NUCLEAR ASTROPHYSICS APPLICATIONS FOR ACCELERATORS

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If you look up into the sky above Bodrum this evening, assuming the weather is good, you should be able to see the star Polaris to the north. Slightly to the west and near the horizon will be the Plough (also known as the Big Dipper or Saptarishi; a major component of the constellation Ursa Major). Slightly to the east of north, and also low down will be the bright star, Capella. 'What is the nature of these heavenly bodies?' is a question that has fascinated mankind throughout its history. Nuclear astrophysics is the modern discipline which tries to provide quantitative answers to this issue, explicitly addressing the questions of what these objects are, and what impact have they had on our environment.

One of the first ways to begin is to categorise the stars according to their appearance. A Hertzsprung-Russell diagram plots the colour of a star, which is related to its surface temperature, to its luminosity. Several distinct populations are observed, for example the red giants, the white dwarfs and the main sequence, which is where our own Sun appears. The energy source of the Sun was an early problem, with simple calculations showing that usual chemical burning could not provide enough energy. Alternative theories such as a cooling of a previously hotter object, or radiation from a slow gravitation contraction, not only provided no adequate historical perspective, but also could only support estimates of ages into the millions of years – far shorter than the evidence of the time that suggested at least a 300 million year age for the Earth. Following the mass-energy relationship discovered by Einstein, in 1920 Sir Arthur Eddington proposed the nuclear fusion of hydrogen to helium. It soon became clear that the stars are nuclear furnaces, and it is nuclear physics which is the key to understanding their nature.

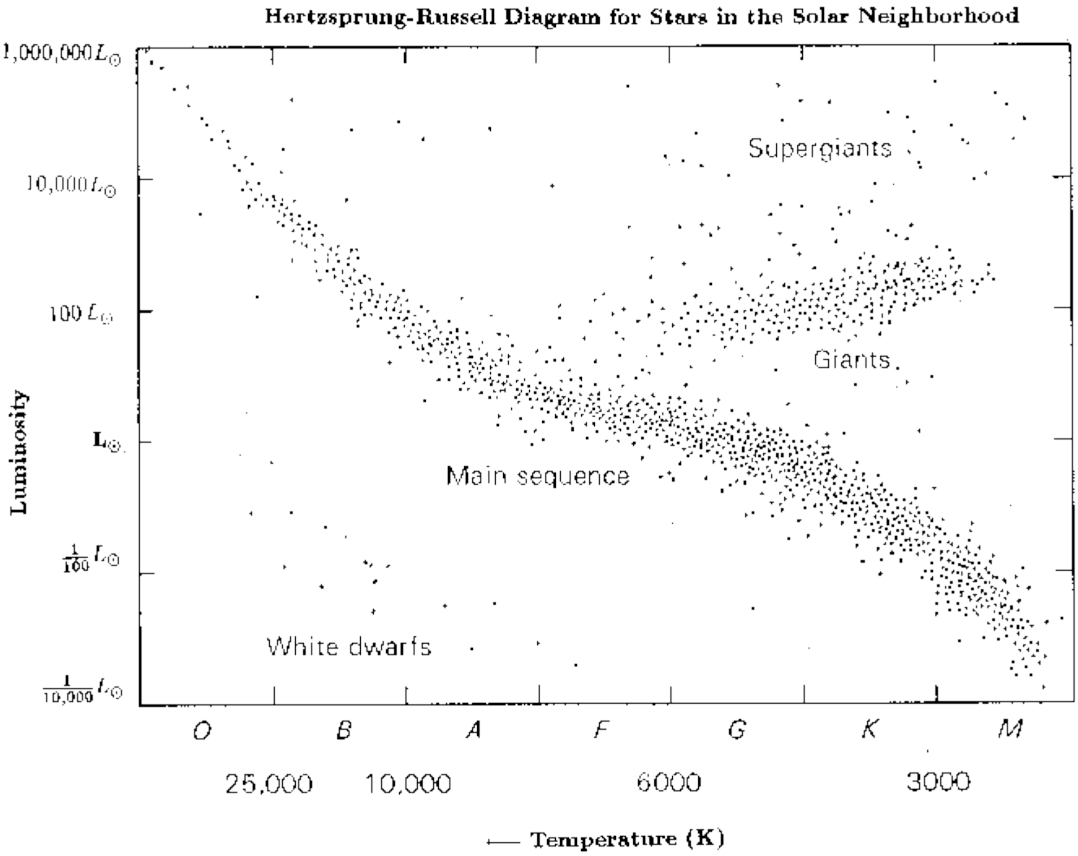

Figure 1: An early Hertzsprung Russell diagram, showing the major populations of star type.

