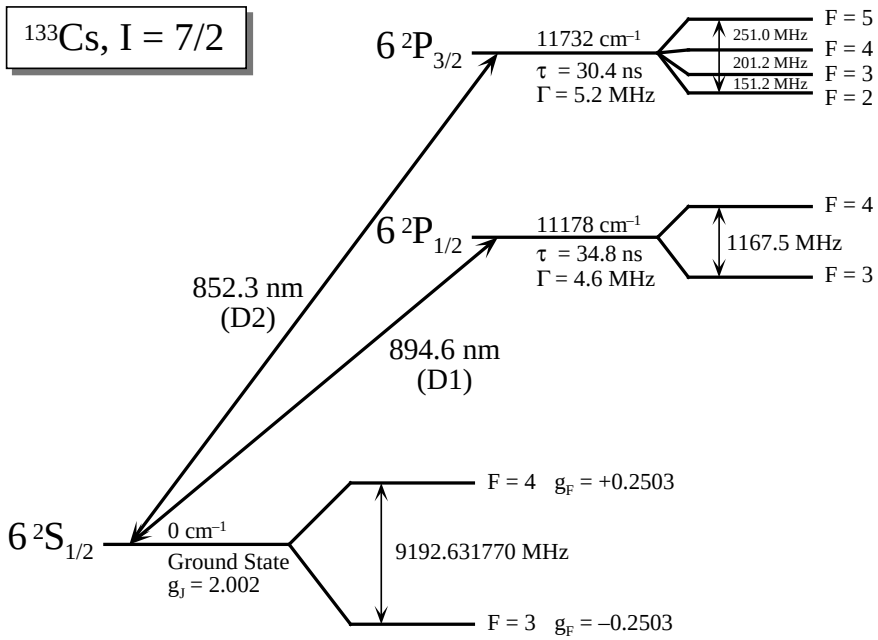

Figure 1: The energy levels of the ^{133}Cs atom. The D1 optically pumps the magnetic sublevels of the 6 $^2S_{1/2}$ F=4 hyperfine level, while the D2 pumps out the F=3 hyperfine level. Figure borrowed from A. Andalkar's Ph.D. thesis [4].

become 'stuck' because the laser light is tuned to a different transition frequency.[4,5]

In our experiment, the goal is to achieve magnetic sublevel pumping—in fact, we do not even want to do any hyperfine pumping at all. The laser that we use to do this—called the 'D1', for historical reasons—unfortunately drives *both* kinds of pumping because of the energy level structure of the ^{133}Cs atom (Figure 1). More specifically, the D1 is tuned to excite electrons from the 6 $^2S_{1/2}$ F=4 hyperfine level to the 6 $^2P_{1/2}$ F=3 hyperfine level. By doing so, the D1 drives hyperfine- and magnetic-sublevel pumping of the F=4 level. In order to combat the D1's undesired hyperfine pumping effect, which keeps some atoms from reaching the desired F=4 Zeeman sublevel, we send in a second laser (called the 'D2') that 'cleans out' the lower F=3 hyperfine level and gets the sample optically pumped into the F=4 dark state.

2.3 Depumping the Sample with RF

It is the *de*pumping of the cesium that we are ultimately interested in measuring, so once we get the sample pumped (this happens very quickly), we can take data. In a magnetic field on the order of 1 gauss, the Zeeman splitting is calculated to be around 350 kHz, so we send in RF photons of this frequency. These photons are of the correct energy to cause stimulated emission of the atoms in the dark state, which then spread back out in a statistical sort of way into *all* the magnetic sublevels of the F=4 hyperfine level. When this happens, the atoms find themselves in states that can

[4]Note that this situation is different from magnetic sublevel pumping; in that case, the laser light is of the correct frequency, but of the wrong polarization. In hyperfine pumping, the light is of the wrong frequency.

[5]The foregoing explanation was derived from Happer and Wijngaarden [3].

