Understanding ^{22}Na Cosmic Abundance through Measurement of the ^{22}Na(p,γ) Reaction Rate

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Abstract

^{22}Na is an elusive cosmic gamma ray emitter that should be abundant as a product of novae, but this isotope is as of yet unobserved except in the central galactic bulge. The discrepancy could be resolved through a recent measurement of ^{23}Mg structure, which discovered a level that may have significant implications on the rate for ^{22}Na destruction via the ^{22}Na(p,γ)^{23}Mg reaction. One of the main goals of this project is to perform a direct (p,γ) measurement of the new resonance using a beam of protons that will be accelerated to impinge on a ^{22}Na radioactive target. The target will be produced at TRIUMF-ISAC in Canada. We are currently in the beginning stages of setting up this experiment at CENPA.

I Introduction

The study of nucleosynthesis is one of today's most active fields of research, largely due to the availability of gamma-ray telescope data and the development of nuclear physics facilities, which can produce the short-lived nuclei that dominate the nuclear burning sequences in stars. Explosive hydrogen burning and nucleosynthesis occur in hot, dense, hydrogen-rich environments, such as novae, x-ray bursts and type II supernovae. In these conditions, a complex series of proton capture and β-decay reactions occur, through which, elements heavier than helium are created and ejected into space. In understanding the rates of various reactions, we gain insight into the process of nucleosynthesis, as well as predictions for the resulting isotopic abundances.

The nucleus ^{22}Na is particularly important in the diagnosis of classical nova outbursts. Novae are thermonuclear explosions, which occur on white dwarfs in binary systems. In a binary system, the white dwarf will steadily accrete gas from the companion star's outer atmosphere if the companion star is close enough to overflow its Roche lobe. The captured gases consist mainly of hydrogen and helium, which are compressed onto the white dwarf's surface by its intense gravity. As more material accumulates, these gases are further compressed and heated to very high temperatures. Hydrogen fusion can occur stably on the surface by way of the CNO cycle, but helium must be heated near the surface of the white dwarf to roughly 20 million Kelvin before nuclear fusion reactions can rapidly convert the helium into other heavier elements. This process liberates a large amount of energy, which blows the remaining gases away from the white dwarf's surface. Roughly 5% of the mass accreted by the white dwarf is fused to power this outburst. Recent observations of gamma rays emitted from these stellar explosions provide strong evidence for active burning, as well as constraints on astrophysical explosion models.

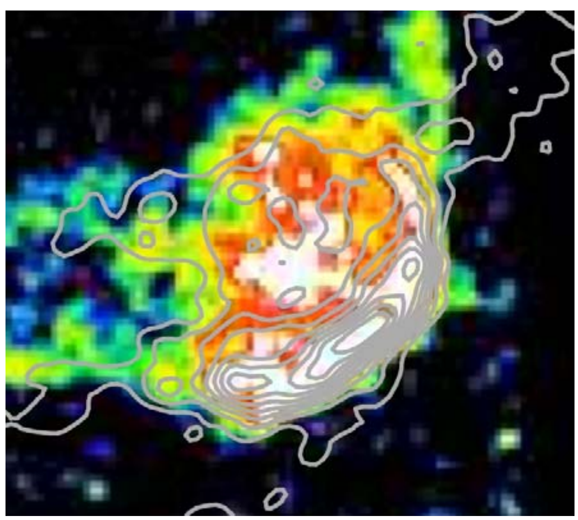

Figure 1: Chandra image of a classical nova
Credit: X-ray: S¸ölen Balman (METU, Turkey) and NASA; Radio: E. Seaquist (U Toronto)

^{22}Na is a cosmic gamma ray emitter with a relatively short half-life of 2.602 years. This radioactive isotope decays into a short-lived state of ^{22}Ne, emitting a 1.275MeV γ-ray in the process. ^{22}Na is an ideal candidate for observation by gamma-ray telescope, living long enough to be seen through the ejected debris and emitting γ-rays with enough energy to be distinguished from background radiation. With such a short half-life, ^{22}Na is spatially and temporally localized near its source. In addition, the production of ^{22}Na in novae is very sensitive to explosive conditions, making the isotope an interesting tracer. Some novae models predict that ^{22}Na should be produced prolifically in novae, but while several experimental searches for the γ-ray signature associated with ^{22}Na have been conducted, this elusive isotope has only been observed in the central galactic bulge.

To resolve the discrepancy between theory and observation, knowledge of the science behind the ^{22}Na production sequences must be advanced. Proton-capture reactions on the "seed" nuclei are responsible for the synthesis of significant amounts of the unstable nucleus ^{21}Na, which, through β decay or additional proton captures, eventually results in ^{22}Na. The $^{22}Na(p,\gamma)$ reaction rate has the largest effect on ^{22}Na production, and at novae temperatures, this reaction rate may be dominated by a single new resonance. Reducing the large uncertainties associated with the $^{22}Na(p,\gamma)$ reaction rate may help to constrain novae models and improve estimates on the amount of ^{22}Na created during novae outbursts.