The development of spectroscopy has allowed the chemical abundances of stars (and other objects) to be evaluated. Several important features are observed. Firstly, the vast majority of material ('matter' – we're not considering dark matter or dark energy here) is composed of hydrogen (typically ~74%, by mass) or helium (typically ~24%). These abundances appear to be primordial. Of the remaining material, older stars appear to have less of certain elements, for example oxygen and iron. Certain astrophysical objects then appear to be enhanced in some elements; novae for example show enhancements in carbon, nitrogen, oxygen and neon, while the abundances of the heavier elements, when observed in the expanding shells of past supernovae, seem to have a uniform pattern of abundances. Occasionally pre-solar grains are found in meteorites, and studies of their compositions reveal strong deviations in the abundance ratios of some elements, information which has been seen as evidence for these grains having formed not in our Solar system, but in the debris of distant asymptotic giant branch stars, supernovae, and other sites. It is clear that the very chemical elements that we and the Universe around us are made of have been produced in stars through nuclear processes. More recently, gamma ray observations have revealed that this nucleosynthesis is an ongoing process: gamma rays with an energy distinctive of ^{26}Al, which has a halflife of around 740,000 years have been seen in the diffuse background of our Galaxy, while gamma rays from ^{44}Ti (halflife around 59 years) have been seen coming from the Cassiopeia-A supernova remnant. When considering the distribution of chemical abundances as a whole, the pattern which is seen shows clear correlation with features from nuclear shell structure, most especially, a link to nuclear stability for even masses and closed shells. Understanding the nuclear physics will provide insight to the origin of the chemical elements of the Universe.

Among many important contributions, two seminal works from the mid 20th century stand out in providing a quantitative basis for nuclear astrophysics. In 1948, Alpher and Gamow explained the origins of the light elements in the Big Bang. While it is claimed that the invitation to Hans Bethe to co-author the paper was frivolous, he went on to make many further important contributions. In 1957, Margaret and Geoffrey Burbage, Willy Fowler and Fred Hoyle proposed mechanisms for the production of the heavier elements through steller nucleosynthesis, a work that is now known as B^{2}FH. The work of Ed Salpeter is likely as important. Collectively, while not correct in all their hypotheses, these papers have formed the foundations for subsequent work.

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Figure 2: The Seminal work of Burbidge, Burbidge, Fowler and Hoyle.

Nuclear astrophysics is almost always concerned with thermonuclear burning processes, although exceptions do exists, for example spallation of cosmic ray nuclei may contribute to the abundance of Li isotopes in older stars. Consequently, the bulk properties of most importance are the temperature and density of the environments. Our Sun has a core temperature of around 15 MK, novae involve temperatures up to around 400 MK and supernovae and the Big Bang involve temperatures maybe as high of several GK (of course, the Big Bang is initially hotter, but above these temperatures no nuclei form). While these may seem high, in the context of nuclear physics the relevant energy scale is given by *kT* (*k* is the Boltzmann constant), meaning that the energy scale for the Sun is just ~1 keV, while the very hottest environments correspond to just ~2 MeV. For any pair of particles, the rate at which they will undergo the nuclear reactions to another final state is governed by the cross section (σ) for the reaction being considered. For an ensemble of particles with an overall temperature, the reaction rate ($<\sigma v>$, with units of $cm^3 mole^{-1} s^{-1}$) can be calculated as the convolution of the energy dependent cross section with the Maxwell Boltzmann energy distribution.

$$<\sigma v> \propto \int_0^\infty \sigma(E) \exp(-E/kT)\, dE$$

Charged particle reaction cross sections typically increase with energy (due to increasing penetrability through the Coulomb barrier). This effect is countered by a decreasing population of high energy particles in a Maxwell-Boltzmann distribution. The consequence is known as the Gamow window, and forms a guide the energy range within which nuclear reaction are contributing to an astrophysical process. Turning this argument around somewhat, we can (loosely) use this to define the energy region within which detailed knowledge of the cross section is important. This is usually of the order of *a few kT*.

