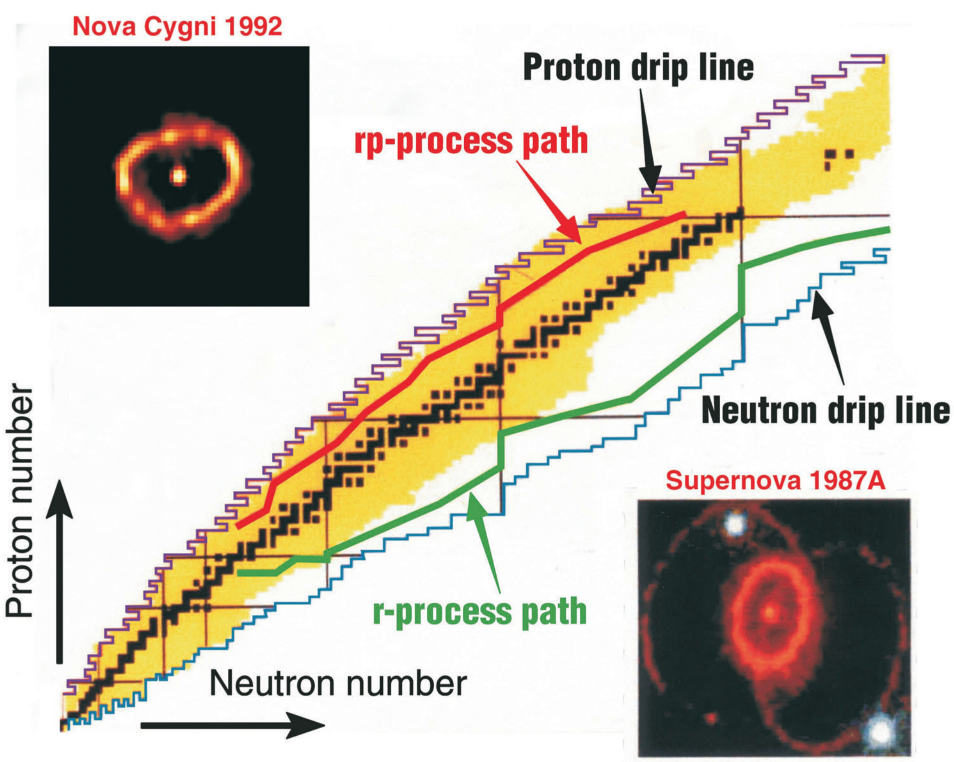
John D'Auria and Patrick Walden

NUCLEAR ASTROPHYSICS WITH DRAGON AND TUDA AT ISAC

One of the most surprising scientific revelations of the 20th century was the discovery that we are all products of matter generated from stellar cataclysms. All heavy elements such as the carbon we are made of, the oxygen we breathe, the very stuff of life, originated in nuclear cooking processes in the interior of stars. "We are" as Carl Sagan noted "made of star stuff." How did the stuff get out of the stars and into the solar nebula that became the solar system?

Some of this material is ejected into space in the death throes of stars contracting to burnt out cinders after the nuclear fires have died, the fate of many stars, including the sun. However this source cannot account for all of the abundance of the light elements such as carbon and oxygen, and it fails completely to account for the existence of the really heavy elements such as iron, gold, lead, and uranium. The difference is made up from stellar cataclysms known as nova, supernovae, and their kin which explode briefly into the brightest objects in the galaxy. Thus the composition of the earth, the rocky planets, indeed all the metallic content of the solar system came from the stuff which spilled out of stars which ripped apart their guts in explosions 4.5 billion years ago. Remnants of recent cataclysms, nova Cygni 1992 and supernova 1987a, are shown in the figure below.

