

Scientific Justification for an Electron Linear Accelerator at TRIUMF-ISAC

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March 17, 2008

The key questions in nuclear physics of how protons and neutrons are bound in nuclei and what are the limits of nuclear stability are intimately connected to the question of how the chemical elements were formed in stars and the early universe. Ultimately, we seek a theoretical understanding of the quantum many-body problem of the atomic nucleus that will enable us to reliably predict the properties of all nuclei and make sense of the observed abundances of the elements. To solve this fundamental problem, it is essential to study nuclei far from stability because our present understanding of nuclear structure is based almost entirely on the properties of stable nuclei. Moreover, most of the nuclei involved in stellar and explosive nucleosynthesis and in astrophysical energy production are unstable; therefore the reactions they undergo are very difficult to initiate in the lab and many have not yet been studied. It is neither possible nor necessary to study every single nucleus and reaction, since important cases have been identified and will be used to test nuclear theory and constrain the necessary extrapolations into unknown territory. Further progress in both nuclear structure and nuclear astrophysics is directly tied to precise new experiments with radioactive beams.

One of the principal goals of nuclear astrophysics is to determine how and where the chemical elements were formed. Both by mass and by sheer numbers, the lightest two elements H and He represent the overwhelming majority of nuclei. This can be seen in Figure 1 which plots the abundances of the isobars. Our understanding of the origin of H and He is relatively complete, with primordial big bang nucleosynthesis and the hydrostatic stellar fusion of H into He accounting for their enormous universal abundances. Apart from the light nuclei with mass number A satisfying $4 < A < 12$, which were produced dominantly by cosmic ray spallation reactions, nuclei with $12 \leq A \lesssim 70$ were produced in both hydrostatic stellar fusion and in supernova explosions. Charged particle induced reactions on nuclei with $A \gtrsim 56$ are generally endothermic and therefore most heavy nuclei are produced by other means, principally neutron capture.

At least two distinct neutron capture processes are thought to be responsible for the production of nearly all the heavy elements, the slow (s) and rapid (r) neutron capture processes. The s process hews close to the valley of β

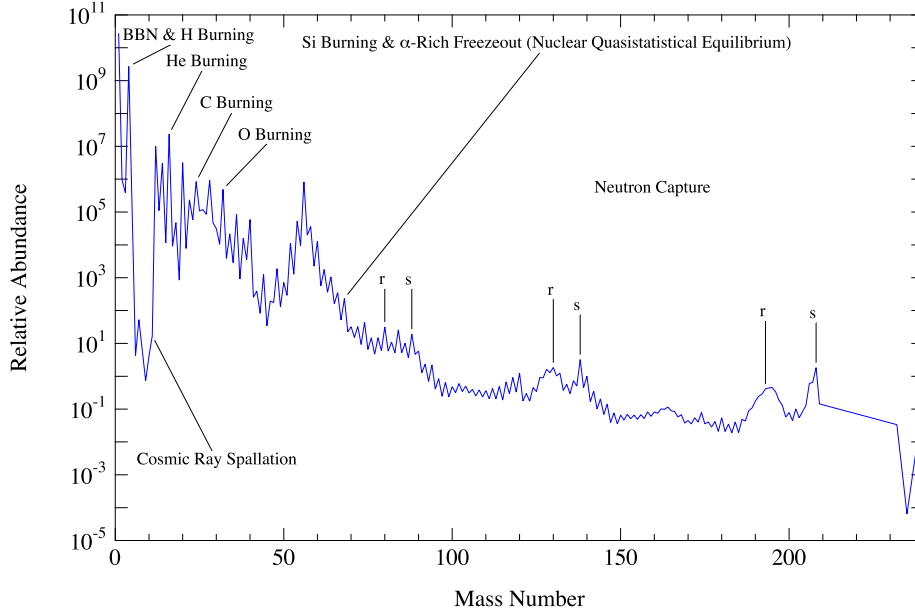


Figure 1: Solar system abundances of the isobars.