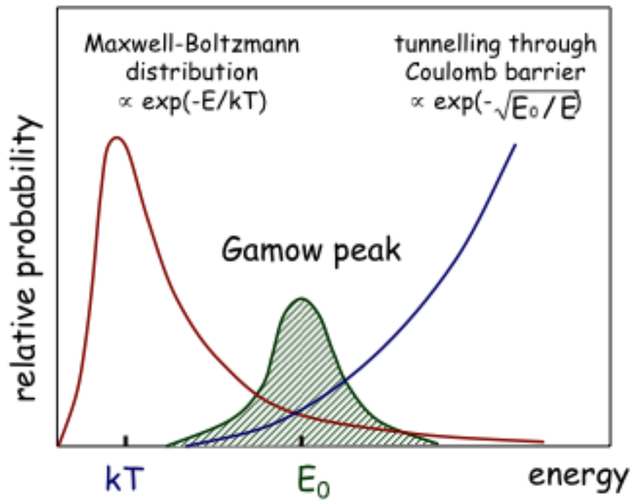

Figure 3: The Gamow window indicated the energy range over which nuclear physics is likely to impact astrophysics.

A further important consequence of these low typical energies is that the absolute cross sections relevant to nuclear astrophysics are also relatively low, with progressively cooler environments exhibiting progressively lower cross sections. (Note: it's just as well the cross sections are low – stars tend to live a very long time!). Higher cross sections, and higher temperatures, by definition, imply shorter timescales, usually meaning explosive rather than quiescent environments. Consequently, research to-date is largely related to explosive astrophysical environments such as big bang nucleosynthesis, novae, x-ray bursters, and supernovae. Furthermore, shorter timescales also imply that nuclei with shorter lifetimes (i.e. exotic nuclei) may be important. This is the essential logic behind the drive towards radioactive ion beam accelerators for nuclear astrophysics.

In the next few paragraphs we will consider some examples of nuclear astrophysics research, highlighting the requirements placed on the accelerators used.

A well defined model for the big bang now exists. The important input parameters are the baryon-to-photon ratio, the number of active neutrino species (which defines the expansion timescale) and the nuclear reaction rates of the nuclei involved. All of these are thought to be well enough defined for a robust network calculation to be performed. However, a significant problem remains in that the predicted abundance of ^{7}Li is around three times the astrophysical observation. Modern attempts to resolve this have included exploring whether individual reaction rates might be in error, considering inhomogeneous big bang models, and even including 'physics beyond the standard model' explanations. An alternative possibility is to extending the reaction network to more nuclei and more nuclear reactions. In Sahin *et al.* (PRC 65 (2001) 038802), the ^{8}Li(d,α)^{6}He reaction was experimentally measured. A large cross section for this reaction could lead of a significant expectation of ^{6}Li (the beta decay product of ^{6}He) in the Universe, which would provide an extra parameter against which to judge the framework. A sputter source was used to produce ^{7}Li which was extracted and accelerated at the Notre-Dame

/Michigan facility using a 10 MV FN Van de Graaff. An ^{8}Li beam was then formed through neutron pickup on a ^{9}Be primary target. A resulting ^{8}Li beam of between 10 and 15 MeV and of 10^{5} pps was used for the experiment. Following scattering of the beam on a 2mg/cm^{2} CD_2 target, ^{4}He and ^{6}He ions were detected in silicon arrays. Unfortunately, the yield measured indicated a cross section insufficient to alter the existing nucleosynthesis prediction.