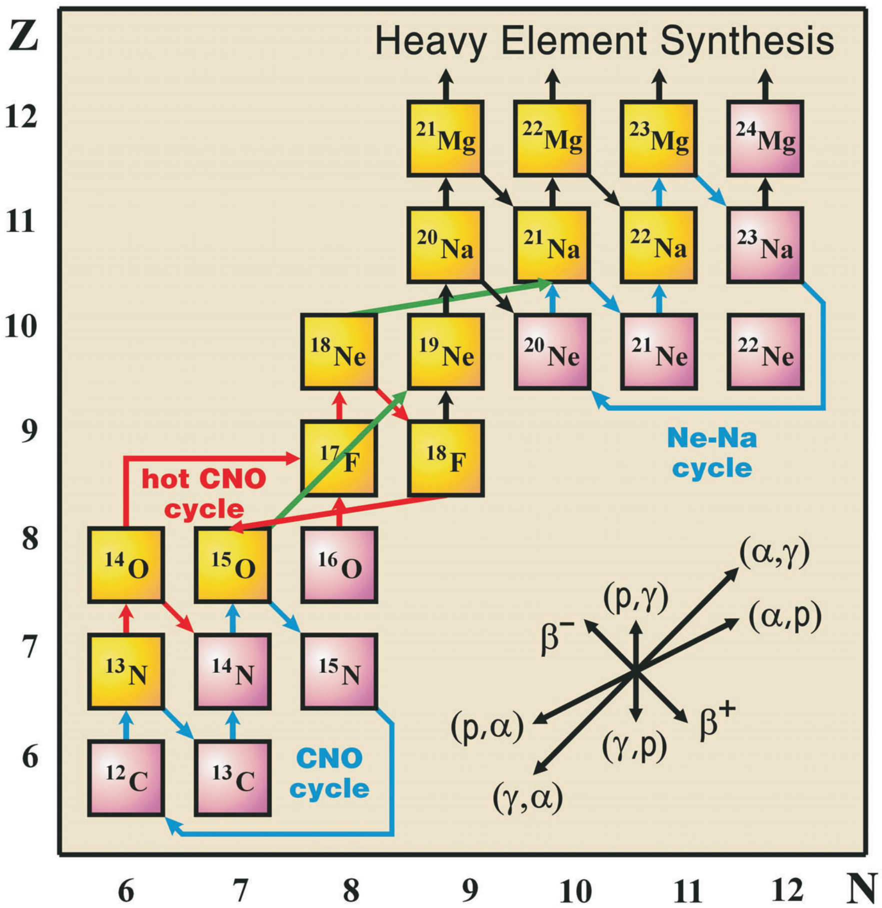
The elements are made in stellar burning by the fusion of nuclei of the lightest elements, hydrogen and helium (99% of all nuclei in the universe), into the nuclei of all heavier elements. Fusion reactions involved in normal stellar burning, like those which now occur in the sun, proceed at a slow pace, slow enough to allow any radioactive nuclei produced to decay to stable nuclei before becoming involved in further reactions. Recreating these reactions in the laboratory is a straightforward and relatively simple process in which beams of either hydrogen or helium strike targets of different stable nuclei. Hence they have been extensively studied and, as a result, are well understood. In 1983 William Fowler won the Nobel Prize in Physics for his leadership in the drive to perform such studies which have led to our understanding of stellar environments and nucleosynthesis.



The reaction paths of heavy element synthesis. The dark squares indicate the positions of the stable nuclei, the yellow the known unstable nuclei. The drip lines enclose the region beyond which it is thought that no nuclei can exist. More details are in the text.

During explosive events, however, things happen so quickly that the radioactive nuclei do not have time to decay. Instead these short-lived exotics are involved in subsequent nuclear reactions leading to a chain reaction in which heavier and heavier nuclei are created. Two nucleosynthesis processes produce these explosive chain reactions, and both are illustrated in the adjacent figure.

The r-process takes place inside supernovae, a catastrophic explosion which is the fate of stars that are heavier than 8 solar masses. When the nuclear fuel in the stellar core is exhausted, gravity is strong enough to cause the core to collapse which generates a flood of neutrons. This touches off the r-process which is a series of rapid neutron captures in which seed nuclei like that of iron are pummelled with the neutrons from the collapse. Heavier nuclei are rapidly built by successive neutron captures and ultra fast beta decays (a beta decay is the emission of an electron leading to a change in the element) via the reaction route indicated by the green line in the figure on the previous page. Once the process has run its course the nuclei have a chance to decay into normal stable heavy elements.



:The CNO, hot CNO, and NeNa cycles of helium synthesis from hydrogen. These cycles are explained in the text. The red boxes indicate the stable nuclei, and the yellow the unstable ones. Green arrows indicate reactions thought to initiate the runaway explosive rp-process. Directional arrows indicate the type of nuclear reaction occurring between the boxes. The symbol (x,y) means particle x hit the nucleus and particle y was ejected. Other symbols are p:proton, α:^{4}He, and γ:gamma. Beta decays, indicated with a β, are ejections of electrons, positive and negative, which turn protons into neutrons and vice versa. ^{n}XX are symbols for the elements where n is the total number of neutrons and protons in the nucleus. The axes indicate the number of protons Z, and the number of neutrons N in each nucleus. Note that the type of element depends on Z only.

