A C++ Program to Simulate the Performance of the St. George Recoil Mass Separator

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ABSTRACT

The last fifty years have seen significant progress in the field of nuclear astrophysics, the study of nuclear reactions in stars and other cosmic phenomena. In the past several years, it has become possible to explore energies in the stellar energy range with a new device, the recoil mass separator. The St. George recoil mass separator currently under construction at the University of Notre Dame is poised to explore helium burning in stars, and later on to investigate hydrogen burning. Indiana University South Bend is working on a mass detector to be installed on the terminal end of St. George. In order to find the timing resolution required by the mass detector to give acceptable precision, a C++ program has been written to simulate fusion reactions at St. George. It has yielded results that will be compared against data collected during testing and the actual experimentation.

INTRODUCTION

Brief Overview of the History of Nuclear Astrophysics

In 1957, E. Burbidge, G. Burbidge, W. Fowler, and F. Hoyle suggested in their paper, Synthesis of the Elements in Stars, that most of the elemental isotopes observed originate in stellar reactions, contradicting the prevailing wisdom at that time that these isotopes were created in the Big Bang [1]. Their seminal work, published in Reviews of Modern Physics in October of that year, laid the groundwork for research into what is now called nuclear astrophysics.

Shortly after this idea, experimental research into how these isotopes are created began in nuclear laboratories. The first experiment into a suspected astrophysical reaction was performed by the researchers Cook, Fowler, Lauritsen, and Lauritsen at Caltech, in which a target of beryllium-11 was irradiated with deuterium particles. Since then, hundreds of experiments have been done to simulate the nuclear reactions that regularly occur in the cosmos [2].

The Recoil Mass Separator

For decades, the only way to do experiments of this kind was the "beam-and-target" method: to bombard a "target" of heavy nuclei with a "beam" of lighter nuclei. For example, in order to investigate the $^{12}C(\alpha,\gamma)^{16}O$ reaction (carbon-12 reacting with an alpha particle to form oxygen-16 and a gamma ray), a target of carbon-12 would be exposed to a beam of alpha particles. A gamma ray detector would be set up to count the number of reactions, since each reaction emits a gamma ray. Gamma ray detectors, however, can only detect a small (but known) percentage of the gammas emitted from the target, and the number of reactions drops off very quickly when the beam energy is decreased. The result was that the reactions in question could only be performed at relatively high energies, higher than the energies typically found in stellar scenarios [3]. This changed with the use of the recoil mass separator (RMS) for nuclear physics. A recoil mass separator makes it possible to study reactions in inverse kinematics, that is, by bombarding the lighter nucleus in a reaction with the heavier nucleus. The RMS then removes the unreacted "beam" particles, hence the "separator" in "recoil mass separator." All of the product ions can, in principle, be detected, rather than only a small percentage in the case of the "beam-and target" method. For instance, the $^{12}C(\alpha,\gamma)^{16}O$ reaction can be performed by hitting a target of helium gas (a helium nucleus is an alpha particle) with a beam of carbon-12 atoms, removing the unreacted carbon-12, and counting the oxygen-16 atoms that reach the end of the device. The result is that nuclear reactions of astrophysical significance can be performed at much lower energies, within the stellar energy range [3].

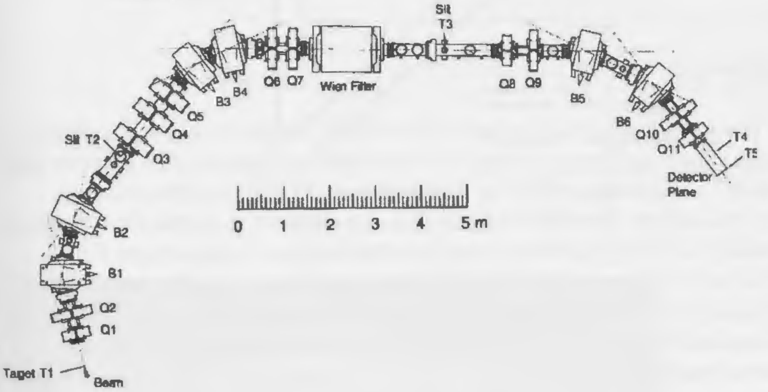

Figure 1. A schematic of the St. George RMS, not showing the ion source, the target, or the mass detector.