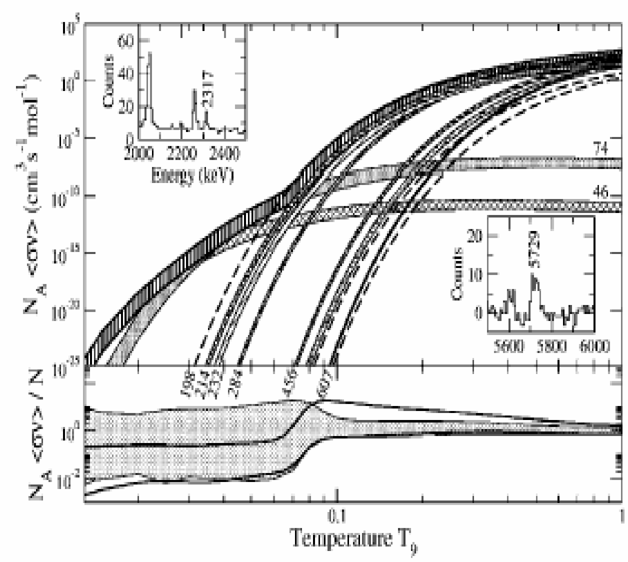

Figure 2: Contribution of individual resonances to the total reaction rate for the $^{22}Na(p,\gamma)$ reaction. The shaded region is the uncertainty in the rates; the solid lines bound the current uncertainty
Credit: Jenkins et al. 2004

The key to an analysis of the astrophysical reaction rate for the $^{22}Na(p,\gamma)$ reaction is a detailed knowledge of properties such as excitation energy, spin, and parity. Conventionally, by bombarding a specially prepared radioactive ^{22}Na target with protons, one can detect the γ-rays that follow proton capture. Using this direct approach, one can then find resonances in the reaction for different energies. A recent measurement of ^{23}Mg structure discovered a state that could have huge implications on the rate of ^{22}Na destruction via the $^{22}Na(p,\gamma)^{23}Mg$ reaction. In this process, a proton with a discrete energy interacts at resonance with ^{22}Na to produce an excited state of ^{23}Mg, which then de-excites and emits a γ-ray. The new resonance was discovered in a γ-ray spectroscopic measurement using the $^{12}C(^{12}C,n)^{23}Mg$ reaction with Gammasphere. Using mirror symmetry arguments, it was estimated that a new ^{23}Mg energy level at 7.769 MeV (with E_p=198keV) could have a resonance strength of up to 4MeV. With a strength of 4MeV, this resonance would dominate the reaction rate at novae temperatures. No direct measurement of this resonance strength has been recorded, however, and other resonances have only been measured to roughly 50% accuracy. Thus, a direct measurement of the $^{22}Na(p,\gamma)$ reaction rate, which focuses specifically on the new E_p=198keV resonance is needed.

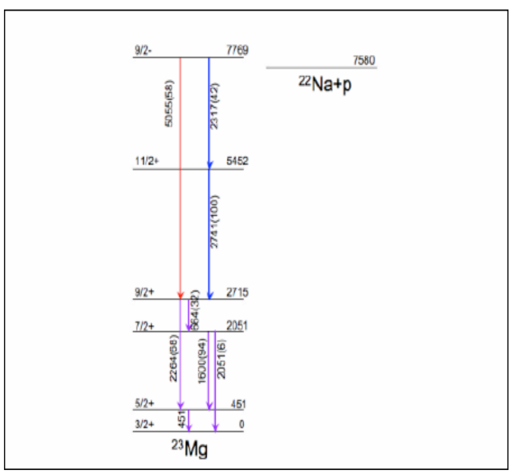

Figure 3: A proton interacts with ^{22}Na to produce an excited state of ^{23}Mg, which then de-excites and emits a γ-ray
Credit: Caggiano et al. 2005

II Experiment

We would like to perform a direct (p, γ) measurement of this new resonance, while also improving the accuracy of other resonance measurements. This experiment will consist of three phases: we will first study target implantation using stable ^{23}Na, then ^{22}Na, and finally measure the ^{22}Na(p,γ) reaction rating using ^{22}Na targets. These targets will be made at TRIUMF-ISAC at a range of thicknesses and activities, none exceeding 20mCi. To measure the reaction, we will bombard a ^{22}Na target, implanted in a Ni substrate, with protons of energies 0.2-0.6 MeV. Using a 100% Germanium detector, we will measure the resulting γ-rays. The measured γ-ray flux in conjunction with the knowledge of the γ-ray energies and branching will be used to determine the resonance strength. For the E_p=198keV resonance, the 5.055 MeV γ-ray will be used, since this γ-ray is in a clean region of the γ-ray spectrum. In previous measurements of the ^{22}Na(p,γ) reaction rate, a 5 cm-thick lead brick was placed between the target and the detector to reduce the high rate of 511keV and 1.275 MeV gamma rays emitted from the target. Using a small diameter target and rastering the proton beam over the entire area of the target, we can reduce the uncertainty regarding luminosity that are due to the uncertainties on beam spot size and target non-uniformity.