The rp-process occurs on the surface of a burnt out star known as a white dwarf. This type of star has about the mass of our sun packed into roughly the volume of the earth. All stars less than 8 solar masses are believed to eventually end up as white dwarfs, a fate that awaits our sun. As can be imagined the gravitational field around the star is very intense. In many cases the white dwarf has a red giant companion star. The red giant's atmosphere is quite extended, vacuous and composed mostly of hydrogen. Part of this atmosphere comes under the intense gravitation attraction of the white dwarf and is sucked onto the surface of the dwarf where it is compressed to unimaginable pressures and subjected to unbelievable temperatures. This hydrogen forms a dense atmosphere around the star and mixes with the dwarf's surface material which is mostly carbon and oxygen. Eventually a flash point is reached and the hydrogen explosively reacts with the carbon and oxygen. Heavy nuclei are rapidly built up along the red path in the figure on page 13, in a proton version of the r-process. The atmosphere of the star is blown off into space in a violent luminous cataclysm known as a nova. Unlike a supernova, a nova leaves the original star intact and the process can be repeated. The light output of a nova is about 10,000 times less intense than that of a supernova.

Theoretical studies of explosive events have reached the stage where sophisticated and time-consuming computer models can follow the evolution of these stellar cataclysms up to and beyond the resultant explosion. However, for the results of such complex and intensive calculations to have any validity they must be based upon experimental data for a number of key reactions. Without this information, these programs may work correctly, but still produce inaccurate results. (Garbage in - garbage out!) For example, using our current experimental knowledge, these models have predicted that nova explosions should result in the production of certain easily identifiable gamma rays (high energy photons or particles of light). However, not all of these gamma rays have been detected by orbiting galactic gamma-ray observatories. This is a clear indication that our understanding is far from complete and that the models require more detailed and accurate information on the key reactions.

These key reactions involving radioactive nuclei thus play an important role in the ignition of nova and supernova explosions. Owing to the extreme difficulty of creating and using the short-lived exotic nuclei involved, the properties and probabilities of the reactions have yet to be measured.

R-process reactions are currently impossible to measure experimentally. Both the nuclei and the neutrons involved in the process are unstable. There is no way in the laboratory to create an unstable nucleus and an unstable neutron and bring them together promptly enough to react before they decay. Conditions on earth cannot be made to duplicate those of a supernova interior. The r-process can only be studied using indirect methods.

On the other hand ISAC, with its ability to produce beams of unstable nuclei, allows us to study the rp-process. The targets are now gaseous hydrogen or helium which are stable and the beams are unstable, short-lived nuclei, as opposed to a beam of hydrogen or helium striking a stable target. This technique will allow us to measure the rates of reactions believed to occur in explosive events. Fowler recognized the need for this in his Nobel Prize lecture: "It is my view that continued development and application of radioactive ion-beam techniques could bring the most exciting results in laboratory Nuclear Astrophysics in the next decade".

ISAC's radioactive beams in combination with new experimental facilities such as DRAGON and TUDA, will allow us to reach the exciting results that Fowler alluded to. Compared to present day major high-energy accelerator laboratories located around the world, ISAC is unique as an excellent low-energy facility, designed to search for the trigger that makes the stardust we are made of.

DRAGON

(*Detector of Recoils And Gammas Of Nuclear Reactions*)

THE FACILITY

The goal of the DRAGON facility is to study the probability of reactions involving the capture of hydrogen or helium by a short-lived exotic isotope which result in the emission of electromagnetic radiation only. In stellar interiors, these radiative capture reactions occur at low rates because the energies of the two participants are low, making it difficult for them to overcome their electrical repulsion and thus to get close enough to fuse. In the laboratory these reactions can only be studied by using a beam of the radioactive isotope striking a gaseous target of hydrogen or helium. To measure the rate of the reaction, the product must be efficiently and cleanly separated from the relatively more intense incident beam and related background sources.