Novae are thermonuclear explosions occurring on the surfaces of white dwarfs. Hydrogen from a companion star is accreted slowly, forming a layer of degenerate material that eventually reaches the critical conditions for explosion. Our present understanding of these objects comes from observations of light curves, spectra and some meteoritic data. The light curves contain limited information, the spectra provide only chemical abundances, and the meteoritic grains are few and provide only final abundances. A new and extremely useful probe would be gamma rays promptly emitted in the explosion itself. These could provide isotope-specific information originating directly from the explosion itself. The INTEGRAL satellite presently in orbit has gamma ray observation from novae as one of its priority mission goals. Should a nova occur in the solar vicinity, the expected gamma ray flux is dominated by 511 keV emission resulting from the $\beta+$ decay of ^{18}F. Exploiting an observed flux to constrain a nova model therefore requires an accurate knowledge of the nuclear production and destruction rates of ^{18}F. Of the relevant nuclear reactions, the one with the greatest uncertainty is ^{18}F(p,α)^{15}O. Measurements of this rate may be obtained directly, or by calculation as the rate is dominated by resonant contributions mediated by states in ^{19}Ne. Direct measurements are extremely challenging because the cross sections within the Gamow window are so low, while accurate knowledge of the nuclear structure of ^{19}Ne is presently lacking.

At TRIUMF (www.triumf.ca), the ISOL technique has been used to produce ^{18}F beams for a series of measurements, probing both the level information of ^{19}Ne, and to provide a direct measurement of the reaction within the Gamow window. In the Isotope Separator OnLine technique, a high energy (500 MeV) proton driver, provided from the world's largest cyclotron, is used to spall radioactive ions from a primary target. Targets include SiC, Ta and UCx. Fragments are ionised, extracted from the target, and accelerated to the desired beam. The initial ISotope ACcelerator (ISAC-I) facility could provide ions of A<40 with energies from 0.25 to 1.6 MeV/A. A recent upgrade with superconducting linacs, ISAC-II, can now provide all masses up to ~6 MeV/A. The accelerator is complemented with permanent and semi-permanent experimental stations including the Triumf UK Detector Array (TUDA), primarily for charged particle nuclear astrophysics measurements, and the Detector of Recoils and Gamma-rays of Nuclear reactions (DRAGON), for astrophysical radiative capture reactions. In Murphy *et al.* PRC 79 (2009) 058801 the thick target technique was used to simultaneously measure the ^{18}F(p,p) and ^{18}F(p,α) reactions between 0.6 and 1.6 MeV, with an R-matrix analysis employed to determine the level information of several important states in ^{19}Ne. In Beer *et al.* PRC 82 (2011) 042801R a direct low energy measurement of the reaction was performed, culminating in a week-long measurement at Ecm=250 keV, *i.e.* inside the Gamow window, in which two events from the reaction of interest were observed. Despite the low statistics, some models of the cross section can now be disfavoured.

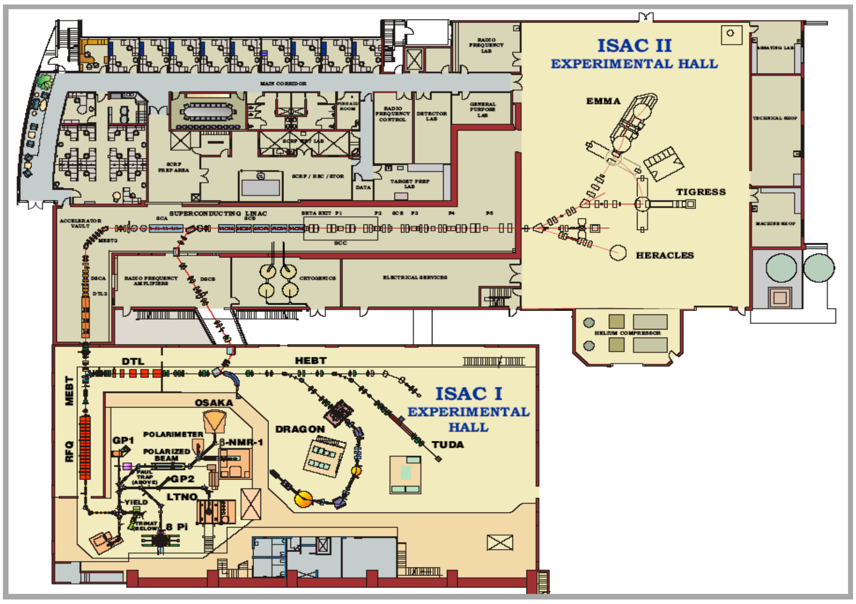

Figure 4: Schematic outline of the ISAC-I and ISAC-II facilities at TRIUMF [TRIUMF website].