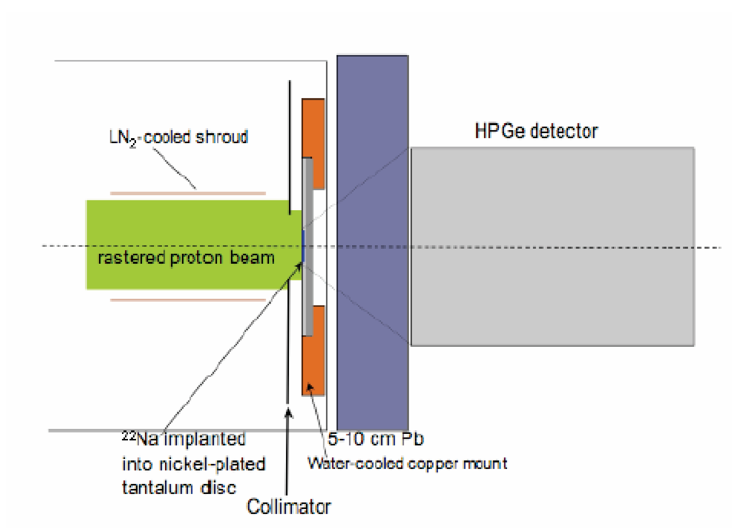

Figure 4: Proposed experimental set-up
Credit: Caggiano et al. 2005

We are currently in the early stages of setting up this experiment at CENPA, which entails dismantling the previous beam-line experiment and assembling all of the parts needed for the current project. To optimize the new set-up, we are performing yield and strain calculations, as well as studying the background radiation in the lab. In addition, using a program called Transport, we are simulating the beam profile and tuning various parameters to minimize the beam spot. We would like to identify features of our experiment that limit precision and efficiency, as well as ways in which our set-up can be improved over previous experiments.

Transport

Transport is a first and second-order matrix multiplication computer program that is intended for the design of static-magnetic beam transport systems. In Transport, a beam-line is defined as a sequence of elements, which may consist of magnets and the intervals between them, as well as specification of the input beam and special configurations of the magnets. Transport steps through the beam-line element by element, calculating the properties of the beam or other quantities where requested. In principle, Transport can search and find the first or second-order solution to any physically realizable problem. By adjusting the distances between quadrupoles and utilizing Transport's fitting capabilities, we attempted to minimize the beam spot size at the target.

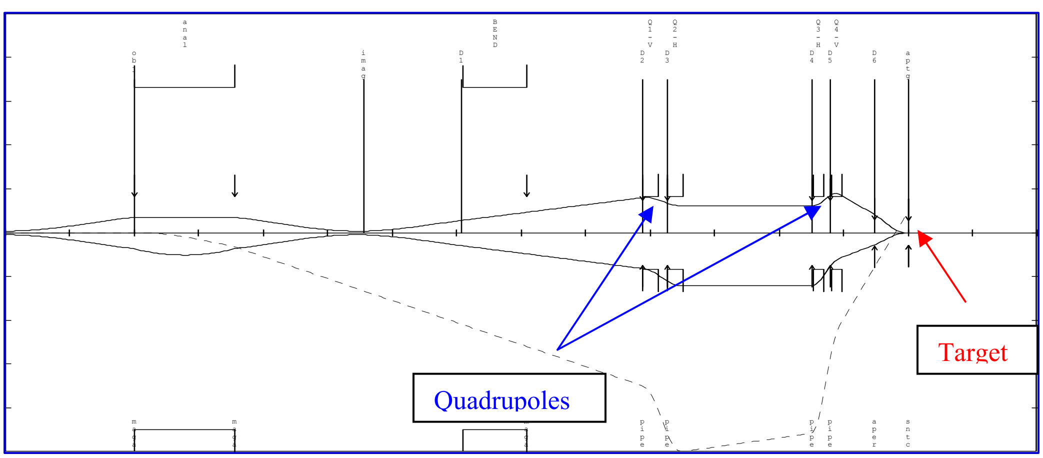

Figure 5: Typical Graphic Transport output, showing beam divergence in x and y direction along the beam-line