The illustration on page 16 is an artist's conception of the 20 meter long DRAGON facility located in the ISAC experimental hall. At the front end we have a windowless gas target into which hydrogen or helium flows. Many high-speed vacuum pumps are needed to maintain the required low pressure on either side of the high pressure region containing target gas. At the centre of the gas target the pressure is almost 10,000,000 times that a few meters on either side of it, despite the fact that the gas is unconfined. The radioactive beam from ISAC passes through the gas target, striking and occasionally fusing with atoms of the gas. Thirty bismuth germinate (BGO) gamma-ray detectors surrounding the gas target are used to detect the prompt gamma radiation from the nuclear fusions that do occur.

Nuclei formed by the radiative capture reaction continue moving in the forward direction along with the incident beam. Both have about the same momentum (mass times velocity) and both, because of atomic collisions with the gas target, are now in several different charge states. These two facts, similar momenta and multiple charge states, make separation of the reaction product from the incident beam very difficult, especially when it is realized that the nuclei in the transmitted incident beam are about a million billion times more numerous than the reacion product nuclei. A complicated system of bending magnets, focusing magnets and electrostatic deflectors is required to carry out this separation. The separation system is followed by a series of nuclear detection systems to count and identify the reaction product.

The DRAGON facility was built over a three-year period using funds from both TRIUMF and NSERC. With this facility, we now have the ability to study a number of nuclear reactions involving short-lived radioactive reactants. These reactions, some of which are shown on page 14, are important to our understanding of the mechanism of nova explosions.

As with any new facility, the first study will set the format for the use of such a complex facility over a long period of time.

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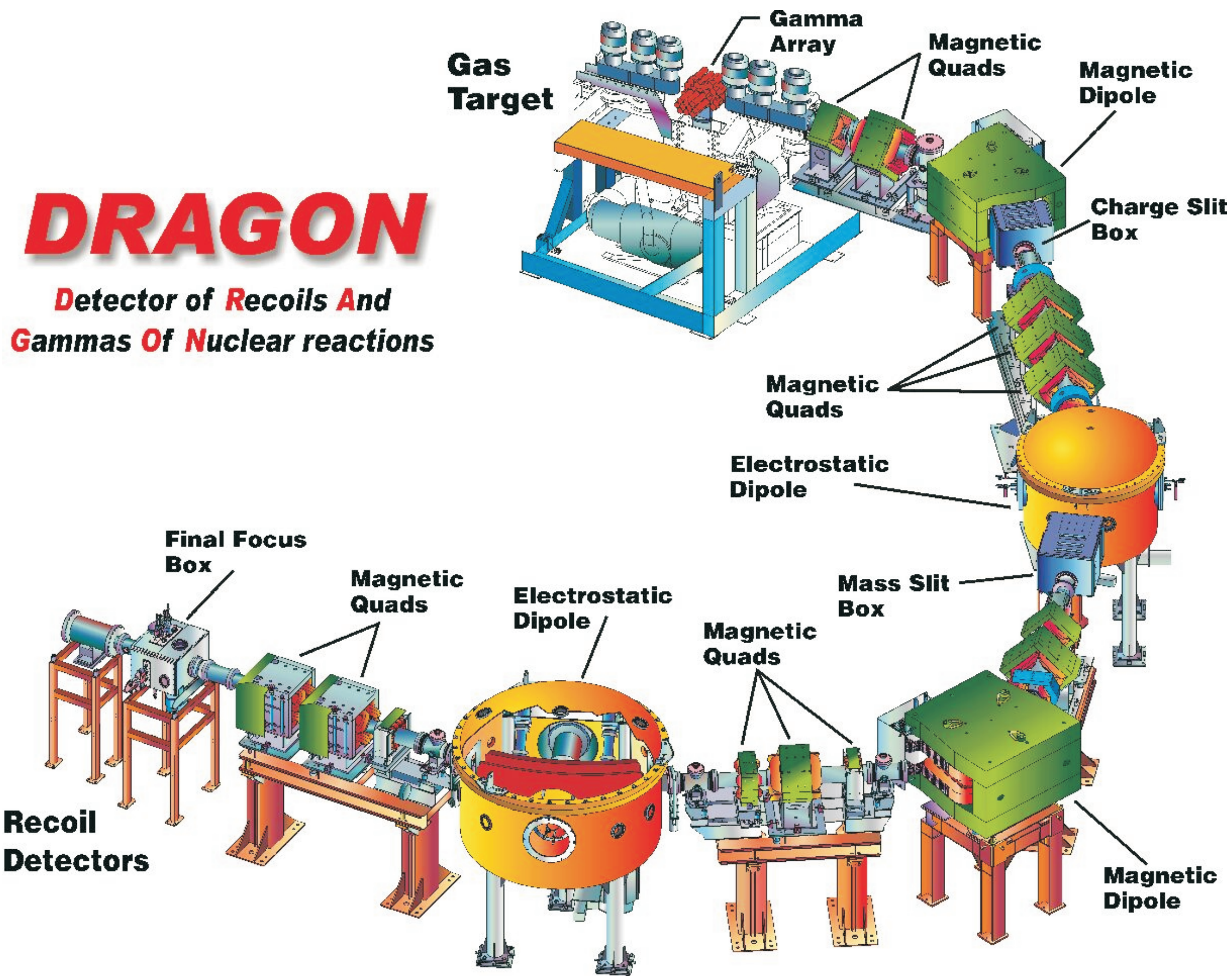
THE FIRST STUDY

