Investigation of Noble Gas Polarization Using Optically Pumped Rb and K

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelor of Science with Honors in
Physics from the College of William and Mary in Virginia,

by

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Abstract

Nuclear physics experiments explore the nature of the neutron using electron scattering from polarized ^{3}He targets. Currently, at the College of William and Mary, ^{3}He is polarized for electron scattering experiments in glass cells, by spin exchange collisions with optically pumped polarized Rb atoms. Studies of alkali metals other than Rb have suggested that K may polarize ^{3}He more efficiently. More efficient polarization would decrease the laser power needed to polarize the alkali metal, or alternatively, decrease the time needed to reach maximum polarization. This is desirable for maintaining high ^{3}He polarization in the presence of the depolarizing effect of the electron beam in scattering experiments. However, because K is more difficult to optically pump than Rb, it is easier to polarize K by another means than optical pumping. In this study, we tested a procedure where a small amount of optically pumped Rb is used to polarize K for spin exchange with ^{3}He. Two of the cells produced for this procedure matched the density and geometry specifications needed for use in experiments at Jefferson Lab. The ^{3}He target cells we produced polarized rapidly and to a high polarization.

Acknowledgements

Thanks to everyone who had the patience to explain, and to put up with me while I was working on this project. My especial thanks to go to Aidan Kelleher, whose help in times of need allow you to enjoy this data today, and to Dr. Todd Averett, who took me in, gave me a research project, copious amounts of time, help, and many words of encouragement. I couldn't have made it without him and his enthusiasm.

Dr. Averett would like to acknowledge the helpful discussion and fruitful collaboration with the polarized target groups of Cates et al. at the University of Virginia, and Jian-Ping Chen et al. at Jefferson Lab.

Introduction

The quark/gluon structure of the nucleus is studied in electron beam scattering experiments. Free neutrons decay too rapidly to use for targets in these experiments, but the anti-alignment of the two proton spins in a polarized ^{3}He nucleus make it a stable alternative. Polarization of the ^{3}He nucleus effectively provides polarization of the neutron. Polarization of ^{3}He is achieved during spin exchange collisions with polarized alkali metals such as K or Rb. Polarization P is defined as:

$$P = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \qquad (1)$$

where $N^{\uparrow}$ is the number of spins aligned and $N^{\downarrow}$ is the number of spins anti-aligned with a magnetic holding field.

There are two competing processes in polarizing ^{3}He. i) The alkali gives its spin to the ^{3}He at a certain rate known as the spin exchange rate, and ii) the alkalis can lose polarization through ordinary collisions with all other atoms in the system, this is known as the spin destruction rate for the alkali. The spin exchange rate is approximately the same for K and Rb [1], but it is believed that K is around 10-15 times less likely to depolarize than Rb through ordinary collisions with other atoms [1, 2]. If true, we would need far fewer photons (less laser power) to polarize a given amount of ^{3}He, or , for a given laser power, we can polarize faster and higher. Because pure K is difficult to directly polarize, a mixture of Rb and K will be used. The goal of this research project was to successfully fill a K-Rb hybrid cell and characterize its behavior.

Theory

Because of the difficulty in directly polarizing ^{3}He, spin is usually transferred to the ^{3}He nucleus from a polarized alkali metal. In the setup of the William and Mary polarized ^{3}He target lab, aluminosilicate glass (General Electric type 180) cells are filled with ^{3}He, N_2, and an alkali metal for polarization. A 795 nm, circularly polarized laser and constant magnetic field provided by a pair of Helmholtz coils are used to optically pump the alkali metal to a desired atomic spin state. Through spin exchange collisions, the alkali metal atomic spin is transferred to the ^{3}He nucleus. The degree of polarization is measured with a nuclear magnetic resonance (NMR) system consisting of three coil pairs.

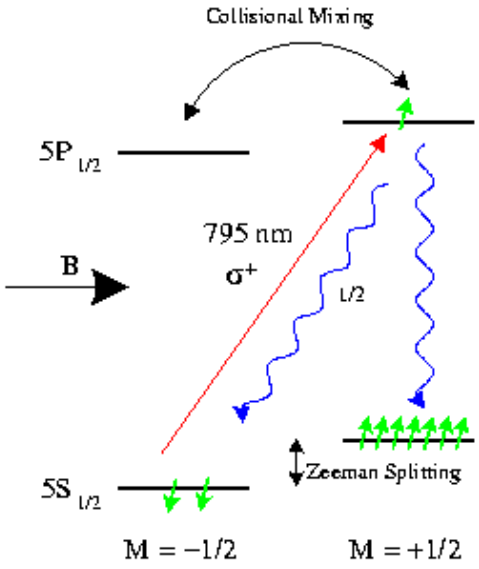

Figure 1. Illustration of the relevant Rb atomic spin states, ignoring the effect of the nuclear spin, in a magnetic field, B. Right circularly polarized laser light can only polarize electrons from the m=-1/2 level. They decay back to the m=-1/2 and m=+1/2 with equal probability, but can't be excited again from the m=+1/2 state

The atomic polarization of an alkali metal such as rubidium is determined by the spin state of its one valence electron. In the process of optically pumping rubidium, a constant magnetic field, produced by a pair of Helmholtz coils, causes Zeeman splitting of the m=+1/2 and m=-1/2 state in the normally degenerate ground state (5 $S_{1/2}$), and first excited state (5 $P_{1/2}$) of the electron (Figure 1). A right circularly polarized 795 nm diode laser directed along the magnetic field excites electrons only from the 5 $S_{1/2}$ m=-1/2 state to the 5 $P_{1/2}$ m=+1/2 state. From the 5 $P_{1/2}$ m=+1/2 state an electron will either decay back to the 5 $S_{1/2}$ m=-1/2 state to be re-excited, or decay to the desired 5 $S_{1/2}$ m=+1/2 state. N_2 is included in the cells to absorb the energy released when the Rb decays; this prevents the Rb from releasing the energy as a randomly polarized photon. Very quickly, most of the rubidium becomes atomically polarized in the 5 $S_{1/2}$ m=+1/2 state [3]. In a pure Rb cell, polarized Rb can depolarize by colliding with other Rb atoms, or, it may collide with ^{3}He. When a rubidium atom collides with a ^{3}He nucleus, spin is exchanged through a hyperfine-like interaction, leading to polarization of the ^{3}He nucleus. The rate of ^{3}He polarization by any alkali metal is given by the following differential equation:

$$\frac{dP_{He}(t)}{dt} = \gamma_{SE}(P_A - P_{He}(t)) - \Gamma P_{He}(t) \qquad (2)$$

where P_A is the average alkali polarization, P_{He} is the ^{3}He polarization, Γ is the overall depolarization rate of ^{3}He due to all possible depolarization mechanisms, and γ_{SE} is the spin-exchange rate between the alkali and ^{3}He. The spin exchange rate $\gamma_{SE} = k_A[A]$, where k_A is the spin exchange coefficient of the alkali with ^{3}He, and [A] is the density of the alkali.

The rate that K gives polarization to ^{3}He during spin-exchange collisions is comparable to the Rb-^{3}He spin-exchange rate, with spin exchange coefficients $k_{Rb}=6.8\pm0.2\times10^{-20}$ cm^3/s, and $k_K=6.1\pm0.4\times10^{-20}$ cm^3/s [3]. However, K is much less likely to lose its polarization in destructive collisions than Rb. In particular, Kadlecek, Anderson and Walker [1] have shown that K-K spin-destruction rates are lower, by a factor of 15, than Rb-Rb rates, and Walker, Thywissen and Happer [2] calculated that K-^{3}He spin destruction rates are approximately 10 times lower than Rb-^{3}He spin destruction rates. A better spin-exchange/spin-destruction rate would decrease the laser power needed to polarize the alkali metal, and decrease the polarization time. Optically pumping K is difficult because a very narrow linewidth is needed from the laser. Commercial lasers capable of producing the high power needed for these targets have linewidths which are too broad. These difficulties could be avoided by polarizing a small amount of Rb, which would give its spin to the K [4]. It turns out that Rb is very efficient at giving its spin to K, with K-Rb spin-exchange rates that are much higher than the K depolarization rates in typical ^{3}He spin-exchange cells[3]. If the K density greatly exceeds that of Rb, most of the ^{3}He polarization will result from the spin exchange with K, and the K will be less likely to depolarize in collisions with Rb. The group Babcock et al. [3] have shown this is possible for small low density cells, but it has not been shown to work for the large high density cells used in nuclear physics experiments.

The polarization of ^{3}He in a K-Rb cell can be described with several equations. The rate of polarization in a K-Rb cell is the same as eqn. (1), where the spin-exchange rate $\gamma_{SE}=k_K[K]+k_{Rb}[Rb]$; k_K and k_{Rb} are the spin-exchange rate coefficients, and the factors in brackets are the alkali densities. Because the K-Rb spin-exchange cross section

is so much larger than typical alkali relaxation rates, the K and Rb have equal spin polarization P_A [3]. Solving equation (1) gives:

$$P_{He}(t) = \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma} P_A (1 - e^{-(\gamma_{SE} + \Gamma)t}) \quad (3)$$

where $\tau = 1/(\gamma_{SE}+\Gamma)$ is known as the "spin up time." In the absence of optical pumping, this equation becomes:

$$P_{He}(t)=P_{init}e^{-\Gamma t} \quad (4)$$

Where P_{init} is the polarization when optical pumping ceases.

Measurement of the cell polarization is done by a process known as adiabatic fast passage (AFP) NMR. In this process, polarized ^{3}He nuclei align their spins with a constant magnetic field, referred to as a holding field. When an oscillating magnetic field reaches resonance at the Larmour frequency, the ^{3}He spins flip. This is measured by a set of pickup coils, oriented perpendicular to the holding field.