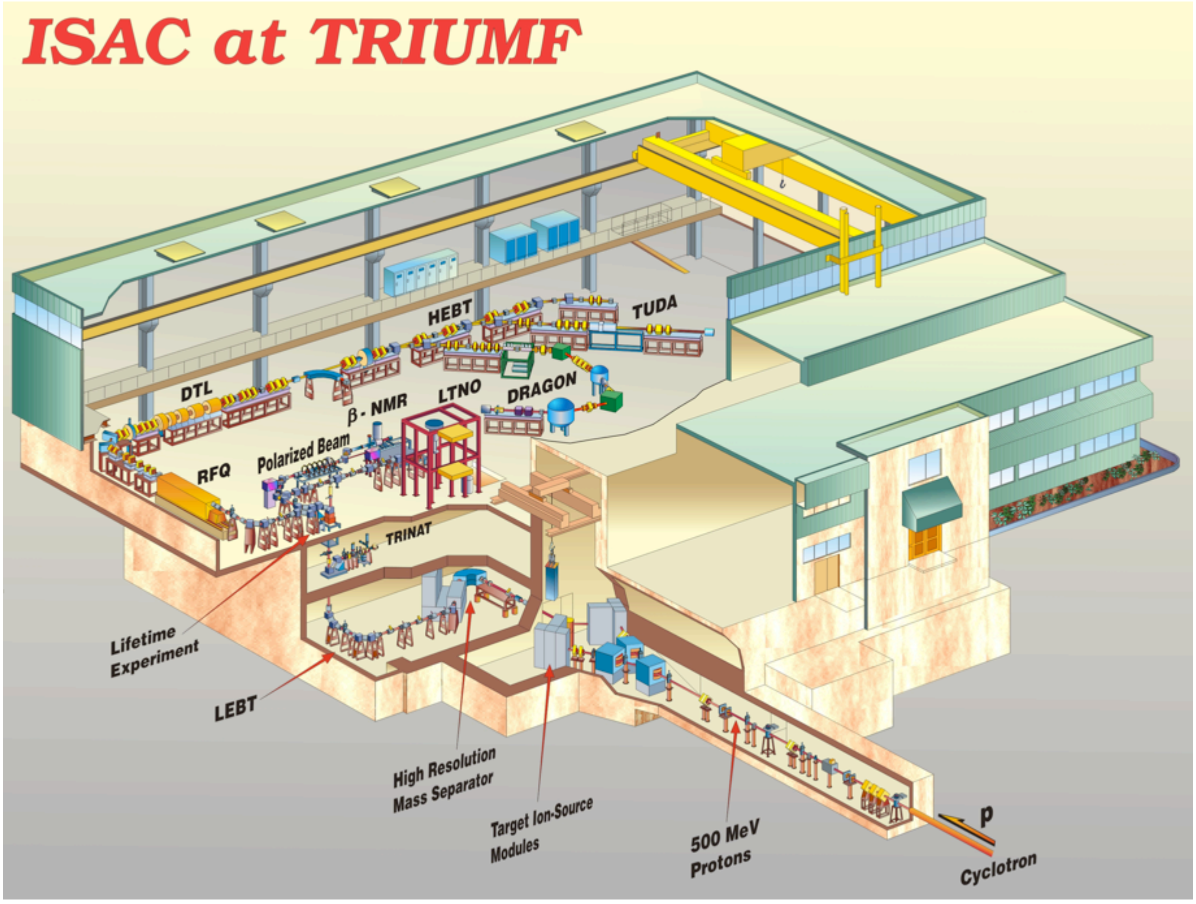

Figure 5: Schematic layout of the ISAC-I hall: TUDA and DRAGON are located in the upper part of the image [TRIUMF website].