stability and involves neutron captures that are slower than the β^- decay rates of the nuclei that participate. In contrast, the r process is a series of rapid neutron captures that takes place in a hot environment with a high density of free neutrons, followed by a series of β^- decays that bring the newly formed, neutron-rich nuclei back to the valley of stability. The s process has at least two distinct components, one responsible for producing light and another for heavy elements [1]. Similarly, abundance differences between light and heavy r process nuclei found in meteorites led to the idea that there are at least two distinct r process components or sites [2]. Elemental abundance data from very old stars support two sites, exhibiting a consistent abundance pattern for nuclei with $Z > 47$ but variations for nuclei with $Z \leq 47$ [3]. The r process involves neutron-rich nuclei about which very little, if anything, is known. Because so little is known about neutron-rich nuclei, we know neither the location of the neutron drip line, beyond which additional neutrons cease to be bound in nuclei, nor through which nuclei the r process flows. The lack of knowledge of the properties of neutron-rich nuclei involved in the r process means that we are unable to uniquely specify the physical conditions such as the neutron density of the explosive environment in which it takes place. This makes it impossible to pinpoint where in the universe the r process occurs.

With experiments at the ISAC radioactive ion beam facility, TRIUMF is already making unique, important contributions at the forefront of understanding hydrostatic and explosive stellar nucleosynthesis, particularly that which takes

place in cataclysmic binary systems (novae and Type I x-ray bursts). A fantastic window of opportunity for science with neutron-rich nuclei can be explored with the proposed 50 MeV superconducting electron linac for the production of radioactive ion beams via electron-induced photofission of an actinide target. This will allow TRIUMF-ISAC to continue as a world leader in radioactive ion beam physics for many years to come. An accelerator project alone would make this possible because ISAC has some of the best detectors, spectrometers, and ion traps in the world already on the floor or under construction. These experimental facilities are designed to precisely measure nuclear masses and reaction rates, and to elucidate the structure and reaction dynamics of radioactive nuclei urgently needed to shed light on the origin of the chemical elements heavier than Ni in the r process.

While the most important experimental data for the r process are masses, β^- decay rates, and β^- -delayed neutron emission probabilities, another key avenue of research is the exploration of the reaction dynamics of neutron-rich nuclei. The recoil mass spectrometer EMMA [4], the γ ray spectrometer TIGRESS [5] and its auxiliary detectors such as SHARC, and the charged-particle spectrometer TUDA [6] are all able to play prominent roles here. The rates of (n, γ) reactions are key ingredients for determining the evolution of r process nucleosynthesis after the reactions fall out of equilibrium. These rates are particularly important for nuclei near closed neutron shells such as $N = 82$. For example, as shown in Figure 2, the neutron capture cross section of ^{130}Sn has a substantial effect on the final abundances predicted by r process models [7]. While (n, γ) reactions on short-lived radioactive nuclei cannot be measured directly, (d, p) reactions lead to the same nuclei and their cross sections have been empirically correlated with (n, n) total reaction cross sections. These (d, p) reactions may be used to infer the (n, γ) reaction rates needed for a quantitative understanding of the final elemental abundances.

Neutron-rich nuclei are crucial for several other reasons. We believe that the crust of neutron stars exhibits a transition starting with stable nuclei at the surface, down through neutron-rich nuclei at higher pressure and density, then moving towards the core through exotic, inhomogeneous phases of nuclear matter [8]. Astronomers using satellite-borne x-ray observatories are now able to study thermal emission from neutron star crusts, in turn learning of their properties. Further, the crust plays an important role in Type I x-ray bursts, which are thermonuclear runaways arising from the accretion of matter onto the surface of a neutron star from a nearby stellar companion. The thermal properties of the crust are particularly important in determining the energy release and ignition depth of superbursts, which are similar to Type I x-ray bursts but are about 1000 times more energetic and are believed to be the result of the explosive thermonuclear fusion of C beneath the neutron star surface. To understand the neutron star crust, we need to systematically understand neutron-rich nuclei, their structure and excitations, and the nuclear equation of state at large neutron excess. Particularly important are the masses and energies of the low-lying excited states, but β^- decay rates are also needed [9]. To understand the x-ray bursts themselves, explosive hydrogen and helium

