Software Development to Determine the Optimal Parameters of a Tape Transport System

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Abstract. To better understand the process of nucleosynthesis in stars today, advanced nuclear physics techniques are needed. At the National Superconducting Cyclotron Laboratory, at Michigan State University, a new tape transport system has been developed for this purpose. Radioactive nuclei can be implanted on the tape system, and after detecting the products of their decay, the tape rotates to remove any remaining unwanted activity. The present work focuses on the development of software to be used for calculating the optimum settings for experiments using the tape transport system.
Keywords: Nucleosysthesis, Radioactivity

1. INTRODUCTION

All of the heavy elements that exist on earth today were formed inside stars through various nuclear reactions and processes. The process of creating elements heavier than hydrogen is referred to as nucleosynthesis. Ever since this process was first described [1], the understanding of stellar nucleosynthesis has advanced significantly. It is currently believed that hydrogen and helium were created during the Big Bang [2] and then the abundance of heavier elements up to iron are created through nuclear reactions inside of stars [1]. The elements heavier than iron are created with different processes, which are termed the s-process, p-process, and r-process [1]. The s-process is a slow process where neutrons are captured and γ radiation is emitted, abbreviated as (n, γ), followed by β decays [1]. The p-process, also known as the γ-process involves the γ-excitation of nuclei followed by the emission of charged particles and neutrons [4]. The r-process is a rapid process of neutron capture reactions followed by β decays.

The r-process is believed to be responsible for producing nearly half of the heavy elements found in nature [5]. Neutron capture rates, β-decay rates, and β-delayed neutron emission probabilities are three important quantities that go into performing r-process nucleosynthesis calculations

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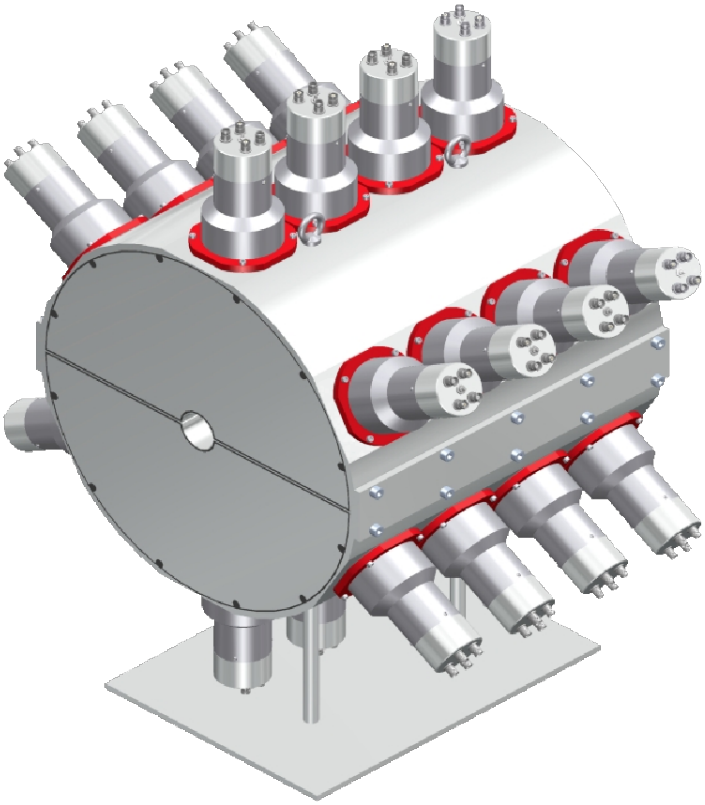

Figure 1. The SuN (Summing NaI(Tl)) detector.

[5]. Therefore in order to better understand the nucleosynthesis of heavy elements, advanced techniques are needed to measure and study decays of the exotic neutron-rich nuclei involved in the r-process and to constrain astrophysical models. For the purpose of this paper we will focus on β-decay rates. Neutron-rich isotopes can often undergo β^- decay, during which one of their neutrons is converted to a proton, and in this way transforms the original radioactive nucleus into a new one. During this process, an antineutrino and electron (β^--particle) are also emitted. This process does not change the atomic mass number of the decaying isotope, but will change the isotope itself. Once the β decay is completed, a new element will exist which may itself be unstable and β decay. This process will continue until a stable isotope is reached.