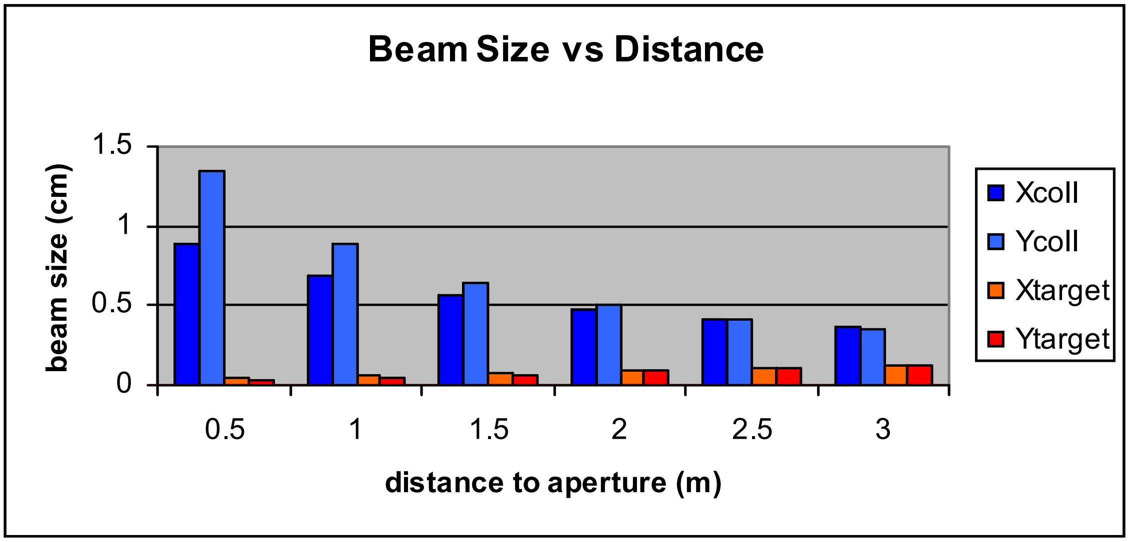

Figure 6: Graph of beam size versus distance between the second quadrupole and target; Values were obtained using Transport, optimizing focus at target for each distance

Yield Calculations

We do not understand the implantation process well enough to predict the density of ^{22}Na atoms on the target, and migration of ^{22}Na atoms can cause densities to change. By measuring yields at different beam energies, in what is sometimes called a "depth scan" we can obtain a relationship between the number of ^{22}Na nuclei and total ^{22}Na target activity. In addition, rastering can provide a uniform and known current density across the entire target, which would simplify the connection between N(^{22}Na) and yield.

To estimate the dependence of yield on target composition, we considered a beam incident on a small area of a target, such that the relative density of target atoms was constant within the range covered by the beam. Using the expression for narrow-resonance reaction yield per incident beam particle of energy E:

$$Y(E) = \frac{1}{2}\lambda^2 \frac{m_b + M_t}{M_t} \frac{\omega\gamma}{\epsilon}$$

where λ is the c.m. de Broglie wave, m_b and M_t are masses of beam and target atoms, ωγ is reaction strength, and ε is the stopping cross section per target/backing combination:

$$\epsilon = (dE/dz)/n_t$$

we were able to predict target activity as a function of proton energy. Here, $\omega\gamma=4\times10^{-3}$eV and λ can be rewritten in terms of E, with E=198keV for the resonance we are studying. Multiplying the yield by detector efficiency and the number of incident protons, we obtained an estimate of the total number of γ-rays detected per second, which could then be converted to detections per day:

$$N_d = Y(E)*efficiency*I/q_p*(86400)$$

where I=10μA is the proton beam current and the efficiency is roughly 5×10^{-4}. We predicted that roughly 50 gamma rays would be detected per day, assuming the values stated above are accurate. Using a spectrum of background radiation, we were also able to obtain approximate background counts, which we estimated to be roughly 2 to 3 per day, depending on the detector and location.

III Conclusions

Future Work

In the coming months, we hope to construct a chamber to house the target. We will also begin collaborating with TRIUMF on the production of targets in a range of thicknesses and activities. To study the implantation process, we will initially work with stable ^{23}Na and proton beams at a range of energies.

Design Issues

There are several design issues that we will need to address as this experiment progresses. Firstly, we will need an effective means of cooling the target, which will help to prevent the migration of ^{22}Na. As for ^{22}Na that does migrate off the target, we will need a way to contain this radioactivity, which can be accomplished through a LN2 trap. We would also like to monitor the migration that does occur. A good vacuum (~10^{-7} Torr) and LN2 trap to prevent carbon buildup are both critical aspects of our design. We would like to allow beam positioning and focusing on target, as well as ways to easily maneuver the radioactive target, so as to minimize exposure time. Due to the high target radioactivity, extra precautions must be taken for safety reasons. Special lead casks will need to be made to keep and transport the targets in the event that they break and release ^{22}Na. Rolling lead shields and lead gloves will be used when handling the target-containing chamber.

IV Acknowledgements

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