# The FRIB Decay Station



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"Close collaborations between universities and national laboratories allow nuclear science to reap the benefits of large investments while training the next generation of nuclear scientists to meet societal needs." – [NSAC15]

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# **Executive Summary**

The Facility for Rare Isotope Beams (FRIB) will provide unprecedented access to exotic nuclei; approximately 80% of the isotopes predicted to exist up to uranium (Z = 92) will be produced. The FRIB Decay Station (FDS) — an efficient, granular, and modular multi-detector system designed under a common infrastructure — will be uniquely positioned for discovery experiments at the extremes of the accessible regions due to the high sensitivity and relatively low beam-rate requirements of decay spectroscopy techniques. In addition, for nuclei produced at higher rates, the FDS will be able to conduct high-precision measurements for thorough characterization of emergent phenomena, which can be used to benchmark and differentiate between leading models. The FDS will have a transformative impact on our understanding of nuclear structure, nuclear astrophysics, fundamental symmetries, and isotopes of importance to applications. The scientific program enabled by the FDS is well aligned with the overarching science goals that have been formulated by the broader nuclear science community, most recently outlined in the 2015 NSAC Long Range Plan. The FDS will contribute to the majority of the seventeen benchmark programs specified in the 2007 NSAC report "FRIB: Opening New Frontiers in Nuclear Science".

The scientific reach accessible through decay spectroscopy of isotopes produced at FRIB will be realized with a new generation of detectors at the FDS. The FDS will bring multiple complementary detection modes together in a framework capable of performing spectroscopy with multiple radiation types over a range of beam production rates spanning ten orders of magnitude. The performance of the FDS hardware and its reach for scientific output depends on the combined efficiency and sensitivity of the instrumentation. The newly developed FDS will surpass previous generation systems through improvements to combined efficiencies (by factors of approximately 10 for  $\beta n\gamma$  and 50 for  $\beta 2n 2\gamma$ ), granularity, background suppression, and resolution. This will increase the scientific output, reduce the rate requirements for many of the spectroscopic techniques, and extend the scientific reach towards the drip line. The FDS will require an infrastructure composed of modular multi-detector systems with the ability to measure nuclear decays and the resulting delayed emissions, which include charged particles, photons, and neutrons. At the core of the FDS is a system to stop the incoming exotic ions and detect subsequent charged-particle decay emissions. Additional detector arrays will surround this system to measure emitted photons, neutrons, or both. The exact configuration of the charged-particle, photon, and neutron detection arrays will be dependent on the specific science goals of each experiment, and it will be adaptable to optimize tradeoffs between energy resolution, time resolution, efficiency, and background. A few scientific highlights where the reach of FRIB will be sensitive to the combined efficiencies of the FDS include:

- <sup>60</sup>Ca region the heaviest nuclei for which the neutron drip line and effects related to weak binding and many-body forces can be studied. The proximity of the neutron drip line may also lead to the formation of exotic structures such as giant neutron halos and Efimov states.
- $^{100}$ Sn region the heaviest N = Z nuclei where the effects of proton-neutron correlations can be studied and where new types of nuclear condensates may form.
- Neutron-rich N = 82 and 126 regions the two regions near the limits of FRIB production where r-process simulations of the natural abundances of the elements reveal increased sensitivity to nuclear data input such as  $\beta$ -delayed neutron branching ratios, half-lives, and neutron-capture cross sections.

The total estimated cost range of the FDS is \$24-30M, which is based on a combination of budgetary quotes and actual costs from prior projects. Due to the inherent modular design, the FDS can be staged (e.g., three even portions of \$8-10M). This can be achieved by first developing the FDS mechanical infrastructure and then using equipment from existing, pastgeneration arrays until it can be replaced by new systems, increasing the resolution and combined efficiencies along the way. The FDS will include three new devices: (1) a large-volume HPGe array, "DEGA", (2) a neutron time-of-flight (TOF) array, "NEXT", and (3) a silicon-scintillator hybrid implant detector, "XSiS". These three workhorse devices constitute 78% of the total budget and represent a major advance over past generation detectors. They will be characterized by high resolution and efficiency, good background suppression, and granularity. For example, the efficiencies of DEGA, NEXT, and XSiS at 1 MeV will be factors of approximately 2, 6, and 2 larger, respectively, than past generation detectors. Combined efficiencies for  $\beta_{n\gamma}$  and  $\beta_{2n2\gamma}$  can be larger by factors of approximately 10 and 50, respectively. The energy resolution of NEXT will increase by up to a factor of 6 over the previous generation. The remaining detectors largely exist and require relatively minor upgrades (i.e., 9% of total budget) for compatibility with the new detector systems and FRIB beams. The remaining cost (13%) covers R&D and project engineering and management. Under a restricted budget scenario,  $2\pi$  versions of the new DEGA and NEXT arrays should be considered as a bare-minimum configuration of the FDS. This would reduce the total budget by \$7-9M to yield a new total budget of \$17-21M. However, this would reduce the science output of both discovery and precision studies for both proton-rich and neutron-rich nuclei. The FRIB Decay Station Working Group and members of the community recommend the nominal  $4\pi$  configurations of DEGA and NEXT as essential to achieve the full discovery potential.

# 1. Introduction and Overview

The Facility for Rare Isotope Beams (FRIB) will provide unprecedented access to exotic nuclei; approximately 80% of the isotopes predicted to exist up to uranium (Z = 92) will be produced [Erl12, Afa13]. *The FRIB Decay Station, which will be used to study the decay properties and structure of these isotopes, will have a transformative impact on our understanding of nuclear structure, nuclear astrophysics, fundamental symmetries, and isotopes of importance to applications.* 

The scientific program enabled by the FRIB Decay Station (FDS) is well aligned with the overarching science goals that have been formulated by the broader nuclear science community, see Table 1 [NSAC02, NRC13, NSAC RIB07, NSAC07, NSAC15]. These principal areas of investigation in nuclear science have been reaffirmed multiple times, most recently in the 2015 NSAC Long Range Plan [NSAC15]. A total of seventeen specific benchmark programs were specified in the NSAC report "FRIB: Opening New Frontiers in Nuclear Science" [NSAC RIB07] that are matched to the broad scientific questions in Table 1. *The FDS will contribute to the majority of the seventeen benchmark programs*.

