ABSTRACT

BALCI, SUMEYRA. Investigation of Possible Changes in Beta Decay Rates Due to the Influence of the Sun. (Under the direction of Christopher Gould.)

There is a growing interest in searching for seasonal effects on nuclear decay rates. Based on this interest, a data set taken at the Nuclear Reactor Program in Burlington Laboratory at North Carolina State University has been studied. A Radium-226 source was used to calibrate a gamma ray spectrometer system on a weekly basis over a 17-year period. The data have been analyzed by subtracting yearly means and by performing a regression analysis with a SAS program. We find a seasonal variation at the $5\sigma$ level, which is however not in phase with the earth-sun distance. A natural explanation, that the variation is due to changes in Radon in the room, is considered, and found to be not consistent with the size of the seasonal effect.
Investigation of Possible Changes in Beta Decay Rates Due to the Influence of the Sun

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Physics
Raleigh, North Carolina
2013

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DEDICATION

To Mustafa Yegen, his many sacrifices have allowed me to achieve this milestone.
BIOGRAPHY

The author was born and raised in Konya, Turkey. She completed her Bachelor’s of Science in Physics at Fatih University in Istanbul, Turkey with honors with a degree in June 2009. Soon after, she went to the U.S. to pursue a graduate degree in Physics at North Carolina State University, in Raleigh, NC, USA. During that time, she discovered an interest in Nuclear Physics, started her research and wrote a Masters thesis on it.
ACKNOWLEDGEMENTS

First and foremost I would like to thank to my advisor Prof. Christopher Gould for all his contributions in the form of corrections, suggestions and valuable guidance throughout my research. I am thankful to my committee members: Prof. John Blondin and Prof. Daniel Stancil for their interest in my work.

I would like to thank Prof. Dave Dickey and Joy Smith for their help during SAS analysis. Also special thanks to laboratory manager Scott Lassell for his patience and support and Gerry Wicks for carrying out a direct radon measurement.

Last but not least, I would like to express my appreciation to my lovely family for their encouragement for my life and my friends, especially Seyma Nur Ozcan, for their love and support.
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Chapter 1

Introduction

1.1 Introduction to Radioactivity

Radioactivity was for the first time discovered by H. Becquerel in 1896 and with the nuclear atom theory of E. Rutherford in 1911, studies made in this field gained speed. Radioactivity can be defined as a process where an unstable element is transformed to a stable and different element physically and chemically by releasing various particles or emitting radiation. Unstable nuclei are transformed to a more stable state by releasing high-energy particles like alpha (\(\alpha\)), beta (\(\beta\)) and gamma (\(\gamma\)). The \(\alpha\) particles are Helium (\(^{4}\text{He}\)) nuclei with two neutrons and two protons. The \(\beta\) particles are high-energy electrons. In some radioactive processes, the products that are the opposite particles of electrons called positrons appear. A gamma ray is a photon, typically with high energy. More detailed information about these three kinds of radiation is given in Ref. [1]

1.2 Radioactive Decay Law

Physically, it is impossible to know when an atom in a radioactive sample will decay. Radioactive decay occurs randomly and arbitrarily depending on time with characteristics determined by probability theory and statistics. The important approach is not to consider nuclei individually but to examine the decay probability of a radioactive nucleus in unit time. This probability is proportional to the radioactive decay constant, which is indicated with \(\lambda\).
According to the decay law of radioactivity, $\lambda$ is a constant whatever the age of the nucleus. For instance, its value for Radon is $\lambda = 0.0075/\text{hour} = 0.000125/\text{minute}$ [2]. The decay number that occurs in unit time interval in a radioactive nucleus is defined as the decay activity of nucleus. If there are $N$ radioactive nuclei at time $t$, and in any moment $dt$ no nuclei are added to the sample, the number of nuclei decaying in the $dt$ time interval will be proportional to $N$.

$$dN(t) = -\lambda N(t) \, dt$$

The minus sign in the equation indicates that the number of nuclei decreases with time. By solving the differential equation above, the exponential radioactive decay law is obtained and shown below

$$\int \frac{dN(t)}{N(t)} = \int -\lambda \, dt$$

$$N(t) = N_0 e^{-\lambda t}$$

Here, $t$ in the equation represents time, $N(t)$ is the number of nuclei at time $t$, $N_0$ represents the number of nuclei at the beginning (time $t=0$) and $\lambda$ is the decay constant of the radioactive sample.

If both parts of the decay law equation are multiplied by $\lambda$, an expression for the activity is found as

$$\lambda N(t) = \lambda N_0 e^{-\lambda t}$$

$N\lambda$ in the expression above is called decay activity of sample and gives decay number per unit time. It is indicated with $I$ and its unit is decays/second.

$$I = I_0 e^{-\lambda t}$$
Here; \( I (= \lambda N) \) is the activity at time \( t \) and \( I_0 (= \lambda N_0) \) is the activity at time \( t = 0 \). [2]

The reciprocal of the decay constant, \( t_m \), is the mean life (or average life) of the radioactive nuclei and it is stated as below

\[
t_m = \frac{1}{\lambda}
\]

The method that is most widely used for representing the rate of radioactive decay is by means of the half-life, \( t_{1/2} \). It can be stated as the time required for the number of radioactive nuclei of a given kind to decay to half its initial value [3]. This time is independent of the amount of the radioactive nuclide present, due to the exponential nature of the decay. So if \( N \) is the set equal to \( \frac{1}{2} N_0 \), then the corresponding time \( t_{1/2} \) is given by

\[
\ln \frac{1}{2} = -\lambda t_{1/2}
\]

or

\[
t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.6931}{\lambda}
\]

So the half-life is inversely proportional to the decay constant and also directly proportional to the mean life, i.e.,

\[
t_{1/2} = 0.6931 t_m
\]

1.3 Types of Decay

A nucleus typically decays in three ways. In alpha and beta decays, an unstable nucleus becomes more stable by emitting alpha and beta particles. In gamma decay, the
nucleus decays from an excited state to a lower state without any change in the type of nucleus.