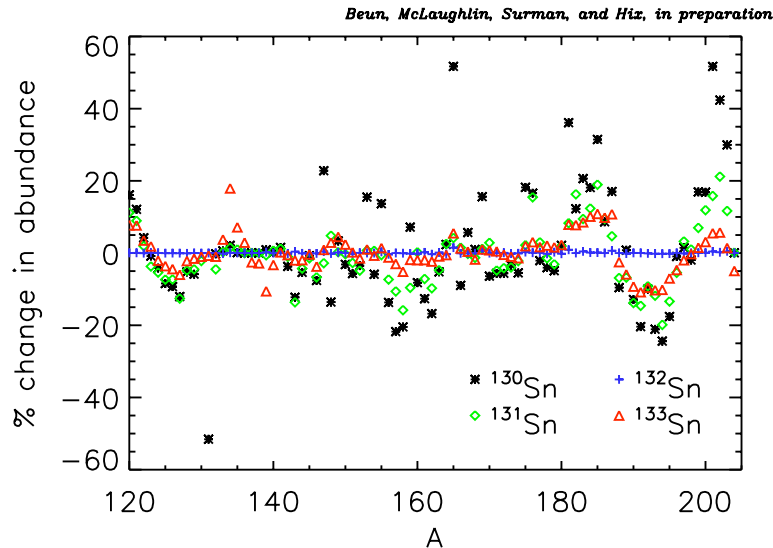


Figure 2: The effect of varying neutron capture cross sections on final abundance distributions in an r process model. In each case, the neutron capture cross section of the indicated tin isotope has been varied by a factor of 100. Credit: R. Surman.

burning on neutron-deficient nuclei must be understood via direct studies of particularly important reactions and the same kind of systematic studies of nuclear structure that are needed for the understanding of the production of neutron-rich nuclei. With the proposed electron linac, TRIUMF would be in an unique position to study the reactions involving both neutron-deficient and neutron-rich nuclei.

Production of radioactive ion beams using an electron linac would enable TRIUMF-ISAC to make significant contributions to our understanding of the r process and neutron star crusts. It is crucial to extend the reach of ISAC to the most exotic, unstable nuclei possible in order to determine masses and half-lives of key nuclei in the r process. The mass spectrometer TITAN [10], the 8π γ -ray spectrometer [5], TIGRESS, and EMMA are among the most advanced instruments capable of measuring these observables. Theory and experiment will work together to identify measurements required for interpolating or extrapolating results to the relevant nuclei where measurements will be difficult or impossible.

The masses of neutron-rich nuclei are not only crucial for astrophysics, they provide key experimental input for building a universal nuclear energy density functional. As shown in Figure 3, taken from Ref. [11], the current theoretical models extrapolate only poorly to neutron-rich nuclei. New mass measurements have to go hand in hand with theoretical advances in solving this fundamental problem. The mass measurement program at TITAN, which started operating

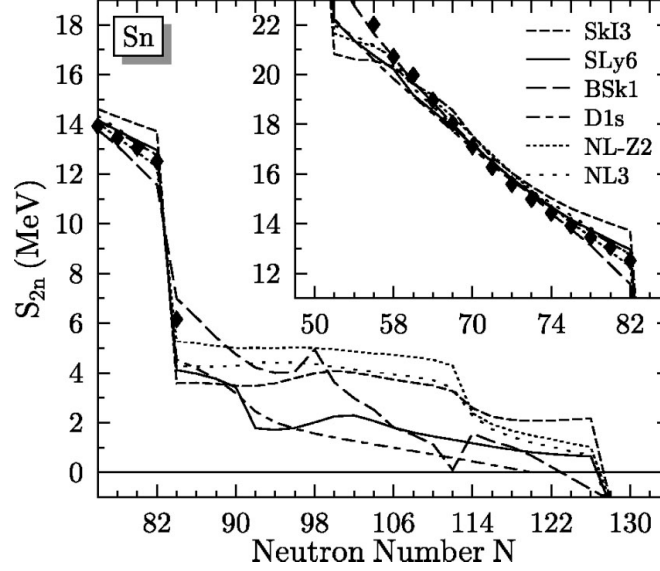


Figure 3: The variation of calculated and measured two-neutron separation energy with neutron number along the tin isotopic chain. Reproduced from Ref. [11]