**Table 1.** The seventeen benchmark programs determined by the NSAC Rare-Isotope beam Task Force [NSAC RIB07] are organized under the four priority questions in nuclear physics identified by the Nuclear Science Advisory Committee [NSAC15] and the National Academy of Sciences [NRC13]; The FRIB Decay Station will contribute to the majority of the benchmark programs (**listed in bold**).

Nuclear Structure	Nuclear Astrophysics	Fundamental Symmetries	Applications of Isotopes
How does subatomic	How did visible matter	Are the fundamental	How can the knowledge and technical
matter organize itself and	come into being and	interactions that are	progress provided by nuclear physics
what phenomena	how does it evolve?	basic to structure of	best be used to benefit society?
emerge?		matter fully understood?	
1. Shell structure	1. Shell structure	12. Atomic EDM	10. Medical
2. Superheavies	6. Equation of state	15. Mass surface	11. Stewardship
3. Skins	7. r-Process	17. Weak interactions	
4. Pairing	8. ${}^{15}O(\alpha, \gamma)$		
5. Symmetries	9. <sup>59</sup> Fe s-process		
6. Equation of state	13. Limits of stability	۲	
13 Limits of stability	15 Mass surface	j j	

The FDS is uniquely positioned to make crucial contributions towards discovery experiments at the extremes of the accessible regions, see FRIB beam rates in Figure 1. The high sensitivity and relatively low beam-rate requirements of the various decay spectroscopy techniques, which are outlined in Figure 2, enable decay measurements at the very limits of the production capabilities at FRIB. In addition, for nuclei produced at higher rates, the FDS will enable high-precision measurements for thorough characterization of emergent phenomena, which can be used to benchmark and differentiate between leading models.

16. rp-process

17. Weak interactions

The scientific reach accessible through decay spectroscopy of isotopes produced at FRIB will be realized with a new generation of detectors comprising the FDS. The FDS will bring multiple complementary detection modes together in an



**Figure 1:** FRIB fast-beam rates between  $10^{-4}$  and  $10^{5}$  pps, [FRIB]. Rates >  $10^{5}$  pps not shown.

efficient, granular, flexible, and modular framework capable of performing spectroscopy with multiple radiation types over a range of beam production rates spanning ten orders of magnitude. Measurements need to be as complete and efficient as possible, given the expected highly complex decay paths. Diverse types of decay emissions must be measured, including charged particles ( $\beta$ -decay electrons, conversion electrons, protons,  $\alpha$  particles, heavy ions),  $\gamma$  rays, and neutrons; many of these emissions must be detected in coincidence and with the highest-possible efficiency and resolution. Example decay chains that illustrate the challenging task ahead of the FDS can be found in Figure 3. To maximize the scientific output of

14. Weakly bound nuclei

15. Mass surface



**Figure 2:** Rate requirements for various decay-spectroscopy techniques [Nak17], assuming efficiences of 50% for  $\beta$  particles, 10% for  $\gamma$  rays, and 20% for neutrons. The FDS will reduce these rate requirements by increasing both individual and combined efficiencies.

the device, modular subsystems that are integrated in design are planned, which can be brought together in different combinations to perform a variety of measurements.

Further scientific breadth will come from the availability of stopped and reaccelerated beam species at FRIB; the FDS will have the flexibility, mobility, and robustness to move between several locations. In the majority of envisioned configurations, an active implantation detector will serve to detect the arrival of rare isotopes and their subsequent decays. The decaying rare isotopes will be surrounded by a sophisticated detector array for photons, neutrons, electrons, and charged particles. Although new subsystems are required, many of the individual components of the FDS and the techniques to use them have already been developed and refined over many years at numerous institutions. With the proper investment, these approaches will be efficiently adapted for experiments using the exotic beams delivered at FRIB. *The construction of the FDS will surpass previous generation systems through improvements to combined efficiencies (by factors of approximately for approximately for efficiencies (by factors of approximately for experiments)* 



**Figure 3:** Examples of  $\beta xn\gamma$  decay chains of new isotopes at the extremes (<sup>122</sup>Nb, <sup>129</sup>Ru), highlighting the unprecedented complexity of successive decays toward stability. The FDS must deploy a flexible and diverse system that is optimized for efficiency, granularity, background-suppression, time resolution, and energy resolution.

10 for  $\beta n\gamma$  and 50 for  $\beta 2n2\gamma$ ), granularity, background suppression, and resolution; this will increase the scientific output, reduce the rate requirements for many of the spectroscopic techniques listed in Figure 2, and extend the scientific reach towards the drip line.

The following section of this document highlights some of the scientific opportunities that can be pursued with the FDS. Subsequent sections describe the pre-conceptual design of the FDS and its constituent subsystems, locations, and funding profile.

# 2. Science Opportunities with the FRIB Decay Station

The FDS experimental program will focus on discovery measurements with the most exotic nuclei and precision measurements with nuclei produced at higher rates. The FDS will be used to pursue research in the four strategic areas of FRIB: nuclear structure, nuclear astrophysics, tests of fundamental symmetries, and applications of isotopes for society.

Several benchmarking science cases have been identified for the FDS, which constitute a challenging but realistic, compelling, and fruitful program at FRIB. These examples are representative of the science goals articulated in the FRIB mission, which will be enabled through the sensitivity of the FDS.

#### 2.1 How does subatomic matter organize itself and what phenomena emerge?

One of the scientific goals of FRIB is to experimentally profile and theoretically describe how nuclear structure emerges and evolves with the number of protons and neutrons, ultimately progressing towards a complete description of atomic nuclei. The combination of results from the FDS and theoretical descriptions of nuclei with predictive power and quantified uncertainties will enable scientists to address key questions:

- What are the boundaries of existence along the neutron (N) and proton (Z) axes?
- What is the microscopic foundation of nuclear shell structure and the emergence of shapes, and how do these evolve across the nuclear chart?
- Are there new phenomena in loosely bound nuclear systems?