Supernovae present one of the most exciting and challenging laboratories for nuclear astrophysics research. Observationally, they are categorised by whether hydrogen, helium and silicon are observed, however the underlying physics appears to correspond to just two basic mechanisms: binary stellar systems in which material from one star accretes to the surface of a white dwarf ("type-Ia"), and massive stars collapsing in upon themselves when energy liberation from nuclear fusion reactions is exhausted (type-Ib, Ic and II). These core-collapse supernovae present a particular challenge. A basic model appears to have been confirmed through the observation of 19 neutrinos from the SN1987a event – after sequential stages of fusion reactions, massive stars (M>8Msolar) develop an 'onion skin' structure with a core of iron and nickel. Further fusion is not energetically favourable, and the resulting loss of thermal pressure allows the core to contract ('~freefall') under gravity. The release of gravitational energy raises the temperature, dissociating material back to protons, neutrons and alpha particles. Pair produced neutrinos are able to escape allowing further contraction and consequent heat generation. The neutrinos from 1987a were detected over a period of several seconds, much longer than the timescale for collapse, appearing to confirm that the neutrinos play a further role in re-energising the collapsed material to provide a delayed explosion. Such a hypothesis is consistent with the vast energy of the neutrino emission, about 99% of the total release.

Figure 6: The Crab nebula, a remnant of a supernova exploding in 1054 AD. It is about 6,500 light years from Earth [NASA].

This model is not without problems though. To date, few models have been able to reproduce robust explosions. Key uncertainties include the treatment of neutrino energy transport, the importance of full 3D effects, especially with regard to rotation and turbulence, and the role of magnetic fields. An additional constraint for modellers to compare to data would be highly desirable. One opportunity might come from gamma-ray observations, and in particular gamma-rays from the decay of ^{44}Ti produced in the explosion. This isotope not only has decay properties that make it well suited to satellite observation, but it is also thought to originate from a key region of the explosion. The amount observed is thought to depend sensitively on the location of the mass cut, that is, the boundary between material which is successfully ejected from the explosion, and that which falls back to form a neutron star or possibly a black hole (material that falls back is so dense that gamma-rays are unable to escape to be observed). Thus an observation of ^{44}Ti gamma-ray flux can in principle provide information on the structure of the collapsed core, effectively seeing deep into the event in a way that no traditional observational technique can do.

To realise this ambition, among other needs, the rates of nuclear reactions that produce and destroy ^{44}Ti must be adequately well known. One of the foremost of the rates requiring increased precision is that of ^{44}Ti(α,p)^{47}V, a reaction that is rather hard to measure because of the beam-target combination. In an innovative approach, one of the aims of the Exotic Radionuclides from Accelerator Waste for Science and Technology (ERAWAST) is to measure this reaction using ^{44}Ti reclaimed from the irradiated beam dumps of the PSI facility. The techniques of nuclear chemistry will be applied to highly irradiated copper, extracting ^{44}Ti in solution, and then bleeding this into a nominally stable ion source. Given the Gamow window for this reaction in the supernova environment, ideally the 1-4 MeV centre of mass energy range would be covered. Significant issues exist over minimising the activation of any sources and beamlines used.

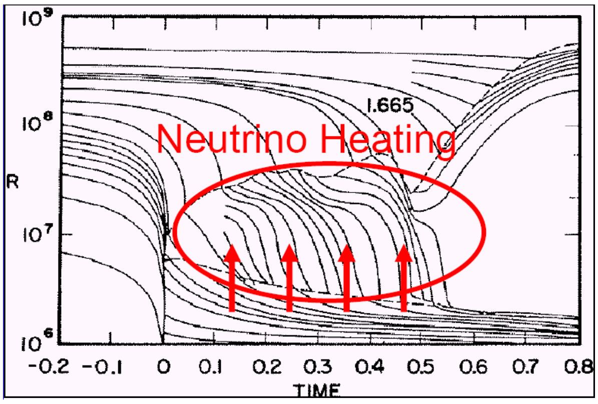

Figure 7: Illustration of the 'mass cut'. The innermost regions of a supernova fail to explode, while farther out, after neutrino heating, the material is ejected [Wilson 1985].

