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Astrophysics at future radioactive beam facilities

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Significant progress in studies of core collapse supernovae, thermonuclear supernovae, X-ray bursts, novae, and other astrophysical phenomena require intense beams of a wide range of unstable nuclei. While some such beams are currently available and being used for important studies in nuclear astrophysics, the beams are often insufficient in intensity, purity, or available isotopes. It is anticipated that a next-generation radioactive beam facility will be built in the U.S. in the next decade to address these shortcomings, and a Working Group has been established to develop and promote nuclear astrophysics research at this new facility. Many of the topics addressed by the Working Group are relevant for the RIKEN RI Beam Factory, the planned GSI-Fair facility, and other advanced radioactive beam facilities around the world.

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1. Unstable Nuclei in Astrophysics

Unstable nuclei play an influential, and in some cases dominant, role in many important and interesting astrophysical phenomena [1]. These include stellar explosions at the core of some massive stars (i.e., supernovae) and on the surface of others (i.e., novae and X-ray bursts). Thermonuclear reactions on unstable nuclei also play an important role in the nuclear physics in ultra-dense neutron stars, in bloated red giant stars, and perhaps in the very early universe. Improved knowledge of the physics of unstable nuclei is needed to help us understand the processes that shape our world (Figure 1) [2] and address some very exciting questions about the universe at its two extremes in length scales: What creates the elements from Iron to Uranium? Why do stars explode? What is the nature of neutron star matter?

These interdisciplinary questions have captured the imagination of researchers and laymen alike. For example, the creation of the heavy elements was cited as one of the eleven most important questions at the interface of particle physics and astrophysics by a recent National Academies study [3]. Recently, sophisticated and expensive observatories, missions, and projects such as the Hubble, Chandra, Spitzer, Sloan Digital Sky Survey, and others have provided incredibly detailed information on astrophysical phenomena over a wide range of wavelengths. Unfortunately, a firm empirical foundation in nuclear science is missing for many theoretical models striving to explain these astrophysical observations – because of our inadequate knowledge of the properties of and reactions involving unstable nuclei.

In core collapse supernovae, for example, it is important to determine weak reactions on unstable nuclei near Fe [4] for the pre-collapse and collapse phases. It is also crucial to measure reactions that create and destroy long-lived radionuclides like ^{26}Al, ^{44}Ti, and ^{60}Fe that can help diagnose the explosion mechanism (via the mass cut location) [5] and the synthesis of light to medium mass nuclei, and to measure the properties of and reactions on neutron-rich unstable nuclei that form heavy elements via the rapid neutron capture process [6, 7, 8].

In nova explosions occurring on the surface of white dwarf stars, it is important to measure capture reactions on proton-rich unstable nuclei to determine the energy generated and the nuclei synthesized in the outburst. This will help address qualitative and quantitative issues in nova models such as the peak temperature, the heaviest nuclei synthesized, and the amount of material ejected [9, 10, 11]. These explosions are driven by thermonuclear reactions on p-rich radioactive nuclei with masses up to $A \sim 40$.

In X-ray bursts – thermonuclear explosions on the surfaces of neutron stars – it is crucial to measure positron decay lifetimes and capture reaction rates on proton-rich unstable nuclei to make calculations of the X-ray luminosity and subsequent neutron star evolution more realistic [12, 13]. These bursts are driven by thermonuclear reactions on p-rich radioactive nuclei with masses up to $A \sim 110$.

For thermonuclear (Type Ia) supernovae, there is a need to determine electron capture rates on unstable nuclei to better understand explosion energetics and element synthesis [4], and to explore systematic uncertainties in using these events as "standard candles" for cosmology.

For red giant stars, the slow neutron capture process (s-process) is thought to form heavy elements in the thermally pulsing He shells of low-mass asymptotic giant branch stars [14]. The reaction flow proceeds from lighter to heavier nuclei along primarily stable nuclei, but there are