A new generation of nuclear models has emerged as a result of efforts to apply ideas from renormalization group and effective field theories, amongst others, to the nuclear Hamiltonians and currents. This has been further catalyzed by the availability of unprecedented computing power to solve the nuclear many-body problem. These developments are also expected to make contributions in areas transcending nuclear structure physics, such as neutrinoless double- $\beta$  decay, r-process modeling, and reactor antineutrino anomalies. The FDS experimental program will guide and constrain state-of-the-art theory for the exotic isotopes produced at FRIB and it will also focus on the possibility of new phenomena that may emerge at the extremes of the nuclear landscape.

#### 2.1.1 Giant halos and continuum coupling effects

Progressing from stability to the edges of the nuclear chart will characterize shell evolution, continuum effects, and manybody forces. The calcium isotopes have been, and will continue to be, a unique laboratory to study these various effects as a function of the neutron-to-proton ratio, ranging from 0.7 to possibly beyond 2. Further, the Ca chain is accessible by theory using a range of methods including ab-initio, mean-field, and configuration-interaction models allowing for comparisons between theoretical treatments to identify key elements driving the observed structure.

The N = 40 <sup>60</sup>Ca region will be a key focus for investigations at FRIB. This is the heaviest region for which the neutron drip line and effects related to weak binding can be studied. The intersection of the Ca chain with the rapid structural changes occurring along the N = 40 isotonic chain also makes <sup>60</sup>Ca an ideal target to benchmark modern theoretical calculations of shell evolution against experimental data [Hag12]. The exact location of the g<sub>9/2</sub> neutron orbital, which naively starts to fill just beyond N = 40, the strength and nature of three-body forces, and the influence of weak binding should all contribute to the structure of <sup>60</sup>Ca. The proximity of the neutron drip line may also lead to formation of exotic structures; examples include a giant neutron halo, predicted by nuclear models (DFT) [Men02] in <sup>60</sup>Ca, and Efimov states in <sup>62</sup>Ca [Hag13]. Due to continuum coupling, the single-particle levels with low orbital angular momentum may cluster together in <sup>60</sup>Ca, and, if occupied by valence neutrons, could lead to an extended radius, making nuclei in this region possibly the heaviest and largest halo nuclei known. Beta-delayed, multi-neutron emission channels could be the dominating decay mode of nuclei in this region [Mar16, Mol03, Mie13, Mol19] — *a possible signature for a giant halo in <sup>60</sup>Ca may be the simultaneous and correlated emission of β-delayed neutrons. The FDS will be more sensitive towards this signature than previous generation systems by more than an order of magnitude.* 

#### Exploration of Exotic Phenomena Beyond <sup>60</sup>Ca

The recent observation of <sup>60</sup>Ca [Tar18] and the likely additional bound neutron-rich Ca nuclei, possibly up to N = 50, highlights a new region of the nuclear chart for exploration. The first check of theoretical predictions, beyond the existence of <sup>59,60</sup>Ca, will come through a half-life measurement of <sup>60</sup>Ca. High-efficiency, high-stopping power detectors are required to stop a high-energy beam of <sup>60</sup>Ca ions produced by FRIB, at a predicted rate of approximately 1 per hour, and record all subsequent  $\beta$  particles and conversion electrons. The reach of the FDS for half-life measurements extends beyond <sup>60</sup>Ca due to the high intensity beam provided by FRIB and high efficiency of the FDS; information on  $\beta$ -decay half-lives can be obtained at the limit of production capability down to rates of 10<sup>-4</sup>-10<sup>-5</sup> pps. Detecting the presence of multiple neutron emission can also be achieved with a high-efficiency thermal-neutron detector (e.g. based on <sup>3</sup>He counters). Measuring the delayed neutron branch will provide the first glimpse of the decay strength above and below the neutron separation energy in these isotopes.



**Figure 4:** (Left) Theoretical single-neutron levels predict clustering of orbitals near the Fermi level; this may lead to new phenomena beyond <sup>60</sup>Ca [Men02] (see also [Hag13]). (Right) Theoretical  $2_1^+$  energies of the Ca isotopes with and without 3N forces [Hol13].

Measuring correlations between the emitted neutrons, which can offer direct information on the wavefunctions of the emitting states [Dan87, Nym90], will require directional neutron detection capabilities from a large, highly-segmented neutron detector. Forming a complete picture of the decay strength and level structures of neutron-rich nuclei will require a flexible system capable of measuring states both above and below the neutron separation energy of the daughter isotope. Fast and discrete neutron detection in the desired energy range of 0.1 to 10 MeV can be achieved with neutron time-of-flight (TOF) arrays coupled with a fast, high-stopping power, moderate energy resolution implant detector. A next generation neutron array would improve the timing, energy, and spatial resolution and increase the overall neutron detection efficiency for  $\beta$ -delayed neutrons for states above the neutron separation energy. Furthermore, ensuring a faithful reproduction of the decay strength above the neutron separation energy requires a coincident HPGe array with high efficiency to tag the population of excited states in the A – 1 mass chain following  $\beta$ -delayed neutron emission.

The experimental methods implemented with <sup>60</sup>Ca will be relevant to investigations of all very neutron-rich nuclei at FRIB. The theory tools and models of nuclear structure tested in this region will be implemented in heavier mass regions of relevance for r-process nucleosynthesis. This is likely the heaviest region of the chart of nuclei where the effects of weak neutron binding energies can be studied in detail both by theory and experiment.

#### 2.1.2 Collectivity, deformation, and islands of inversion

Deformation is a universal feature of finite many-body quantum systems such as nuclei. It dominates the structure of nuclei that lack closed shells and it occurs in closed-shell nuclei as manifested by shape-coexistence phenomena [Hey11]. In certain mass regions, shape coexistence is well established as giving *rise to sudden changes in ground-state properties* when a more deformed and a less deformed structure switch their energy ordering. This occurs notably and widely in the neutron-deficient  $Z \sim 82$  (Pb) region; and very locally in the neutron-rich  $Z \sim 40$  (Zr) and  $N \sim 20$ , 28 regions. The latter regions have become known as "islands of inversion", where 'inversion' refers to the switch in energy ordering. A "map" of the occurrence of well-established shape coexistence is presented in Figure 5 [Hey11].



**Figure 5:** A map of well-established regions of shape coexistence [Hey11]. This phenomenon can give rise to sudden changes in the ground-state properties of exotic nuclei, particularly along "shell closures".

