Studies of Elemental Synthesis in Exploding Stars Using DRAGON and TUDA with Radioactive Beams at ISAC

Introduction

One of the most surprising scientific revelations of the 20th century was the discovery that we are all products of matter processed in stars, or as Willi Fowler used to say, "We are all nuclear debris." All heavy elements such as carbon and oxygen originated in nuclear cooking processes in the interior of stars. Some of this material is ejected into space in the death throes of stars contracting to white dwarfs after the nuclear fires have died—the fate of many stars, including the sun. However, this source cannot account for the abundance of light elements and it completely fails for the many elements heavier than iron, such as gold and uranium. The difference is made up of stellar cataclysms such as supernovae and novae. An excellent general description of such events can be found in the article by M. Aliotta [1]. Elements are made in stellar burning by the fusion of nuclei of the lightest elements, hydrogen and helium, into the nuclei of all heavier elements. Fusion reactions in normal burning proceed at a slow pace. The ability to recreate these reactions in the laboratory have been extensively studied using beams of hydrogen and helium striking targets of different stable nuclei. In exploding stars the stellar burning process is much more rapid (seconds as compared to billions of years) and short-lived radioactive nuclei are involved. Until recently the technology has not been available to obtain required information on the rates of reactions involving such short-lived species, with the exception of the first measurement performed at the Louvain-la-Neuve facility some years ago [2]. With the advent of an increasing number of high intensity radioactive beams facilities, combined with the required experimental facilities, such measurements can now be performed more readily.

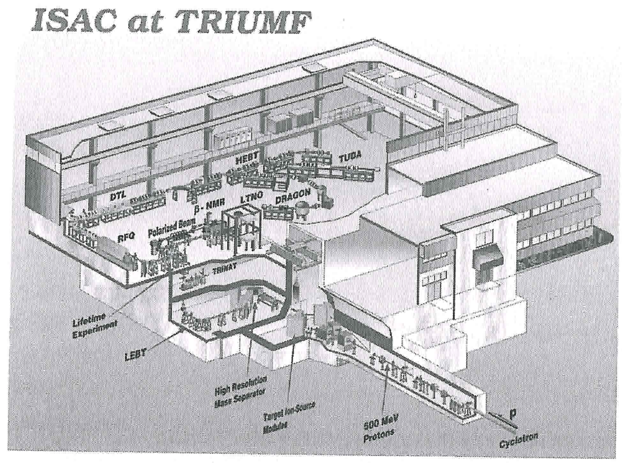

Figure 1. *The ISAC Radioactive Beams Facility at TRIUMF.*

The DRAGON Facility

The new DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) facility is located at the ISAC Radioactive Beams facility [3] in Vancouver, Canada (Figure 1).

The goal of the DRAGON experimental program is to study the probability of reactions involving the capture of hydrogen or helium by a short lived exotic isotope, which results in the emission of electromagnetic radiation only. 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 much more intense incident beam and related background sources. This is done using the DRAGON recoil separator. The rate is obtained from a determination of the absolute yield of the product as a function of beam flux.

Figure 2 is an artist's conception of the 21 meter long DRAGON facility located in the ISAC experimental hall (Figure 3). At the front end there is a recirculating, windowless gas target in which hydrogen or helium gas flows. Many high-speed vacuum pumps are needed to maintain the required low pressure on either side of the high pressure region (~4 Torr) containing target gas. At the centre of the gas target the pressure is almost 10^7 times more than a few meters on either side of it despite the fact that the gas is unconfined. The radioactive beam from