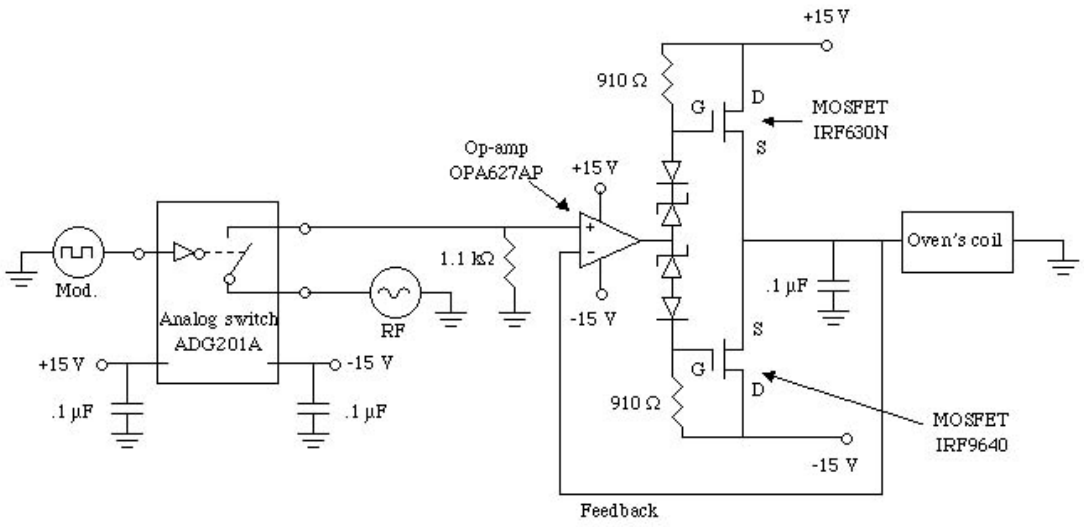

Figure 2: The RF magnetic field amplifier, a MOSFET push-pull with an analog switch for lock-in detection.

satisfy the $\Delta m_l = \pm 1$ requirement, so they suddenly start absorbing the D1 laser light again, and the laser transmission through the sample drops. It is the D1 transmission that we measure as a function of the RF frequency.

3 Data Acquisition and Analysis

3.1 RF Scanning

The creation of RF photons is accomplished by sending an AC current through a coil that is wrapped around the cesium sample. This of course produces an oscillating magnetic field, which in turn creates an oscillating electric field—and so we get EM radiation bombarding the atoms. The coil is hooked up to a function generator via a push-pull MOSFET amplifier that I built (with much design help from Rob Lyman; Figure 2) that drives the AC signal. A computer slowly scans the AC frequency through the ∼350 kHz resonance while measuring the D1 transmission through a lock-in amplifier. It plots the data when the scan is finished and saves it to a file that can be imported into the Igor data analysis program for further study.

When the RF is off-resonance, it cannot depump the sample, and so the absorption of the D1 laser light remains low. This is because the cesium atoms are all stuck in the dark state. As the RF sweeps towards resonance, suddenly the atoms find themselves back in magnetic sublevels from which they can absorb D1 light, and so consequently the D1 absorption increases. Finally, as the RF scans away from resonance, the D1 is no longer counteracted by the RF, so it pumps the cesium atoms back into the dark states and absorption drops again. It is this absorption/transmission line that we characterize.

3.2 Igor

In order to better be able to analyze our data and make plots, we import them into data-analysis software called 'Igor' on the lab MacIntosh (named 'Hysteresis'). In order to make this importing easier on the user, I wrote a small Igor macro (i.e. 'procedure') that automates much of the laborious process of selecting files to import, naming them, and so on. The macro is named 'ImportData()' (case insensitive); here I give a brief description of how it works and how to use it for the benefit of others who may need to use it in the future.

I have placed an alias to the ImportData() procedure in Igor's standard startup files, so that it is automatically loaded every time the Igor application program is run. ImportData() works like so: it looks at a selected file, determines what folder that file lives in, and then imports *all* 'general text' files in that folder as 'waves' (including the selected file itself, if it is general text). In order to run the procedure, all that is necessary is to type 'importdata()' into the Igor console window. Doing this will bring up a dialog window from which a file can be selected. Voilà: all data are imported.

