Formation and Lifetime Measurement of Radioactive ^{11}C

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Abstract

The operation of the Tandem Van De Graaff Accelerator and General Ionex 860A Inverted Sputter negative ion source, was explored. A proton beam was created by first creating negative ions in the 860A and extracting them to the Van De Graaff where they were accelerated and stripped of their electrons. This beam was focused and directed at a target made up of ^{11}B for approximately 10 minutes, thus creating a 'hot' source of radioactive material. Confirmation of the sources identity as ^{11}C was achieved by determining the positron emission rate through gamma-gamma coincidence measurements. The time constant was determined through χ^2 minimization of Fit(y) = $(N_1/\tau_1)e^{-\frac{y}{\tau_1}} + (N_2/\tau_2)e^{-\frac{y}{\tau_2}} + C$ and was found to be 1751.81 $\pm$ 68.8s , with a normalized X^2 of 1.0854, corresponding to a 95.54% accuracy. This time constant corresponds to a half life of 20.238 $\pm$ 0.795 minutes which is within 0.47% of the accepted half life for ^{11}C of 20.334 minutes.

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1 Introduction

1.1 Overview

^{11}C is created through the reaction ^{11}B(p,n)^{11}C or more explicitly as

$$p + \ ^{11}B \rightarrow \ n + \ ^{11}C \tag{1}$$

leaving us with a neutron poor Carbon atom. The protons in the ^{11}C nucleus are unstable and decay, due to the fact that the daughter ^{11}B nucleus has a lower total energy then the ^{11}C. Outside of the nucleus this kind of reaction is impossible. This is because the proton has a slightly smaller mass than the neutron and requires energy in order to increase it's mass to that of a neutron. This energy comes from the fact the binding energy (the energy required to break a nucleus) of the ^{11}B is greater than the ^{11}C. It is therefore favorable for the unstable ^{11}C nucleus to give up that extra binding energy to the proton and find a more stable home as ^{11}B[4],[5].

$$p \rightarrow \ e^+ + \ n + \ v_e \tag{2}$$

$$^{11}_{6}C \rightarrow \ ^{11}_{5}B \ + e^+ + v_e \tag{3}$$

The rate of this reaction can be easily determined by measuring the rate of positron emission. When a decaying ^{11}C atom releases a positron, that positron finds an electron and completely annihilates. This results in 2 gamma ray bursts directed at 180° from one another. The energy of these rays must then be equal in magnitude to the energy of each annihilated particle; 511keV.

1.2 Detection

In this experiment we are measuring gamma-gamma coincidences from positrons emitted from the proton decay reaction within the ^{11}C. This is done with a pair of NaI(Ti) scintillator detectors. Scintillators work by emitting light in response to ionizing radiation. For this reason, the NaI is doped with Ti, a much larger atom. This breaks up the atomic lattice of the NaI, promoting recombination and thus light emission. This light is then passed through a special semiconductor window which, due to the photoelectric effect, responds to the light by emitting electrons. A photomultiplier tube is used to amplify this signal. The photomultiplier works by using a series of dynodes at successively higher voltages. The electrons travel to the lowest dynode causing secondary emission. These extra electrons travel to the next dynode(at a higher V than the lowest) and cause additional secondary emissions. The electrons continue to cascade, effectively amplifying the original signal.

1.3 Resolving Time and Accidentals

The resolving time is an important consideration in gamma-gamma coincidence measurements as it allows us to distinguish real coincidences from accidental

ones. The resolving time is essentially the amount of overlap between two pulses separated in time, whereby they will still be considered coincident. This can be easily measured by introducing delays in each line and measuring the change in coincidence rate.

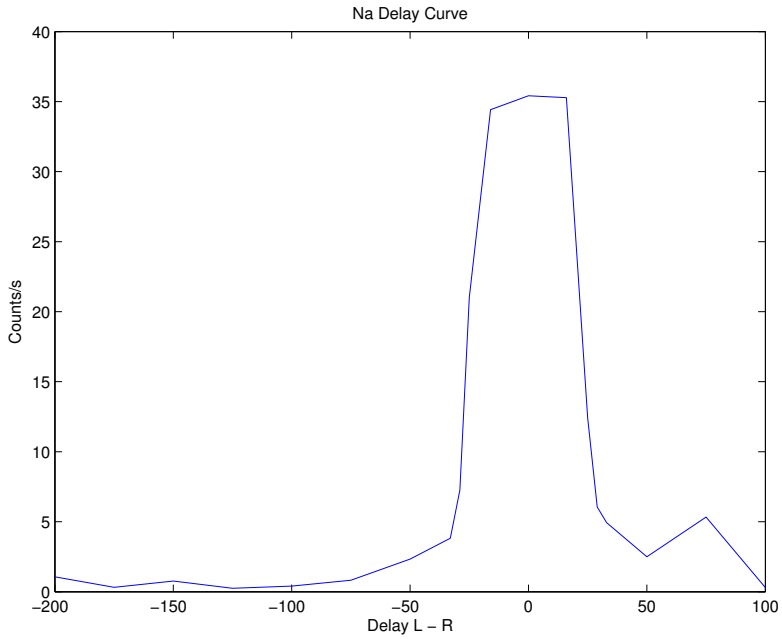

Figure 1: Resolving time is the FWHM of the ^{22}Na Delay Curve Peak $\approx$ 50ns for a 25ns pulse width