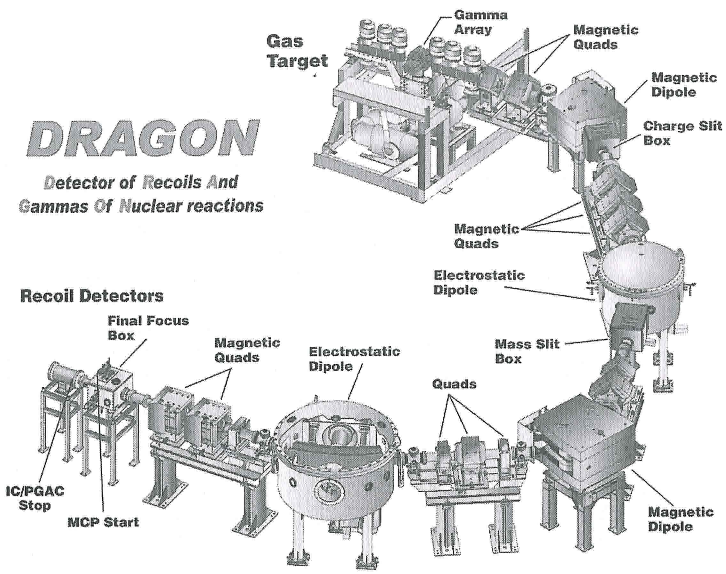

Figure 2. *Artist's conception of the DRAGON Facility*

ISAC passes through the gas target, striking and occasionally fusing with atoms of the gas. 30 bismuth germinate (BGO) γ-ray detectors surrounding the gas target are used to detect the prompt γ-radiation from the nuclear fusions. Nuclei, formed by the radiative capture reaction, continue in a forward direction along with the incident beam. Both have about the same momentum and because of atomic collisions with the gas target are now in several different charge states. These two facts make separation of the reaction product from the incident beam very difficult, as the transmitted incident beam is about $10^{12} - 10^{15}$ times more numerous than the reaction product nuclei. Taking advantage of the small energy difference between product and beam, a complicated system of bending magnets, focusing magnets, and electrostatic dipoles is used to carry out this separation. A series of nuclear detection systems at the final focus is used to identify and count the reaction product.

THE FIRST STUDY: $^{1}H(^{21}Na,^{22}Mg)\gamma$

The radioisotope, ^{22}Na exhibits a lifetime of 3.8 years and emits a γ-ray of 1.27 MeV. Figure 4 displays the NeNa reaction network cycle that occurs in a nova explosion and where ^{22}Na is a possible product. It has been predicted, based upon the present understanding of a nova explosion, that the presence of ^{22}Na through its gamma emission should be observed using γ-ray satellite observatories such as INTEGRAL, but it has not yet been seen.