Since the process of β decay is important in understanding the r-process, many advanced techniques and detectors have been created for the purpose of understanding it. At the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU), a γ-ray calorimeter (known as SuN) was developed for this purpose [6]. The Summing NaI(Tl) (SuN) detector shown in Fig. 1 is used to study β decays in neutron-rich nuclei. This detector is a barrel shaped scintillator,

divided into eight optically isolated segments of NaI(TI). Each segment is read by three photomultiplier tubes (PMTs), for a total of 24 signals from the detector [6]. It is highly efficient and has a 45 mm bore-hole through its center for use around a beam pipe.

For isotopes with a relatively short half-life (roughly less than 1 second), an implantation-β decay correlation method with fast beams can be used [3][7]. However, this technique is not applicable if the half-life of interest is long and the total implantation rate high. For this reason, for longer half-lives it is necessary to use alternative techniques.

Neutron-rich isotopes can be far from stability with subsequent daughter isotope decays introducing unwanted background radiation. This could mean that after only a few seconds following implantation, the decays picked up by SuN could be decays from the daughter isotope instead of the mother isotope. In cases where the decaying mother isotope is of interest, this poses an issue. To reduce this background radiation, a new experimental setup was developed at the NSCL that couples the SuN detector with a tape transport system.

The premise is that after implantation onto a section of tape, the tape is moved to remove long-lived isotopes from the active volume of the SuN detector. Hence, one can reduce the issue of the daughter isotope decays becoming more prominent than the mother isotope decays. The idea of implementing a tape station has been around for over 40 years, e.g. see Ref. [9]. Since then, there have been advancements and new ideas in the way a tape station is implemented such as SATURN (Scintillator And Tape Using Radioactive Nuclei) created at Argonne National Laboratory (ANL) [10].

2. SUNTAN SYSTEM

At the NSCL, SuNTAN (SuN Tape-system for Active Nuclei) was developed (Fig. 2). The tape station consists of a main tube that fits inside of the SuN detector where tape can be fed from an isolated chamber to the end of the tube and back via motors. The entire station is vacuum sealed and the physical tape is stored in a large chamber outside of the SuN detector. A small portion of tape is exposed at the end of the tube which serves as the implantation point for a rare isotope beam inside of SuN. After a period of implantation (the duration of which is isotope dependent), the tape is moved to expose a clean section of tape to the beam and remove unwanted daughter activity.

In conjunction with SuNTAN, a new scintillating detector (Fig. 3) developed at Hope College was characterized for use with SuN. It is attached to wavelength shifting fiber optic cables to work in conjunction with the tape station for the detection of β particles. The detector utilizes two PMTs that are attached to the fiber optic cables in order to detect β decays in coincidence between one another. SuNTAN and the fiber detector will be the focus of a forthcoming publication. This publication's focus is on new software that accompanies SuNTAN and helps to guide the decision for the appropriate tape cycle.