### 1.3.1 Alpha Decay

The nucleus emits an alpha particle consisting of two protons and two neutrons (Figure 1.1). In this way, as seen in equation below, the atomic number of the decayed nucleus decreases by 2 and its mass number by 4. (Atomic number of the nucleus, mass number, and neutron number are Z, A, N respectively.) Rutherford proved that an alpha particle is actually a He nucleus.

\[
\frac{A}{Z}X \rightarrow \frac{A-4}{Z-2}X' + \frac{4}{2}He
\]

Alpha decay is seen more frequently in nuclei of which the mass number is bigger than 190 in general. Its energy spectrum is discrete, typically varying between 4 and 10MeV. Because it is a charged particle, it interacts intensely with electrons of the matter it passes through. [4]

![Alpha decay of a nucleus](image)

*Figure 1.1 Alpha decay of a nucleus. An unstable nucleus becomes more stable by emitting the α particle.*
1.3.2 Beta Decay

Beta decay is of three kinds: beta-minus decay, beta-plus decay, and electron capture.

Beta-minus decay; if instability of a radionuclide is a result of a neutron surplus in the nucleus, a neutron is converted into a proton and emits an electron and an anti-neutrino, which can be shown as

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

The atomic number of a radionuclide that makes beta emission in this way increases by one. This decay is called an isobaric decay as its mass number does not change as seen in the reaction below (\( \bar{\nu}_e \) is an anti-neutrino) [5].

\[ \frac{A}{Z}X_N \rightarrow \frac{A}{Z+1}X'_{N-1} + e^- + \bar{\nu}_e \]

Schematic of beta-minus decay for Tritium is shown in Figure 1.2.

![Schematic of beta-minus decay for Tritium](image)

*Figure 1.2. The decay level schematic of Tritium (or \(^3\)H).*
Beta-plus decay; if instability of atom is the result of lack of neutron or proton surplus, the weak interaction converts a proton into a neutron while emitting a positron and a neutrino, which can be shown as ($\nu_e$ is neutrino and $e^+$ is positron)

$$p \rightarrow n + e^+ + \nu_e$$

In this way, the atomic number of the radionuclide that releases the positron decreases by one [5].

$$^2_ZX_N \rightarrow ^2_{Z-1}X'_{N+1} + e^+ + \nu_e$$

Electron capture occurs if one of the electrons in a near orbit (K, L) is captured. The electron and the proton combine creating a neutron and a neutrino. (It is shown in the equation below). In this decay, no particle is released from the nucleus but the proton number decreases by one as in positron decay. The mass number remains the same. (In the equations below; $p$, $e^-$, $n$, $\nu_e$ are proton, electron, neutron, and neutrino respectively)

$$p + e^- \rightarrow n + \nu_e$$

$$^2_ZX_N + e^- \rightarrow ^2_{Z-1}X'_{N+1} + \nu_e$$

In all three beta decays stated above, though the numbers of protons and neutrons change by one unit, their mass numbers remain constant. Particles called neutrino and antineutrino are emitted by these three decays. The existence of neutrinos was first proposed by Pauli in 1930 and later, they were called neutrino by Fermi [6]. Energies of electrons released in beta decay have a continuous spectrum as seen in Figure 1.3.
1.3.3 Gamma Decay

Alpha or beta decay often does not proceed to the ground state of a nucleus. The nuclide that is formed in the decay may remain in a semi-stable state, which releases the excitation energy in the form of gamma radiation. Gamma decay is seen in Figure 2.2. The atomic number and mass number of a nuclide decaying in this manner do not change.

Half-life of gamma decay is very short when compared to other decays: less than 10^-9 seconds in general. However, some meta-stable states have half-lives of an hour and even a day. The energy spectrum from gamma decays is discrete [7].

Figure 1.3. Energy spectrum of beta decay electrons from Bismuth-214. The x-axis represents the kinetic energy in MeV and the y-axis represents intensity. The figure shows that energies of electrons have continues spectrum.
1.4 Literature Review

In the past few years there have been new thoughts about nuclear decay rates. These ideas start with Jerkins et al. [8] and Fischbach et al. [9] who find that there is a periodic annual modulation in the decay rates measurements. Other studies argued that these changes in nuclear decay rates were due to environmental influences and caused by other systematic effects [10]. However the group, which started these investigations, countered that the variations cannot be explained by environmental effects such as temperature, pressure, humidity etc. [11].

Then these kinds of experiments are re-examined by several people. Norman et al. [12] could not find any evidence for seasonal variation. Another study examined and found correlation between decay rates and winter-summer changes [13]. In Cooper at al. [14] some data are analyzed and no significant variations are found from the exponential decay. Not only seasonal variation but also east-west asymmetry and north-south asymmetry are the
subject of investigation in nuclear decay rates [13].

To study these questions further, we obtained a unique data set from the Nuclear Reactor Program at North Carolina State University. As part of the Neutron Activation Analysis program, daily calibrations of High Purity Germanium Detectors have been carried out with a Radium-226 source. These calibrations extend back over 17 years.

As a result, we are able to undertake a search for seasonal variations in an unusually complete set of decay rate data. In this thesis I present an analysis of these data, and present some estimates of whether the seasonal effects I see could be due to Radon in the room where the detector operated.
Chapter 2

Nuclear Reactor Program

2.1 PULSTAR Reactor and Neutron Activation Analysis Program

A nuclear reactor is a device designed to initiate, control and maintain a chain reaction. It produces a steady flow of neutrons generated by the nuclear fission of heavy nuclei.