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

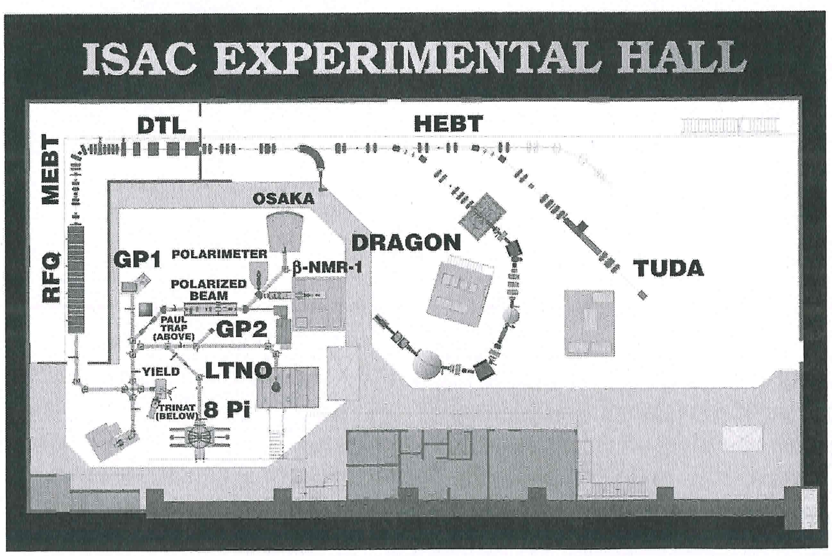

Figure 3. *The ISAC Hall showing the various facilities.*

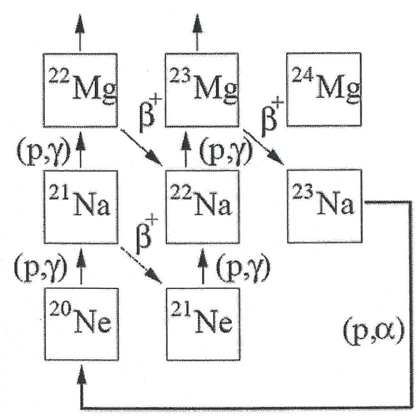

Figure 4. *The combined hot and cold NeNa reaction network cycles.*

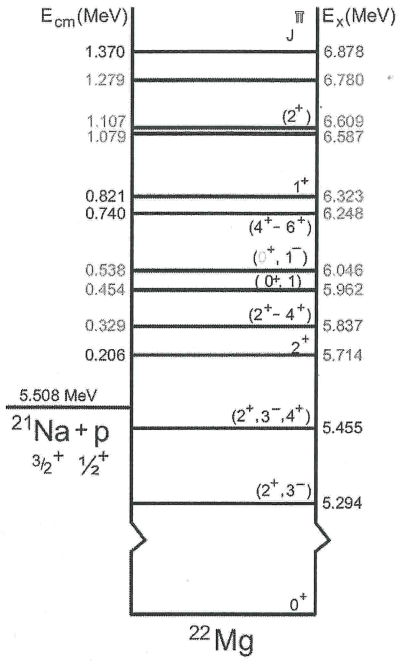

Figure 5. *Levels of ^{22}Mg close to and above the proton threshold.*

^{22}Mg and a γ-ray.

This reaction clearly plays an important role but its rate as a function of temperature has not been measured. This became the first experiment performed using DRAGON. A beam of ^{21}Na ions (lifetime of 32.4 s) was generated using the ISOL technique by bombarding a thick target of silicon carbide with 500 MeV protons from the TRIUMF cyclotron. The resulting ^{21}Na were ionized using a hot surface ion source, then extracted, mass analyzed, and accelerated (0.15 – 1.5 MeV/u) in the ISAC1 linear accelerator (Figure 3). This beam then entered DRAGON, striking and reacting with the hydrogen gas target.

Figure 5 displays the levels of ^{22}Mg above the proton threshold (4). A novae explosion is believed to exhibit a temperature of the order of 0.4 GK which corresponds to an energy of about 150 – 200 keV above the proton threshold. The state at an excitation energy of 5.714 MeV (resonance energy of 0.206 MeV) is believed to play the dominant role in a radiative proton capture on ^{21}Na in a nova explosion. To measure the resonance strength of this level, ^{21}Na beam energies of the order of 220 keV/u were employed.

Currents of ^{21}Na at the DRAGON target in this experiment were as high as 1 x 10^9 s^{-1}. At the center of the windowless, recirculating gas target system is a gas cell of 9 cm in length with a 6 mm entrance and an 8 mm exit collimator (both collimators tilted at 30°) that allows passage of the recoil nuclei within an opening angle of 20 mrad. The target pressure is typically between 4.5 T and 7.7 T monitored by a capacitance manometer. A silicon detector is positioned 30° off the beam axis to record elastically scattered protons for the normalization of beam currents. The beam flux is also monitored using an external beta detection system after the first electrostatic dipole (separates beam from recoils) to measure the radioactivity from the stopped, separated beam.