The St. George RMS

As a result, the St. George (Strong Gradient Electro-magnetic Online Recoil separator for capture Gamma Ray Experiments) RMS has been commissioned at the University of Notre Dame to investigate the phenomenon of helium burning in stars, and later to conduct research in hydrogen burning [4]. This research is of utmost interest in the field of nuclear astrophysics, because practically all stars undergo nuclear reactions involving hydrogen or helium.

The RMS itself consists of a series of electromagnets and a Wien filter, all surrounding a beamline under high vacuum. The other devices associated with the RMS are a beam ion source and accelerator, a chamber containing an usually gaseous target, and a particle identifier [5]. St. George is planned to use a helium jet and later a hydrogen jet as a target, and a mass detector as the particle identifier. The beam ions are accelerated from the ion source to the target chamber. In the chamber, some of the beam ions fuse with target atoms to form product ions, but the vast majority of ions do not undergo reactions. The unreacted beam ions travel with the product ions through the rest of the RMS, which uses additional electromagnets and the Wien filter to remove nearly all of the unreacted beam ions. Nevertheless, about one out of 10^{12} of the unreacted beam ions reaches the terminal end of the RMS, where the mass detector is [6]. The mass detector's task is to discriminate between the beam and product ions by mass, enabling a count of the number of product ions. The number of product ions resulting from a measured number of incident beam ions, the gas target density, and the energy of the beam ions yields the cross-section for that reaction (roughly speaking, the probability that the reaction will occur).

Phase 1: (α,γ) reactions	**Phase 2: (p,γ) reactions**
$^{16}O(\alpha,\gamma)^{20}Ne$	$^{14}N(p,\gamma)^{15}O$
$^{18}O(\alpha,\gamma)^{22}Ne$	$^{31}P(p,\gamma)^{32}S$
$^{34}S(\alpha,\gamma)^{38}Ar$	$^{40}Ca(p,\gamma)^{41}Sc$
$^{36}Ar(\alpha,\gamma)^{40}Ca$	
$^{12}C(\alpha,\gamma)^{16}O$	

Figure 2. Sample reactions to be performed by St. George. These are of paramount astrophysical importance.

The Mass Detector for St. George

Indiana University South Bend has been given the task of designing, constructing, and testing a mass detector for St. George. The mass detector consists of two parts: a transmission detector and an energy detector, separated by a distance of 50 cm. The ions pass through the transmission detector and are stopped by the energy detector. The transmission detector gives the time at which an ion passes through it, while the energy detector gives both the time an ion hits it and the energy dissipated by the ion as it is absorbed by the energy detector. The difference between the transmission time and the absorption time is the time of flight (TOF), which yields the speed when combined with the separation distance of the two parts of the device. The mass of an ion is found from this speed and the energy.

The transmission detector consists of a sheet of carbon foil, a microchannel plate (MCP) detector, and an electrostatic mirror. When an ion impinges on the carbon foil, some electrons are knocked from the carbon atoms. These electrons enter the electrostatic mirror along with the ion. While the ion is barely affected by the mirror, the electrons are redirected from the beam path into the MCP, which acts as an electron detector. The MCP gives an electric signal when electrons strike it, which is used as the "start" signal in the TOF measurement. The ion continues through the mass detector until it reaches the silicon detector, which gives the TOF "stop" signal and the stopping energy.

As shown in Figure 3, the electrostatic mirror consists of three wire grids held at constant potentials inside a metal case, as well as the associated circuitry. As the electrons liberated by an ion enter the device, they pass through a positively charged wire grid. The second grid and the case of the electrostatic mirror have the same positive charge, forming a Faraday cage. When the electrons exit the Faraday cage through the second wire grid, they come very close to a third wire grid with a strong negative charge. They are diverted 90°, back into the Faraday cage, and ultimately reach the MCP, where they are detected.