The occurrence of shape coexistence is currently understood at the microscopic level as the competition between structures dominated by independent-particle behavior in a spherical mean field and structures dominated by large correlation energies that are, consequently, deformed [Hey11, Lau16]. This extends to so-called intruder states in odd-mass nuclei near closed shells, where near-degenerate spherical and deformed states coexist [Hey11]. Some of the regions where there is a presence but lack of characterization of shape coexistence, notably neutron-rich nuclei in the N  $\sim$  20, 28, 50 regions, will be accessible at FRIB for more detailed and conclusive characterization. *One simple spectroscopic signature for islands of inversion will be rotational band energy patterns in regions expected to be spherical*.

There are very good guides to what has been achieved and what might be expected in the <sup>32</sup>Mg region [Ney11]. The N ~ 28 region around <sup>42</sup>Si [Bas07] and <sup>44</sup>S [Par17, For10, Che12] requires detailed spectroscopy to understand the character of the structures involved. Furthermore, there are some exciting new predictions for the <sup>78</sup>Ni region [Now16], as shown in Figure 6, which indicate the presence of a possible fifth island of inversion.

A particularly interesting circumstance is one where a nucleus has a low-energy excited  $0^+$  state. A few examples include <sup>74</sup>Kr [Cha97], <sup>186</sup>Pb [And00], and <sup>68</sup>Ni [Suc14]. There is a critical need to explore the incidence of low-energy excited  $0^+$  states in closed-shell nuclei, particularly those that are expected to have j = 1/2 orbitals near the Fermi surface because, through mixing and depression of the ground states, they can give rise to high first  $2^+$  state energies which can be misinterpreted as signs of subshell closures [Hey11]. This may have happened in <sup>52,54</sup>Ca and needs to be explored. In turn, <sup>60</sup>Ca can be expected to exhibit a "high" first  $2^+$  state as shown in Figure 4. *If the first excited state is a*  $0^+$  *state, conversion electron and internal-pair spectroscopy will be required.* 

A successful strategy for establishing unequivocal structure has been via the observation of seniority isomerism, which is a characteristic signature of nucleons in a spherical mean field. This has been used to demonstrate the survival of spherical shells in the neutron-rich N = 48, 80, and 82 isotones [Wat13] and the Z = 50 [Sim14] and 82 [Got12] isotopes. The issue of seniority dominance has also been recently addressed in the neutron-rich Ni isotopes [Maz05, Mor18], approaching <sup>78</sup>Ni.

It will be a worthwhile challenge to reach for information in the extreme neutron-rich nucleus  ${}^{62}$ Ca, which should exhibit a  $(1g_{9/2})^2$  seniority structure. Absence of isomerism that is followed by an 8-6-4-2-0  $\gamma$ -decay sequence would indicate either a breakdown of shell closure or the presence of low-energy intruder states that provide a faster decay path.

The FDS will search for hints of new structure towards the extremes of the accessible regions, e.g., towards beam rates of ~10<sup>-4</sup> pps. The FDS should be optimized for the simple signatures described above. *This will require, in part, highly efficient implant (implant, \beta, and E0), large-volume HPGe (\gamma ray), and neutron TOF (discrete neutron energy and channel selectivity) detectors. The furthest reach will depend upon the combined efficiencies of the array subsystems; doubling the efficiencies of two or more devices will significantly improve overall sensitivity.* 



**Figure 6:** Theoretical spectra with the PFSDG-U interaction at N = 50 [Now16], predicting <sup>78</sup>Ni as the portal to the fifth island of inversion.

#### Characterization of the Island of Inversion at N = 28

Detailed structure studies that establish an unequivocal view, e.g., of low-energy quadrupole vibrations [Gar18], at higher production rates are invaluable to our understanding of nuclear structure. The FDS will need the flexibility to handle both discovery and precision spectroscopy over several magnitudes of production rates. For example, states in  ${}^{42}$ Si (2p above  ${}^{40}$ Mg) will be populated through the  $\beta$  decay of  ${}^{42}Al$  and  $\beta$ -delayed neutron decay of  ${}^{43}Al$ , which will provide different selectivity to the excited states. The production rate of <sup>42</sup>Al is expected to be 6 pps (i.e., several orders of magnitude larger than that required for half-life measurements) with an expected  $\beta$ 0n branch of approximately 25% [Mar16]. Gamma-ray and conversion-electron spectroscopy can provide information on excitation energies and changes in spin-parity. Excited  $0^+$  states can be identified through  $\gamma$ - $\gamma$  angular correlations, large E0 transition strengths, and/or inferred through a lack of  $\gamma$  decay to the ground state. Level lifetimes can be extracted from a combination of fast electron and photon detectors using either the slope fitting method or centroid shifts to access lifetimes greater than a few picoseconds. The same experimental techniques applied to the N = 28 region are equally well suited to study heavier mass nuclei. The improved access to heavy, neutron-rich, rare isotopes provided by FRIB will greatly extend the reach of coexistence investigations. Consequently, GeDSSD, XSiS, n-TOF (NEXT), HPGe (DEGA), and LaBr<sub>3</sub>/CeBr<sub>3</sub> detectors are required for these measurements.

#### 2.1.3 Proton-neutron correlations and N = Z nuclei

Unstable isotopes with an equal number of protons and neutrons are unique systems where the proton-neutron correlations are expected to imprint on the properties of nuclei. The proximity of the drip line introduces opportunities to study threshold effects and rare decay modes. The large decay  $Q_{\beta}$  values enable access to highly excited states. A diverse spectrum of phenomena can be studied along the N = Z line at FRIB. Below <sup>100</sup>Sn, a new range of nuclei with N < Z can be accessed up to the proton drip line. Isospin effects can be studied experimentally for nuclei between Ca and Sn in the presence of strong and rapid structural changes [Sat16]. Nuclei with sizeable proton-neutron asymmetry can be reached such as doubly-magic <sup>48</sup>Ni, where Z / N = 1.4. The key interest in this region is to establish the role of proton-neutron interactions [Fra14], which are suppressed in heavy N > Z nuclei. One of the rarest of decay modes, two-proton emission, occurs in this region of the nuclear chart for <sup>45</sup>Fe, <sup>48</sup>Ni, <sup>54</sup>Zn and, recently discovered, <sup>67</sup>Kr [Goi16, Wan18]. Two-proton correlations are thought to reflect the structure of the decaying nucleus [Gri03].