in autumn 2007, is a perfect match to the photofission products that would be provided by the electron linac. TITAN has proven its capability to carry out highly precise mass determinations ($\delta m/m \sim 10^{-8}$) on isotopes with half-lives as short as 8 ms, nearly an order of magnitude shorter than is possible at any other Penning trap facility. Moreover, measurements require only ~ 10 ions/s. In nuclear theory, there is a world-wide effort to develop a universal density functional based on microscopic nuclear interactions (see e.g. Ref. [12]). With the expected advances, theory will be able to point to changes in mass patterns towards the neutron drip line, where measurements would be most important. In addition, new global trends in masses emerge only when one has access to significant ranges in chains of isotopes. In this context, systematic investigations of the isospin dependence of pairing gaps are very promising [13]. Their theoretical origin could be due to contributions beyond BCS theory (“induced interactions”) or due to deformation effects. Further, pairing in nuclei with $A < 100$ can have significant impacts on the cooling of the outer crust of neutron stars and therefore affects superbursts. Complementary to certain key masses (for example at r-process waiting points), advances in our theoretical understanding of nuclear binding energies rely on global studies of mass systematics. Here the high yields of neutron-rich nuclei achievable via photofission will allow for a targeted experimental program.

One of the central questions of modern nuclear structure physics is how the

observed shell structure forms and how shells evolve toward the drip lines. New shells of stability can emerge (“new magic numbers”) and the conventional shell hierarchy can be inverted (“island of inversion”) [14, 15]. These questions are at the foundations of understanding nuclei. With photofission, we have the possibility to study the evolution of shell structure further towards the neutron drip line in the medium-mass region than with other next generation facilities. On the theoretical side, there are first indications [16, 17] that the formation of shells and their evolution near the drip lines is connected to three-nucleon interactions. Three-nucleon interactions are a frontier in the physics of nuclei, and with the recent advances in nuclear theory, it is for the first time possible to investigate their contributions to heavier systems ($A > 12$). New results [18] support the idea that phenomenological monopole shifts in shell model interactions are due to three-nucleon contributions. This links understanding the shell model and the limits of existence to three-nucleon forces. With the proposed electron linac, TRIUMF would be at the forefront of an exciting experimental and theoretical exploration.

ISAC has unique, state-of-the-art instrumentation and experimental facilities for nuclear structure and astrophysics research in DRAGON, TACTIC, TIGRESS, TITAN, and TUDA. But ISAC also has a very strong capability in materials science research with its β NMR facility. Calculations indicate that by employing a target made of ^9Be instead of an actinide, the (γ, p) reaction can be harnessed to produce copious quantities of ^8Li for the β NMR program using the proposed electron linac. Moreover, it would be possible to run simultaneous experiments with one low energy and two accelerated radioactive beams.

It is clear that there is a tremendous amount of physics to be extracted from the study of neutron-rich nuclei. Using electron-induced photofission to produce beams is advantageous for a number of reasons. P. Bricault and M. Dombsky have calculated the yields for the electron linac proposed for ISAC and for 500 MeV protons from the TRIUMF cyclotron incident on a $25 \mu\text{g cm}^{-2}$ U target. The production of radioactive nuclei calculated with these simulations demonstrates the power of the technique for ISAC. Figure 4 shows the calculated photofission yields for the proposed electron linac along with the r process progenitors according to a classical r process calculation using the finite range droplet mass model [19]. The nuclei included in a state-of-the-art neutron star crust calculation [20] are shown in Figure 5. It is clear that the electron linac would produce essentially only nuclei that are neutron-rich, and overlap well with the regions of interest for both the r process and neutron star crusts. With other production mechanisms, such as proton-induced fission and spallation, a greater range of nuclei are created, but there is significant contamination from neutron-deficient isobars and from α -emitting isotopes of uranium and thorium. This contamination can severely restrict the capacity to make clean and definitive studies of the most neutron-rich nuclei, which are produced at the lowest rates.