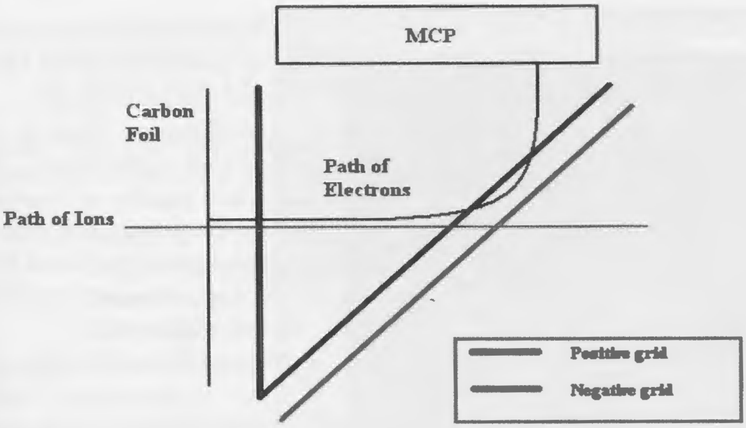

Figure 3. A simple schematic of an electrostatic mirror. The strong electric field between the two larger grids diverts the electrons into the MCP.

Figure 4. A photograph of the prototype electrostatic mirror used by the St. George mass detector. The negative grid is in the foreground, and the positive Faraday cage is the triangular structure behind it. The wires in the grids are too small to be seen in this picture, in order to be transparent to particles.

Some uncertainty in the number of product ions is introduced by the characteristics of the device. Contributors to this uncertainty include, but are not limited to, the combined time resolution of both the transmission detector and the energy detector (see Figure 5), the energy resolution of the silicon detector, the distance uncertainty caused by the ions traveling in a narrow cone rather than in a straight line, and the energy straggling (broadening of the energy distribution) introduced by the carbon foil. The result is that there is some uncertainty in mass: a plot of number of counts versus mass would show what appear to be two Gaussian peaks centered on the beam and product atomic masses (see Figure 6). Depending on the beam-to-product ratio and the mass uncertainty, these peaks may overlap, obscuring the number of product ions that were detected by the mass detector. The percentage of the area of the beam peak that overlaps with the product peak is referred to as the percent contamination of the product by the beam.

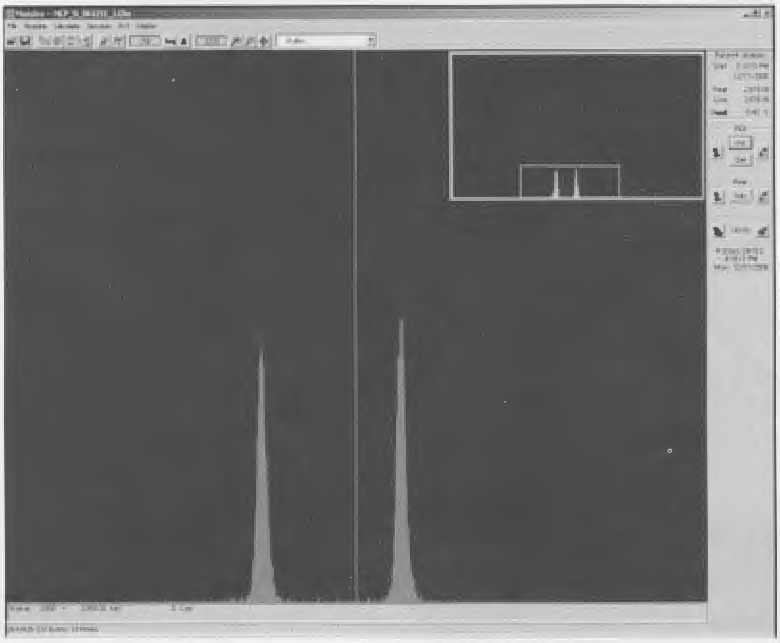

Figure 5. Time resolution measurement of the MCP and silicon detector combination. Time is plotted on the x-axis, while number of counts is on the y-axis. The time resolution was found to be 3.4 ns, measured by the full width of the approximately Gaussian curves at half-max. This number may be improved as the mass detector continues to be refined. The separation of the two peaks is established by delaying the stop signal by an additional 40 ns.

