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Method of Performing Indirect Stellar Nuclear Reaction Rate Measurements and Calculations

Personal Section

Despite the changes in custom and language that occurred simultaneously in my life as I moved from South Korea to America, math was the one thing that made me feel secure and confident. Math provided me with a sense of direction through the confusion and cultural difference I had to overcome. Therefore, I began to devote my time to mathematics, taking advantage of all the research opportunities that were available in the field. Then, as part my school's Math Research Program that I enrolled in sophomore year, I was truly able to focus on my interest in mathematics. Year after year, I produced pure math projects that many others did not bother to understand. Nevertheless, math was my academic passion and I continued to expand my knowledge through research. However, at the end of my junior year, I had a choice of either going to a research program over the summer or finding a private mentor to continue my studies in mathematics. When I was accepted into the High School Honors Science Program at Michigan State University, I decided to get an experience of what laboratory research was like.

Therefore, in summer of 2010, I was provided a list of research. Having always been a mathematically engaged student, I searched for a purely mathematical project only to find none available. Adjusting to the circumstances, I decided to apply all my mathematical skills to an astrophysics project, which requires the ability to generate and modify formulas. When the High School Honors Science Program was able to provide me a position to research alongside Professor Georgios Perdikakis at the National Superconducting Cyclotron Laboratory, the opportunity to experience researching in a realistic environment was undeniable. Moreover, during the initial research to further understand nuclear astrophysics, I began to take interest in not only the mathematical aspect of the project, but also the makeup of the universe: stars. Every element that can be found on Earth as well as Earth itself is a result of various types of nuclear reactions that occur in stars. Being able to research the fundamental aspects of life is an eye-opening opportunity that cannot be passed. It provides a chance to view the world in a new curious perspective and take one step further in understanding the beginnings of everything known to mankind.

I had not initially held an interest in astrophysics, but this project helped me develop a new inquisitiveness. This project introduced me to a realm of science that captured my attention from the start. It is a type of science that cannot be physically observed but has tremendous effects on life on Earth: nuclear physics. Not only has it expanded my interest in science, it was also a preview of the reality of research. It showed that science requires hard work, but great findings cannot come about without a bit of luck as well. It clarified that, in order to succeed as a researcher, patience is a critical quality. However, as an overachiever, the *uncertainty* in the probability of success in research did not appeal at first. Despite this fact, the actual experience I had this summer showed never-ending possibilities and an infinite number of branches of research. Finally, this project opened my eyes to the various ways in which I can apply my inquisitive love for mathematics to science. By researching astrophysics using computer science, I was able to explore a different branch of mathematics.

All of this sounds easy and eye-opening, but the process of this research wasn't as easy as it sounds. On my first day at the laboratory, I met with Professor Perdikakis. As he was explaining what the goals of this research were, I drew a blank in my mind. Having only taken honors physics in high school at the time, astrophysics was not something that I had learned about in school. Truth be told, I had no idea what was being said and pretended to understand everything in front of my mentor, while back in my room, I began to panic and started to read articles and textbooks pertaining to my research. Every book was covered with post-it notes and every article was marked in different colored highlighters. I wanted to know as much as I could about astrophysics. I did not want to disappoint not only my mentor but also myself.

Of course I did not understand everything I read. I had to read the same lines over and over again until I got the slightest gist of the meaning of it. For those of you who are afraid to speak up and ask questions, now is the time to face your fears. When visiting mentor every morning to sign in, I had several questions written down, ready to ask. At first, I was hesitant to ask any question whatsoever in fear of being looked down upon as a student who is not prepared to fulfill her duty as a researcher. However, my mentor rather encouraged me to ask questions. Textbooks and articles cannot fully provide the necessary understanding to proceed onto the next step in research. But talking in person with my mentor who has all the knowledge about the research really helped me link the information I gained from reading the books and articles with the goals of my research. In the end, I found that half of what I read was not related to my research at all. Had I neglected to speak to my mentor about any questions I had, I would have been lost in a pool of new information, and would never have been able to focus on what my research was truly about.