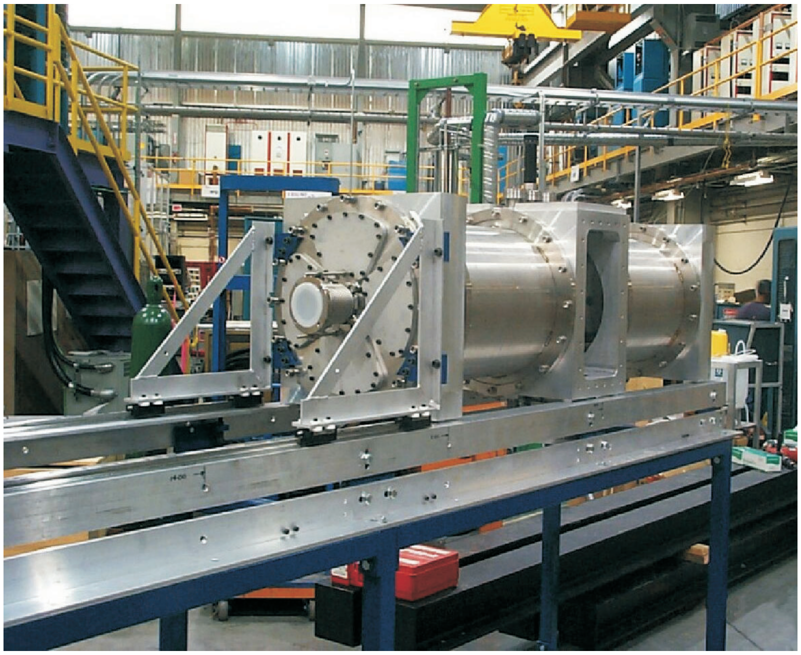
It is speculated that the NeNa cycle of nuclear reactions plays an important role in certain Nova explosions. Through a series of radiative proton capture reactions and beta decays neon is converted into the unstable isotope, ^{22}Na which decays with a lifetime of 3.8 years to the stable isotope ^{22}Ne. Current models predict that after a nova explosion the ^{22}Na will decay with the emission of a characteristic 1.3 MeV gamma ray. The ^{22}Ne product of this decay is not involved in the rp process, hence is not linked to other nuclei in the diagram on page 14. Sensitive gamma-ray telescopes should be able to observe this gamma-ray. While other gammas have been observed, this one has not. Hence our input to the models are most likely incorrect. One of the important reactions in the production of ^{22}Na during a Nova explosion is the fusion of protons with the unstable isotope, ^{21}Na producing ^{22}Mg and a gamma ray. The rate of this reaction as a function of temperature has never been measured. This is the first experiment planned for the new DRAGON facility. If the rate found is considerably different than currently assumed, we would have a reason for the lack of the 1.3 MeV gamma rays and a better understanding of what occurs during explosive events.

A beam of ^{21}Na ions (lifetime of 22.5 s) will be generated by bombarding a thick target of silicon carbide with 500 MeV protons from the TRIUMF cyclotron. The resulting ^{21}Na are ionized using a hot surface ion source, then extracted and accelerated in the new ISAC linear accelerator. This beam will then enter the DRAGON apparatus, striking and reacting with a hydrogen gas target. All of the reaction products move in the forward direction and are captured by the electromagnetic entrance of the DRAGON. There they will be separated from the much more numerous, but similar,



A drawing of the DRAGON facility

beam particles. The fusion product from the reaction of interest will be detected at the end of DRAGON using sensitive, thin-window gas counters. Since the energy range of interest in stellar interiors for these studies is quite low the reaction products have energies that make them difficult to distinguish from the the incident beam.