Procedures

Cells and cell fill procedure

As a proof of principle, four spherical test cells, named 4.1-4.4, were filled and characterized. These one inch aluminosilicate spheres all arrive from the glassblower suspended from a pyrex string (Figure 2). One end of the string contains a dip and two retorts, while the other is used to attach to the vacuum system. Before putting the cell under vacuum, each retort has either a rubidium ampoule or a potassium ampoule broken and dropped into it, and is then sealed. For several days, the cell is then kept under a high

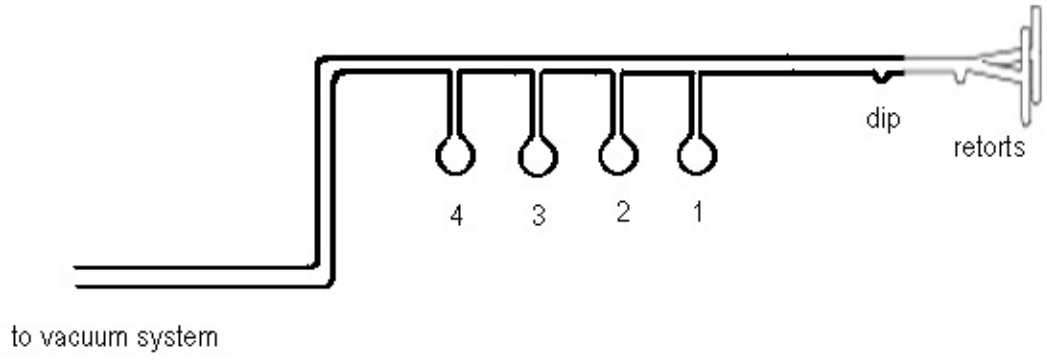

Figure 2. Schematic diagram of test sphere string which is attached to vacuum. K was sealed into one of the retorts and Rb was sealed into the other.

vacuum (~10^{-9} Torr) and in a 470°C oven, in an attempt to remove impurities from the glass. Parts of the glass tubing that are not heated by the oven are flamed three times a day with a hand torch during this time. As condensed material is vaporized by the heat and removed from the system by the vacuum pump, the vacuum improves. When it seems that flaming will not improve the vacuum any more, a hand torch is used to vaporize enough rubidium to deposit a very thin layer in the dip. Then the Rb retort is

pulled off. On top of this layer, approximately 100 times as much K is added. The K retort is then pulled off. This process is inexact and the precise ratios of K and Rb are not known. A few days later, the oven is removed and a small amount of the combined alkali metals are chased from the dip into each sphere, using a hand torch. At this time, 3 amagats of ^{3}He, and a small quantity of N_2 gas are allowed to mix in the cell string. Each sphere is pulled off by melting the glass attaching it to the string while being cooled with liquid nitrogen. The low temperature reduces the cell pressure to below 1 atm, allowing the glass to seal. Based on the successful polarization of these test spheres, two double chambered ^{3}He

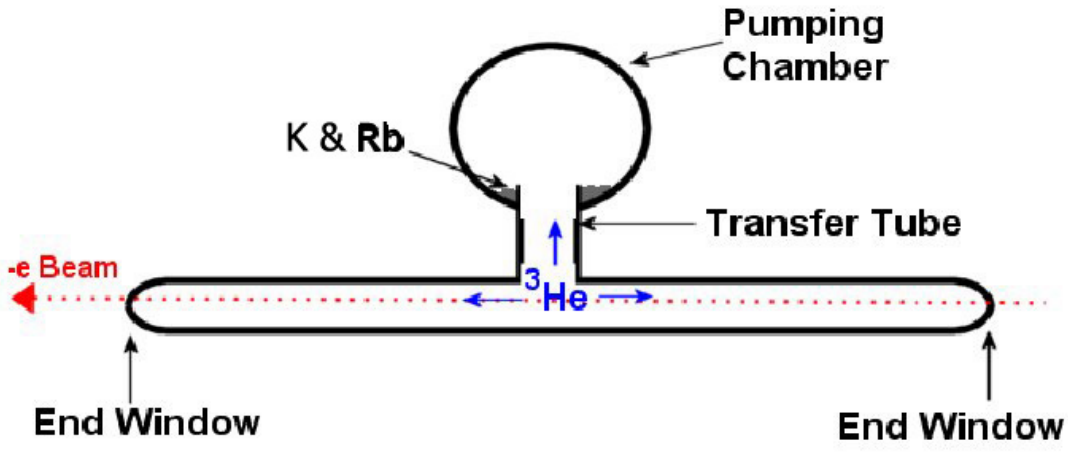

Figure 3. The optical pumping chamber is spherical with an approximate radius of 30mm. The chamber has a lip around the connecting transfer tube to keep liquid alkali metal from running into the target chamber. The cylindrical target chamber is approximately 40cm in length with a radius of ~10mm. The end windows of the target chamber are about 100 μm thick, which minimizes glass interactions with the electron beam.

target cells, named Viagra and V12, were filled and characterized in this project. These cells were both blown from aluminosilicate glass at the University of Virginia to the same specifications as typical ^{3}He target cells used at Jefferson Lab. ^{3}He target cells usually have a two-chambered design, with an upper spherical optical pumping chamber and a

lower cylindrical target chamber, connected with a thin tube (Figure 3). The optical pumping chamber contains the alkali metal and is heated during polarization to vaporize the metal. Because the target chamber is at room temperature, it contains no alkali metal vapor. This is the chamber that the electron beam is sent through when neutron studies are done.

The preparation of each double chambered cell is identical to that of the test spheres up to the point of the gas fill. At this time, the cell is filled with approximately 8 amagats of ^{3}He, and approximately 0.05 amagats of N_2 gas, and pulled off the vacuum system by melting the glass at the pull off point (Figure 4). During the pull off, the cell is

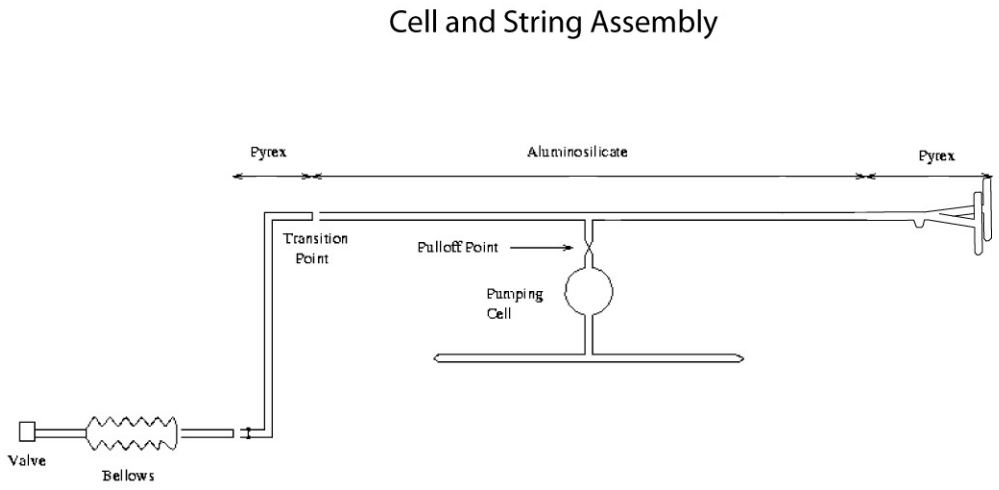

Figure 4. Schematic diagram of test sphere string which is attached to vacuum. K was sealed into one of the retorts and Rb was sealed into the other.

cooled to 4K with liquid helium to reduce the pressure to below 1atm. After filling, the cell is allowed to slowly warm to room temperature.

Optical Pumping and Characterization

Once filled, the cell is installed in a torlon oven, suspended in the middle of three coil pairs for NMR characterization (Figure 5). The main coils provide the holding field, and the pickup coils measure the spin flips as the ^{3}He spins sweep through resonance. The pickup coils are adjustable so the cell can be placed between them, and then pushed as

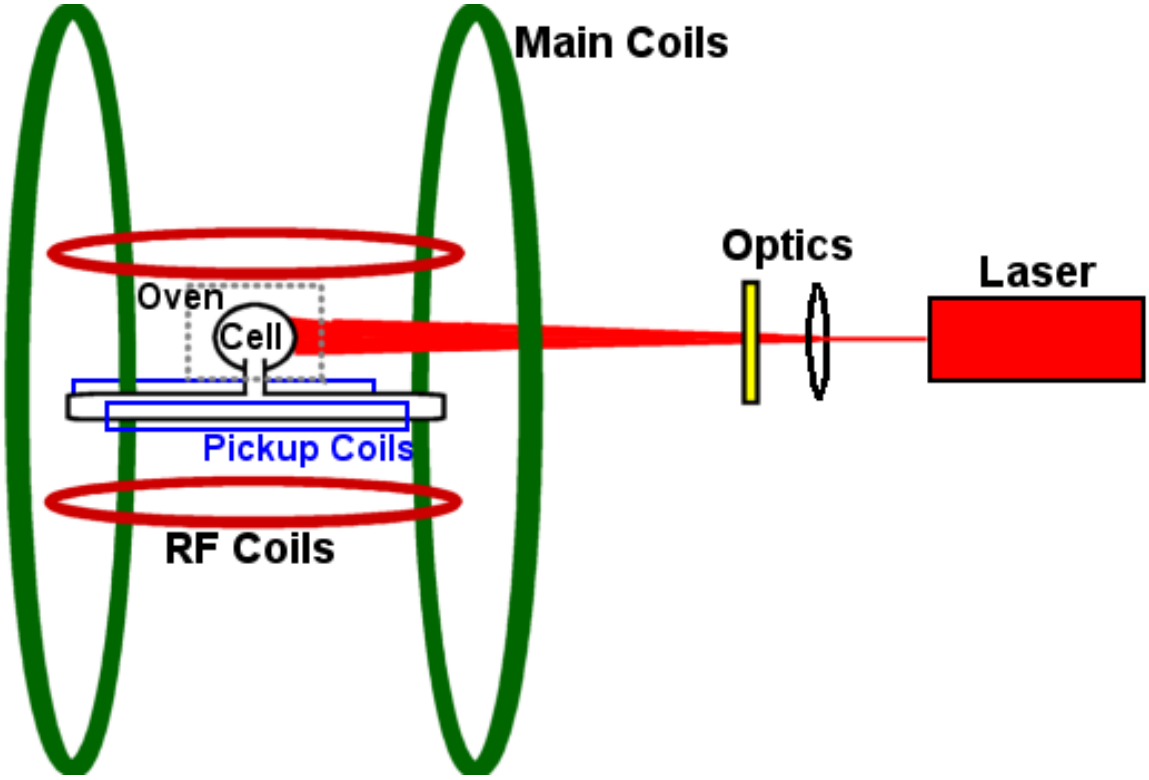

Figure 5. schematic diagram of NMR system

close to the chamber as possible without risking rupture to the cell. When an NMR sweep takes place, the pickup coil response is measured in millivolts and fit with a best

fit curve to find the voltage peak height. This peak height is proportional to the ^{3}He polarization.

A cell is polarized by the optical pumping process described previously, using two 795 nm right circularly polarized diode lasers with 60 Watts of total power, and a 25 Gauss holding field. The temperature in the pumping chamber is varied incrementally between 170°C and 230°C. The optimum temperature for a pure Rb cell is 170°C, but because the K vapor pressure is somewhat smaller than Rb at this temperature, a smaller amount of K will be in vapor form at 170°C. With a limited supply of Rb, however, higher temperatures will give higher K/Rb density ratios. NMR measurements are taken every four hours during polarization and the voltage peak heights are graphed and fit using equation (2).

Once polarization levels off at a peak value, the lasers and oven are turned off and the cell is allowed to depolarize. This depolarization is referred to as the spin down. NMR measurements are taken every four hours during the spin down; however, the NMR measurements themselves have a depolarizing effect on the cell. To measure the polarization losses, five NMR measurements are taken in rapid succession on the depolarizing cell. The average depolarization found between these measurements is known as the AFP (adiabatic fast passage) loss, and is used to correct the spin down data for this loss. The AFP corrected voltage peak heights are graphed and fit using equation (3). In this equation, $1/\Gamma$ is defined as the cell lifetime, a measure of the quality of the cell.

Data

Test Spheres

4.3

Three of the test spheres were successfully polarized; the fourth has not yet been evaluated. Because Hybrid sphere 4.3 had a long lifetime (Figure 6), it was chosen for further characterization. Spin ups on 4.3 were done at temperatures of 170°C (Figure 7), 220°C (Figure 8), and 230°C (Figure 9). These results are summarized in Table 1.