**Figure 7:** Numerous phenomena relevant to nuclear structure and astrophysics converge at <sup>100</sup>Sn, which is expected to be a double-magic nucleus.

<sup>100</sup>Sn is the heaviest N = Z doubly magic nucleus, and it is a crucial reference nucleus for benchmarking first-principles based nuclear theories [Mor18b] before they can be implemented for more complex systems. Its  $\beta$  decay has the largest observed transition matrix element [Hin12], and its precise determination and interpretation is one of the critical experimental challenges for experiment and theory, respectively. The FDS paired with FRIB rates in this region will enable studies with unprecedented detail, and it will address multiple experimental challenges such as  $\beta$ -decay strength distributions and  $\beta$ -delayed and direct proton emissions. A peculiar type of isomerism, which involves proton-neutron interactions in spherical nuclei, has been observed in nuclei near <sup>100</sup>Sn. It expands the concept of seniority isomerism into cross-shell excitations generating spin-gap isomers [Bla04, Nar11, Dav17]. Such isomers need further inquiry, but they could provide simple signatures for the survival of spherical shells beyond the limits of stability.

Decay studies at FRIB will complete the mapping of the proton-unbound landscape for nuclei up to lead and establish the decay modes of nuclei at the drip line, providing a stringent test of nuclear models. The ordering of single-particle levels and the evolution of shapes in the proximity of the proton drip line influence the separation energies as well as the decay modes. This region is well known for its long-lived proton emitters in spherical and deformed nuclei [Bla08].



#### Direct and Delayed Charged-Particle Emission Near the Proton Drip Line

The decay of <sup>104</sup>Te and <sup>108</sup>Xe are expected to elucidate the mechanism of nuclear clustering through superallowed α decay [Mac65, Aur18]. Furthermore, <sup>103</sup>Te is predicted to be a candidate for two-proton emission, which would make it the heaviest 2p emitter to be discovered [Ols13]. High production rates of lighter 2p emitters <sup>45</sup>Fe, <sup>48</sup>Ni, <sup>54</sup>Zn and <sup>67</sup>Kr will enable detailed studies of proton-proton correlations for spherical and deformed nuclei. Betadelayed proton spectroscopy is a rich source of nuclear structure information with strong relevance to nucleosynthesis in accreting systems [Sch01].

The experiments at FRIB will focus on charged-particle spectroscopy combined with high-resolution and total absorption  $\gamma$ -ray spectroscopy. Precision spectroscopy of charged-particle decays will be achieved with segmented semiconductor detectors. Fast decays can be investigated with newly developed segmented scintillator arrays.

Particle-particle correlations can be measured with the use of particle-tracking detectors, e.g. time-projection chambers. Gamma-ray spectroscopy with high-resolution arrays will identify decay modes of bound and unbound states following  $\beta$  decay. Total absorption spectroscopy will establish accurate absolute branching ratios.

Studies of N = Z < 50 nuclei overlap with nuclear astrophysics through the rp-process, and hydrogen and helium burning. Decays of odd-odd N = Z nuclei have been traditionally used to test the unitarity of the CKM matrix. Superallowed  $\alpha$  decay addresses the phenomenon of clustering in nuclear matter.

#### 2.1.4 Search for axial and reflection asymmetric shapes

Collective shape degrees of freedom have been a major direction in the study of the nuclear finite many-body problem. A leading challenge has been to experimentally establish regions of triaxial deformation (axial asymmetry, squashed American football) and octupole deformation (reflection asymmetry, pear shape). There is widespread evidence for quadrupole deformation, primarily of large prolate spheroidal deformation with axially symmetric rotor degrees of freedom. This naturally leads to the question of whether or not axially asymmetric or reflection asymmetric rotor degrees of freedom are exhibited by any nucleus. With respect to best cases for observation of axially asymmetric shapes, two regions stand out. The first is the Os-Pt region where a seminal Coulomb-excitation study by Wu et al. [Wu96] was carried out on the stable isotopes  $^{186,188,190,192}$ Os and  $^{194}$ Pt. The second is the neutron-rich Zr-Mo-Ru region where low-energy  $2_2^+$  states are consistent with such an interpretation [Mol06, Mol08, Wat11, Pau17, Jan17, Doh17]. With respect to best cases for observation of reflection asymmetric shapes, two regions also stand out, namely northeast of <sup>132</sup>Sn and <sup>208</sup>Pb where orbitals differing by both j and  $\ell = 3$  are near the Fermi surface [Sco80, Gaf13, Buc16, Mit16, Buc17]. FRIB will provide access to a number of new regions where deformed asymmetric shapes are predicted [Mol06, Mol08]. Decay spectroscopy will serve two purposes for these new regions: (1) search for new asymmetric shape candidates towards the extremes of the accessible regions through the identification of low-lying  $2_2^+/3_1^+$  and  $1_1^-/3_1^-$  states and (2) provide guidance and detailed spectroscopic input closer to stability for subsequent Coulomb-excitation studies which rely on such information to extract E2/E3 matrix elements through the use of reaccelerated beams. The first will involve discovery/first spectroscopy and the second will involve precision spectroscopy; HPGe and neutron TOF detectors with high efficiency, granularity, and backgroundsuppression are critical for such studies. Furthermore, fasting timing  $\gamma$ -ray detectors such as those made from LaBr<sub>3</sub> and CeBr<sub>3</sub> will be able to provide lifetimes for many of the excited states, which will establish or constrain several E2 and E1 transition matrix elements.

Axial and reflection asymmetric shapes in open-shell nuclei are also connected to astrophysics in that they can influence the ground-state mass [Mol06] and, consequently, abundance calculations. Furthermore, searches for octupole deformation have considerable overlap with permanent electric dipole searches, which would indicate physics beyond the Standard Model (discussed in Section 2.3.2).