The array of 30 BGO detectors (5 cm x 15 cm, hexagonally shaped) surrounds the target cell covering a solid angle of almost 4π for γ-rays produced at the center of the target. The segmentation of the BGO detector array allows an approximate reconstruction of the original position of γ-rays

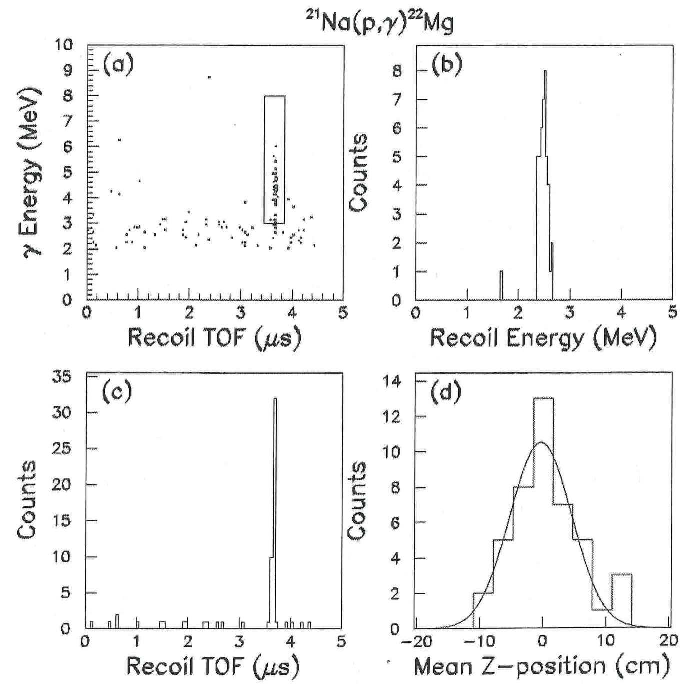

Figure 6. *Spectra when using a ^{21}Na beam energy of 220keV/u showing evidence of a resonance. (a) gamma energy vs. time-of-flight distribution through the separator; (b) gated recoil events in the DSSSD; (c) TOF projection of panel (a); (d) Hits of (-rays onto the BGO array as a function of the (z) position in the gas target with the center at z = 0.*

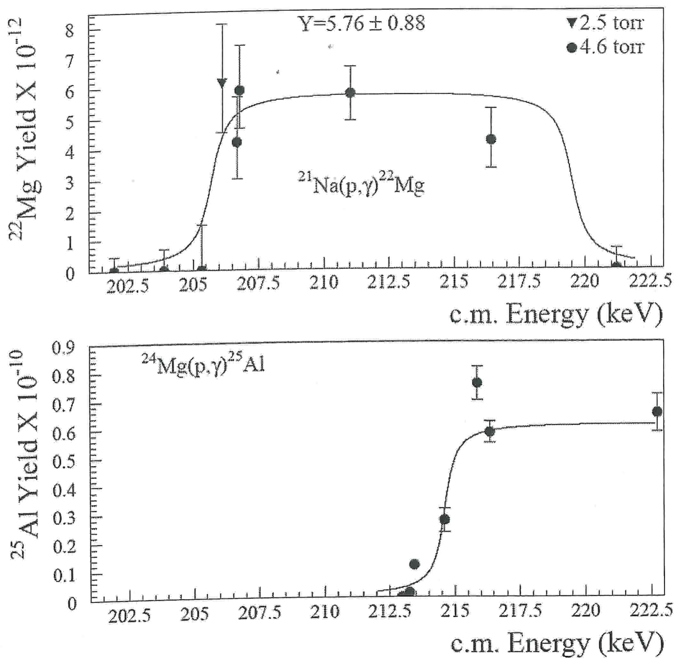

Figure 7. *(a) Excitation function of the p(^{21}Na,γ)^{22}Mg in the vicinity of the E_{cm} = 206 keV resonance. (b) In comparison, the excitation function for a stable beam ^{24}Mg(p,γ)^{25}Al reaction with a similar resonance.*

produced at different locations in the gas target. In the course of the experiment, a high γ-flux of 511 keV γ-rays from the decay of deposited ^{21}Na was observed. Therefore, a first-hit threshold has been set for a 2 MeV γ-energy and a subsequent (multiple) hit threshold of 1 MeV. γ-events above these thresholds that are scattered into multiple detectors can be reconstructed from this information.