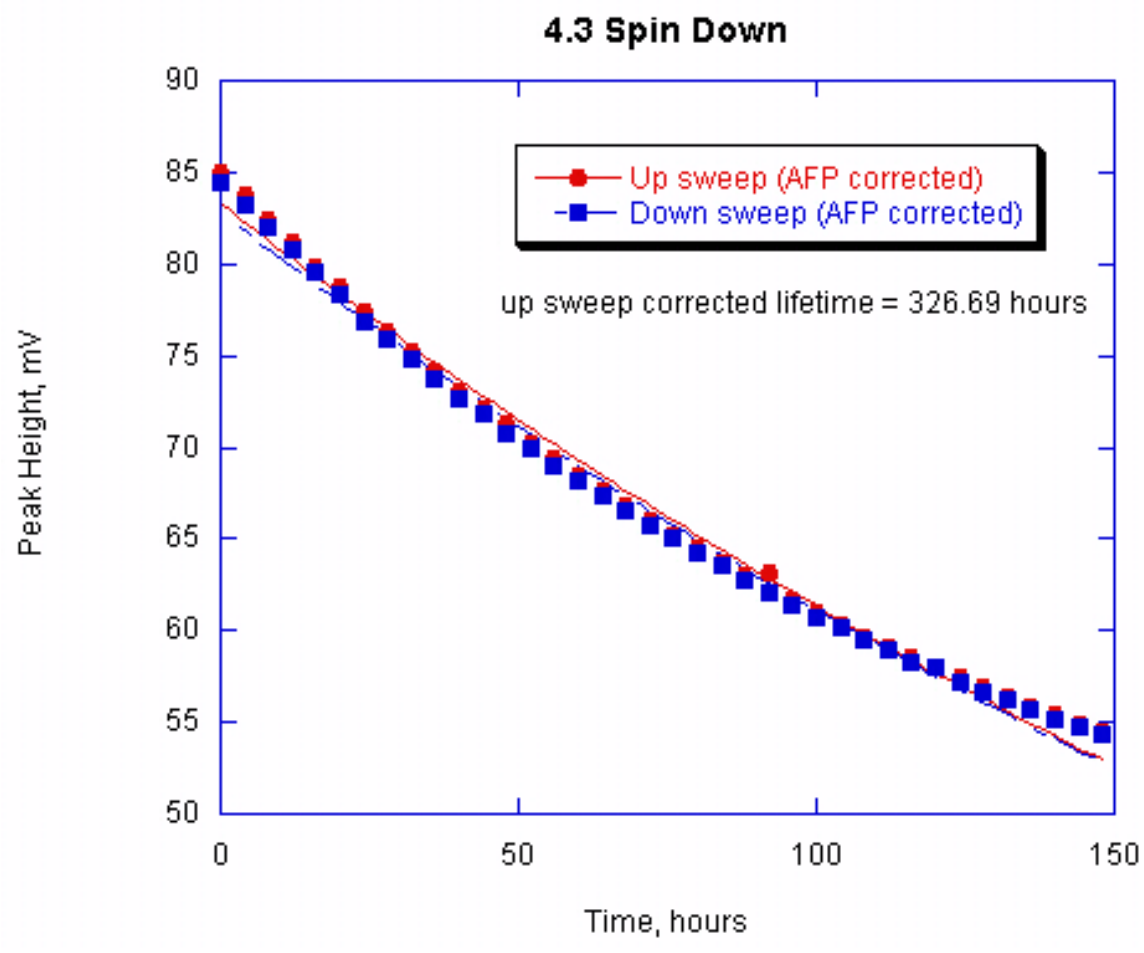

Figure 6. Spin down graph of cell 4.3, with data corrected for AFP loss. A fit to equation (3) gives a lifetime of 326.7 hours. The up sweep is the signal from sweeping up through resonance, and the down sweep is the signal from sweeping back down.

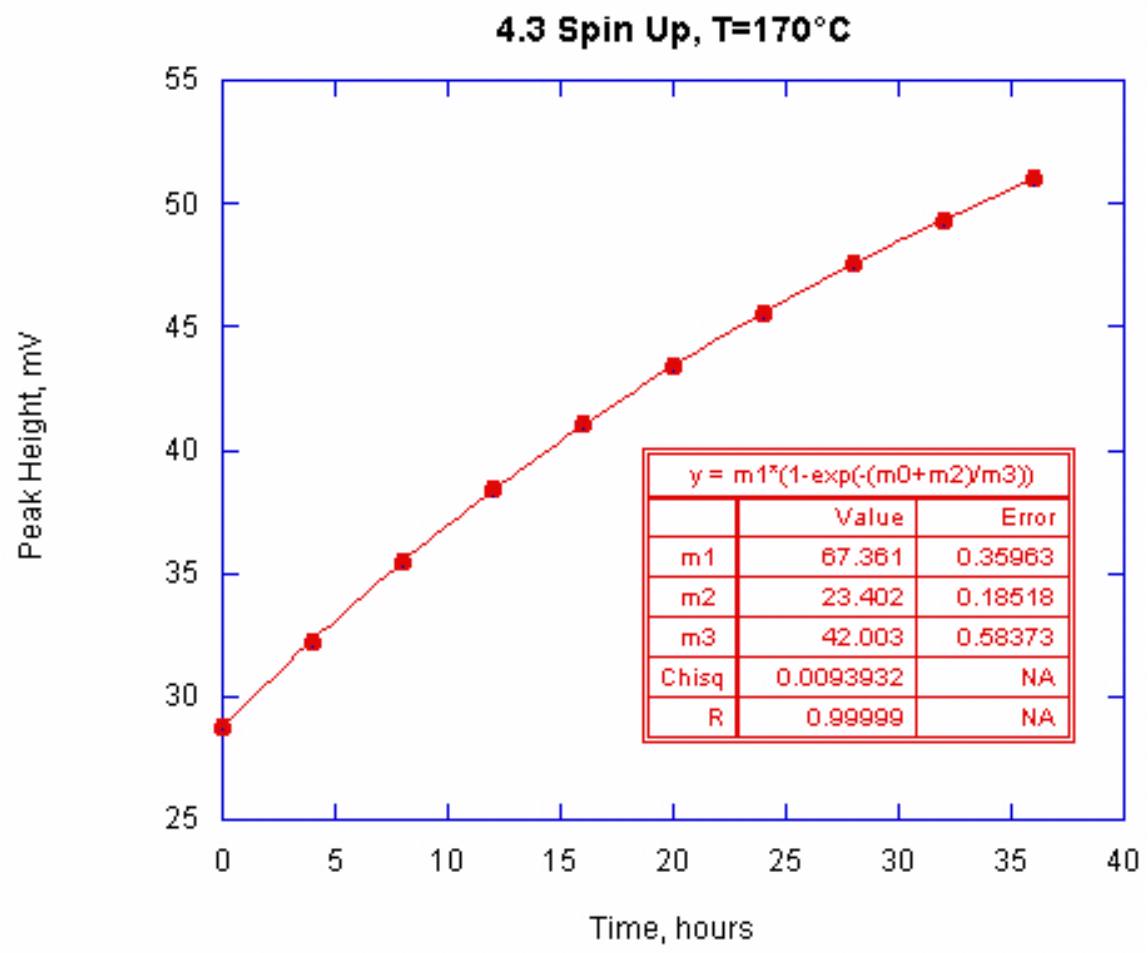

Figure 7. Spin up of cell 4.3 at 170°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 67.4mV, and a spin up time of 42.0 hours.

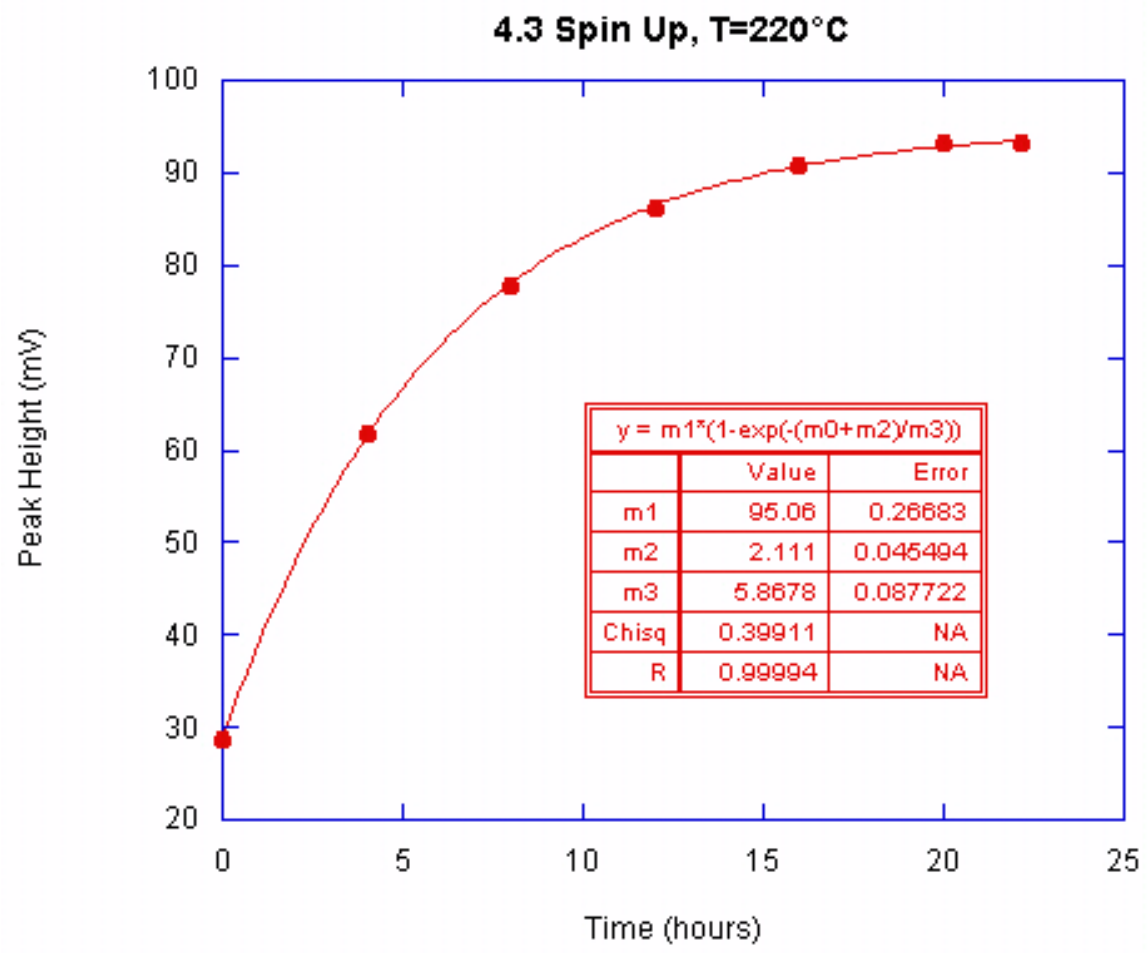

Figure 8. Spin up of spherical cell 4.3 at 220°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 95.1mV and a spin up time of 5.9 hours.