#### 2.2 How did visible matter come into being and how does it evolve?

Decay data are paramount to astrophysics simulations that attempt to describe the natural abundances of the elements and the FRIB Decay Station has the opportunity to play a pivotal role on this frontier. The measurements of key resonances on proton-rich nuclei, or lifetimes and branching ratios on neutron-rich nuclei can be used directly as input data. Other data can be used to constrain the nuclear models used to interpolate and extrapolate data not experimentally accessible. Example regions where decay data will have high-impact on r-process simulations are illustrated in Figure 8 with dark colors, which are concentrated near exotic shell closures and include "transitional" nuclei. The  $\beta$ -delayed neutron branching ratios and half-lives of these influential nuclei will be measured by the FDS and used as direct input to r-process simulations. The neutron-capture cross sections will be constrained using decay data. Many of the influential nuclei are near the beam-rate limits of decay spectroscopy techniques; access to these nuclei will be sensitive to the combined efficiencies of the FDS.



**Figure 8:** Nuclei of importance for the final r-process abundances in the astrophysical conditions of a neutron star merger [Mum16a]. More influential nuclei are shaded darker. The reach of FRIB is indicated by the black lines, which represents  $10^{-4}$  pps.

"A study of these reactions, and of the decay and structure characteristics of the nuclei along the reaction path, provides fundamental insight into the nature of these processes, the rapid timescale of the explosion, the associated energy release, and, of course, nucleosynthesis." – [NSAC15]

#### 2.2.1 β-decay properties and r-process nucleosynthesis

 $\beta$ -decay properties are key inputs for calculations of rapid neutron capture (r process) nucleosynthesis. With the recent discovery of the neutron star merger gravitational wave event, GW170817, and its associated kilonova [Abb17, Abb17b], there is dramatic confirmation that at least some r-process elements can be made in mergers. However, many open questions remain, including the nature of the nucleosynthetic sites within the merger, and whether mergers can account for the galactic production of all r-process elements. Definitive answers require a reduction in the uncertainties entering r-process calculations. When there are no direct experimental input data, different theoretical approaches can be used, but they often lead to different r-process abundance predictions as illustrated in Figure 9 [Sha16].



**Figure 9:** Comparison of predicted r-process abundances in hot, cold, and neutron-star-merger environments [Sha16] for various theoretical structure inputs. The FDS will provide experimental input and constrain theoretical input.

Half-lives control the reaction flow to higher mass, setting the timescale to reach the heaviest elements and determining the relative abundances of the isotopic chains. During the late stages of the r process,  $\beta$  decay competes with neutron capture to govern the decay back to stability and to set the final pattern of abundances. Beta-delayed neutron emission becomes particularly important later by controlling the availability of neutrons for late-time captures and shaping fine abundance pattern features. Finally,  $\beta$  decay contributes to powering any associated kilonova.

A neutron-star-merger r process may populate nuclei out to the neutron drip line, which may not be experimentally accessible for heavy nuclei. Thus, other information is desirable to inform and drive improvements in theoretical approaches. Here, half-lives are not sufficient: a program to map out  $\beta$ -strength functions in key regions of the nuclear chart is required. Neutron capture rates can be inferred in neutron-rich nuclei using  $\beta$  decay [Spy14, Esc16] to populate high-energy states in daughter nuclei and watching the subsequent deexcitation. Furthermore,  $\beta$ -delayed neutron emission probabilities  $P_n$  are needed; only a handful of such measurements are available, and many have large uncertainties. Because  $P_n$  values are most important at late stages of the r process, when the nuclear flow is not so far from stability, dedicated FRIB campaigns will make a major impact in reducing these uncertainties.

The FDS will be able to reach and target much of the needed input data for r-process simulations such as half-lives,  $\beta$  strength functions,  $\beta$ -delayed neutron emission probabilities, and neutron capture rates using the exotic beams produced at FRIB.

#### **Complete Decay Measurements of r-Process Nuclei**

FRIB will provide access to the vast area of nuclei which have been listed in previous sensitivity studies as critical for modeling of the r process in various astrophysical scenarios (see Ref. [Mum16a], Figure 8, and Figure 9). Half-life measurements will focus on key bottleneck regions of the r process, e.g., in the regions of the N = 50, 82, and 126 closed shells. Beta-decay half-lives and  $\beta$ -decay strength-function measurements will be performed to provide direct experimental input, where possible, and to validate the theoretical models that are used to predict the nuclear properties of unavailable isotopes. As examples, along the N = 82 and 126 closed shells, half-life measurements will be possible out to the region around <sup>122</sup>Mo and <sup>194</sup>Er; four and 26 neutrons further from the most neutron-rich Mo [Lor15] and Er [Wu17] isotopes, respectively, measured to date.

The neutron-capture rates needed for astrophysical abundance calculations are difficult to obtain due to the fact that neither the nucleus of interest nor the neutron itself are sufficiently long-lived to be formed into a target for direct measurements. As a result, indirect techniques are necessary to provide experimental constraints on neutron capture rates [Esc16]. One such indirect technique uses  $\beta$  decay [Spy14], combined with a large total absorption spectrometer, to infer the population of excited states in a daughter isotope and the subsequent photon emission. The increased production rates at FRIB for nuclei along the N = 82 shell closure are required to continue these studies in a region of direct relevance to nuclear astrophysics. The competition between direct and statistical neutron capture could be explored in heavier mass nuclei by combing the  $\beta$ -decay data with complementary reaction-based measurements in selected nuclei.

Beta-delayed neutron and  $\gamma$ -ray emission are prevalent decay modes for the r-process nuclei. Several of the most important r-process nuclei are expected to emit an average of two or more neutrons [Mum16]. Lifetime measurements can be achieved with high-efficiency segmented charged-particle detectors, e.g., low-resolution, high-efficiency scintillator (Z < 50) and semiconductor (Z > 50) detectors. The critical element for these studies is a hybrid neutron- $\gamma$  array. For measuring branching ratios, efficient and granular neutron and  $\gamma$ -ray counters are needed. When more detailed spectroscopy is required to understand the underlying structure, discrete neutron and  $\gamma$ -ray detectors are required. An efficient and high-resolution  $\gamma$ -ray system is also required for reconstruction of the decay paths.

Measurements of r-process nuclei are also of critical importance to nuclear structure studies. Therefore, rprocess oriented experiments will simultaneously aim for detailed spectroscopy to maximize the science output for each measurement. Exotic r-process nuclei in their ground and isomeric states provide an opportunity to search for new nuclear structure phenomena.