Experimental Results

The expected and observed counting rate was of the order of a few counts per hour for the resonance of interest (206 keV). Data are displayed in Figure 6 obtained over a period of weeks at the ISAC facility. These represent a time coincidence signal between the γ-ray detector array and a double-sided Si strip detector (DSSSD) located at the focal plane of DRAGON, detecting the separated recoiling reaction heavy ion. Clearly there is a strong correlation displayed in Figure 6a with a time of flight of about 3.5 μs—the transit time passing through DRAGON. Figure 6d displays the transverse coincident γ-ray activity in the BGO array, indicating the resonance occurring in the center of the gas target.

The excitation function of the radiative proton capture reaction for the resonance of interest is displayed in Figure 7. The energy of the beam (on the x-axis) was measured using the first dipole magnet of DRAGON. The magnetic field was measured using an NMR-based probe and calibrated using known resonances from stable beam reactions. The observed resonance energy (Figure 7a) gave an energy different than that in the literature. The excitation function of Figure 7b shows a measurement for a resonance of similar and well-known energy and for which we determined the correct value with our approach. It now appears that the mass of ^{22}Mg presented in the literature was inaccurate by about 6 keV.

Using the thick target yield point at the center of the excitation function (Figure 7), the rate of the reaction was deduced. This value is different than previous theoretical estimates. Incorporating this into an elaborate code of a true stellar nova explosion indicted that the amount of ^{22}Na left at the completion of a nova is much less, as there is more ^{22}Na produced during the explosion, which then reacts away during the explosion itself. More complete information is found elsewhere (4). Reaction rates involving additional levels of ^{22}Mg were also been measured but these are of greater interest for X-Ray bursts.

TUDA

A second facilty operating at ISAC for studies of nuclear astrophysics is the TUDA (TRIUMF UK Detector Array) facility. While DRAGON is designed for radiative capture studies, TUDA is used for reactions involving particle emissions. The ISAC TUDA facility is a very flexible apparatus that can be modified to meet the needs of a variety of nuclear science experiments. These are scattering experiments where ion beams from ISAC are focused on targets inside the chamber and products from nuclear reactions between the ion beam and the target material are detected downstream or upstream in an array of silicon strip detectors (LEDA). The beam entrance section houses a collimator wheel, the middle section

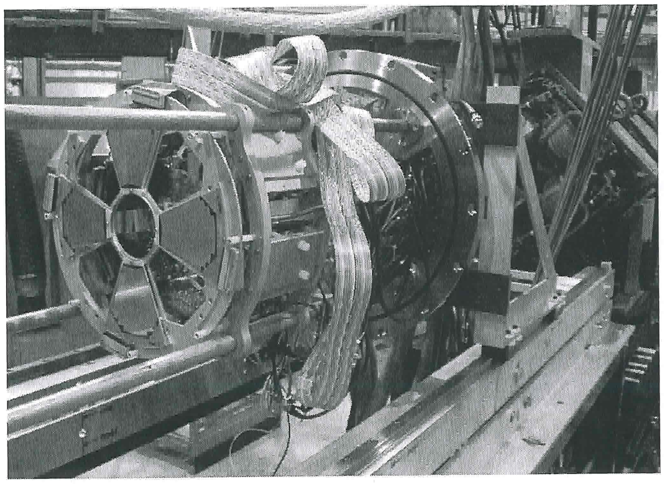

Figure 8. *General view of the TUDA detector system.*

holds the target, and the end section houses the downstream flange to which the detectors are mounted. In Figure 8, the downstream flange has been pulled back from the chamber to expose four segments of a LEDA and its mounting. As shown, the LEDA detector (the flat plate with the cross) is mounted on long forks attached to the downstream flange. The structure behind the LEDA detector houses the electronics. The detector is composed of pie-shaped segments that are divided into 16 individual concentric silicon strip detectors, 0.3 mm thick. Each detector has eight segments, i.e., up to 128 individual independent channels. 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.