The PULSTAR reactor is a 1-MW pool-type nuclear research reactor. It is in the Burlington Laboratory at North Carolina State University and is administered by the Nuclear Reactor Program. The fuel of the PULSTAR is 4% enriched, pin-type fuel consisting of UO$_2$ (Uranium dioxide) pellets with Zircaloy cladding. This fuel gives the PULSTAR Reactor response characteristics that are very similar to commercial light water power reactors. These characteristics allow teaching experiments to measure moderator temperature and power reactivity coefficients including Doppler feedback. In Figure 2.1 a schematic of nuclear reactor at NCSU is shown.
Figure 2.1. Schematic of PULSTAR Reactor. There are 4 types of facilities working currently. Neutron Powder Diffraction Facility (NPDF), Neutron Imaging Facility (NIF), Intense Positron Beam (IPB), Ultra-Cold Neutron Source (UCNS). Their locations are shown in the schematic.\textsuperscript{1}

\textsuperscript{1}http://www.ne.ncsu.edu/nrp/facilities.html
Neutron Activation Analysis is one of the most sensitive analytical methods used for the quantitative multi-component examination of major, minor, and trace components in samples from almost every imaginable field of technical and scientific interest. The neutron irradiation and activation utilized by the 1-MW PULSTAR Nuclear Reactor facility (as an intense neutron source) is shown in Figure 2.2. During neutron irradiation, some stable isotopes of elements that form the samples are turned into radioactive isotopes by neutron capture.

Figure 2.2. Neutron activation process. An incident neutron is absorbed by a target nucleus and a compound nucleus is formed. The compound nucleus emits prompt gamma ray and also a radioactive nucleus may be formed. The radioactive nucleus emits a beta particle, delayed gamma rays.

http://www.ne.ncsu.edu/nrp/naa.html
2.2 Detector and Electronics

Germanium is a semiconductor element. (See Figure 2.3 for details about Germanium’s place in semiconductors.) It is a good material for detectors and widely used in gamma-ray spectroscopy.

![Figure 2.3. Range of the resistivity and conductivity for insulators, semiconductors, and conductors. Semiconductors are in the shaded region. [15]](image)

Semiconductor gamma-ray detectors contain mainly some solid materials in which electrons and holes are produced when a gamma ray is absorbed. Then an electric field in the material collects these electrons and holes to provide an electric signal and this electric signal is a measure of the energy of the gamma ray. So one of the important requirements of any material used for a detector is to produce charge carriers in it. That is why Germanium...
detectors have been the mainstay of high-resolution gamma-ray spectroscopy for almost 50 years and also why they are used in our study [16].

Its applications are found not only in nuclear physics but also in astrophysics, nuclear nonproliferation, and medical imaging [17]. The Germanium detector used in this study is shown in Figure 2.4 and Figure 2.5.

The PULSTAR reactor is used for doing neutron activation analysis and for that reason people who are working in the Burlington Laboratory have been calibrating the detectors for almost 18 years. In this research, advantage of these data sets of measurements on HPGe Gamma Detectors (High Purity Germanium Gamma Detectors) is taken in order to search for seasonal variations in beta decay rates.
Figure 2.4. The picture of the High Purity Germanium Detector in Burlington Laboratory at NCSU. The detector cryostat is inserted into the liquid nitrogen dewar below. The detector housing contains the germanium crystal and a solid-state preamplifier all cooled to $-196^\circ$C.
As shown in Figure 2.4 and Figure 2.5, the detector has a cylindrical shape. The radioactive source, Radium-226 in our case, is placed in one of the plastic cases (right on the detector) and this plastic case is put in the detector from the side. The Radium source should be put on the middle of the cylindrical Germanium plate symmetrically. The detector shield has a side door that should be closed while the detector is working. It also has a top cover not shown in the picture. There is a liquid Nitrogen dewar for cooling the detector located under the detector.
Figure 2.5. Another picture of the HPGe Gamma Detector used in Burlington Laboratory at North Carolina State University.
When radioactive Radium-226 decays (for more information see Table 2.1) gamma rays are emitted. By looking at the energy of the gamma ray, it can be determined what isotopes were present. In this study, a 609.3 keV gamma ray (first excited state of Polonium-214) means that there is Polonium-214 present after two beta decays. The decay scheme (from Bismuth-214 to Polonium-214) is shown in Figure 2.6. Counting how many 609.3 keV gamma rays are emitted in a fixed time tells us whether there is any variation in the beta decay rate or not.
Figure 2.6. The level scheme for the decay of Bismuth-214 to Polonium-214. The first excited state of Polonium-214 is at 609.3 keV.\(^3\)

\(^3\)http://www.nndc.bnl.gov/chart/getdecayscheme.jsp?nucleus=214PO&dsid=214bi%20bM%20decay&unc=nds
Now let’s talk about the electronics used in this experiment. When the gamma rays are detected by the Germanium crystal (solid crystal), the gamma rays ionize as positive charges inside of the Germanium. If all of the gamma ray energy is positive then a certain amount of current comes out the crystal. It gives a signal and it is converted to a voltage in a preamplifier and then comes over to the MCA (multi channel analyzer). This MCA converts that analog signal of the voltage into a digital signal, which can be displayed graphically. MCA is shown in Figure 2.7.
Therefore the signal comes out first to the preamplifier then goes to the multi channel analyzer, which gives a spectrum. After that point a computer program (called Genie 2000 3.2) is used. This software is a widely used program that connects the detector to electronics and can be seen in an individual screen. Figure 2.8 shows a sample screen shot of Genie 2000. Here on the top window, it shows the cursor is set at 609.3 keV (the energy of interest
to us). The bottom window shows the entire spectrum and it is just the zoomed area of the peak part of the top window. It is called the interactive peak fit. Actually, there is a fit to the data, which is called Gaussian fit on the top graph of the bottom window (the x-axis is energy and the y-axis is the counts). The bottom graph of the bottom window is about residual. The line between these two graphs in the bottom window separates the number of counts and the residuals. We are not interested in the residuals now because the most important thing is the number of counts used to look for the seasonal variation in this study.