#### 2.2.2 Explosive hydrogen and helium burning, p and rp processes

While neutron-rich heavy elements are synthesized in the s and r processes, there are a number of stable nuclei that are shielded against these processes by the valley of stability. These nuclei are commonly referred to as the p-nuclei. They are synthesized by the p process, sometimes referred to as the  $\gamma$  process, which is a complex network of ( $\gamma$ ,p), ( $\gamma$ ,n), (n,p) reactions, and  $\beta$  decays that occur on s- and r-process seed nuclei [Bur57, Arn03]. The nucleosynthesis is driven by ( $\gamma$ ,n) reactions to the proton-rich side of stability where the reaction flux is maintained by ( $\gamma$ ,p) and ( $\gamma$ , $\alpha$ ) reactions until these isotopes  $\beta$  decay back toward stability. The exact site of the p process is still under debate [Arn03, Tra11, Rau13], though it is understood that temperatures between 1.5 - 3.5 GK are required for p-process nucleosynthesis to take place [Arn03].

Another important reaction network also takes place on the proton-rich side of stability: the rapid proton-capture process, or rp process. The rp process is a network of  $(p,\gamma)$ ,  $(p,\alpha)$ ,  $(\alpha,\gamma)$ , and  $\beta^+$  decays that occur in hydrogen-rich environments at  $T \ge 0.3$  GK, and it is thought to occur in accreted hydrogen layers on neutron stars, resulting in X-ray bursts [Wor94]. In these explosive environments, the rp process pushes nucleosynthesis towards the proton drip line ending near A ~ 100 [Jos10]. While this material is not ejected from the neutron star, nucleosynthesis during the rp process is important for explaining the X-ray burst light curve [Cyb16] and the composition of the neutron star crust, which in turn impacts other observables used to diagnose the nature of dense matter [Mei18].

Modeling the abundances of the p-process nuclei or the shapes of X-ray burst light curves requires large reaction network calculations. These calculations require a wealth of nuclear data input relating to half-lives, masses, spins, parities, isomers,

particle capture reactions, particle decays, and more. Thermonuclear reaction rates involving low level densities depend on the energies, lifetimes, and branching ratios of individual resonances. Reactions involving high level densities are modeled with Hauser-Feshbach theory, which requires particle potentials, level densities, as well as  $\gamma$ -strength functions [Rap06, Arn03].

Sensitivity studies have been performed for both the rp and p process [Wor94, Rau02, Rap06, Par08, Par09, Tra11, Cyb16, Sch17]. Looking specifically at X-ray bursts, there are several astrophysical parameters that can be tuned to understand the X-ray burst light curves. However, it has been shown that uncertainties in the nuclear physics input from the large reaction network, as well as ashes from previous bursts, contribute to variations in structures of the X-ray burst light-curve [Cyb16, Mei17]. The  ${}^{15}O(\alpha, \gamma){}^{19}Ne$ ,  ${}^{59}Cu(p, \gamma){}^{60}Zn$ , and  ${}^{59}Cu(p, \alpha){}^{56}Ni$  reaction rates are amongst the most dominant uncertainties.

FRIB will provide opportunities to measure critical nuclear properties for modeling the p and rp processes using radioactive decays [Rap06, Jos10]. Many of the reaction rates that are influential in astrophysical processes cannot be measured directly at present. The  $\beta$ -Oslo technique could constrain  $(n,\gamma)/(\gamma,n)$  and  $(p,\gamma)/(\gamma,p)$  reactions across the nuclear landscape [Spy14, Esc16]. Charged particle,  $\gamma$ -ray, and X-ray emissions following the decays of <sup>20</sup>Mg and <sup>60</sup>Ga could be used to determine resonance properties in the <sup>15</sup>O( $\alpha, \gamma$ )<sup>19</sup>Ne, <sup>59</sup>Cu(p,  $\gamma$ )<sup>60</sup>Zn, and <sup>59</sup>Cu(p,  $\alpha$ )<sup>56</sup>Ni reactions [Wre16, Har76]. Therefore, the FDS needs to be capable of detecting multiple radiation emission types such as  $\beta^-$  and  $\beta^+$  particles,  $\gamma$  rays, and characteristic X-rays emitted after electron capture.

#### 2.2.3 β-decay rates: predicting nuclear properties for unknown territories

A fundamental quantity in the  $\beta$  decay of exotic isotopes is the  $\beta$ -decay strength distribution which defines the overlap, and thus the  $\beta$ -decay intensities, between an initial parent nucleus and all states in the daughter nucleus, see Figure 10. The  $\beta$ strength function is a critical component in the description of  $\beta$ -decaying nuclei. The distribution itself is intimately tied to nuclear structure and changes as a function of neutron and proton number. The predominant transitions of interest in neutronrich nuclei are Gamow-Teller (GT) transitions in which the neutrino and electron carry zero or one unit of spin from the nucleus. This process imposes a very rigid spin selectivity on the nuclear transformations, herewith providing a very clean and elegant probe of nuclear structure effects. First-forbidden transitions also play a role in exotic nuclei, but their inclusion in theoretical models is not yet ubiquitous. Many nuclei relevant to astrophysical processes cannot be synthesized and studied in a laboratory. Reliable theories that are calibrated or verified with experimental data will be required.



**Figure 10:** Schematic of  $\beta^2$  decay and the role of the strength distribution and phase space on the observed intensity.

The  $\beta$ -decay strength function is directly related to the nuclear half-life needed for astrophysical calculations. The percentage of strength to states above various separation energies defines the maximum possible  $\beta$ -delayed nucleon emission probabilities, though other effects may lower these values significantly [Mum16, Yok18]. Accurate predictions of  $\beta$ -decay strength functions in exotic regions, thus, for example, define the overall timescale of the r process and the availability of late-time neutrons following  $\beta$ -delayed neutron emission at the end of the process.