Once I overcame the initial difficulty of starting my research, it felt like everything else fell right in place. I knew exactly what I was doing and what I was looking for. While other students at the program may have been struggling with their research, I was able to understand my research goals and achieve them before the summer program even ended. This allowed me to continue on with my research in a new direction. This time, my mentor gave me the choice to decide what I wanted to do with all my data now that the goals have been met. Hence I was able to expand my research above and beyond what was expected.

Not being chased by time was essential in *enjoying* my research. I began to develop genuine interest in astrophysics without the pressure of completing a project to submit for Intel. I even had the time to relax and rest my brain from all the work, all because I had a concrete understanding of my project from the very beginning. Within seven weeks, I grew from a girl who knew absolutely nothing about astrophysics to a girl who can now explain anything her project pertains to. So, to my fellow high school researchers, I would like to emphasize how important it is to research, not just to have a project to compete with, but to learn something new and actually enjoy and appreciate learning it. For me, becoming an Intel Semifinalist was not only a confidence booster, but a realization that I can do whatever it is if I set my heart on it. Don’t be afraid of a new challenge, even if you know nothing about it. Tackle it, and you’ll be amazed.

Research Section

In a broader sense of the world, every element that can be found in the universe is created in one way or another through nuclear reactions in stars. Stellar nucleosynthesis has been studied in the recent years to understand thermonuclear reactions in greater depth. In stars, the fusion of a heavy nucleus into a lighter one liberates kinetic energy in the process. This kinetic energy, KE, is created at the expense of mass. With the newly gained KE, consequent nuclear reactions are fueled. These nuclear reactions include proton-, alpha-, neutron-, and gamma induced reactions, depending on the stellar environment. The most important type of reaction in Novae is the hydrogen-burning proton-induced reaction – specifically, the proton capture reaction: (p, γ). Yet, the probability of such reactions is uncertain and remains a question. The uncertainty is stemmed from two reasons – first, certain elements involved in stellar nucleosynthesis do not exist on Earth because of their extremely short lifetimes. Thus, a lasting reaction target that could be studied in the laboratory cannot be created; second, the nuclear interaction is much too complex to calculate exactly and scientists are forced to simplify their models. Hence, the problem that remains at task is to establish which of the numerous nuclear reactions can be measured with the equipment available in the present state of the art, to determine how well these manmade equipments can perform and detect stellar nuclear reactions, and also, to estimate with what cross section such reactions will occur. Currently, the National Superconducting Cyclotron Laboratory (NSCL) is building ReA3, a particle re-accelerator, which will accelerate beams of unstable nuclei with energies suitable for such experiments. However, even with this facility, measurements of (p, γ) reactions will be very difficult.

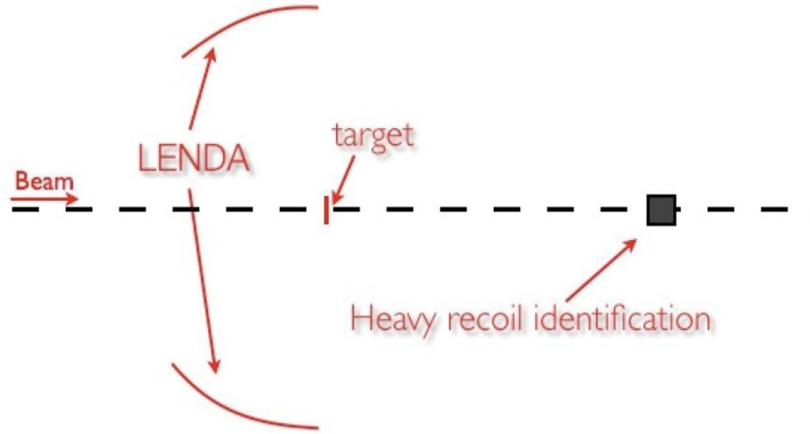
An alternative to the (p, gamma) reaction that can be studied in the laboratory is the (d, n) *direct proton-transfer reaction* performed via *inverse kinematics*. This method allows for easy capture of protons, which populate various excited energy levels of the final nucleus. Thus, in many cases, the (d, n) direct proton-transfer method is more efficient than others in determining the rates of various nuclear reactions. This type of direct proton-transfer reactions can be denoted by A(d, n)B: a deuteron, which is a hydrogen atom with mass number of 2, delivers its proton to an unstable nucleus A, releasing a new neutron and a new radioactive element B.