General view of the TUDA target and detector system.

According to estimates based upon our understanding of the nuclear structure of the species involved in the study, we expect a counting rate of the order of a few counts per hour. Such studies usually take many days to complete to the required degree of accuracy (about 15%) due to the low reaction rates. An important aspect of such studies will involve a good understanding of how this complex facility, DRAGON, really does perform. This will be obtained over a period of months using beams of stable heavy ions to properly commission and calibrate DRAGON before the experiment begins.

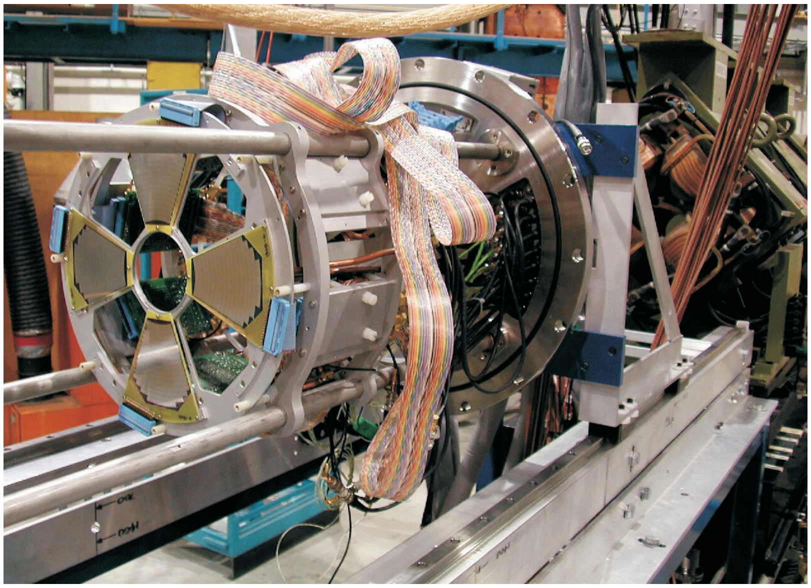
TUDA

(TRIUMF U.K. Detector Array)

The two new facilities, DRAGON and TUDA, are complementary. DRAGON is designed for radiative capture studies where uncharged gamma rays are emitted. TUDA is used for the study of nuclear reactions in which all outgoing particles have an electric charge.

The ISAC TUDA facility is an extremely flexible nuclear physics apparatus which can be modified (internally) to meet the needs of a variety of experiments. These are scattering experiments in which radioactive ion beams from ISAC are focussed onto targets inside the chamber and products from nuclear reactions between the ion beam and the target material are detected downstream in an array of silicon strip detectors.

The chamber itself is divided into three rectangular sections separated by two cylindrical sections. The cylindrical sections provide drift space for the beam and nuclear reaction products. The rectangular sections house the internal apparatus. The beam entrance section houses a collimator wheel, the middle section holds the target, and the end section houses the downstream flange to which the detectors are mounted. In the picture below the downstream flange has been pulled back from the chamber to expose a detector pancake and its mounting. As shown, the detector (the flat plate with the cross) is mounted on long forks attached to the downstream flange. The structure behind houses the electronics. The detector shown is composed of 8 pie shaped segments (only 4 are installed in the picture) that each have 16 individual concentric silicon strip detectors, 0.3 mm thick. Thus each detector pancake has 128 individual independent chan-



The TUDA detector system.

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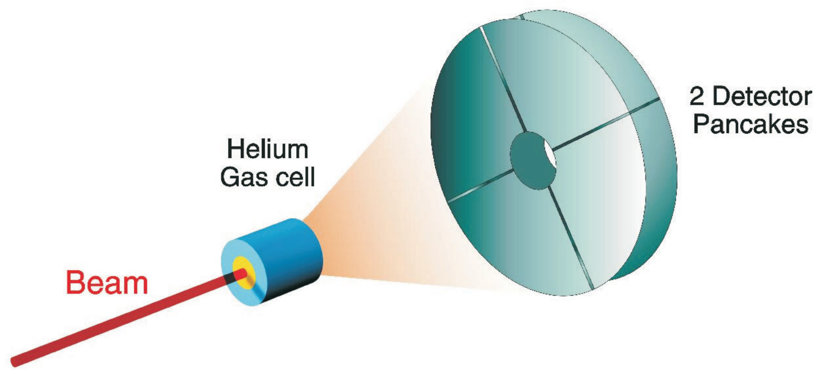


A schematic of TUDA showing the relationship between the target gas cell and the detector system for the ^{15}O reaction study.

nels. When one of the individual strip detectors detects a particle not only is the energy measured, but also the position is determined. The hole in the centre of the array allows the unscattered beam to pass through. It is possible to stack several detector pancakes together and assemble TUDA experiments in a variety of configurations depending on the reaction being studied.