Figure 2.8. Genie 2000 3.2 software used to analyze the MCA spectra.
2.3 Radium Beta Decay Source

As discussed in Chapter 1, if $N$ is the number of radioactive nuclei present any time $t$, the decay rate is given by

$$\frac{dN}{dt} = -\lambda N(t)$$

In this study we are looking into whether there is an additional term in this equation (for example, due to the changing earth-sun distance) so that the equation should be

$$\frac{dN}{dt} = -\lambda N(t) + f(t)$$

where $f(t)$ is an unknown function of time.

The National Nuclear Data Center provides information about the basic properties of atomic nuclei. An interactive chart of nuclides is shown in Figure 2.9. In this chart it is seen that the x-axis shows the number of neutrons and the y-axis shows the number of protons in a nuclei.
In this study, the radioactive decay process using HPGe Gamma Detector at Burlington Laboratory is shown below in Table 2.1. Ra-226 undergoes three alpha decays and two beta decays, and one more alpha decay before it reaches stability at Lead-210.

Figure 2.9. Chart of Nuclides\(^4\) and color code of the interactive chart of nuclides. Half-lives of the elements are stated in seconds.

\(^4\)http://www.nndc.bnl.gov/chart/
Table 2.1 Nuclides, Half-lives, Decay Modes, and Daughter Nuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$t_{1/2}$</th>
<th>Decay Mode</th>
<th>Daughter Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radium-226</td>
<td>1600.7 years</td>
<td>Alpha Decay</td>
<td>Radon-222</td>
</tr>
<tr>
<td>Radon-222</td>
<td>3.8 days</td>
<td>Alpha Decay</td>
<td>Polonium-218</td>
</tr>
<tr>
<td>Polonium-218</td>
<td>3.1 minutes</td>
<td>Alpha Decay</td>
<td>Lead-214</td>
</tr>
<tr>
<td>Lead-214</td>
<td>26.8 minutes</td>
<td>Beta Decay</td>
<td>Bismuth-214</td>
</tr>
<tr>
<td>Bismuth-214</td>
<td>19.9 minutes</td>
<td>Beta Decay</td>
<td>Polonium-214</td>
</tr>
<tr>
<td>Polonium-214</td>
<td>163 microseconds</td>
<td>Alpha Decay</td>
<td>Lead-210</td>
</tr>
</tbody>
</table>

2.4 Analysis the Spectra

In the Burlington Laboratory at North Carolina State University, energy calibration, efficiency and resolution have been checked since 1996. The data sets have been collected either every day or every few days. There are sets of data for eight different detectors having efficiencies 21%, 23%, 24%, 25%, 26%, 38%, 42%, 65%.

The data set obtained from the 21% efficiency detector was collected from July 1997 to April 1999, the one obtained from the 23% efficiency detector was collected from September 1996 to August 2003, the one obtained from the 24% efficiency detector was collected from July 1997 to June 2003, the one obtained from the 26% efficiency detector was collected from September 1996 to March 2002. The one obtained from the 25% efficiency detector is collected from August 203 until now, the one obtained from the 38% efficiency detector is collected from September 1996 until now, the one obtained from the
42% efficiency detector is collected from September 1996 until now, and the obtained from the 68% efficiency detector is collected from July 2003 until now.

In this thesis, the data from the 42% efficiency detector (Figure 2.4 and Figure 2.5) is examined and analyzed. This detector was used over the longest period of time and also had the second highest detection efficiency. The detector was refurbished twice during the period 1996-2013.

The data collection is done to check that the Nuclear Reactor located in Burlington Laboratory is working properly every day. A crystal (Radium-226) that emits gamma rays is used. If the rate of the gamma rays does not change, the detector works properly. Because radioactivity is a characteristic of the element, it does not change, so the detector should detect the same everyday.

People working in the laboratory are collecting spectra for 300 seconds and making a correction for lifetime versus dead time by using a program to analyze the data that subtracts a background and fits to a peak (Figure 2.8). Then they record these counts on a piece of paper that is shown in Figure 2.11. In this paper energy calibration, detector efficiency, and detector resolutions are recorded. As stated earlier, only the counts from the 42% efficiency detector are studied in this thesis.
Figure 2.10. A picture of a sample page of the data collected in the Burlington Laboratory at North Carolina State University over a 17-year period.
Chapter 3

Analysis of the Data

In this chapter, data analysis will be described step by step. Because counts are not taken everyday, the data sets are not equally spaced in time. Thus, the regression analysis is an appropriate method to analyze the data sets due to the gaps in the date of the data collected. In order to do the regression analysis, SAS (Statistical Analysis System) program is used as a statistical program by following the suggestions of Prof. Dave Dickey.

First the data were written down on the Excel file with respect to counts by the date. As stated in the previous chapter, the 42% efficiency detector started to work from September 1996 and still continues, and in this analysis the data set until March 2013 was used.

3.1 Results from the 42% Efficiency Detector

In Figure 3.1, the graph of the raw data is shown which needs to be cleaned and detrended. The x-axis and the y-axis represent the time and the counts in 300 seconds respectively.
Figure 3.1. SAS output: The raw for the 42% efficiency detector. The data collection starts from 1996 and ends in 2013.

There is an obvious drop off at the end and long-term movement after 2011. The reason for this unusual change in counts is the refurbishment of the detector. The detector was sent out for repair in during that period. This part should be shifted prior to a least squares analysis, using SAS. (For more information, the SAS code is in the Appendix)

Here in Figure 3.2 is a series created by subtracting yearly means as well as adjusting for the mean of the right hand the segment of low values. The reason we subtracted the yearly mean is there is some long-term multiyear movement in the data. Thus, all the years
have mean zero. We can now focus on the item of the interest, which is to look at the yearly cycles.