The Accidental rate of emission is given by the product of the singles rate in each detector and the resolving time $\alpha_{[1]}$.

$$N_{acc} = N_1 N_2 \alpha \tag{4}$$

The singles rate for ^{22}Na in each detector was approximately 5000 counts per second. So with a resolving time around 50ns we should expect to see in the neighborhood of 1.25 accidental counts per second outside of the main peak, which is confirmed by the graph.

2 Methods

2.1 Overview

The reaction to create our ^{11}C sample was accomplished physically by directing a high energy proton beam at an ^{11}B target sample. The energy of the

proton beam had to be great enough to overcome the Coulomb barrier of the target Boron and so a Tandem Van De Graaff Accelerator was used to give the beam an energy of 8MeV.

Our proton beam began with the creation of H^- ions in a General Ionex 860A Inverted Sputter negative ion source. These negative ions were extracted from the 860A by with a 15kV potential. They were selected using a mass selector, then focused and accelerated to the center of the Van De Graaff, which sits at 4MV. In the center of Van De Graaff the ions pass through a 20 micron thick carbon sheet which strips the ions of their electrons leaving H^+ ions(protons), which are then accelerated away from the 4MV potential. It is in this manner that we are able to use the high voltage of the Van De Graaff twice to accelerate our proton beam. The beam is then turned into the target room using another mass selector and focused onto the ^{11}B target. Once the ^{11}B target was 'hot' enough, the beam was turned off and the sample was extracted to the measurement room.

In this experiment we were looking for coincident signals which correspond specifically to an energy of 511keV (the energy of the two annihilated particles). However, due to Compton scattering within the 2 Bicron NaI(Ti) detectors used, many of the pulses are at different energy levels(according to the Compton P vs. E curve$_{[2]}$). It is important to adjust the triggering on the oscilloscope using the ^{22}Na source(another positron emitter) in order to find the signal which stands out the most(corresponding to 511keV). It is important to distinguish the lower energy 'most common' pulse from the higher energy 'most common' pulse (corresponding to 1274keV). This represents the lowest energy level of the ^{22}Na's daughter, ^{22}Ne, which comes out coincident with the positron. A Phillips Scientific 710 Octal Discriminator is then used to select only those pulses which are above the triggering voltage. A Lecroy 364 AL 4 fold Logic Gate(AND gate) then selects only the occurrences that happen in both detectors simultaneously. Ordinarily, an Ortec 871 counter is then used to count these pulses but I instead decided to improve the data collection techniques using a home built 16 bit counter with a binary output, and an Arduino Mega 2560 micro-controller. This device recorded the data to a text file on an SD card. A full explanation of the operation of this counter can be found in attached user manual within the appendix.

2.2 Negative Ion Source

The ion source works by firing Cs^+ ions at Titanium hydride pellets. The Cs vapor we need is provided by an insulated Cs boiler. This consists of a glass bulb filled with Cs, surrounded by a 40W resistive heating element. The vapor enters the main chamber(vacuum) where it comes in contact with a tantalum coil heated to 1200°C(Our ionizer was set to 8.630V). The tantalum has a work function of 4.25eV while the Cs has an ionization potential of 3.89eV. As