A complete reenactment of a stellar nucleosynthesis is impossible to be carried out to the same extent as those constantly taking place in stars. However, some important nuclear reactions can be studied at facilities such as the NSCL. It is predicted that many significant reactions will occur in light, radioactive nuclei and at relatively low stellar temperatures. Understanding the most proficient method of setting up the equipments and the conditions in which most reactions occur will provide an in-depth knowledge of the details of reactions occurring at stellar levels.

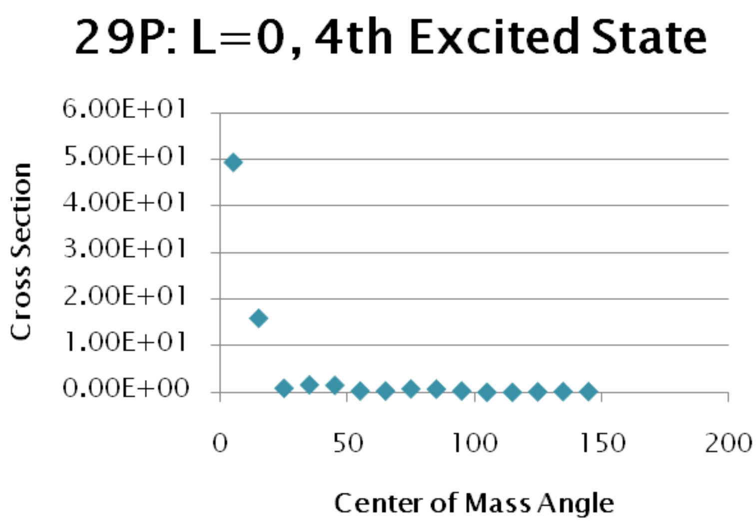
Prior to conducting any experiments, data for different radioactive elements and their reactions were collected through programs such as Q-Value calculator, Nuclear Reactions Video Project, and ENSDF database in order to precisely set up the equipments. Q-Value, measured in MeV, is the amount of energy involved in the reactions that will either be consumed or liberated due to mass differences of the nuclei. On the other hand, the Nuclear Reactions Video Project online program was used to calculate kinematics regarding final angles and energies of emitted neutrons. The ENSDF database, which represents the Evaluated Nuclear Structure Data File, was also referred to for different energy levels of the radioactive nuclei. Using these three online sources, energy level graphs were then constructed on a computational notebook as well as on Microsoft® Excel. Lastly, to find out which reactions occurred most readily, and therefore have the highest probability (or cross section) of taking place, a software known as TWOFNR was used. It coordinates cross sections with lab angles, as well as center of mass angles, based on the input data including spin and parity of every particle involved in the reaction. A glitch was found in the program, but with basic programming knowledge, TWOFNR was debugged and updated to adapt to different parameters.

Ultimately, the optimum set up of detectors and beams for the experiment were studied, which was used to provide the most accurate collection of cross sectional data. This research was primarily based on a Low Energy Neutron Detector Array (LENDA).

This picture above is an image of ½ of the full array of LENDA. LENDA measures the amount of neutrons that can be emitted at various angles during nuclear reactions. The distances at which LENDA will be placed from the actual beam of radioactive particles were determined by two equations: $\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$ and



This is the expected setup of LENDA when the actual experiment will be conducted. Though this research was mostly simulations, promising results were yielded and graphed on Excel.



Finally, the application of this research is essential. Studying the various unstable nuclear reactions will ultimately determine which reactions are feasible for the equipment available at the moment. By narrowing down the choices for the reactions that can be studied in the given environment, other researchers can focus on a more defined and reduced set of experiments. Furthermore, research on the setup of equipments with the current technology would allow for a more accurate analysis of (d, n) reactions for prospective experiments. For future researchers in the same field, this research will provide them with the optimal method of setting up the detectors at appropriate angles, distances, etc. Once all data is gathered, being able to reproduce certain radioactive nuclear reactions will introduce a new spectrum of knowledge about stars in Novae. Cross sections acquired from calculations and measurements can further help determine each reaction's role in a reaction path of a star. Understanding the reactions will in turn assist in figuring out how stars evolve.