Measuring the Half-life of R-Process Nucleus $^{137}$Sb

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Abstract

I analyzed data taken from an experiment on nuclei near $^{137}$Sb. After cutting out noise, calculating the background rate, and removing unwanted particles from the data, I made reasonable decay curves for $^{136}$Sb and $^{137}$Sb. I believe that the half-life of $^{137}$Sb, previously unmeasured, is $0.36 \text{ s} \pm 0.14 \text{ s}$.

Introduction

Nuclear astrophysicists tend to be very interested in the origins of the elements making up the universe, and it’s a topic of great interest for the overall scientific community and the general public. The elements up to iron (atomic number 26) can be accounted for by nuclear fusion fueling stars like the sun, but this process still leaves the elements heavier than iron unaccounted for. Currently, it is understood that about half of the elements heavier than iron are created immediately after the supernova explosions of very massive stars in a chain of events known as the r-process.\(^4\)

During a supernova, a star’s iron core begins to collapse into a neutron star, starting with the inside and spreading outward. The collapse sends out a shock wave that dissociates some of the matter on the outside of the core into protons and neutrons and sends it flying out into space. The newly formed neutron star immediately begins cooling through neutrino emission, and some of the released neutrinos and anti-neutrinos interact with the protons and neutrons. Because anti-neutrinos encounter less interference from the matter inside the neutron star than neutrinos, the anti-neutrinos can emerge from the deeper and hotter portions of the neutron star and will therefore have more energy on average than the neutrinos. This means that the reaction
\[ \nu_e + p \rightarrow n + e^+ \]

is more common than the reaction

\[ \nu_e + n \rightarrow p + e^- \]

Thus there is an excess of neutrons. An equal number of protons and neutrons will cool and coalesce back into matter, but these excess neutrons will remain, providing a high neutron flux.\(^4\)

This is the point at which the r process begins. Heavy isotopes are created through neutron capture reactions, such as

\[ ^{56}\text{Fe} + n \rightarrow ^{57}\text{Fe} + \gamma \]

If the neutron flux is sufficiently high, an atom can essentially absorb several neutrons before it knows what hit it. Once enough neutrons are absorbed though, the neutron capture cross section of the nuclei may be very low in comparison to the intensity of the neutron flux, leaving an unstable, neutron-rich isotope waiting to decay. Eventually the atom will beta decay. In beta decay, a neutron in the nucleus decays into a proton

\[ n \rightarrow p + e^- + \nu_e \]

and thus the atom changes into another element with atomic number increased by one and an electron is emitted. In the r-process, a beta decay brings the nuclei closer to stability and thus able to absorb additional neutrons. This process can continue to produce very heavy nuclei, and only stops when the half-life of the isotopes created becomes too small in comparison to the neutron capture rate. Figure 1 shows a typical path for the r-process.\(^1\)
As nice as this explanation is, however, it doesn’t provide sufficient information to accurately model the r-process after a supernova. To actually determine the abundance of the various isotopes that are produced, we need more information about the nuclei that decay because they can’t capture any more neutrons, called waiting point nuclei. Specifically, we want to know the half-lives of the nuclei, since this value determines which nuclei will most likely decay and which will most likely absorb neutrons, and therefore helps determine the final abundance of each isotope. We can discover these values through experiments performed right here on Earth. As an added bonus, we may learn more about the fundamental nature of nuclear structure. In this paper, I will present my analysis of experimental data dealing with four isotopes of antimony (\( {\text{Sb}} \)) and tellurium (\( {\text{Te}} \)), including a measurement of the half-life of an unknown waiting point nucleus, \( {\text{Sb}} \).