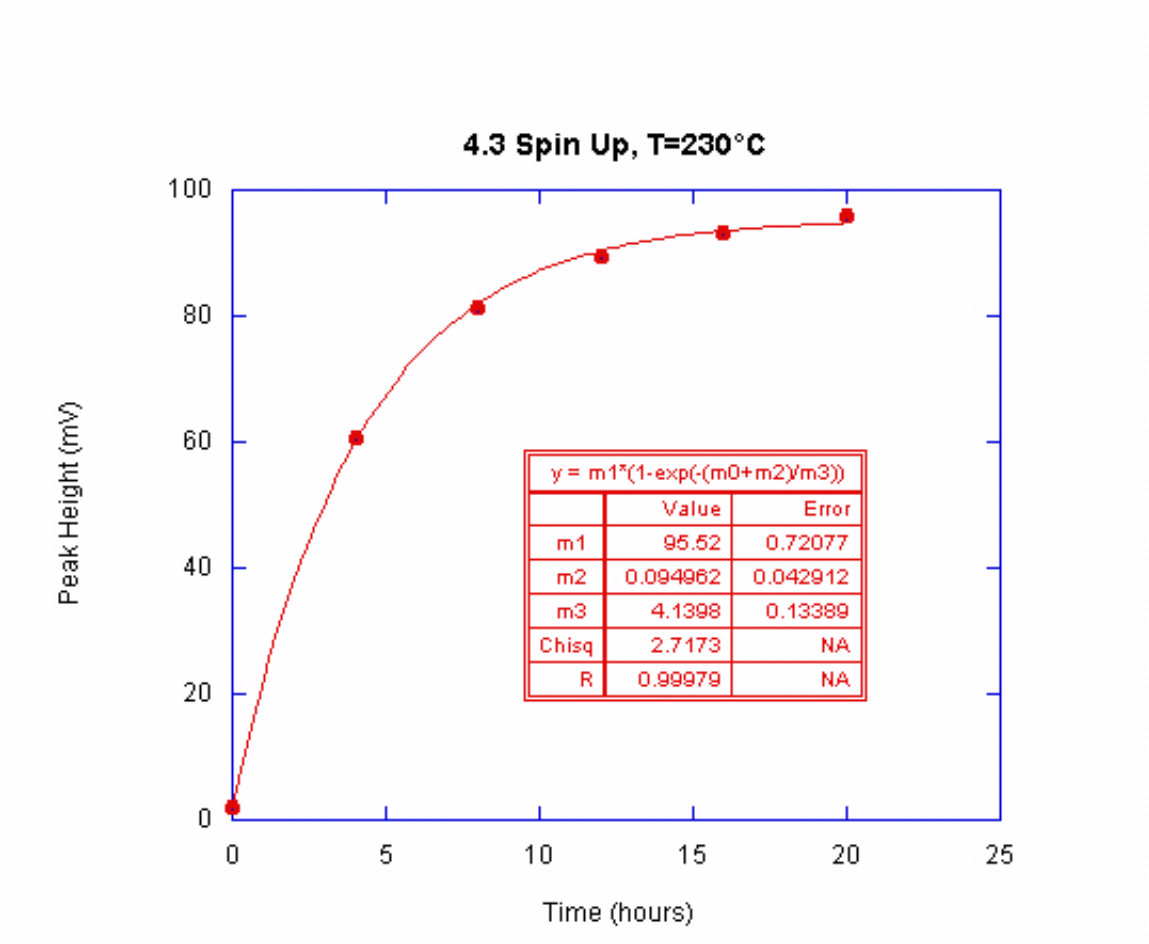

Figure 9. Spin up of spherical cell 4.3 at 230°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 95.5mV and a spin up time of 4.1 hours.

Spherical cell 4.3

Temperature (°C)	Spin up time (hours)	Maximum Polarization (mV)
170	42.0	67.4
220	5.9	95.1
230	4.1	95.5

Table 1. Summary of spin up data collected from spherical cell 4.3.

Double Chambered Cells

Viagra

The cell Viagra was spun up at temperatures of 170°C (Figure 10), 190°C (Figure 11), 210°C (Figure 12), and 230°C (Figure 13). The spin up graphs are combined for comparison in Figure 14, and the spin up results are summarized in Table 2. The cell was depolarized between each of the spin ups by running multiple NMR sweeps, or by taking typical spin down measurements (Figure 15).

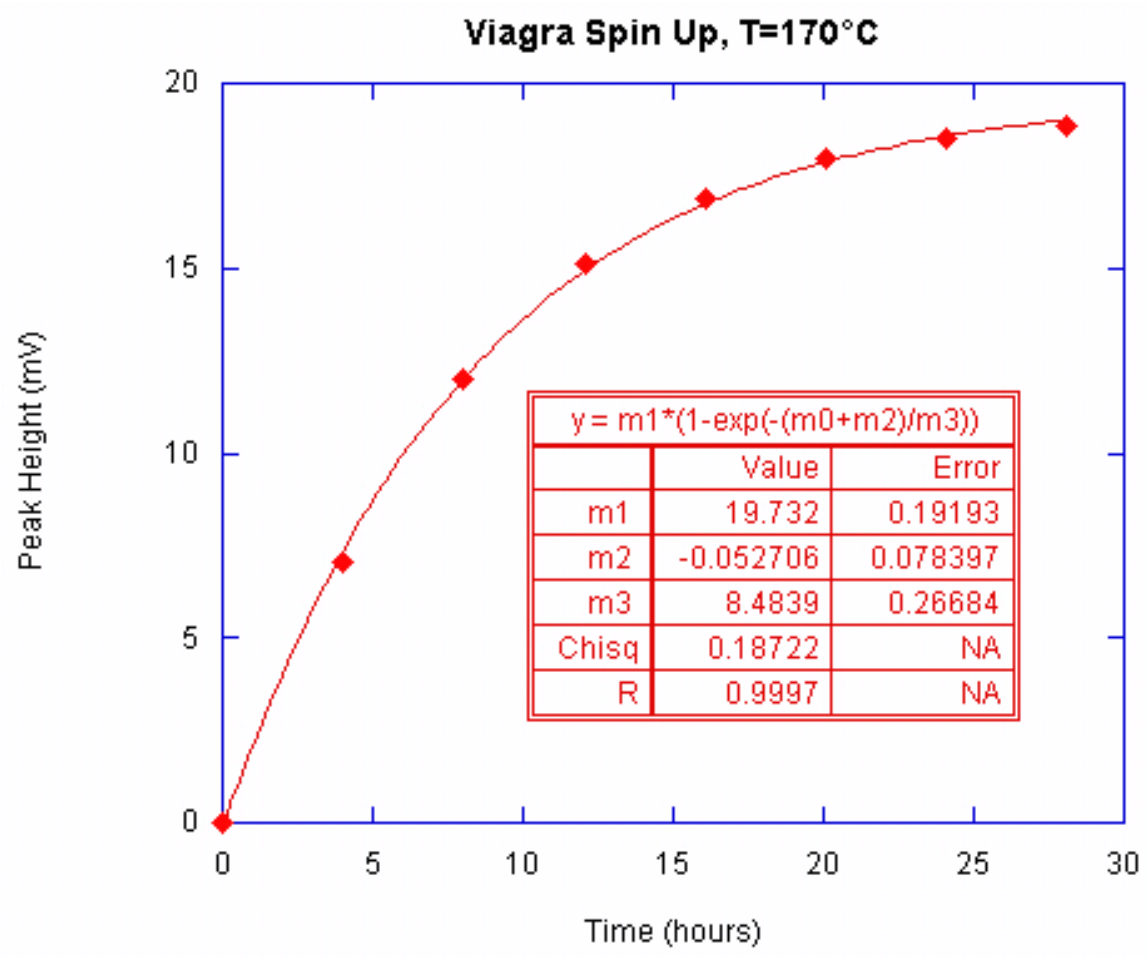

Figure 10. Spin up of cell Viagra at 170°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 19.7mV and a spin up time of 8.4 hours.

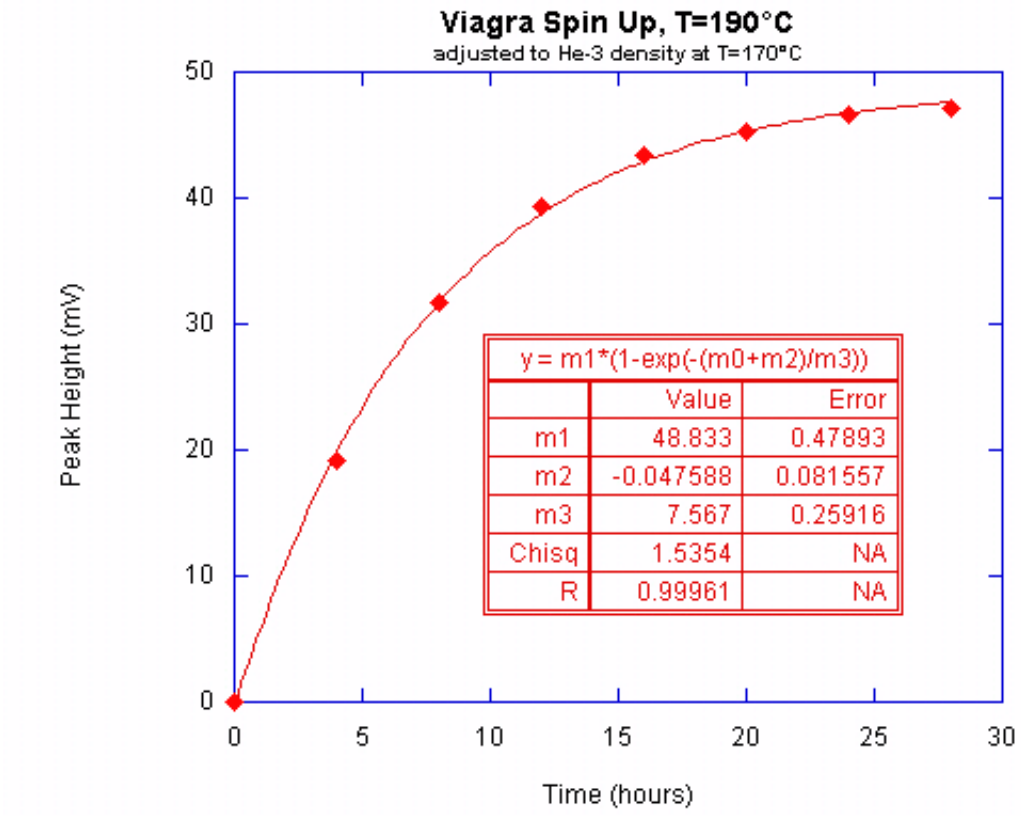

Figure 11. Spin up of cell Viagra at 190°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 190°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 48.8mV and a spin up time of 7.6 hours.