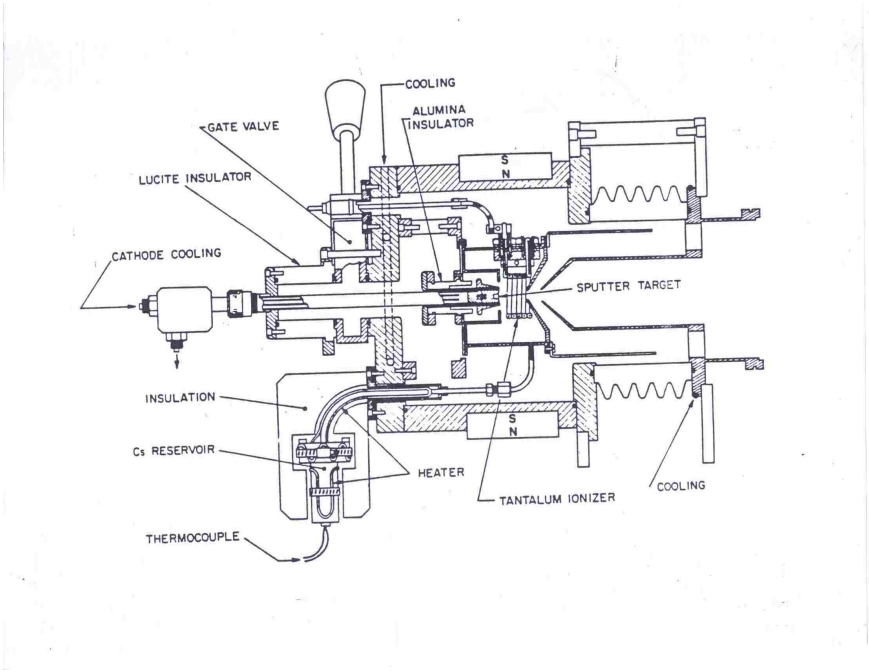

Figure 2: General Ionex 860A Inverted Sputter Negative Ion Source

a result the Cs atoms are compelled to donate an electron and become Cs^+. Additionally, Cs has a very high vapor pressure at 1200°C. The cathode then draws the positive ions to the titanium hydride target with a potential around $^-3$ to $^-5$kV. We set our cathode voltage to a 4.18kV potential. The Cs^+ ions bury themselves several atomic layers deep causing the production of a variety of different ions. The negative particles are sputtered backwards and extracted from the chamber with a 15kV potential. They were focused with an Einzel Lens which we had set to 3.987kV. This was followed by a 'y' steerer set to 97.400. An inflection magnet is then used to filter out the H^- ions from others created in the process. Our magnet was set to 7.819. All of the equipment just mentioned sits on a table at -0.4MV. The beam then travels through a set of steerers, which we had set to 0 and then through the ground station triplet. The 'x' focus of the triplet was set to 0.850kV and the 'y' focus of triplet was set to 1.071kV. The beam travels through one more steerer on the LE side of the Van De Graaff with the 'x' set to -0.730V and the 'y' steerer set to 1.4V. This is followed be a pneumatically operated Faraday cup to measure the beam current before the beam enters the VdG. This is the only piece of diagnostic equipment at this stage. All of the settings are adjusted using LabView control software.

2.3 Tandem Van De Graaff

The Van de Graaff generator works by delivering charge mechanically across a large potential difference, resulting in a high voltage buildup. We are using the eighth King Tandem Van De Graaff, FN-8 made by the High Voltage Engineering Corporation. The main components are suspended inside of a 25m long pressure vessel using compressed 4x4 x 8' glass beams. The pressure vessel is filled with about 10 tons of SF_6 to prevent corona discharge(sparking). This pressurized chamber setup is used because arcing caused by the Van De Graff is highly undesirable. An open air Van De Graaff can discharge an arc several meters long which, needless to say, presents extreme hazard to the user. SF_6 is non-flammable and, under high pressures, it can have a dielectric strength of 90 to over 300kV/cm[3], which is 3 to over 10 times the dielectric strength of air.

The charge is brought to the center of the VdG through a 12m long aluminum, stainless steel and plastic chain called the Laddertron. It can deliver up to 250μA of current, and revolves at 12m/s. A negative high voltage inductor of around -50kV induces a positive charge on the metal links by passing a current through them while they are in contact with the grounded conductive pulley. The links are separated from each other by plastic insulators. When each link breaks contact with the pulley, a positive charge is left, since the only path to ground is now through the plastic. A negative high voltage suppressor in the center of the VdG receives the charge, followed by a positive high voltage inductor to induce a negative charge on the links traveling back to ground. In this manner, the Laddertron essentially delivers charge the center terminal twice, once by giving positives, and again by removing negatives. The charge then has three paths to return to ground; the beam, the support columns and a corona discharge circuit.

The glass beams support a series of rings, inside of which lie the beam-pipe and the VdG support columns. The columns consist of a series of 200 metal planes separated by glass, and electrically split with 800MΩ resistors to give a total resistance per column of about 80GΩ. This assembly provides two additional functions besides support. The first is that it provides the high potential difference between the center of the VdG and ground, and the second is that the resistor network helps to guide the beam along the pipe with a potential gradient. We desire a regulated voltage of 4MV and so we must regulate the amperage to 50μA by $V = IR = 50 \times 10^{-6} A \times 80 \times 10^{9} \Omega = 4MV$. We achieved this by providing a 70μA Laddertron current, and removing 20μA from the corona discharge circuit.