At TUDA an elastic scattering experiment of radioactive ^{21}Na ions on a hydrogen [$(-CH_2)_n$] target has been performed for energies of 0.45–1.4 MeV, a study complementary to the radiative capture reaction $^{21}Na(p,\gamma)^{22}Mg$. As for DRAGON, the ^{21}Na was produced from SiC at the ISAC production target. The total ^{21}Na current was limited to $5x10^7$ $^{21}Na\ s^{-1}$ to avoid high dead times in the data acquisition system as well as to prevent rapid degradation of the $(CH2)_n$ targets. With thick targets a complete coverage of the excitation function was obtained by appropriately stepping the beam energy, while thin targets were used to investigate selected energy regions in more detail.

The TUDA facility was configured for this experiment using two LEDA arrays with 192 channels in total, and covering angles from 4.5° to 12° and 14° to 33°, respectively. One detector was positioned 20 cm downstream of the target, while the other detector was positioned 62.8 cm downstream. From the timing clock of the linear accelerator system a signal of 86 ns interval is received and used in the timing of TDC channels. This interval corresponds to the ^{21}Na beam bunch separation received from the DTL. Typical bunch widths were less than 1 ns (FWHM). For all data resulting from beams scattered at the target, a clear correlation between timing and energy is observed, while signals from the β-decay of deposited beam particles are uncorrelated.

Recoil protons emanating from the

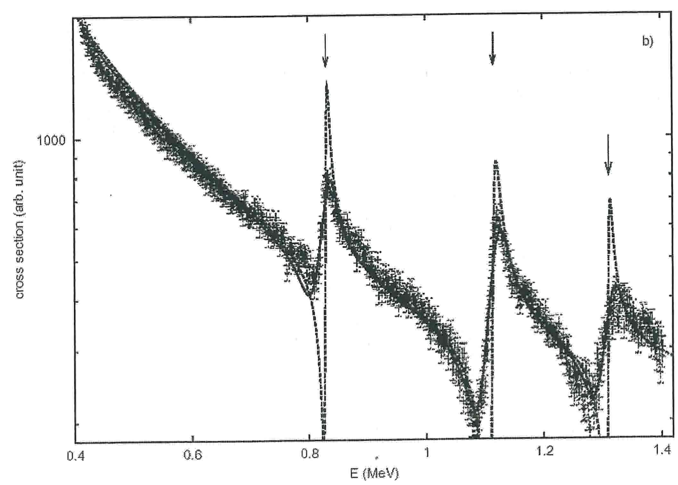

Figure 9. *Excitation function from thick target data derived by summing and combining the recoil proton spectra from all detector elements at 4.7° (lab). The cross-section (y-axis) is in arbitrary units. The figure shows the data, as well as the convoluted and calculated (dashed) fits. Positions of states from the fit are marked by arrows.*

$(CH2)_n$ target were observed as the primary signal. Their energy distribution in the recoil peak directly reflects the excitation function corresponding to the beam energy loss in the target. Runs at different energies that overlap in the excitation function range were combined to yield the composite excitation function. Figure 9 shows the composite excitation function derived from several thick target measurements using eight detector elements at 4.7° (lab).

Four prominent states of ^{22}Mg have been identified in the elastic scattering of radioactive ^{21}Na ions on hydrogen and four additional states have been identified in the inelastic proton scattering to the first excited state of ^{21}Na. These are likely to be of an s-wave nature corresponding to known analog states in ^{22}Ne and ^{22}Na. These states will dominate high temperature burning as well as influence the low temperature stellar rate of this reaction.

Summary

DRAGON and TUDA are now operational facilities at the high intensity, ISOL-type ISAC radioactive beam facility. They are complementary facilities providing new information on radiative capture and particle reactions at low energies, relevant to reactions occurring in explosive nucleosynthesis events in novae, X-ray bursts, and possibly supernovae. One of the studies involving the mechanism leading to the production of the observable isotope, ^{22}Na, was described but many other studies are in the planning stages.