![Graph showing yearly cycles](image)

*Figure 3.2. SAS output: The data set created by subtracting yearly means from the data of Figure 3.1. The resulting data set has zero yearly mean.*

Now let’s talk about how to look for a seasonal variation. There are 365.25 days in a year. So the frequency we want to look for is

\[
\frac{2\pi}{365.25} = \omega
\]
\( \omega \) is here the fundamental frequency which is one cycle per year. Then let’s create two
variables; sine1 and cosine1 (will shown as s1 and c1 respectively).

\[
s_1 = \sin(\omega t) = \sin \left( \frac{2\pi t}{365.25} \right), \quad (t = 1, 2, 3, \ldots, n)
\]

\[
c_1 = \cos(\omega t) = \cos \left( \frac{2\pi t}{365.25} \right), \quad (t = 1, 2, 3, \ldots, n)
\]

Both sin and cosine variables are needed because we need to get the amplitude (A) and the phase shift (\( \delta \)). Then they are lined up with the data. So we suppose to start with

\[
A \sin(\omega t + \delta) = A \sin(\delta) \cos(\omega t) + A \cos(\delta) \sin(\omega t), \quad \delta = \text{phase shift}
\]

\[
= \beta_1 \cos \omega t + \beta_2 \sin(\omega t)
\]

Thus, the amplitude and the phase shift can be fitted to the data correctly by the sample regression on \( \sin(\omega t) \) and \( \cos(\omega t) \). (There is not just pure sine wave. If we make an analogy; when you listen to the music and you play the middle c, which is a note, on a piano, and also you play that middle c on a guitar, they sound different. The middle c here is the fundamental frequency, just like \( \omega \) here. But the reason that the middle c sounds different on the piano and on the guitar, is because of the harmonics.) Then we need the harmonic, which is a wave that has frequency \( 2\omega \), or \( 3\omega \), etc… So these harmonics go through 2 cycles per year, or 3 cycles per year, or etc… They change the wave shape but still that wave repeats every year. Thus we created a few harmonics which are s2 and c2 that used \( 2\omega \) frequency; s3 and c3 that used \( 3\omega \) frequency; s4 and c4 that used \( 4\omega \) frequency; and finally s5 and c5 that used \( 5\omega \) frequency.
Then we needed to check and see if we can leave some of these high frequencies out. We leave these harmonics if they are statistically insignificant, in other words if there is not a contribution from these harmonics. So we used a statistical test, which is the t test in order to do this. (A t test is a kind of statistical test that has a t distribution under the null hypothesis. It is used to fit the data set identify the model that best fits the population from which the data were sampled. The exact t test mainly arises when the models have been fitted to the data using the regression analysis [19].) The idea of this statistical test is that suppose there really is not a harmonic that (for instance) is the fifth one; and seek what is the probability of getting an estimated coefficient for this. If something is unlikely under a hypothesis then this hypothesis is rejected. In this case; if this probability were less than 0.05 (called alpha; the levels of significance) a value which is the traditionally agreed upon by scientists [20] we would reject the hypothesis. More information can be found in Weisberg et al. [21]. Based on this system the SAS output of the parameter estimates are shown in Table 3.1.
Table 3.1. SAS output: (Coefficients for the sinusoidal components where the 0 degree angle is at the beginning of the year) Parameter Estimates. Variables consist of intercept and fundamental frequencies and all 4 pair of harmonics. DF represents degree of freedom. Parameter estimate attempts to approximate the unknown parameter using the measurements. Standard error is actually standard error of the mean; refer to estimates of the unknown quantity. T value shows that t test used as a regression procedure, calculated by program automatically. Pr > |t| (probability of giving t value in this model) is obtained by using a table (called the t test distribution table) that scientist are agreed on.

| Variable | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|----------|----|--------------------|----------------|---------|--------|
| Intercept| 1  | 1.10441            | 5.34492        | 0.21    | 0.8363 |
| s1       | 1  | -40.72268          | 7.32808        | -5.56   | <.0001 |
| c1       | 1  | -43.57262          | 7.78428        | -5.60   | <.0001 |
| s2       | 1  | -12.87050          | 7.34846        | -1.75   | 0.0800 |
| c2       | 1  | 15.71425           | 7.74918        | 2.03    | 0.0427 |
| s3       | 1  | 4.59663            | 7.49234        | 0.61    | 0.5396 |
| c3       | 1  | 13.30389           | 7.59133        | 1.75    | 0.0798 |
| s4       | 1  | -0.98987           | 7.46022        | -0.13   | 0.8945 |
| c4       | 1  | 2.63183            | 7.59414        | 0.35    | 0.7290 |
| s5       | 1  | -10.37018          | 7.34026        | -1.41   | 0.1579 |
| c5       | 1  | -10.76859          | 7.72991        | -1.39   | 0.1637 |

Repeatedly, in order to test the null hypothesis that a parameter is 0 in the model, t statistics is used. It can be seen from Table 3.1 that only s1 and c1 variables are statistically significant because their p values are Pr < 0.0001 (Again, the p value tests whether parameter
estimates are different from 0 or not). It appears that other variables do not substantially improve the model fit.

As a result, if we have five of these harmonics in there, it could be a good fit to the data. But if we leave out the last three harmonics, it is still a pretty good fit to the data. Consequently, leaving these last three harmonics really doesn’t do much in terms of helping the model, so we left them out.

Then let’s do a smaller model that might contain s1, c1 as the fundamental frequencies and s2, c2 as the harmonics. According to Table 3.2, the parameters s1 and c1 are significantly important and, the s2 and c2 harmonics are borderline, one is bigger and one is slightly smaller. Hence these s2 and c2 harmonics can be included in the model or not, and they are included in order to be safe.