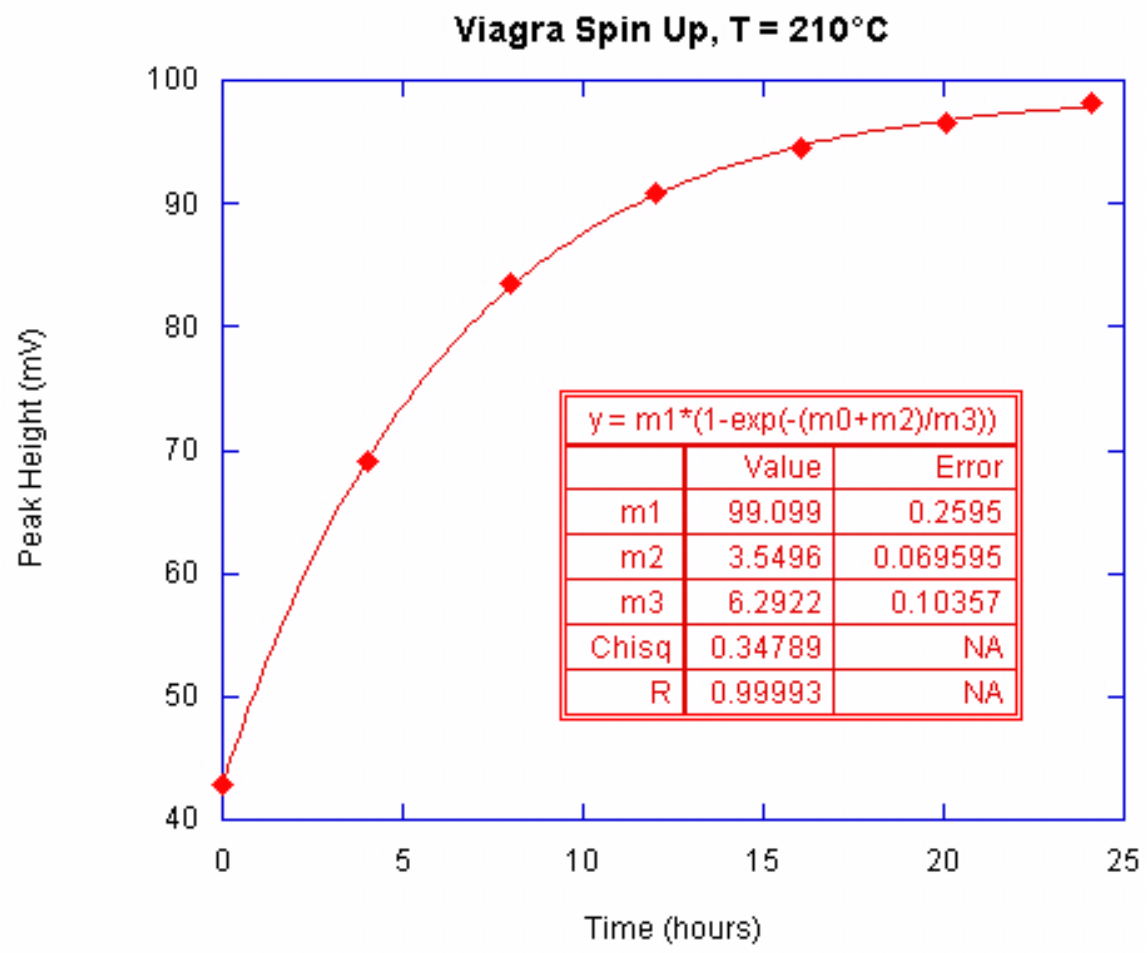

Figure 12. Spin up of cell Viagra at 210°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 210°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 99.0mV and a spin up time of 6.2 hours.

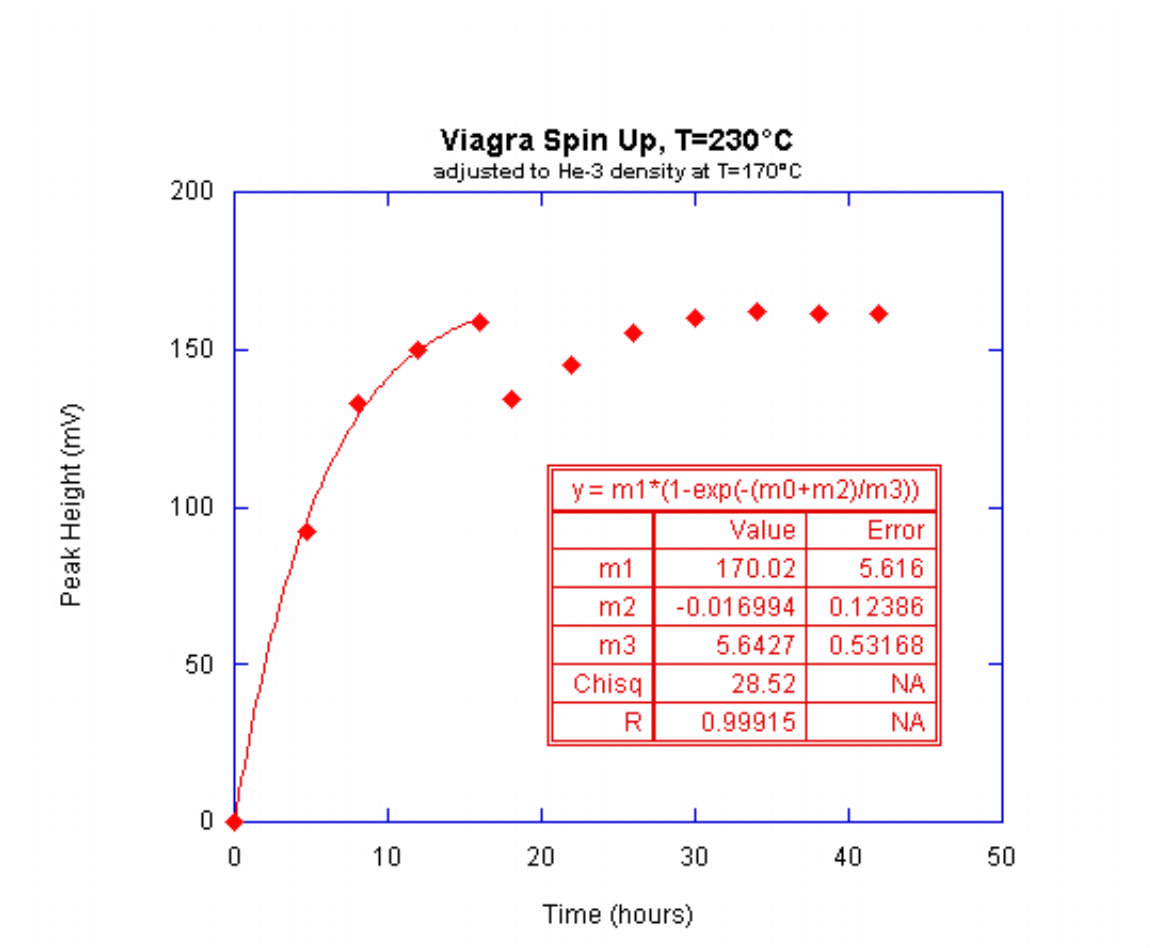

Figure 13. Spin up of cell Viagra at 230°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 230°C. This spin up was interrupted by a power outage between 16 and 20 hours. A fit of the data from 0-16 hours to equation (2) (shown in red) gives a maximum polarization of 170.0mV and a spin up time of 5.6 hours.

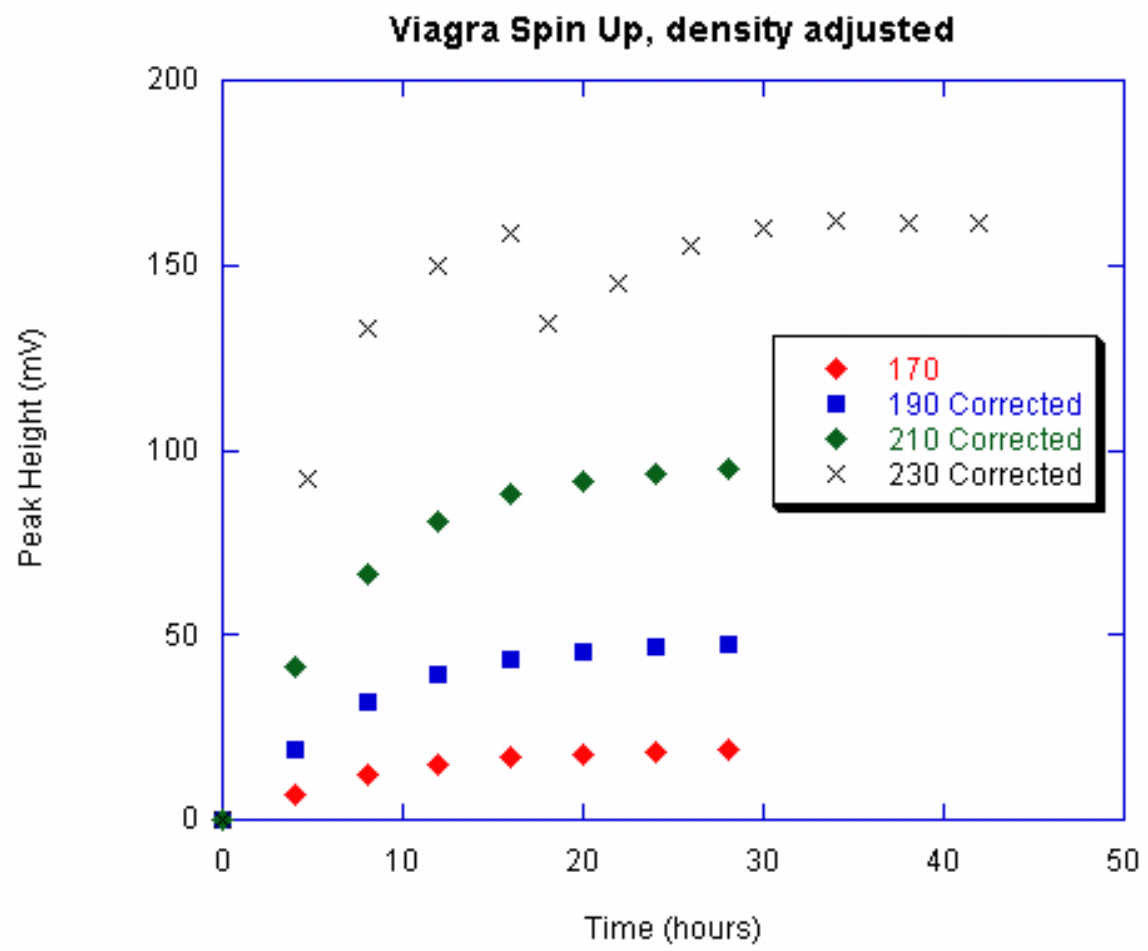

Figure 14. Spin ups of Viagra at temperatures of 170°C, 190°C, 210°C, and 230°C, combined for comparison. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and the other temperatures.

Viagra

Temperature (°C)	Spin Up Time (hours)	Maximum Polarization
170	8.4	19.7
190	7.6	48.8
210	6.2	99.0
230	5.6	170.0

Table 2. Summary of data on the cell Viagra from Figures 10-13.