METHODS

Percent_contam.cpp

In order to quantify this percent contamination, a C++ program, percent_contam.cpp, was written to take various attributes of the RMS and the mass detector and provide an estimate of the percent contamination. This figure will, in turn, enable a determination of the time resolution needed for the mass detector to be sufficiently precise. The program takes into account the time and energy resolution of the mass detector, the ion masses and energy ranges of the reaction in question, the energy straggling introduced by the carbon foil, the product-to-beam ratio, the path length of the mass detector, and other factors.

The program calculates the mass uncertainty in terms of δm, the standard deviation of the peak, for both the beam and product peaks. It repeats this for five different values in the entered energy range, and uses these uncertainties to estimate the percent contamination of the product peak by the beam peak. The algorithm is as follows:

1.) Ask the user to select a reaction from the displayed table.
2.) Ask the user to enter the parameters of the device: length, full-width at half-max (FWHM) of the time resolution, carbon foil thickness, and beam-to-product ratio.
3.) Apply programmed characteristics of the beam ion and ask user for the energy ranges of the beam and product.
4.) Find five evenly spaced energies in the range.
5.) For each of the five energies:
    i.) Using the range reduction method, find the energy loss as the ion travels through the carbon foil.
    ii.) Calculate the velocity of the ion as it leaves the foil and the energy straggling.

iii.) Use these data in the calculation of δm.
iv.) Display and save the values of m.
6.) Repeat steps 3 through 5 for the product ion.

Note: steps 7 through 13 treat the δm's of the beam and product as standard deviations of a Gaussian curve to find the percent contamination of the product by the beam.

7.) For the δm of the product pertaining to the lowest energy, find the point $2\delta m$ from the center of the product peak in amu.
8.) Determine how far this is from the center of the beam peak in amu.
9.) Convert this distance to units of δm of the beam.
10.) Round this number to a high value and a low value (`ceil` and `floor` in C++).
11.) For each value, find the fractional area of a Gaussian curve from the number of standard deviations found in step 9 out to infinity. (The program uses a table in a text file to do this.)
12.) Multiply these by the product-to-beam ratio and divide by the ratio plus one.
13.) Multiply these numbers by 100% and display them as the range of estimated contamination of the product peak by the beam peak. Save the results in a text file, log.txt.
14.) Repeat steps 7 through 13 for the other δm's.
15.) Average and display the results for percent contamination.
16.) Output the prompt "Continue? (y/n)." If user inputs "y" or "Y," start over from step 1 (using a `while` statement). If not, quit.

The current version of the program also has an option for alpha particles, in order to compare the program's results with the data gained from preliminary testing at IUSB using alpha particle from an americium-241 source, before full-scale testing at Notre Dame with the ion source begins. An agreement between the program's results for alpha particles and the results of the testing would indicate that the program is accurate.

RESULTS & DISCUSSION

According to the estimates made by the current version of the program, the highest percent contamination experienced by the St. George RMS under the current design parameters should be approximately 25%. This estimate is made for the reaction with the greatest percent contamination, $^{34}S(\alpha,\gamma)^{38}Ar$, when the time resolution is 3.4 nanoseconds and the beam-product ratio is 2:1. According to the program, the maximum percent contamination can be brought to an acceptable level of under 10% if the time resolution is improved to 1.4 nanoseconds. If the time resolution can be brought to 0.8 nanoseconds, the greatest percent contamination is estimated be only about 1%. Even with the current measured value of 3.4 nanoseconds, the percent contamination is very close to 0% in some of the reactions, but increases if the energy, beam-to-product ratio, or atomic mass increases. These results will be tested against the actual data when testing of the mass detector begins later this year.