Table 3.2. SAS Output: Coefficients for the sinusoidal components where the 0 degree angle is at the beginning of the year. The same definitions are stated in the Table 3.1.

| Variable | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|----------|----|--------------------|----------------|---------|------|---|
| Intercept| 1  | 0.58208            | 5.31224        | 0.11    | 0.9128 |
| s1       | 1  | -40.30413          | 7.32183        | -5.50   | <.0001 |
| c1       | 1  | -44.76425          | 7.69171        | -5.82   | <.0001 |
| s2       | 1  | -12.35282          | 7.34097        | -1.68   | 0.0926 |
| c2       | 1  | 15.29218           | 7.69397        | 1.99    | 0.0470 |
As a result, the Pr > |t| is the probability of getting a result like this from the data in which there is no seasonal component (as modeled by 2 sinusoids) and under the standard regression assumptions, namely the white noise errors, most of the modeled variation (i.e. the power spectrum) is due to the fundamental frequency with statistically significant but minor contribution from the first harmonic. A model with the 4 harmonics and a fundamental frequency showed no need to go beyond the fundamental and 1 harmonic.

Consequently, it is clearly understood from the s1 and c1 frequencies that there is a yearly pattern. There is almost zero probability to see the data like this if there were no seasonal variation. In other words, here is a very strong evidence that there is a yearly cycle. Something repeating close to being a pure sin wave. In Figure 3.3 the red line shows the predicted value by using the equation below.

\[ \hat{Y} = 0.58208 - 40.30413 \, s1 - 44.76426 \, c1 - 12.35282 \, s2 + 15.29218 \, c2 \]

In this equation, the parameter estimate of variable intercept is 0.58208, the parameter estimate of variable s1 is -40.30413, the parameter estimate of variable c1 is 44.76426, the parameter estimate of variable s2 is -12.35282 and the parameter estimate of variable c2 is 15.29218.
Figure 3.3. SAS Output: A plot of the detruded data of Figure 3.2 and fitted sinusoids using the fundamental (one cycle/year, 365.25 days/year) and one harmonic (two cycles/year, (365.25)/2 days/year). The red line (the fit) is not smooth due to the small harmonic term.
Chapter 4

Possible Explanations for Seasonal Variation

There could be lots of reason for changes in the detector count rates such as the environmental influences about the detector system, some systematic effects, changes in the temperature, pressure, humidity, etc. But as discussed in Chapter 3, we find the variation to be seasonal. Hence, the reason of this change in the beta decay rates is examined in this chapter. Two possible explanations will be discussed below.

4.1 Sun-Earth Distance

There are two important distance points between the earth and the sun. One is named the aphelion, which occurs when the earth and the sun are the farthest apart. This happens around July 4 and the distance is approximately 152,171,522 km (or 94,555,000 miles). The other is called the perihelion, which occurs when the earth is the nearest to the sun. This happens around January 3 and the distance between the earth and the sun is approximately 147,166,462 km (91,455,000 miles). These numbers are calculated by using the earth’s elliptical orbit around the sun [22,23].

In order to compare the variation in the distance due to these aphelion and perihelion points with the oscillation in the data, we model the solar distance with a sinusoidal variation. The solar distance at time t is denoted by r. If the solar maximum is taken as 1.017 AU
(Astronomical Unit is $149.6 \times 10^6 \text{km} = 92.956 \times 10^6 \text{miles}$) [24] then $r$ in AU is related to $t$ in months by

$$\frac{1}{r^2} - 1 = \frac{1}{\left[1 - 0.017 \cos \left(\frac{2\pi (t - 1)}{11}\right)\right]^2} - 1$$

To relate this to the SAS analysis we see the equation below, where -40.30 is the parameter estimate for the variable s1 and -44.76 is the parameter estimate for the variable c1. The mean of the counts is taken as 27500 and $t$ represents the time in months.

$$\frac{\text{SAS}}{\text{mean}} = \frac{-40.3 \sin \left(\frac{2\pi (t - 1)}{11}\right) - 44.76 \cos \left(\frac{2\pi (t - 1)}{11}\right)}{27500}$$

Then by using these calculations, graphs of the time versus $\frac{1}{r^2} - 1$ and $\frac{\text{SAS}}{\text{mean}}$ can be compared (Figure 4.1) The red line is the variation detected by using SAS, and the blue line is the earth-sun distance variation in 12 months. We see the experimental variation we detected is not in phase with the solar distance and has a much smaller magnitude. However, just because they are out of phase, it does not mean that it is not still a geometric effect associated with the motion and the wobble of the earth going around the sun. Our SAS analysis corresponds to a phase shift of 228 degrees, or on a scale of 0-1, a phase of 0.633. An in-phase variation with the earth-sun distance would give a phase shift about 0.008 (January 3), seemingly eliminating any association with the solar distance. However, according to Sturrock et al. [13], the possibility of a north-south asymmetry of the flux from the sun, owing to the tilt of the sun’s rotation with respect to the plane of the earth’s orbit should also be considered. Combining the two possible effects, the earth-sun distance variation and the solar north-south asymmetry, they show that the phase must be between 0-
0.183 or between 0.683-1 if the flux enhances the decay rate. The value we found falls outside of that range. However, if the flux suppresses the decay rate, then the phase must fall within the complementary range or between 0.183 and 0.063. Consequently, if the effect of an as yet undetermined solar flux suppresses the decay rate, a possible solar-distance explanation of the observed annual variation cannot be ruled out solely in the basis of the data and the analysis presented.

Figure 4.1. The graph of the comparison between variation in the data (red curve) and the earth-sun distance (blue curve). The x-axis represents the 12 months of a year and the y-axis represents percentage of the amplitude. The observed variation is smaller, and not in phase with the variation in the earth-sun distance.