The proposed electron linac would extend the reach of ISAC in neutron number beyond that available from proton beams on a U target. If sufficient power can be dissipated in the target to induce more than 10^{13} fissions s^{-1} ,

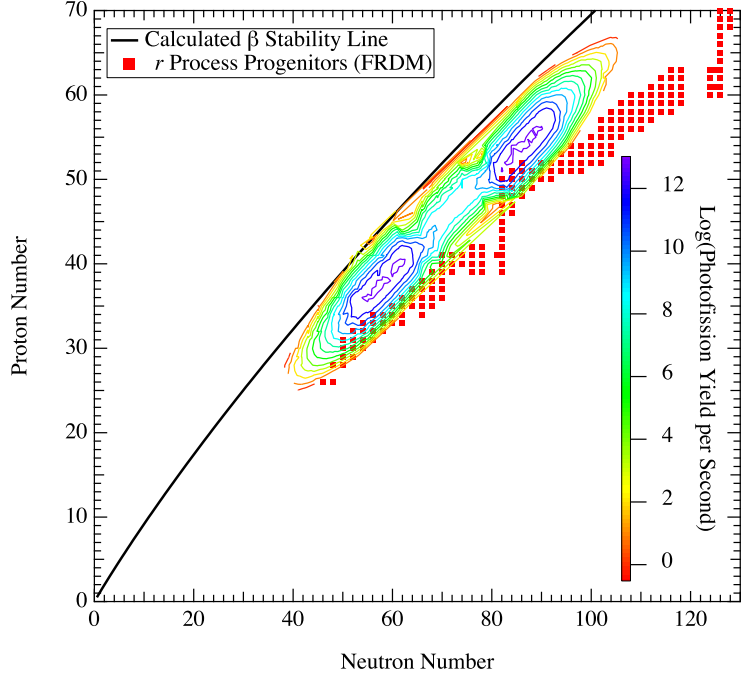


Figure 4: Contour plot of calculated photofission yields from the proposed electron linac superimposed on the r process progenitors in a classical r process calculation based on the finite range droplet model.

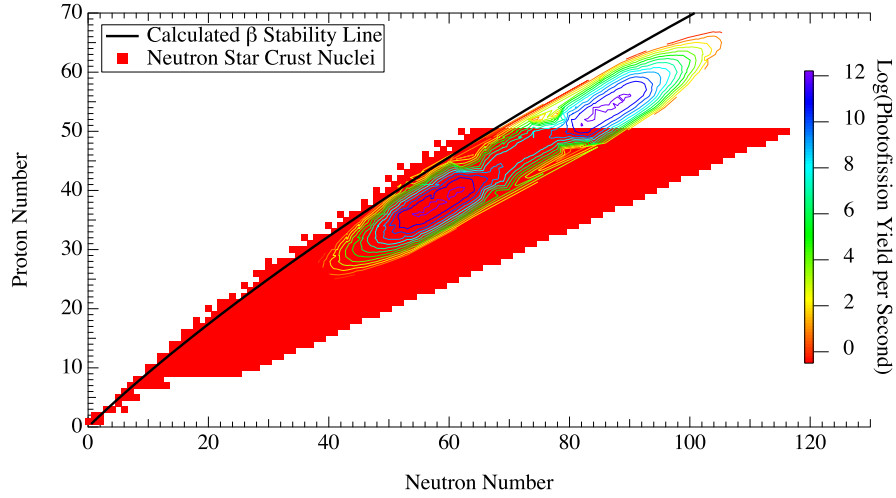


Figure 5: Contour plot of calculated photofission yields from the proposed electron linac superimposed on the nuclei included in a state-of-the-art neutron star crust calculation.

photofission would allow ISAC to push to the greatest extremes of neutron number accessible experimentally, thereby making the greatest impact on our understanding of neutron stars and the origin of the heavy elements.

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