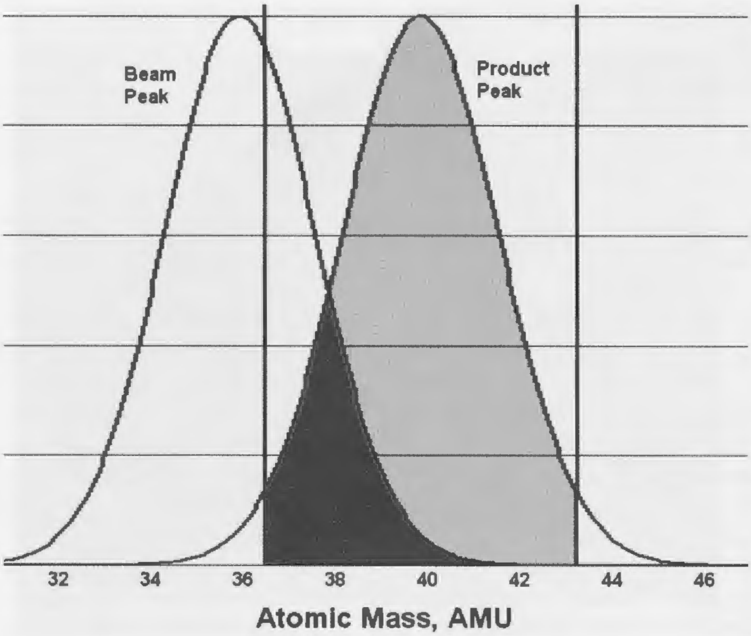

Figure 6. Results of the program simulation for the $^{36}Ar(\alpha,\gamma)^{40}Ca$ reaction at the highest energy planned to be investigated. The gray and black areas under the product peak lie within $\pm 2\delta m$ of the center of the peak, the region that the program integrates over to find the percent contamination. The percentage of this area that is black is what the program defines as the percent contamination of the product by the beam.

Current Work and Future Directions

The current goal is to complete and test a final version of the mass detector, and deliver it to Notre Dame. To this end, another program, electromirror.cpp, is being written to simulate the performance of the electrostatic mirror. By improving the design of the electrostatic mirror, it is hoped that the timing resolution of the transmission detector can be optimized, shrinking the percent contaminations for all the reactions. Later, once the research at St. George is completed for helium reactions, a second Wien filter and more electromagnets will be added to the RMS to further improve the mass resolution, enabling experimentation into hydrogen burning in stars [7]. The St. George RMS is expected to lay the groundwork for a future generation of recoil mass separators, permitting a deeper understanding of the stars.

REFERENCES

[1] E. M. Burbidge, G.R. Burbidge, W. A. Fowler, and F. Hoyle, Reviews of Modern Physics **29**, 547 (1957).

[2] George Wallerstein et al., *Reviews of Modern Physics* **69**, 995 (1997).

[3] Christian Iliadis, *Thermonuclear Reactions in Stars* (Wiley-VCH, Berlin, 2007), p. 176.

[4] M. Couder, C. Angulo, W. Galster, J.-S.Graulich, P. Leleux, P. Lipnik, G. Tabacaru, and F. Vanderbist, Nuclear Instruments and Methods in Physics Research Section A **506**, 26 (2003).

[5] Michael Joseph Lamey, M.Sc. Thesis, Simon Fraser University, 2004.

[6] Georg Berg, "Design of a Fragment Separator St. George for the University of Notre Dame" (unpublished).

[7] M. Couder, G. P. A. Berg, J. Görres, P. J. LeBlanc, L. O. Lamm, E. Stech, M. Wiescher, and J. Hinnefeld, Nuclear Instruments and Methods in Physics Research Section A (to be published).

Gregory is a junior and will graduate in 2010 with a BS in Physics. He wrote this paper for Dr. Hinnefeld's S406.