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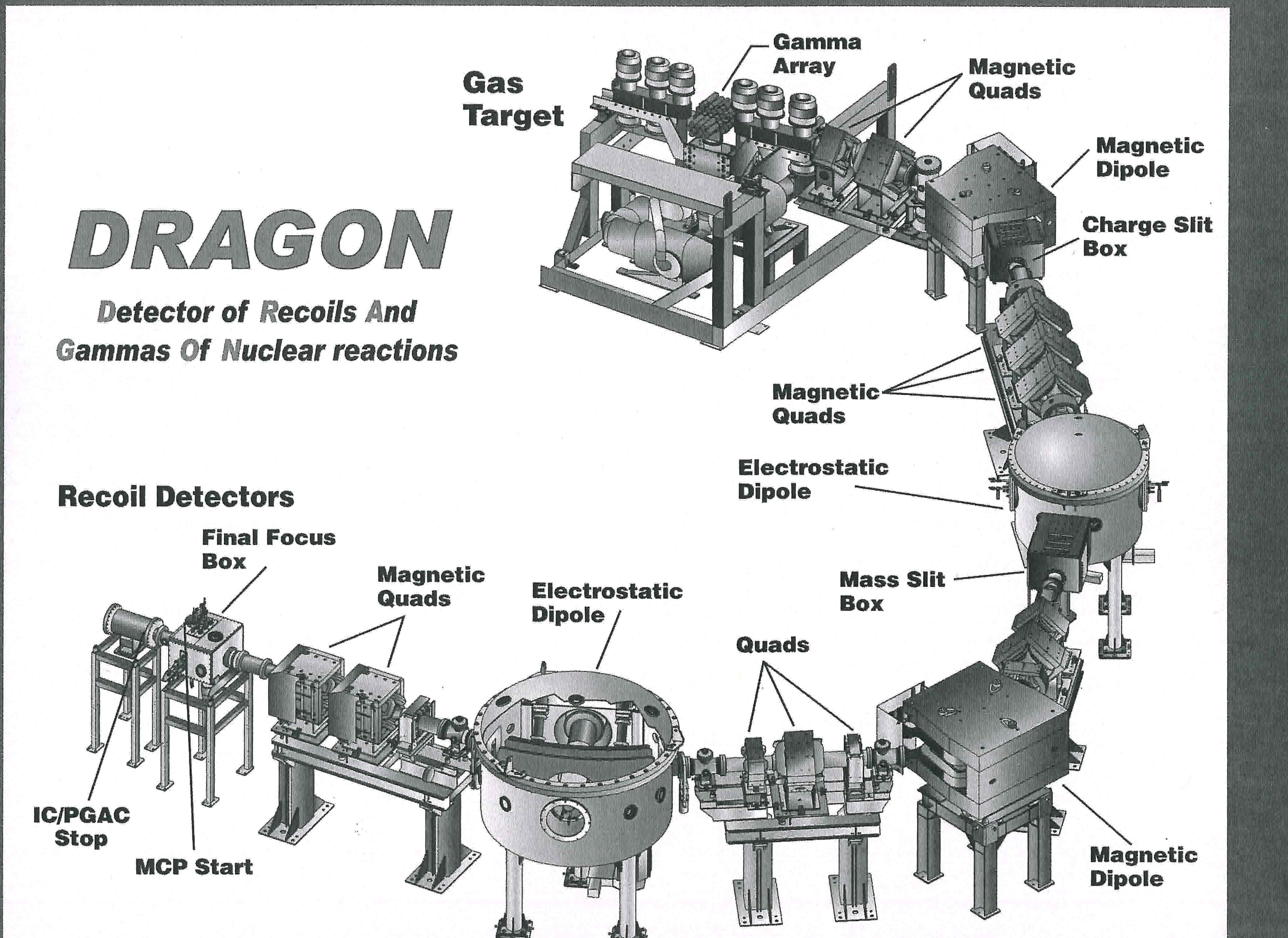

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