**Experimental Setup**

In March 2000, an experiment was performed at the GSI accelerator in Darmstadt, Germany to measure the decay properties of r-process nuclei near and including \( {\text{Sb}} \),
and we have now reached a stage where we can do some final analysis of the data. These exotic isotopes are difficult to produce, so everything had to be carefully calibrated in order to make and detect them. Some of the nearby isotopes were important because even if they were already well studied, they provided a way of verifying the results.3

The isotopes were produced by colliding high velocity $^{238}$U atoms with a 1.006g/cm$^2$ lead target. The uranium beam was accelerated to 750 MeV per nucleon by a synchrotron accelerator $^3$, which is a modified version of the traditional cyclotron accelerator. In a cyclotron, the atoms travel in a circular path controlled by a fluctuating magnetic field supplied by large electromagnets above and below the acceleration chamber. With each orbit through the accelerator, an atom gains additional energy and thus greater velocity. The Lorentz force on the particle is

$$F = qvB = \frac{mv^2}{r}$$

so the radius of the particle’s orbit increases with its velocity. Eventually it spirals out of the chamber, and thus a steady stream of high energy particles can be produced. The problem with the cyclotron is that relativistic effects limit the energies that can be achieved. This is remedied by varying the frequencies of the particles. The end result is that the maximum achievable energy increases, but the particles come out in bunches rather than in a continuous beam.$^1$

When a uranium atom hit the lead target, its nucleus essentially shattered into smaller parts in a random fashion, a process called induced fission. The atoms were usually completely ionized, or stripped of all their electrons. Because of the high initial velocity, the new nuclei continued moving forward. At this point different nuclei were
separated by a series of magnetic fields and materials according to their
momentum/charge ratio.\textsuperscript{3}

Now various detectors were used to actually identify the nuclei. The atomic
number of a given nucleus was identified by measuring the amount of energy the nucleus
lost in a gas chamber. Two scintillators at the beginning and end of the flight path
measured the time of flight for each particle, and this determined the mass/charge (a/q)
ratio. With these two measurements, each particle could be identified. The nuclei then
passed through a degrader which reduced their energy such that the desired nuclei would
be implanted in one of a series of four silicon strip detectors. Once a nucleus implanted in
a detector, the detector sent a signal signifying where the particle had implanted in both
the x and y directions. Figure 2 illustrates the experimental setup.\textsuperscript{3}
Analysis

Once a particle was implanted, we would expect it to beta decay and thus deposit additional energy at the implant point. If such energy was detected within ten seconds of the particle’s implant at close to the same location as the implant, a correlation (that the particle that implanted was the same one that decayed) was assumed. Occasionally, multiple decays were detected within the correlation time, meaning that in addition to the mother nucleus, the daughter or even granddaughter nucleus decayed as well. Four similar runs were performed, and for each run the time and location of each implant and decay event was recorded to disk for later analysis.3

To actually determine a half-life value, I used several programs designed to analyze the data. The first step was to determine which decay signals to consider. Since the silicon strip detectors converted the energy of decays into electrical signals we could measure, they were highly sensitive to noise—either random sources of signals or interference from the experiment electronics themselves. Using the program paw++, I graphed the logarithm of the number of counts at a particular energy versus the energy of a signal. It became apparent that very low-energy signals had an unrealistically high number of counts, so I eliminated these counts. These graphs had to be examined for all of the 128 x-strips and 16 y-strips for each of the four runs—that’s 576 graphs, so it took a while, but someone had to do it. Figure 3 shows one of these original graphs, and Figure 4 shows the same graph with the unwanted events cut out.
Once I determined the proper noise cuts, I input them into a file and ran a
program that put the data into a form that could be read by paw++ to determine many
things about the data. I loaded the a/q ranges expected for each isotope and saw what
isotopes were detected. Since the nuclei were fully stripped of electrons, the a/q value along with the atomic number could be used to unambiguously identify each implant. I identified four isotopes of interest which occurred in significant quantities—the unknown $^{137}\text{Sb}$, and three known isotopes which had half-lives close to the expected half-life of $^{137}\text{Sb}$: $^{135}\text{Sb}$, $^{136}\text{Sb}$, and $^{138}\text{Te}$. I looked at the a/q peaks to make sure they were centered within the a/q limits for each isotope. I could also observe how many atoms implanted in each detector. If the implants occurred mainly in the center detectors, as with $^{136}\text{Sb}$ and $^{137}\text{Sb}$, their decays were more likely to be properly detected. If they were concentrated at the beginning or the end, as with $^{135}\text{Sb}$ and $^{138}\text{Te}$, the data was more suspect. This is because there was an unusually large amount of noise in the first detector, and some of the strips in the final detector were apparently not working.