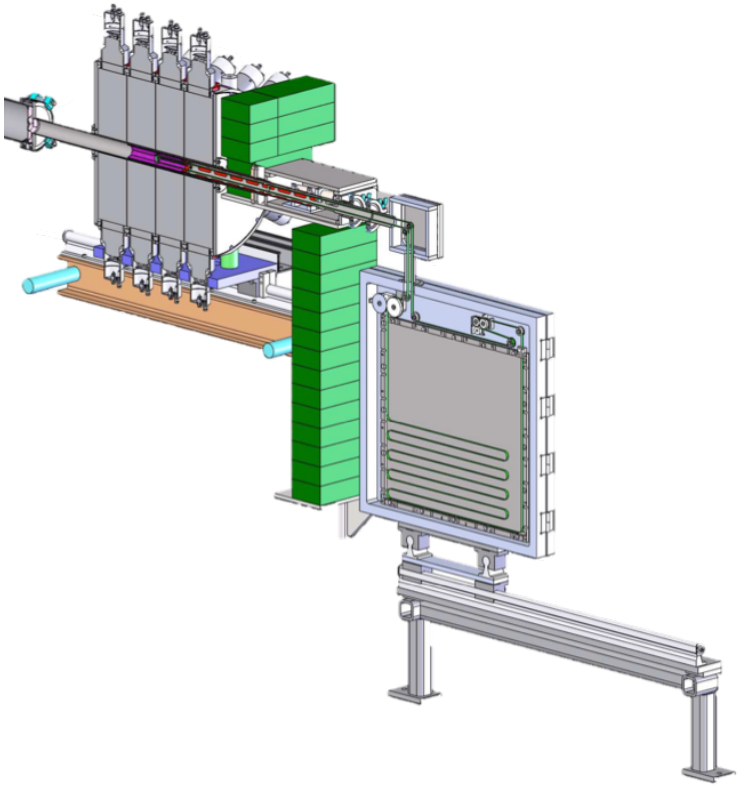

Figure 2. A cross section of the SuNTAN system connected to the SuN detector. On the bottom right is a railing system for moving the tape station into and out of SuN. Above that is the tape box where the new and used tape is located. In the top left is the SuN detector with a beam pipe going through its center. Lead bricks (green) act as a barrier to isolate the tape from within SuN.

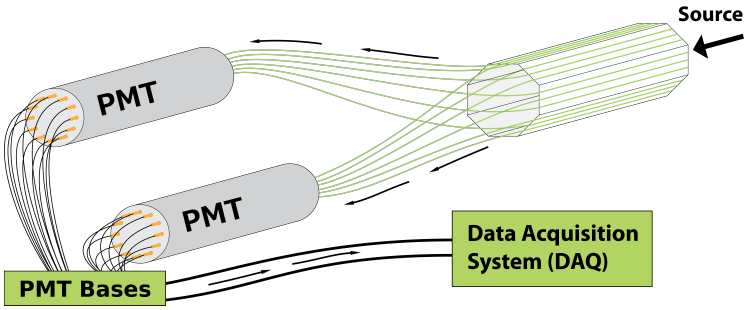

Figure 3. The scintillating detector attached to wavelength shifting fiber optic cables that carry the signal to two PMTs. After entering the PMTs the signals are recorded via the NSCL digital data acquisition system [11].

3. GINA PROGRAM

Generations of Implanted Nuclear Activity (GINA) is a program designed to work with a tape station. To demonstrate the need and functionality of GINA, the test case of ^{42}S is used. The primary isotope of ^{42}S has a half-life of $T_{1/2} = 1.03 \pm 0.03$ seconds [8]. This means that on average, half of a sample of ^{42}S will decay in that time. ^{42}S will β decay into ^{42}Cl which has a half-life $T_{1/2} = 6.8 \pm 0.3$ seconds [8]. The daughter isotope will decay to the granddaughter isotope of ^{42}Ar, having a half-life of $T_{1/2} = 32.9 \pm 1.1$ years [8]. This decay chain is perfect for the commissioning of SuNTAN due to the short half-life of the primary and daughter isotopes, and long half-life of the granddaughter.

The decay rate for an isotope is given by

$$\frac{dN(t)}{dt} = -\lambda N(t) = -\frac{N(t)}{\tau}, \tag{1}$$

where N is the number of radioactive nuclei, λ is the decay constant, τ is the mean lifetime of the particles within the material, and t is time. The decay constant is related to the half-life ($T_{1/2}$) by

$$\lambda T_{1/2} = \ln(2) \implies T_{1/2} = \tau \ln(2). \tag{2}$$

The rare isotope beam of the primary isotope will be continually implanted onto the target tape. Thus, the number of primary isotopes at the target location will continually increase as the beam is being deposited. The decay rate is directly proportional to the number of nuclei of the isotope that is present and thus the rate of decay will eventually reach equilibrium with the rate of deposition. The daughter isotope will similarly do this, but over a much longer time, due to a slower decay rate. This will cause the decay rates of the daughter isotope to slowly approach the decay rates of the primary isotope which will make it difficult to distinguish which isotope is decaying in the detectors for a given event. At the start of this cycle, the primary isotope decay rates are prominent over the daughter isotope (as there are little to no daughter nuclei present) and thus it is favorable

to collect data at this point. When it is determined that the daughter isotope is providing too much contamination, the tape of SuNTAN can be moved so the system can return to this favorable state. Two important factors to consider when running an experiment with this system are to maximize the number of primary (mother) decays and to minimize the contamination from other isotopes decaying.