4.2 Radon Background in the Laboratory

Radon is a commonly occurring radioactive, colorless, odorless, tasteless, noble gas, often used in introductory nuclear physics experiments [25]. The background radiation is a
known situation, Radon can be found all over the U.S. Generally, the radon background can be caused by the natural radioactivity of uranium in soil, rock or water. Radon gets into the air you breathe. Here in this study, we are interested in the radon signal getting into the detector. In fact, the radon atoms leak (in other words escape) into the room with random directions and increase the radon background in the room/basement where the experiments are carried out. There is a health limit of the radon background determined by United States Environmental Protection Agency and this limit is approximately 148 Bqm$^{-3}$ (equals to 4 pCi/L)\(^5\). The reason we test it for Radon is that it is the only one is in the gas phase and other radioactive elements used in the experiment are in the solid phase. Because Radon is a gas it expends all around the room.

To explore the Radon question further, we asked the NRP staff to perform two additional measurements in June 2013. One is the Radon background in the room (measured directly) and the other one is the background counts, which are from the detector with no source presents. The Radon background in the laboratory was measured and found to be 7 Bqm$^{-3}$ (G. Wicks, private communication). The measured background counts were around 30 in 300 second, associated with a very small but noticeable peak in the spectrum. This can be compared with the annual variation seen in the SAS analysis which is of order 60 counts in 300 seconds.

The aim of the calculations that will be shown below is to test whether the radon background in the basement is consistent with the observed seasonal variation or not.

\(^5\)http://www.epa.gov/radon/pubs/citguide.html
Following the procedure from Gould et al. [26], the 609 keV gamma ray flux from the experiment is found from

\[ \phi = \frac{N E_\gamma}{k(E_\gamma) \in (E_\gamma) m T} \]

\[ = \frac{(60)(609keV)}{(2.84 \times 10^{-8} \text{erg g}^{-1} \text{yr}^{-1} \text{cm}^2)(0.2)(1.277 \times 10^3 g)(300s)} = 26.4 \times 10^{-3} \gamma \text{cm}^{-2} \text{s}^{-1} \]

The definitions in the equation are:

- \( \phi = \text{flux (gamma rays m}^{-2} \text{s}^{-1}) \)
- \( N = \text{Number of the estimated counts (}= 60) \text{ in time t (300s)} \)
- \( E_\gamma = \text{Energy of the gamma ray (}0.609\text{MeV }= 0.96 \times 10^{-6} \text{ergs}) \)
- \( k = \text{The counts to fluence function (}= 2.84 \times 10^{-8} \text{erg g}^{-1} \gamma \text{cm}^{-2}) \)
- \( \epsilon = \text{Photopeak efficiency (~0.2)} \)
- \( m = \text{Mass of the detector in grams} \)

The flux \( \phi \) striking the detector can be related to the radon decay rate \( \rho \) by assuming a uniform density for the Radon in a spherically symmetric room of radius \( r_{\text{max}} \) and integrating over the appropriate solid angle for each volume element in the room. The result is

\[ \phi = \rho r_{\text{max}} \]

where \( \phi \) is in gamma rays m\(^{-2}\)s\(^{-1}\), \( \rho \) is in Bqm\(^{-3}\), and \( r_{\text{max}} \) is in m.
Now we need to substitute $26.4 \times 10^{-3} \gamma cm^{-2} s^{-1}$ for $\phi$ and solve the equation for $\rho$ (Then $\rho$ will be compared with the experimental value of the Radon background in the room). But first $r_{max}$ should be determined and there are two possible geometries for the value of the $r_{max}$.

First option is that the detector is closed by side and top. So $r_{max}$ would be the radius of the inside of the detector and it can be taken as approximately 10cm. Solving the equation by assuming a completely enclosed detector is shown below

$$\rho = \frac{\phi}{r_{max}} = \frac{26.4 \times 10^{-3} \gamma cm^{-2} s^{-1}}{10 cm} = 26.4 \times 10^{-4} \gamma cm^{-3} s^{-1}$$

$$\rho = 26.4 \times 10^{2} Bq m^{-3}$$

This value is very high compared to the EPA limit (which is around 148 Bq per cubic meter) and not consistent with the direct measurement. So it is not a plausible estimate.

Another option is that the detector is not shielded. So for a room spherically symmetric has the value of the $r_{max}$ can be taken approximately 3m (=300cm). Solving the equation by assuming the unshielded detector is shown below

$$\rho = \frac{\phi}{r_{max}} = \frac{26.4 \times 10^{-3} \gamma cm^{-2} s^{-1}}{300 cm} = 8.8 \times 10^{-5} \gamma cm^{-3} s^{-1}$$

$$\rho = 8.8 Bq m^{-3}$$

This value is close to what was measured directly but is inconsistent with the geometry of the detector, which is shielded. As a consequence, the modeling of Radon distributed uniformly in the air in the room is not consistent with the size of the effect. The
variation in the room is not due to Radon unless there is an additional source or a mechanism we have not come up with.
Chapter 5

Summary and Future Works

In this chapter, a summary of the thesis is stated and future work is defined. The PULSTAR reactor located at North Carolina State University is the source of this study. Radium-226 is used as a radioactive source and High Purity Germanium Detector is used for detection of the gamma rays. The people working in the laboratory have taken the data sets for 17 years and we take advantage of these data sets in this thesis. Analyzing the variances and the regression method is used by SAS program. The results show that there is a yearly cycle in the data. After doing some calculations and comparisons, no relation is found with the Radon background in the laboratory, also no simple explanation for a relation with the earth-sun distance in a year is found.

As a consequent, these arguments have not presented any evidence of the solar origin yet. The most we can say is that these two possible explanations can be ruled out. We are going to look now at the 38% efficiency detector to see if it confirm or refutes the effect we saw with the 42% efficiency detector.