Before actually examining the decay data, it was necessary to determine the effect of the background on the remaining data. Of the signals detected which were consistent with beta decays, only a small percentage were actually correlated with implants. The rest could have been from random particles getting into the detectors, the detector’s miss-firing, or actual beta decays from previous implants with long half-lives. Most of these random events wouldn’t occur in the correct place or at the correct time to be correlated with an implant and thus treated as a decay, but there is a statistical probability that some will. I ran another program to make data files with the background rate for every pixel. I originally used a program called xmgrace to get the average background for each detector and calculated a net background based upon this, but I soon abandoned this method in favor of a C++ program I wrote to determine the background by looking individually at each pixel. It counted the number of signals for each pixel, then took the background for
each pixel and got an average background weighted by the counts per pixel, and thus found the net background for a particular run and isotope. By taking another weighted average of the background for each run, weighted by the number of implants of a particular isotope in each run, I got background rates for each of the four relevant isotopes.

Only now was I ready to make actual decay curves, using the combined data of all four runs. For each of the four isotopes, I plotted the number of counts for various decay times (counting only the first decay detected if there was a series). Since unstable nuclei of the same type have an equal probability of decaying per unit time regardless of the age of the nuclei, the activity of a group of such nuclei decreases exponentially with time. Specifically, the number of nuclei remaining at any particular time is expected to be

\[ N = N_0 e^{-\lambda t} \]

, where \( N_0 \) is the original quantity of the isotope, and \( \lambda \) is the decay constant,

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

, where \( t_{1/2} \) is the half-life of the nuclei, or the expected time for half of a sample to decay.\(^1\) I expected to observe an exponential decay in each of the graphs (though not perfectly smooth because of the relatively low statistics). In reality, \(^{135}\)Sb had a seemingly random rate of decay, and the graph of \(^{138}\)Te somewhat resembled an exponential decay, but not closely enough to get reasonable results. These problems were probably caused by a large effect from the background and the short correlation time in comparison to the half-life of the isotopes. Ideally, a period of five to ten times the half-life should be examined, but \(^{135}\)Sb has a half-life of 1.68 s and \(^{138}\)Te has a half-life of 1.40 s\(^2\), and in the end only four seconds worth of data could be reasonably
examined, as will be explained shortly. The decay data for the other two isotopes had a
definite resemblance to an exponential decay, but did have a significant problem. As
mentioned previously, the synchrotron accelerator releases the beam in bunches. For
these runs, the frequency of these bunches, or spill rate, was set to a 1 s spill every 4.5 s.³
During each spill, some light particles would get into the detectors and give false decay
signals, so this created peaks in the decay curves. The problem was not nearly as easy to
fix as to identify, though, so I went ahead and tried to fit a decay curve to the data.

For the actual fitting, I initially used a program which fit the data with an
exponential decay curve and an exponential background curve, and assumed that each
decay was of the implanted nuclei. I put the previously calculated background rate into
the program, and paw++ varied three parameters—the amplitude of the exponential
decay curve, the amplitude of the background exponential curve, and the half-life of the
nucleus of interest—and gave the curve that best fit the data. From this, it gave a half-life
estimate along with the statistical error from the fitting. Fitting over the entire ten second
period, I got values of 0.51 s for ¹³⁶Sb (compared to the accepted 0.92 s ²) and 0.28 s for
¹³⁷Sb. I obviously couldn’t have too much confidence in these numbers, so I tried
limiting the fit to the first three or four seconds before a spill period began, which limited
the statistics further but avoided trying to fit the incorrect background peaks. Now, I got
0.75 s for ¹³⁶Sb and 0.33 s for ¹³⁷Sb. These values were definitely an improvement, but
still far from ideal. Figures 5 shows the useless decay data for ¹³⁵Sb. Figures 6 and 7
show the original decay curves for ¹³⁶Sb and ¹³⁷Sb.
Figure 5