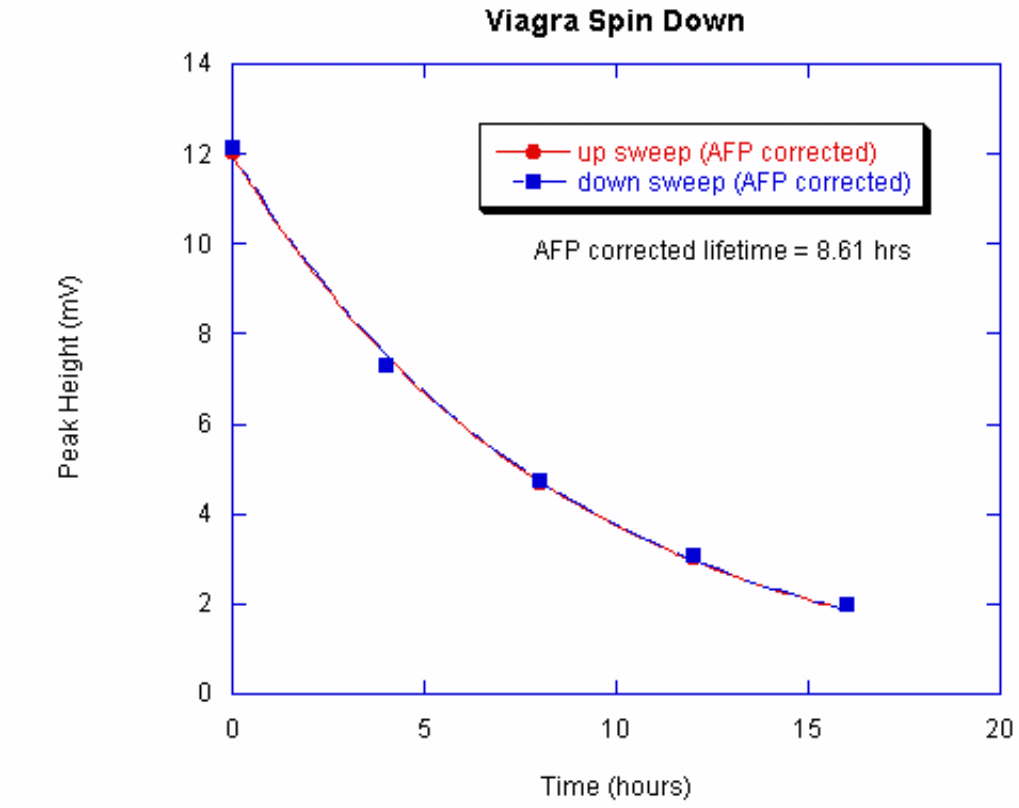

Figure 15. Spin down graph of cell Viagra, with data corrected for AFP loss. A fit to equation (3) gives a lifetime of 8.61 hours. The up sweep is the signal from sweeping up through resonance, and the down sweep is the signal from sweeping back down.

V12

The cell V12 was spun up at a temperature of 170°C (Figure 16) until there was little increase in polarization between NMR measurements. Then, immediately after a measurement, the temperature was raised to 190°C (Figure 17). Spin ups at 210°C (Figure 18), 230°C (Figure 19), and 240°C (Figure 20) were begun in the same manner. However, there was a break in data collection after the 190°C spin up and the 210-240°C data was collected at a later time. The 210°C spin up was begun after the cell had polarized to the maximum 190°C value so that the data would mesh with the 170-190°C

data when the time axis was adjusted. Figure 21 shows the complete spin up graph, and the spin up results are summarized in Table 3. The spin down data for V12 is shown in Figure 22.

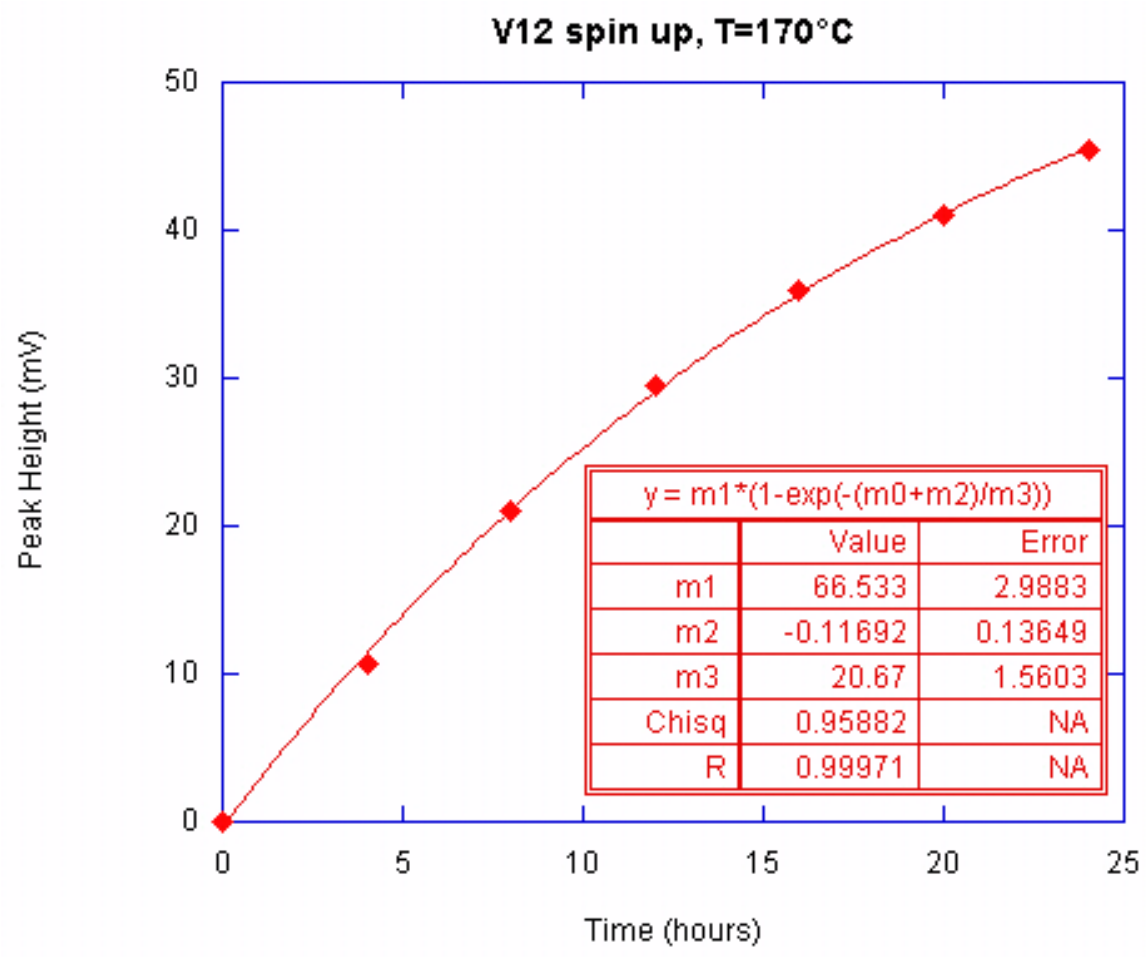

Figure 16. Spin up of cell V12 at 170°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 66.5mV and a spin up time of 20.7 hours.

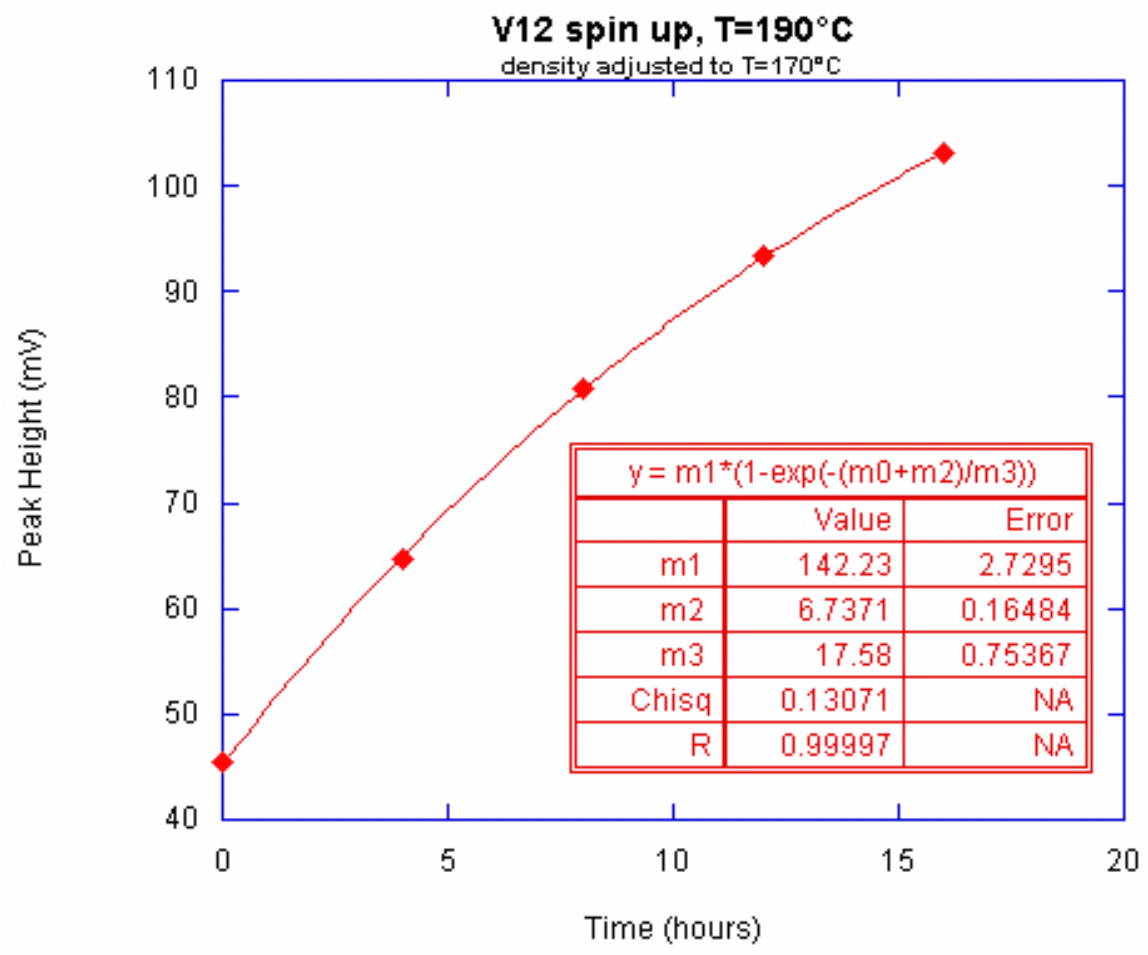

Figure 17. Spin up of cell V12 at 190°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 190°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 142.2mV and a spin up time of 17.6 hours.