As a future study, other data sets (which are taken from the 21%, 23%, 24%, 25%, 26%, 38%, 65% efficiency detectors) should be examined and analyzed, in hope of confirming the existence of a seasonal variation.
Another idea for the future is making a comparison between the reactors on and the reactor off while taking data with the detector, so that changes in the background can be examined.
REFERENCES


APPENDIX
SAS Code 1

***data.sas;
options formdlim='' ls=80 orientation=portrait;
libname in '.';

%let pct=42pct;

data in.count&pct;
infile "&pct.Weekdays.csv" dlm=',' dsd missover firstobs=2;
input date :mmddyy10. count;
format date date9.;
If date>lag(date) then order=0; else order=1; *check for out of order dates - errors;
run;

proc print data=in.count&pct; *check for out of order dates - errors;
where order=1;
run;
run;

ods listing close;
ods pdf file="&pct Count Data with Means and Plots.pdf";
proc means data=in.count&pct;
class date;
format date monyy7.;
run;
DM "GRAPH;CANCEL;"; ** to close the graph window;

proc datasets library=work mt=cat nolist;
delete gseg;
run;

axis1 label=(h=3 a=90 'Count')
   value=(h=2)
   minor=(n=3)
   offset=(3);
axis2 label=(h=3 'Date')
   value=(h=2)
   minor=(n=2)
   offset=(3);

symbol1 c=black i=spline font= v=dot;
symbol2 c=black i=hiloj font= v=circle;
symbol3 c=black i=hiloj font=marker v=U;
symbol4 c=black i=hiloj font= v=square;
symbol5 c=black i=hiloj font=marker v=P;
symbol6 c=black i=join font= v=diamond;
symbol7 c=black i=join font=marker v=C;

***use this to send to printer; *goptions dev=psl ftext=zapf
   rotate=landscape lfactor=2;
***use this to see in window;    goptions dev=win ftext=zapf
   rotate=landscape lfactor=2;

proc gplot data=in.count&pct;
plot count*date / vaxis=axis1 haxis=axis2 href=('01oct2001'd,
'01feb2011'd);
format date year4.;
Title "&pct All Data Reference Lines at Oct 1, 2001 and Feb 01, 2011";
run;
quit;

proc gplot data=in.count&pct; where count between 26000 and 29000;
plot count*date / vaxis=axis1 haxis=axis2 href=('01oct2001'd,
'01feb2011'd);
format date year4.;
Title "&pct 26000-29000 Reference Lines at Oct 1, 2001 and Feb 01, 2011";
run;
quit;

ods pdf close;
title;
ods listing;
**models.sas;**

%let pct=42pct;

ods html close;
ods listing close;
ods pdf file="&pct Models.pdf" style=journal;

title "&pct Models.pdf";
*libname in 'C:\temp\ChrisGould';
*libname in 'C:\Users\seyma\Desktop\42%SAS';
libname in '.';

Data Dave;
** (1) Remove outliers **;
set in.count&pct;
if (. <count< 26000) and (year<2003) then count=.;
if count > 29000 then count=.;
lastpart = date> "01apr2011"d;
freq = 2*constant('pi')*date/365.25;
s1=sin(freq); c1=cos(freq);
s2=sin(2*freq); c2=cos(2*freq);
s3=sin(3*freq); c3=cos(3*freq);
s4=sin(4*freq); c4=cos(4*freq);
s5=sin(5*freq); c5=cos(5*freq);
year = year(date);
run;

proc means data=Dave;
goptions reset=all;

axis1 label=(h=2 a=90 'Count')
   value=(h=2)
   minor=(n=3)
   offset=(3);
axis2 label=(h=2 'Date')
   value=(h=2)
   minor=(n=2);

symbol1 c=black i=spline font=  v=dot;
symbol2 c=black i=hiloj font=  v=circle;
symbol3 c=black i=hiloj font=marker v=U;
symbol4 c=black i=hiloj font=  v=square;
symbol5 c=black i=hiloj font=marker v=P;
symbol6 c=black i=join font=  v=diamond;
symbol7 c=black i=join font=marker v=C;

***use this to send to printer;  *goptions dev=psl ftext=zapf
   rotate=landscape lfactor=2;
***use this to see in window;  goptions dev=win ftext=zapf
   rotate=landscape lfactor=2;

proc gplot data=Dave; plot count*date/ vaxis=axis1
   haxis=axis2;
format date year4.;
run;

**(2) Remove seasonal means & graph;
**proc glm data=Dave; class year; model count = year lastpart;**
output out=out1 residual = count_yrmean;

**proc gplot data=out1; plot (count count_yrmean)*date/ vaxis=axis1 haxis=axis2;**
symbol1 v=none i=join c=black;
format date year4.;
run; quit;

**(3) Compute spectrum using sinusoids;**

**proc reg data=out1; model count_yrmean=s1 c1 s2 c2 s3 c3 s4 c4 s5 c5;**
Harmonics2: test s3=0, c3=0, s4=0, c4=0, s5=0, c5=0;
run;

** (4) It seems harmonics 3 through 5 are not needed. Refit and test;**

**proc reg data=out1; model count_yrmean=s1 c1 s2 c2;**
output out=out2 predicted = P;
run;

**proc gplot; plot (count_yrmean p)*date/overlay vaxis=axis1 haxis=axis2;**
symbol1 v=none i=join c=black w=1;
symbol2 v=none i=join c=red w=3;
format date year4.;
run;

**(5) Try ARMA(1,1) error term;**

**proc arima data=out1;**
i var=count_yrmean crosscor = (s1 c1);
e input=(s1 c1) p=1 q=1 ml plot;
run; quit;
odspath close;
odslisting;
title;