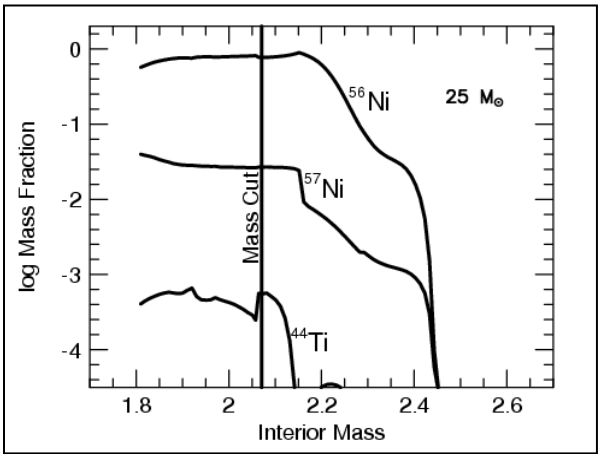

Figure 8: ^{44}Ti is produced in the vicinity of the mass cut. If the mass cut occurs at a smaller radius, much more ^{44}Ti is ejected (and vice versa) [Timmes 1996].

A particularly important aspect of core collapse supernovae is that they are widely viewed as the most likely site of the r-process, thought to be responsible for synthesising approximately half the elements heavier than iron. In this scenario, high temperature and high neutron flux allows a series of neutron captures to occur. Successive neutrons are captured until the beta decay lifetime becomes so short as to inhibit further captures. If one has high enough neutron fluences and temperatures, the boundaries for progression happen near the driplines and at magic numbers. Cessation of the high temperature then allows the highly exotic matter to beta decay back towards stability. Network calculations suggest that such a process could recreate the correct abundance pattern for many of the heavy elements. Further improved agreement (to the 'left' of the main mass peaks) can be obtained by the inclusion of neutrino reactions, adding to the case of the process occurring within the neutrino driven wind of a nascent supernova.

The present limitation to simulations of r-process nucleosynthesis comes from lack of nuclear information. In particular, mass differences and beta-decay lifetimes are required to determine the path of the rp-process, that is, how far away from stability does the process run. Much of the path is likely to be in regions of the nuclear chart that have yet to be explored, particularly in the N>82 region. The existence and modifications to nuclear shell gaps will be of key importance, and thus this research has significant overlap with studies of exotic nuclear structure. Such is the strength of the (combined) science case that it has been one of the major drivers for the FAIR facility development at GSI, the biggest ever investment in nuclear physics in Europe.

One of the first r-process motivated studies will use the new SuperFRS recoil separator. Through fragmentation, the primary driver beam will produce intense beams of ions ranging from hydrogen to uranium with energies up to 1.5 GeV/A. High energy fragmentation is chemistry independent, allowing many new isotopes to be examined, with the design for the separator allowing many of these to be studied simultaneously. Near stability, intensities as high as 10^{13} pps are expected, while the rate far from stability, in regions relevant to the r-process, the rate may be as low as one per week. To extract the most science from the new investment, major new

Figure 9: Artist's impression of the completed FAIR facility at GSI. By 2016 this should be real!

instrumentation projects are underway. For the r-process studies, one of the foremost is the AIDA project (www2.ph.ed.ac.uk/~td/DSSD/), in which an array of novel high position resolution silicon wafers will be deployed for implantation-decay studies. To cope with the high data rates and vast number of channels, these will use ASIC technology with onboard FPGA, allowing fast recovery from high energy implantations for decay measurements of ~1MeV with spectroscopic energy resolution. The first prototype modules are now complete and are undergoing performance tests.

Nuclear astrophysics is an exciting field of research in which the techniques and implications of nuclear physics are used to develop our understanding of astrophysics. There are many open challenges covering a hugely diverse range of environments, employing a similarly broad range of experimental techniques. With both well-established and newly-conceived accelerator technologies having important roles to play, it is inevitable that nuclear astrophysics will remain one of the central themes of nuclear physics for many years to come.