In order to determine sufficient timing parameters for tape rotation, a method was established to calculate decay rates per isotope of decay chains consisting of multiple generations. The GINA program performs this method and provides various information for determining how to optimize the favorable collection period of a decay of interest. GINA performs multiple functions related solely to the radioactive isotopes at the target location with other features relating to the isotopes being sent through the SuNTAN system. The GINA program uses a Graphical User Interface (GUI) programmed to work with up to four generations of decay, and the method used is generalized to work with any decay chain.

First, GINA calculates the number of radioactive isotopes at a target location based on some initial and constant rate of isotope implantation over some time. Let N denote the number of radioactive isotopes at a location and $T_{1/2}$ denote the half-life of a nucleus. Suppose we allow the superscript to denote the generation as a number, where (0) refers to the mother nucleus, (1) the daughter nucleus, (2) the granddaughter nucleus and so on such that (i) would represent the i^{th} generation nucleus. The number of mother nuclei only depends on the number of implanted nuclei and the number of nuclei that have decayed over some small amount of time Δt. If the total amount of elapsed time for a system is given by $n\Delta t$, where $n \in \mathbb{N}$ $(n = 1, 2, 3, \dots)$, then one can represent the number of existing nuclei at any point by

$$N_n^{(0)} = N_1^{(0)} + N_{n-1}^{(0)} e^{-\frac{\Delta t}{T_{1/2}^{(0)}} \ln(2)}. \tag{3}$$

Representing the values in a series such as this was useful for programming purposes.

Next, for a later generation, the number of nuclei will depend on how many of that generation's nuclei decayed as well as how many of the previous generation's nuclei decayed into it. This gives

$$N_n^{(i)} = N_{n-1}^{(i-1)} \left(1 - e^{-\frac{\Delta t}{T_{1/2}^{(i-1)}} \ln(2)}\right) + N_{n-1}^{(i)} e^{-\frac{\Delta t}{T_{1/2}^{(i)}} \ln(2)}. \tag{4}$$

If it is assumed that the last stage has a near infinite half-life, the limiting case will produce a final step of this chain to be equivalent to

$$N_n^{last} = N_{n-1}^{last} + N_{n-1}^{d} \left(1 - e^{-\frac{\Delta t}{T_{1/2}^{last-1}} \ln(2)}\right). \tag{5}$$

These relations can be proven by induction and are demonstrated in Fig. 4 for the example chain ^{42}S $\rightarrow$ ^{42}Cl $\rightarrow$ ^{42}Ar.

During the experiment, the important number is not necessarily the number of nuclei but the number of decays. Therefore, GINA uses this information to determine the radioactive decay rates

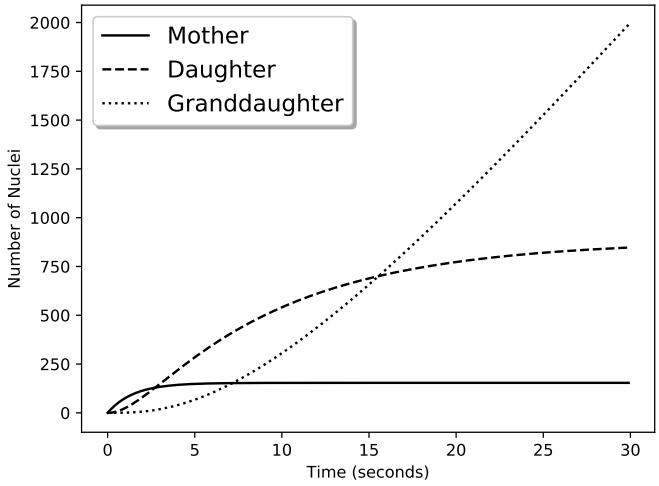

Figure 4. Using an input rate of 100 particles per second, this demonstrates the total nuclei count for an implanted isotope (as generated by the GINA program) of ^{42}S (solid line) which decays into ^{42}Cl (dashed line) and ^{42}Ar (dotted line).

of each isotope at the implantation point. The values N_n^0, and N_n^i all represent a total number of particles of a specific isotope. Eq. 1 defines the decay rate of an isotope. Using the total particle numbers calculated in Eq. 3 - 5, one can determine the decay rate to be

$$D_n^i = \frac{dN_n^i}{dt} = \frac{N_n^i \ln(2)}{T_{1/2}^i}. \tag{6}$$

These represent the total decays per second and are demonstrated in Fig. 5.