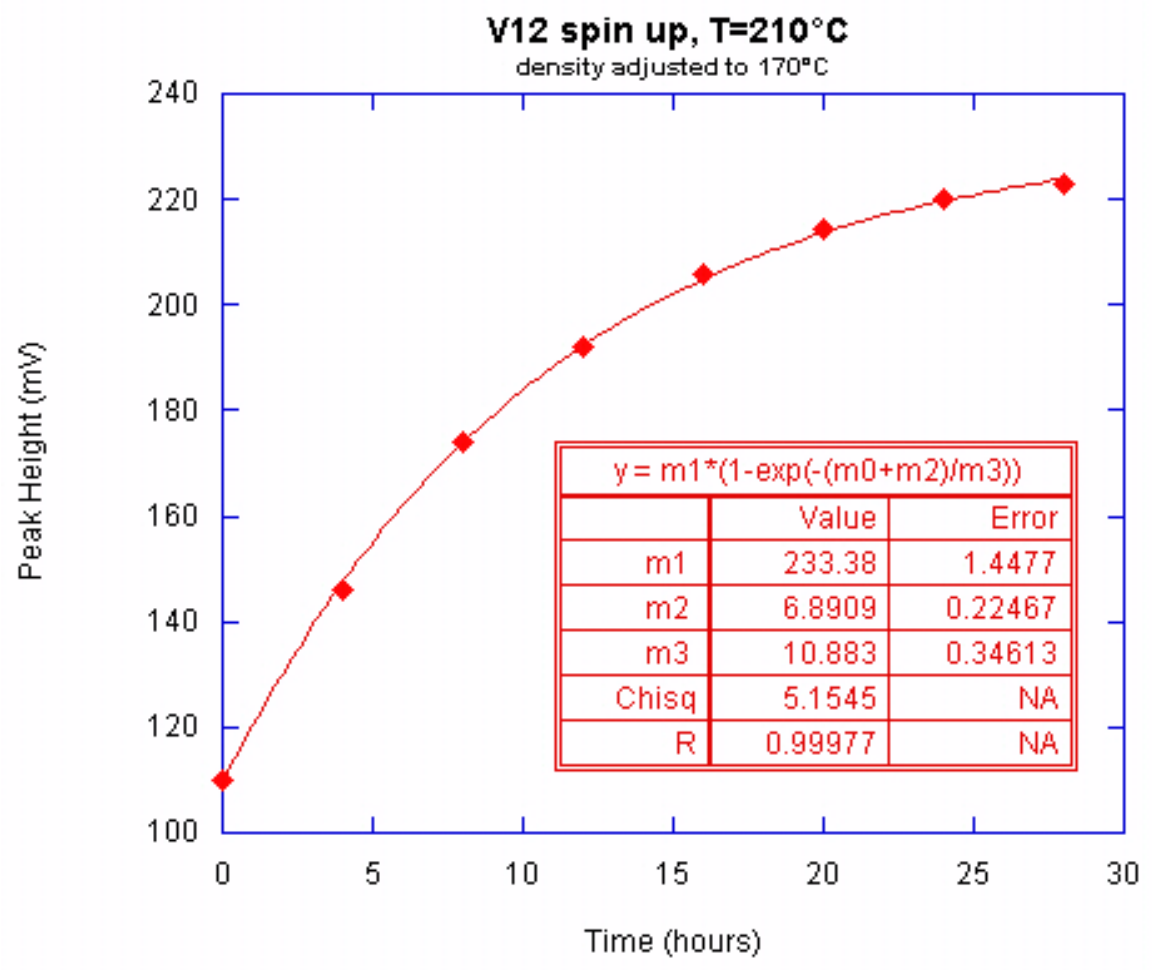

Figure 18. Spin up of cell V12 at 210°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 210°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 233.4mV and a spin up time of 10.9 hours.

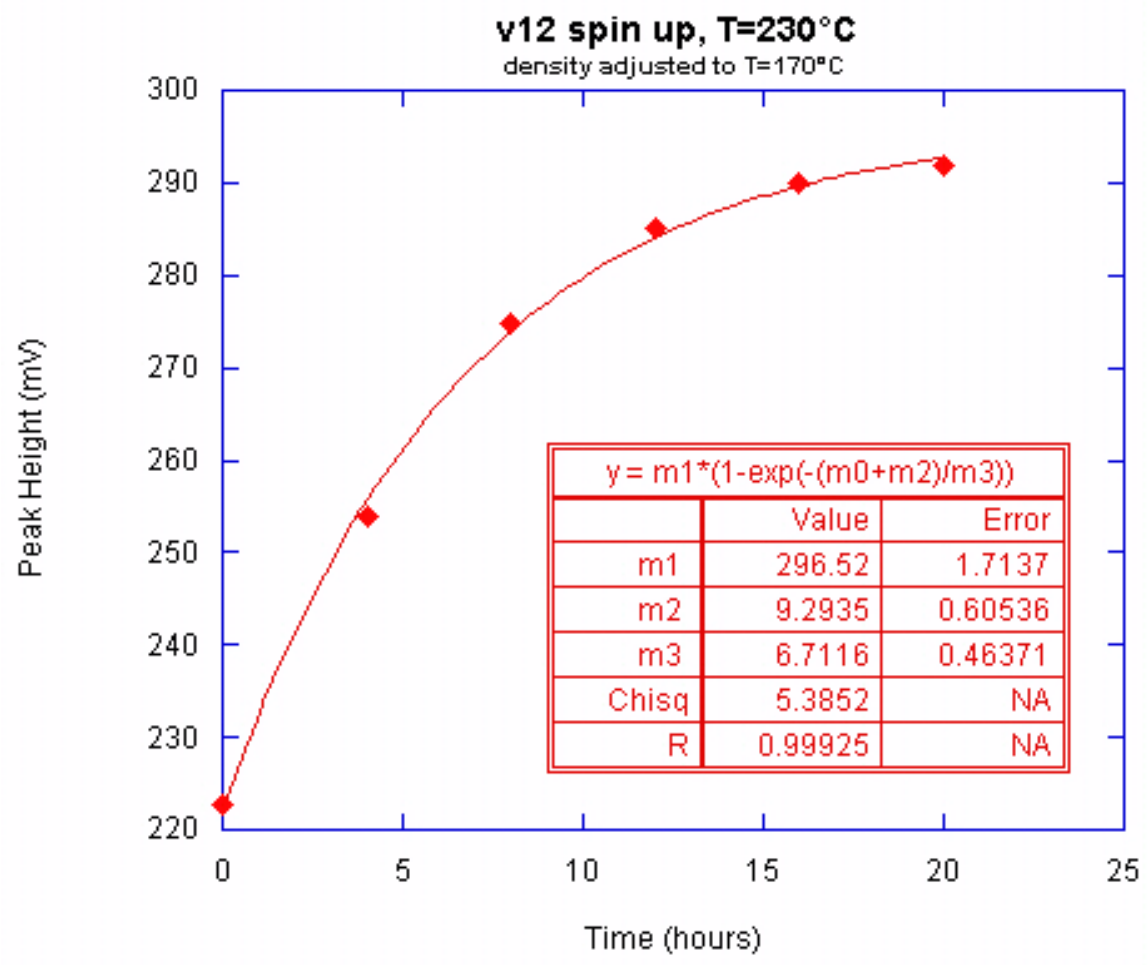

Figure 19. Spin up of cell V12 at 230°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 230°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 296.5mV and a spin up time of 6.7 hours.

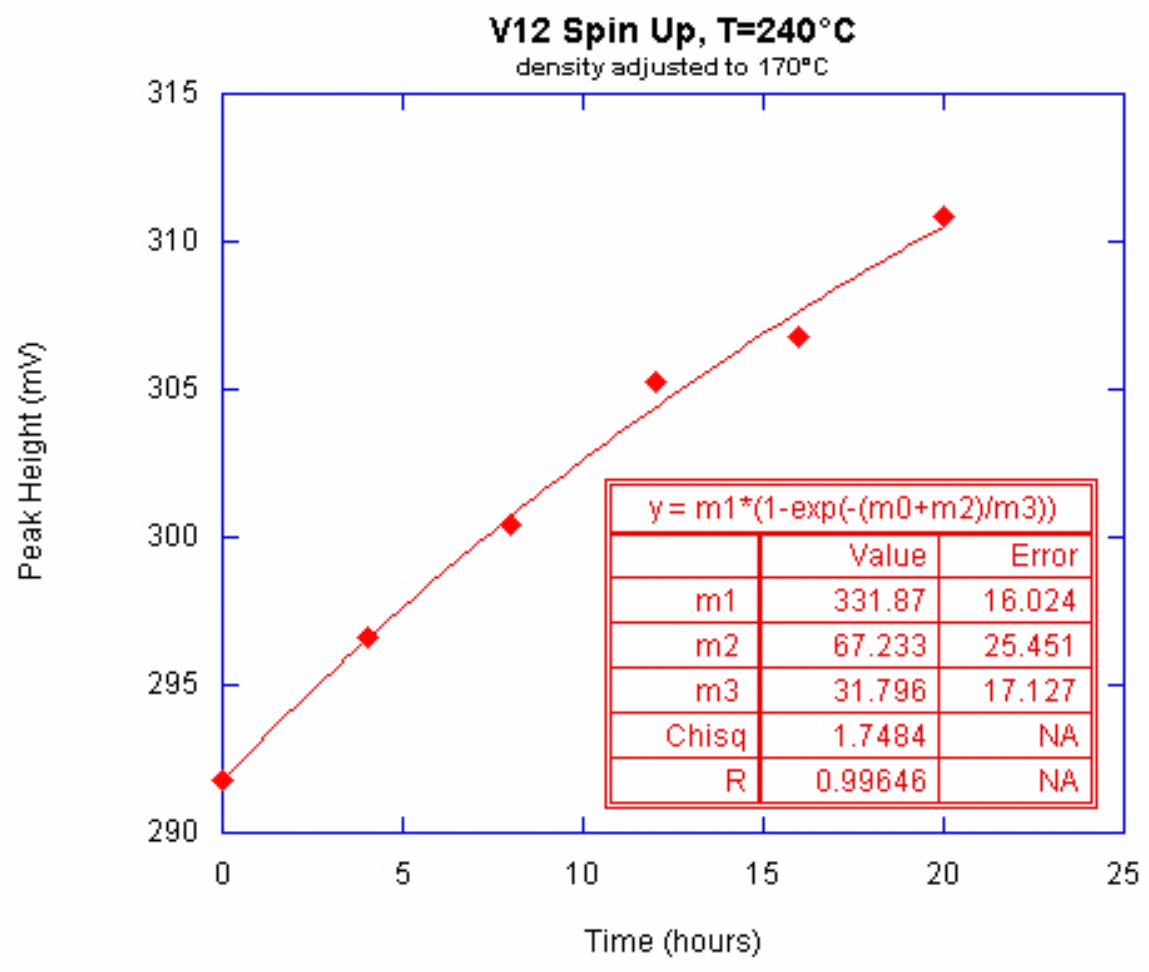

Figure 20. Spin up of cell V12 at 240°C. This data has been adjusted to account for the difference in the ^{3}He density in the lower chamber at 170°C and 240°C. A fit of the data to equation (2) (shown in red) gives a maximum polarization of 331.9mV and a spin up time of 31.8 hours.