3.3 A Problem with Asymmetry

We expect the RF absorption lines to be fairly symmetric, but unfortunately, as real life never behaves ideally, we discovered that our lines were in fact quite *a*symmetric. We had several theories about why this might be so, and investigated the most obvious possibilities. The first suspect was the D1 laser, a home-built external cavity diode apparatus. We became suspicious of its mode structure and thought that it might be causing our graphs to come out asymmetrically, but after making quite sure that it was single mode the asymmetry did not go away. So we crossed it off our list.

The next suspect was the comfortable, swiveling chair that resided in front of the data acquisition computer. We noticed that if the occupant of the chair swiveled during a scan, the data had a strange sinusoidal component running through it. We determined that the chair had a big enough magnetic field that it was causing problems. We removed the chair from the room and replaced it with an uncomfortable wooden chair to eliminate this problem, but the asymmetry remained.

We had also become aware of the fact that the Seattle Metro electric bus system was undergoing construction that had the unfortunate side effect of sending spikes of current going through the bus lines outside our lab. This in turn led to sudden spikes in magnetic field inside our lab. We calculated, though, that these spikes were small enough not to be causing any problems.

Finally, our advisor, Professor Fortson, determined that the cause of the asymmetry was due to a lightshift (i.e. the AC Stark Effect) from the incoming D1 photons. Essentially, this means that the incoming photons' electric field was causing an asymmetrical shift in the magnetic sublevel energies, thereby introducing asymmetry into the system and ultimately causing us to perceive asymmetrical absorption lines.[6] Luckily, there is an obvious remedy to this problem: lower the laser light intensity and the lightshift is minimized. We found that as we lowered the intensity of the incoming D1 light, the absorption line became more and more symmetric. Thus are we were able to measure the RF absorption line.

[6] In this instance, too, my knowledge is not thorough enough to give any further details.

4 Conclusions and Further Research

As of this writing, we are very close to finally characterizing the width and strength of the RF line. Once we have that information in hand, we will be able to move from the small (∼1 gauss) magnetic field to the larger 8–10 kG field next door. We will again characterize the same absorption line, although in this instance the depumping radiation will be microwave instead of RF because the external magnetic field is larger. Finally, we should know enough about the absorption to move to an even larger 5–10 Tesla (or 50–100 kG) magnetic field and look at the transition again, this time hoping to observe the effects of cesium's anapole moment. If all goes well, the experiment may be moved to the National High Magnetic Field Laboratory in Tallahassee, Florida.

It is hoped that, once this experiment is completed, we will be able to verify or refute the results of Wieman, et al. [2] concerning the magnitude of ^{133}Cs's anapole moment. If our results corroborate theirs, then it will be more likely that corrections are needed to current nuclear theory and to the Standard Model.

5 Thanks

I would like to thank the following people and organizations:

The NSF and American taxpayers for funding the REU programs that allow undergraduates to gain valuable research experience,

U. of Washington and the Institute for Nuclear Theory for hosting and implementing the REU,

Professor E. Norval Fortson, my advisor while at UW, for his help in explaining some subtler aspects of atomic physics to me,

Dr. Roahn Wynar, Dr. Amar Andalkar, and Rob Lyman, my colleagues in the lab, for their invaluable help in learning experimental technique, and

all the rest of the members of the Fortson atomic physics lab for their help and good company.

References

[1] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, "An experimental test of parity conservation in beta decay", *Phys. Rev.* 105 (1957), p. 1413.

[2] C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, C. E. Wieman, "Measurement of Parity Nonconservation and an Anapole Moment in Cesium", *Science* 275 (1997), p. 1759–63.

[3] W. Happer and W. A. van Wijngaarden, Princeton University, "An Optical Pumping Primer", J.C. Baltzer A. G. Scientific Publishing Company, *Hyperfine Interactions* 38 (1987), p. 435-470.

[4] A. Andalkar, "Spontaneous Spin Polarization and Hysteresis in Cesium Vapor Pumped by Linearly Polarized Light: an Experimental, Theoretical, and Computational Study", Ph.D. dissertation, University of Washington, 2001.

[5] R. Gautreau and W. Savin, Modern Physics, McGraw-Hill Publishing Company, 1978.

[6] L. Lamport, LaTeX: a document preparation system, 2^{nd} ed., Addison-Wesley Publishing Company, 1994.

[7] For further diagrams and figures, see the accompanying PowerPoint presentation.