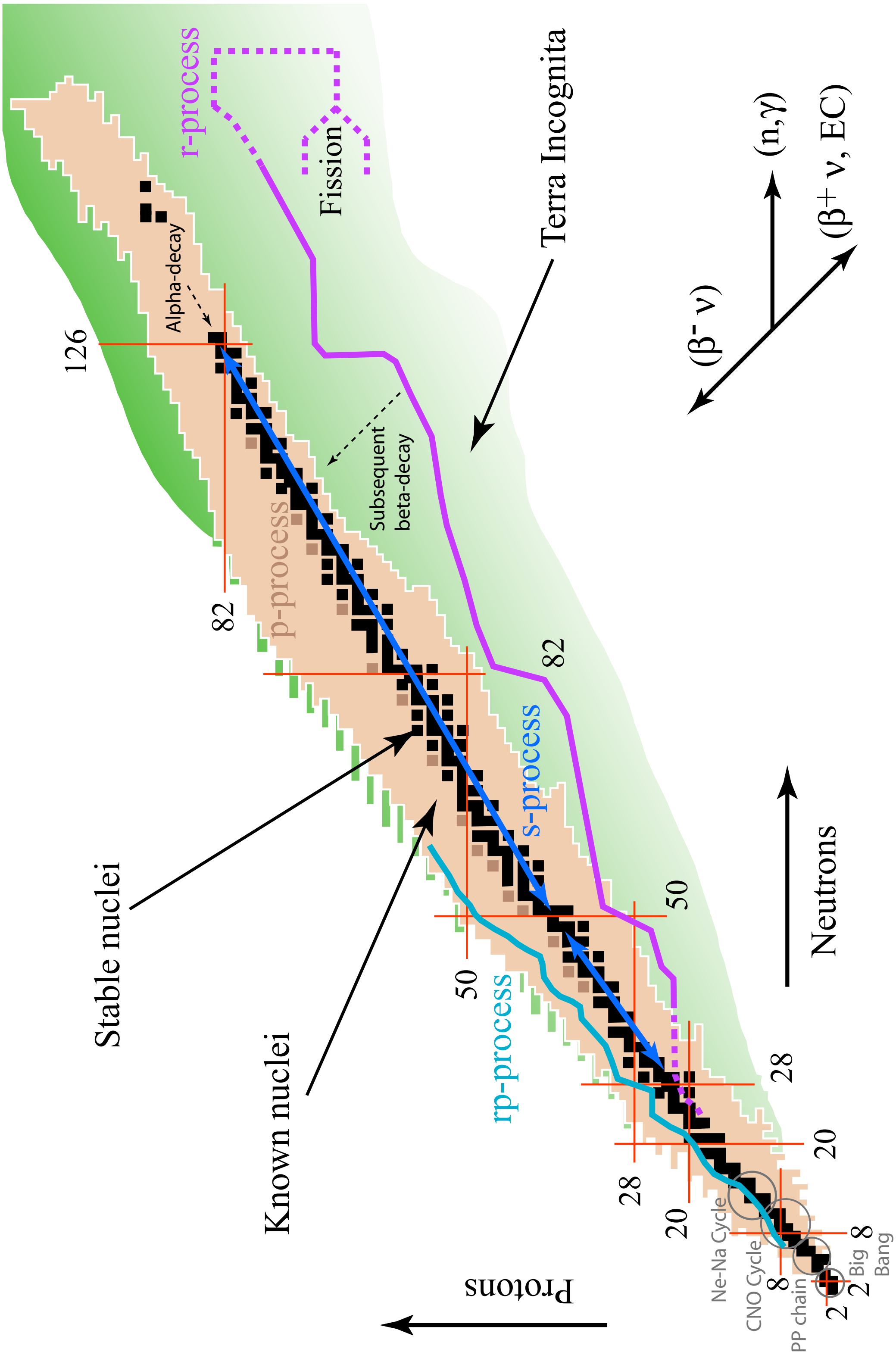

Figure 1: Unstable Nuclei in Astrophysical Processes [2]

$\sim$ 60 radioactive nuclei that also play a role. These isotopes are one neutron richer than stability and have half lives sufficiently long that beta decay competes with neutron capture. The reaction flow develops two paths at these "branch point nuclei", and a knowledge of the neutron capture rates on these nuclei can be used to diagnose the temperatures and densities characteristic of s-processing burning [15].

In the early universe, reactions on neutron-rich unstable nuclei play a role in the element synthesis that occurs in models featuring spatial inhomogeneities in the baryon density [16]. Such models, although still viable [17], are highly constrained by observations of the primordial deuterium abundance and the total baryonic matter density consistent with Cosmic Microwave Background Radiation observations [18].

2. Next-Generation Radioactive Beam Facility in the U.S.

While some beams of unstable nuclei are currently available and being used for important studies in nuclear astrophysics, the beams are often insufficient in intensity, purity, or available isotopes. It is anticipated that a next-generation radioactive beam facility will be built in the U.S. in the next decade to address these shortcomings. The facility will likely produce intense beams of unstable nuclei via a number of complementary techniques, including a combination of projectile fragmentation techniques, Isotope Separator on-line (ISOL) techniques, and a hybrid technique involving fragmentation, gas stopping, ionization, and reacceleration. The facility is currently envisioned to produce beams with energies ranging from unaccelerated to over 10 MeV/amu.

There have been a number of recent developments in plans to construct an exotic beam facility in the U.S. Efforts were previously focussed on the Rare Isotope Accelerator (RIA) [19], a proposed billion-dollar facility that would employ all of the beam production techniques mentioned above at optimum production energies for all nuclei. In February 2006, a decision was made to move forward with a more targeted facility costing approximately half as much, and to have preliminary engineering designs in place by 2011. This is the first time that a world-class exotic beam facility has been put into five year plan of the Office of Science of the primary funding agency for U.S. nuclear science, the U.S. Department of Energy. This is an encouraging step toward the realization of this important goal. Future developments can be followed at the RIA website [19].

3. Working Group

We envision that a next-generation U.S. facility will usher in a new era where advances in observations, theory, *and nuclear science* synergistically improve our understanding of the cosmos. To maximize the potential of the nuclear astrophysics research program at this facility, a Working Group was established. Topics of discussion include the science motivation, types of experiments, facility issues, detection systems, layout of experimental halls, as well as associated observational and theoretical needs for a successful program. Some specific topics include: the most important science questions to address; devising sets of representative experiments and associated equipment; and mechanisms to build a broad, interdisciplinary community in nuclear astrophysics to take full advantage of this new facility. Many of these issues are relevant for nuclear astrophysics research programs at advanced radioactive beam facilities such as GSI-Fair and the RIKEN RI Beam Factory. We encourage membership in the Working Group of anyone interested in the scientific or technical aspects of nuclear astrophysics research with radioactive beams, including experimentalists, theorists, and observationalists. For more information and to become a member, visit the Working Group website **ariaweb.org** [20].

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