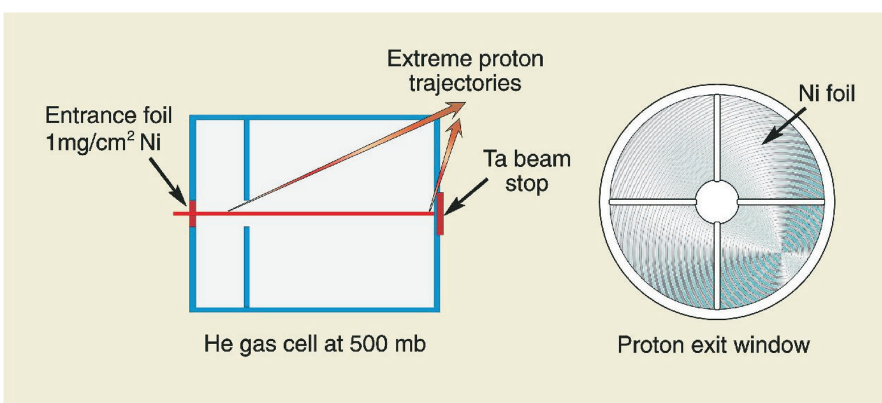
One reaction that will be investigated is a possible trigger for the rp-process. The figure on page 14 shows the nuclear reaction processes that take place on the surface layer of a proto-nova. One process, called the CNO cycle (blue arrows), converts hydrogen nuclei (protons) into helium nuclei (alpha particles or ^{4}He) with a subsequent emission of energy. Carbon, Nitrogen, Oxygen (hence the name CNO) and other nuclei are used as catalysts for this conversion and are not consumed. This cycle also goes on in the sun and is the source for a small fraction of the sun's energy.

When the density and temperature are high enough (T=0.2-0.4 billion degrees) branches of the CNO cycle (the Hot CNO cycle, red arrows) are initiated where unstable nuclei (yellow boxes) are involved because they successively capture protons and alpha particles before they have a chance to decay. Two such nuclei are ^{15}O and ^{18}Ne with lifetimes of 176and 2.41 seconds, respectively. At the flash point of a nova, it is thought that alpha particle captures (thick green arrows) on these two nuclei will create ^{19}Ne and ^{21}Na nuclei. Both these unstable nuclei are seed nuclei for the runaway rp-process (black arrows) and explosive heavy element nucleosynthesis leading to a nova explosion

The ^{15}O reaction involves a gamma emission and, as such, is part of the DRAGON experimental program. The ^{18}Ne reaction has two charged particles in its final state, a proton and a ^{21}Na nucleus which can be studied with TUDA. The setup to study this reaction is shown in the adjacent figure. A beam of ^{18}Ne (2.41 seconds is lots of time to create a ^{18}Ne and transport it to TUDA) hits a helium gas target (alpha particles). The ^{18}Ne captures an alpha and spits out a ^{21}Na and a proton. The ^{21}Na does not get out of the target but the proton has enough energy to reach the detectors. To eliminate background, the helium gas cell (see the figure below) has been designed with baffles such that protons from beam interactions in the nickel entrance foil cannot reach the detectors. Likewise to prevent background from any exit foil, the beam will be stopped in a tantalum plug. The plug is thick enough to prevent any charged particle from escaping. The protons produced by the ^{18}Ne reactions with the helium can reach the detectors (see arrows) through the thin exit nickel foils.

Reactions rates for this process will be measured at a variety of beam energies. These rates will be a crucial piece of information in modelling the rp-process and heavy element synthesis. It is only through a detailed understanding of this reaction and others that we can start to understand how stars explode.

John D'Auria is Professor of Chemistry at Simon Fraser University. Patrick Walden is a Research Scientist at TRIUMF.



Details of the TUDA target gas cell. The radioactive beam enters through a thin foil and is stopped by the tantalum disk. Charged particles from reactions in the cell exit through a thin nickel foil.