The corona discharge circuit consists of several needles which pick up the ambient charge from the corona, and provide a path to ground. The 'resistance' of this path is governed by a vacuum triode. This triode contains a grid in the center which acts as an electrical barrier. It can either promote or hinder current, depending on the grid voltage. This voltage can be regulated by a GVM

using a reference voltage, however, in our case a beam slit resolution feedback system was used. This measures the edge currents of the beam and adjusts the grid voltage accordingly.

After the beam leaves the Van De Graaff, it is further focused by a magnetic quadropole and tuned. It passes through another mass selector which turns the beam into the target room(through the beam slit resolution feedback system). In the target room the beam is turned down the 30° beampipe and allowed to hit a current dump(really just a piece of metal at the end of the pipe), while passing through the frame used for the target. The current from the frame and the current dump is measured to determine the proper focusing and beam tuning. Once the current on the frame is zero and all of the current is on the dump, we can be sure that the beam is traveling directly through the center of the target. The boron can then be put in place for targeting.

Startup Checks Due to technical difficulties with the ion source, particularly a lack of cesium which required replacement, the startup checks and procedures for the ion source and VdG were performed mostly by Richard Lefferts. However, it's important to mention that certain startup procedures must be followed for safety. The full list of these startup checks can be found in the lab manual for this experiment.

3 Results

Coincidence measurements were counted and recorded on the aforementioned 16 bit counter and micro-controller in one second intervals. These measurements

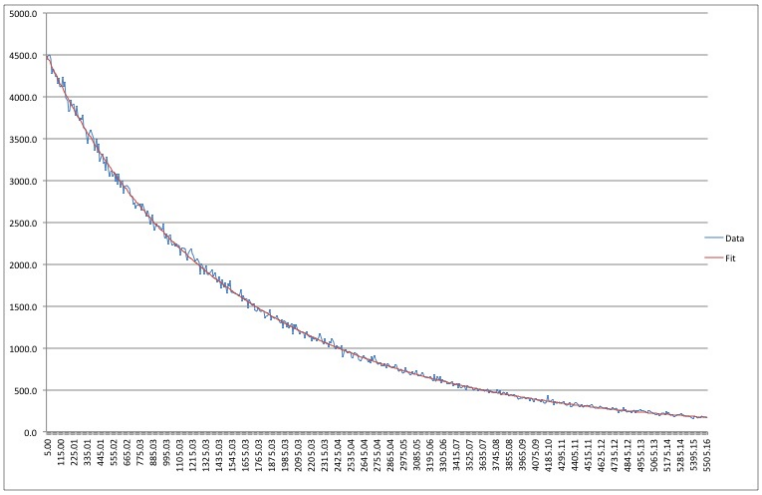

Figure 3: Graph of Counts vs. Time[s] with Data and Fit

were then binned further into 10 second intervals. The proposed fit for the decay curve was CountRate(t) = $(N_1/\tau_1)e^{-\frac{t}{\tau_1}} + (N_2/\tau_2)e^{-\frac{t}{\tau_2}} + C$. Where one exponential represents the actual ^{11}C decay, while the second represents the accidental rate. The fit was accomplished through χ^2 minimization, yielding a result of $N_1 = 6958736$, $N_2 = 324186$, $\tau_1 = 1751.81$s, $\tau_2 = 616.09$, and $C = 0.00167$. C was constrained to be equal or below this value because a ten minute period passed with no background counts. This indicated a less than 0.1/min(0.00167/s) count rate. χ^2 was minimized to 1.0854 which corresponds to a probability of likelihood equal to 95.54% . The half life was found to be 20.238 ± 0.795min which is within 0.47% of the accepted half life of ^{11}C which is 20.334.

4 Conclusions

Over the course of this experiment we learned about the theory and operation of an ion source and Tandem Van De Graaff Accelerator. There are a large number of stages and components, which all must be in check for the proton beam to work properly. Additionally, we also confirmed that the proposed reaction in the introduction indeed occurred and left us with a sample of radioactive ^{11}C. The theory of coincidence measurements was also explored. We learned how to appropriately trigger our equipment to insure proper recording of only the pulses we want and can consider actual coincidences. The N_2 (accidental) value was found to be just below 5% of N_1, but what is perhaps more interesting is that the accidental rate seemed to fall of a little faster than we'd expect, decaying about 2.84 times faster than the 'real' rate. According to the proposed theory $N_{acc} = N_1 N_2 \alpha$(N_2 here is the rate in the second detector), so we would expect the rate to fall off as 2N. It's possible that the geometry of system may have contributed the this 'extra' speed of the accidental decay. Efforts were also taken to improve the recording of these measurements through modern digital techniques.

5 Acknowledgements

We would like to thank Richard Lefferts for his help and guidance throughout this experiment. Also we'd like to thank our T.A's Carlos Marques and Ludwig Krinner for help and advice for our data analysis.

6 Works Cited

[1]

[2]

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7 Appendix