Finally, GINA does a calculation of the contamination on the implantation point relative to the primary isotope. The contamination is defined as the number of decays the non-primary isotopes are producing with respect to the number of decays the mother nuclei are producing. The contamination can be expressed as a percentage using

$$C_n = \frac{1}{D_n^{(0)}} \sum_{k=1}^{\infty} D_n^{(k)} \times 100\%. \tag{7}$$

Following this, another useful value to determine proper experimental parameters using the tape station is the deposited implant loss, L. This is the total percentage of implanted particles that have decayed and is given by

$$L_n = \frac{1}{nN_1^{(0)}} \sum_{k=i+1}^{\infty} N_n^{(k)}. \tag{8}$$

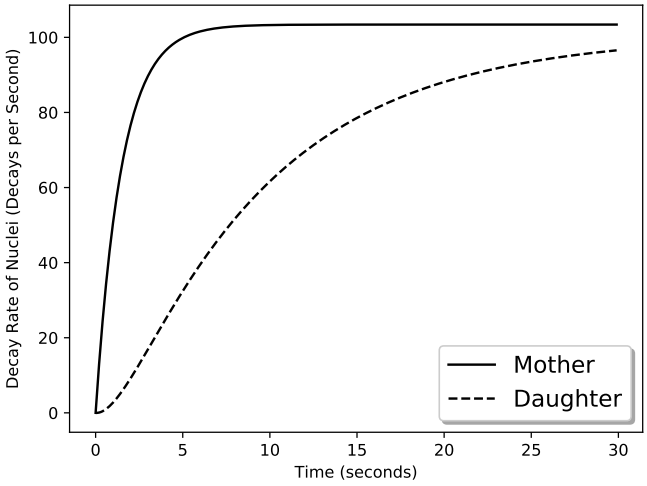

Figure 5. Using an input rate of 100 particles per second, this demonstrates the total nuclei decay rate (as generated by the GINA program) for an implanted isotope of ^{42}S (solid line) which decays into ^{42}Cl (dashed line) and approximating ^{42}Ar to be stable.

Both of these values are demonstrated in Fig. 6.

From the sequences listed above, the only needed inputs are the half-lives of each isotope. Because of this, GINA takes the half-lives of the primary isotope and each generation isotope up to four isotopes as initial input values. These are what is used to perform the calculations described above and no other values are needed. For the case of ^{42}S, one can see how the contamination percentage increases over time. The acceptable amount of contamination can be determined based on the detectors and methods being used for the specific setup as it was for the SuNTAN commissioning experiment.

4. CONCLUSION

Future experiments using SuNTAN have been planned and the GINA program is available and ready to use for the preparation of these experiments [12]. The program is not limited to use with SuNTAN and is made to be easily adapted for use with an arbitrary number of generations within a decay chain. The GINA program along with SuNTAN will help to further increase the understanding of the r-process and will lead to the study of isotopes that have not been studied previously.

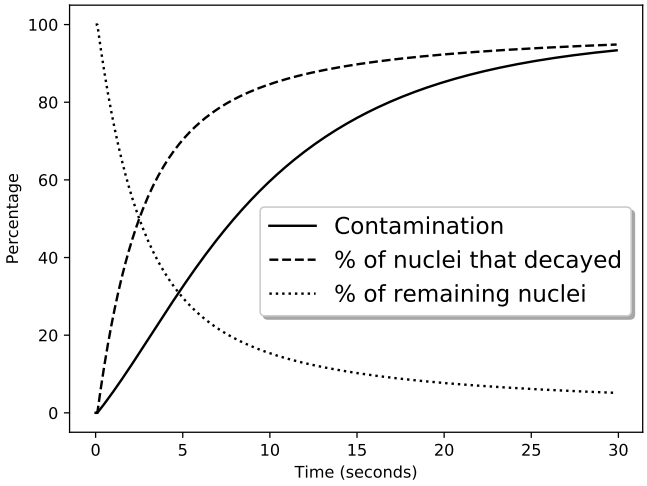

Figure 6. This demonstrates the total nuclei contamination (solid line) rate and implantation loss (dashed line), as generated by the GINA program, for an implanted isotope of ^{42}S which decays into ^{42}Cl and approximating ^{42}Ar to be stable.

5. ACKNOWLEDGMENTS

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