Figure 6
The next step was to try to reduce the spill structure by identifying which beta decay signals were actually caused by other particles. Luckily, there were some important differences between real and false signals. For one thing, the electrons released by beta decays tended to bounce around the detectors randomly, setting off widely separated pixels in a short period of time. The other particles, on the other hand, often traveled through the detectors in a straight line. Also, these particles often deposited more energy in the detectors than the legitimate electrons. After experimenting with various cuts to eliminate these particles (trying to cut out data from the spill periods but not in-between), I decided to use four distinct cuts. One cut out all particles traveling in a straight line in both the x and y directions. Two of the original cuts dealt with the x direction and y direction individually, but I found that these cuts alone eliminated real data as well as false, so I added a stipulation that the particle energy
be above 2000 channels. Finally, I got rid of any particles whose energy was greater than 4000 channels. These four cuts eliminated a large number of false events, and also showed that in addition to the two spill events evident, there were many false events for very quick decays, which helped to explain the poor results even when the data was limited to short decays. Figure 8 shows the events cut out by this method.

![Particle Cuts](image.png)

**Figure 8**

Applying these cuts, I re-scanned the data and recalculated the background. Displaying the decay data, the peaks were clearly reduced, but still present. So, I refitted the data as before, using only the data before the first visible spill period. Since many false events from the beginning were removed, the changes were still significant, and the results much closer to what was expected. I also tried fitting with a similar program which considered the possibility that some of the first decays detected were actually the
decay of the daughter isotope. For this program I entered the decay constant of the
daughter isotope as well as the background rate. The results only changed significantly
for $^{137}$Sb, which makes sense since the daughter of $^{136}$Sb has a much longer half-life. So,
the best results attained so far came from this fitting, and are $1.04$ s ± $0.21$ s for $^{136}$Sb and
$0.36$ s ± $0.14$ s for the unknown, $^{137}$Sb. The errors for the one usable calibration isotope
was large, but the actual half-life fell within the given range, so there is strong reason to
believe that the half-life of $^{137}$Sb actually is between $0.22$ s and $0.50$ s. Despite the large
range, this is significant progress because it is a large improvement over theoretical
calculations. The half-life is listed as $0.20$ s by the KHF theory, $0.97$ s by QRPA-1, and
$4.73$ s by QRPA-2. So, only the KHF theory is even close to my results. Hopefully
further analysis of the data will reduce these error bars, but progress has already been
made. Figures 9 and 10 show the final decay curves.
There is one final portion of the analysis to note, which is somewhat of a footnote because it didn’t work at all. In addition to beta decays, there is a chance that a neutron-rich isotope will experience beta-delayed neutron decay, in which a regular beta decay is simultaneously accompanied by the ejection of a neutron. The probability of this happening for a decay is called the $P_n$ ratio.\footnote{A Mainz $4\pi$ neutron detector surrounded the silicon detectors in order to correlate neutron emissions with particular decays\cite{3}, but far fewer neutrons were detected than expected. Assuming the detector operated with an efficiency of 35\% (typical for such detectors)\cite{3}, I calculated $P_n$ values of 5.3\% for $^{136}\text{Sb}$ (compared to the accepted 23.2\%\cite{2}), 2.5\% for $^{138}\text{Te}$ (compared to the accepted 6.3\%\cite{2}), and 4.9\% for $^{137}\text{Sb}$. I tried to fix this by calculating the efficiency needed to give the correct results for the known isotopes, and got an average efficiency of 11\%, yielding a}{\text{}}
Pₙ of 15.7% for $^{137}\text{Sb}$. This is probably incorrect, since we would expect the Pₙ of $^{137}\text{Sb}$ to be greater than that of $^{136}\text{Sb}$.³ Yet another fitting program was intended to consider Pₙ ratios when calculating half-life, but since the difference in half-life caused by assuming Pₙ values of 0% and 100% were much less than the statistical errors of the fits from before (a difference of 0.06 s compared to the error of 0.14 s), the suggested half-life was not effected. Still, the Pₙ value for an isotope is necessary for truly accurate r-process calculations, and hopefully a source of error will be found that allows for its accurate measurement.
Bibliography