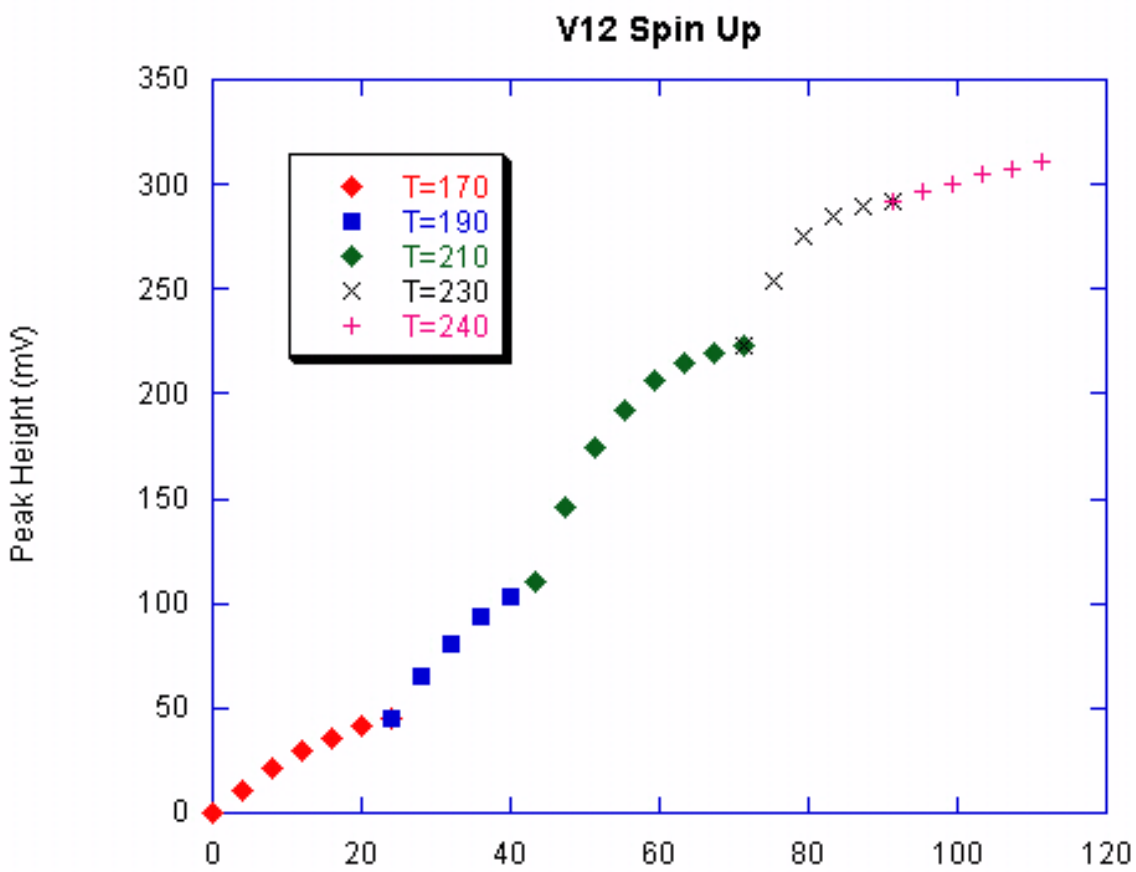

Figure 21. Spin up of V12 as the temperature was raised from 170°C, to 190°C, and 210°C, to 230°C, to 240°C. This data has been adjusted to account for the difference in the ^{3}He density at different temperatures.

V12

Temperature (°C)	Spin Up Time (hours)	Maximum Polarization (mV)
170	20.7	66.5
190	17.6	142.2
210	10.9	233.4
230	6.7	296.5
240	31.8	331.9

Table 3. Summary of the data on cell V12 from figures 16-19.

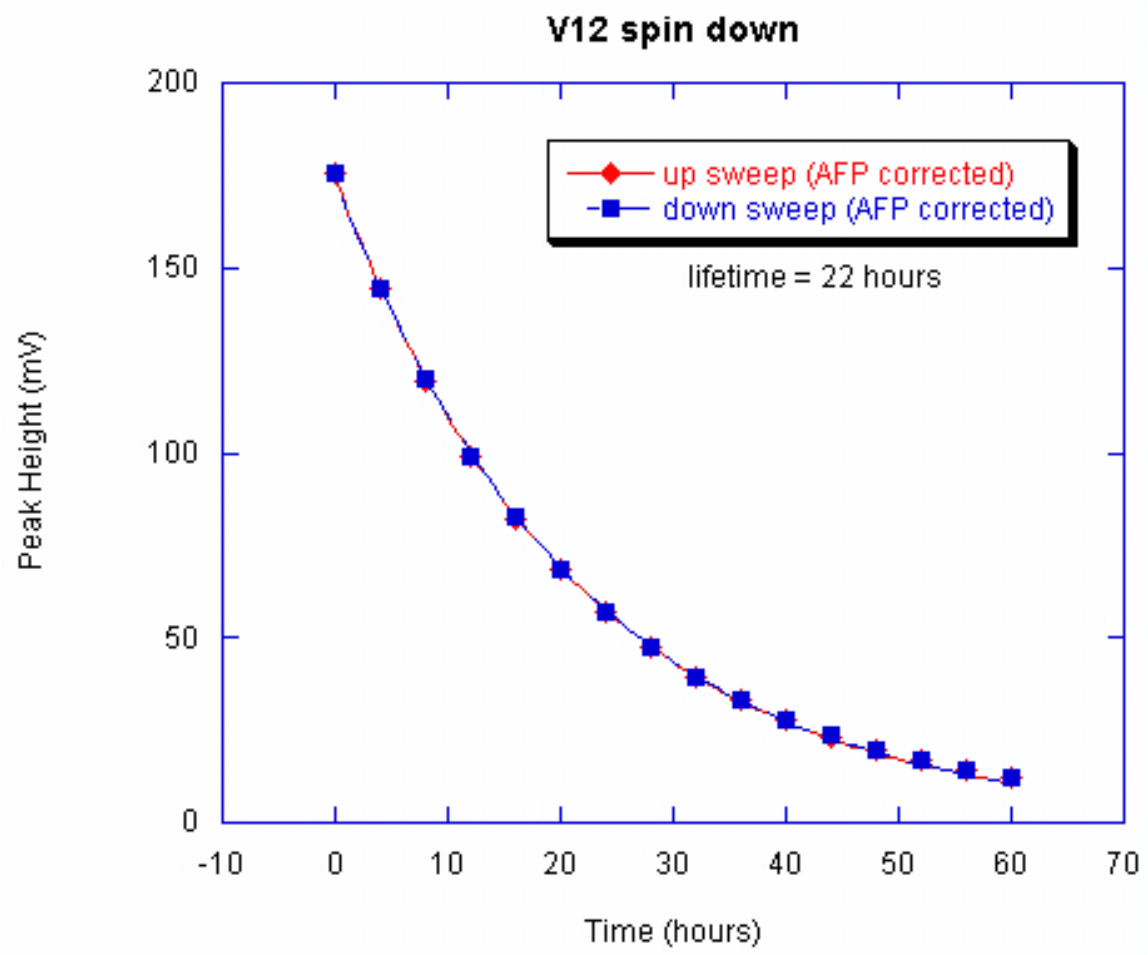

Figure 22. Spin down graph of cell V12, with data corrected for AFP loss. A fit to equation (3) gives a lifetime of 22 hours. The up sweep is the signal from sweeping up through resonance, and the down sweep is the signal from sweeping back down.

Pure Rb cell, Queen Mary

The cell Queen Mary is a double chambered cell of the same design as the hybrid double chambered cells, but contained only pure Rb. It was polarized at the Thomas Jefferson National Accelerator Facility using approximately 50% more laser power (three lasers) than the hybrid cells (two lasers) (Figure 23). Though it required more laser power, its spin up time of approximately 8 hours is comparable to the spin up on the hybrid cell V12 using only two lasers at 230°C.

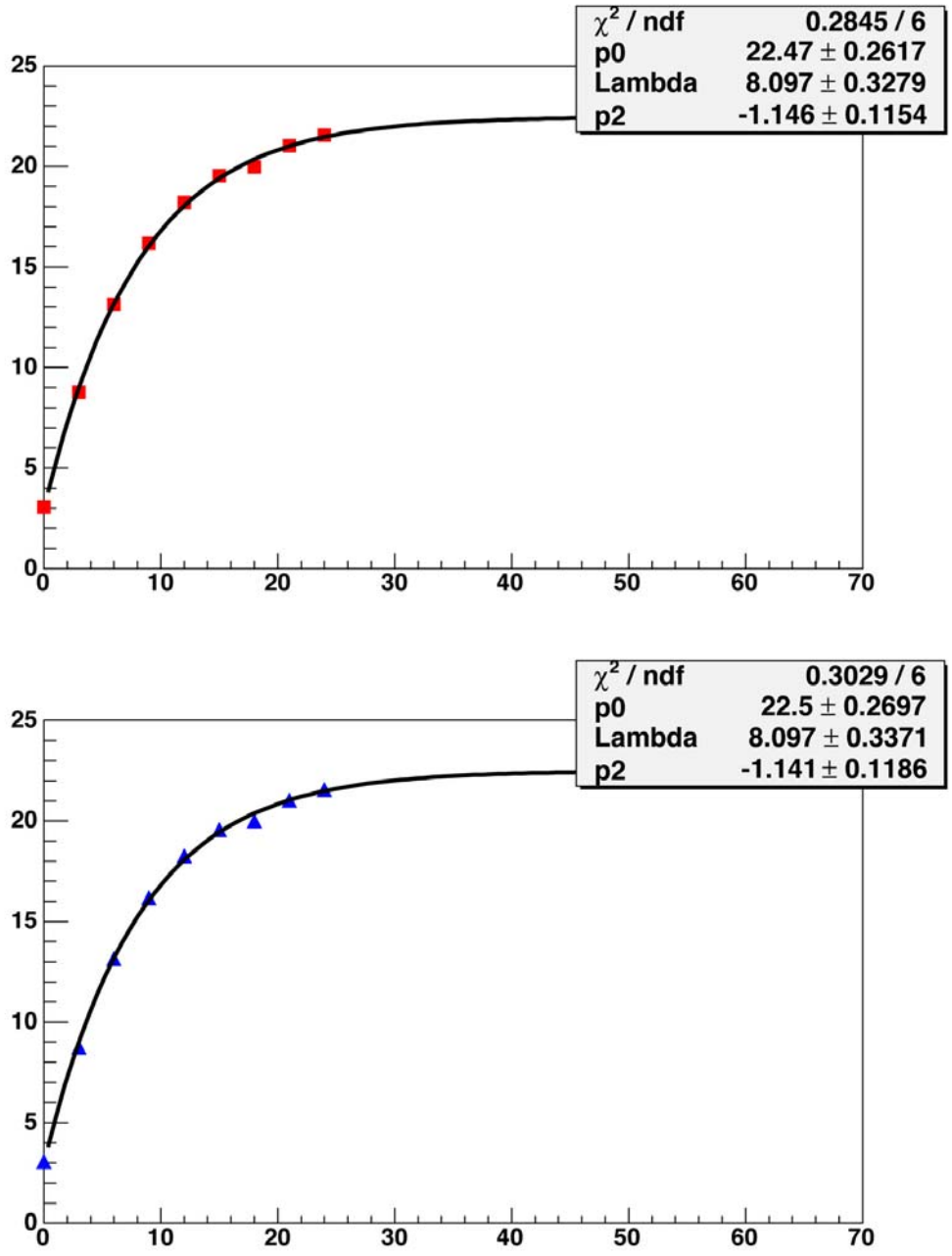

Figure 21. Spin up of Queen Mary done at TJNAF with three lasers. The number to note is lambda, the spin up time, which is 8 hours.

Conclusions

We successfully made and polarized both test spheres and J-lab geometry hybrid cells. The results of this study demonstrate that hybrid K-Rb ^{3}He spin-exchange cells polarize ^{3}He more efficiently than those containing Rb alone. Over the range of temperatures we studied, all the cells that were tested showed faster spin up rates and higher maximum polarization at higher K densities (higher temperatures), with the exception of the 240°C spin up of V12. This spin up showed improvement, but not much, which could indicate that we were near optimum at 230°C and as the temperature was raised, the potassium started to depolarize more. In addition, the double chambered cells polarized at higher temperatures demonstrated shorter spin up times than a comparable pure Rb cell spun up with ~50% more laser power. Further study is left in finishing the characterization of the test spheres, and characterizing all the cells at a wider range of temperatures. Characterizing a pure Rb cell using two lasers at William and Mary and at a variety of temperatures would help in comparing the two types of cells. Being able to convert the response from the coils into actual polarization would allow better comparison between cells. Also, more precise knowledge of the K/Rb ratio would be of use in finding the most efficient conditions for optical pumping of K-Rb, as well as in comparing cells.

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