Experimentally determined GT transition strengths are typically smaller than theory predicts requiring renormalizations called GT quenching [Ber82, Eri73, Ose79, Tow79]. Ab-initio calculations, up to the  $A \sim 40$  region, suggest GT quenching

is one of the most fundamental problems of nuclear physics, and its roots are sought in the deficiencies of nuclear models [Men11], the role of the form of the GT operator [Eks14], or even by invoking intra-nucleonic excitations [Gro83]. These first principle approaches have been tested in light nuclei, but they have to be implemented for heavier and more complex systems where robust calculations are needed, e.g., for r-process nuclei. The unique case of very strong GT decay of <sup>100</sup>Sn will be explored and precise measurements of the decay strength distribution will be able to verify the validity of the current understanding of the GT quenching. The access to heavy nuclei with N < Z will allow to study states in daughter nuclei populated in both Fermi and Gamow-Teller transformations and allow to investigate the persistence of mirror-symmetry near <sup>100</sup>Sn. Extreme sensitivity of particle-detection techniques will enable measurements of very exotic  $\beta$ -delayed proton emitters.

#### Beta-Decay Measurements to Constrain Nuclear Theory for Astrophysical Processes

The  $\beta$ -decay strength near double-magic nuclei with very large  $Q_{\beta}$  values will be measured on both the proton- and neutron-rich sides of stability. The neutron-rich nuclei  ${}^{68-78}$ Co,  ${}^{132}$ In, and beyond will be used in comprehensive experiments, as will proton-rich nuclei near and beyond  ${}^{100}$ Sn.

Discrete particle- and neutron- $\gamma$  coincidence spectroscopy is required for p- and n-rich nuclei, respectively; e.g., for identifying decay paths and precise addition of neutron and  $\gamma$ -ray energies. Total absorption spectroscopy measurements are required to establish the absolute  $\gamma$ -decay contribution to the strength distribution, particularly for high-Z isotopes.

A significant theory effort is committed to predict nuclear matrix elements for neutrinoless double-beta decay  $(0\nu\beta\beta)$ , which can be linked to the GT operator for single  $\beta$  decay [Shi18]; observation of  $0\nu\beta\beta$  will be direct proof that neutrinos are their own antiparticles. Several advanced studies are actively searching for  $0\nu\beta\beta$  near the valley of stability. The contribution of FRIB is through a better understanding of  $\beta$ -decay properties on a fundamental level. The decay rate for this process is proportional to the square of a nuclear matrix element and it has to be calculated with high accuracy [Bro14]. Beta-decay measurements will serve to validate the theory and help constrain the calculations.

# **2.3** Are the fundamental interactions that are basic to the structure of matter fully understood?

Decay studies can be performed for specific nuclei to test fundamental interactions and search for new physics beyond the Standard Model of particle physics. Precision  $\beta$ -decay studies, for example, probe some of the same electroweak physics as the LHC, although at much lower energies. Such experiments typically require large quantities of the isotope of interest to collect sufficient statistics for high-precision measurements. In addition, many of these experiments will require stopped beams where the experimental conditions can be well controlled and systematic effects can be minimized. Four example topics include tests of CKM unitarity, structure of the electroweak interaction, permanent Electric Dipole Moment (EDM) searches, and the reactor antineutrino anomaly. The implementation of "commensal/parasitic beams" at FRIB would be ideal for many of these studies.

Investigations of the first two topics (i.e., tests of CKM unitarity and structure of the electroweak interaction) will depend on components of the FDS but will likely require more specialized and dedicated setups; only a few details will be given. Investigations related to the reactor antineutrino anomaly and permanent EDM will be directly enabled by the FDS, and these topics will be discussed in more detail.

The CKM unitarity test, tests of the conserved-vector-current hypothesis, and searches for an intrinsic scalar contribution to the electroweak interaction current could all be improved through detailed determination of the log(*ft*) values of a wider variety of superallowed 0<sup>+</sup> to 0<sup>+</sup>  $\beta$ -decay transitions, such as in the decays of <sup>20</sup>Mg, <sup>24</sup>Si, <sup>28</sup>S, and <sup>32</sup>Ar. Additional tests of the structure and symmetries that arise from the Standard Model description of the unification of the electromagnetic and weak nuclear forces can be performed through detailed studies of  $\beta$ -decay angular correlations. Measurements of  $\beta$ -neutrino angular correlations require determining the recoil momentum imparted to the daughter nucleus following  $\beta$  decay. In some cases, this momentum can be determined from the kinematic shifts imparted to  $\gamma$  rays or protons emitted following the  $\beta$ decay. For these experiments, the FDS detector systems could provide the desired segmentation and efficiency that, when paired with stopped FRIB beams and other instrumentation (e.g., traps), could enable some of the most sensitive tests and searches for new physics.

#### 2.3.1 Neutrino physics and the reactor antineutrino problem

Decay spectroscopy provides critical information needed to understand neutrino physics; its origin and evolution have been inseparable from  $\beta$ -decay studies [Fer34]. While various aspects of neutrino physics are now viewed as independent subfields, strong connections with  $\beta$ -decay studies remain. Two recent connections between  $\beta$ -decay and antineutrino physics are the so-called reactor antineutrino anomaly and reactor antineutrino shoulder anomaly [Mue11, Men11b, Hub11, Dwy15]. The discrepancy between the measured reactor neutrino flux and its predicted value has led to many hypotheses, including physics beyond the Standard Model [Sch80, Moh80, Kop11, Giu13, Bra12]. In particular, the possibility of a new fourth generation (sterile) neutrino has been introduced to explain the discrepancy.

Incomplete or inaccurate nuclear data is one possible source of the reactor antineutrino anomaly, as illustrated in Figure 11. FRIB will produce all neutron-rich nuclei contributing to the reference antineutrino flux in nuclear reactors. Calculating the flux of antineutrinos from a reactor is a challenging task. The predicted flux is calculated in three primary ways: the conversion method [Men11b, Hub11], the summation (or cumulative) method [Fal12, Son15], or a mixture of both [Mue11]. For example, the summation method involves measuring individually the  $\beta$  decay of each fission product, and then organizing fission products by fuel type to predict the antineutrino flux. While each fuel type has over 800 fission products, the dominant fission branches are much less numerous [Dwy15, Son15]. Unfortunately, the  $\beta$  decay of most individual fission products is currently not measured well. Due to a systematic bias in  $\beta$ -feeding intensities measured with low-efficiency  $\gamma$  detectors, the so-called 'pandemonium effect' [Har77], the measured  $\beta$ -decay feeding to low-lying excited states is consistently overestimated. This leads to an overestimation of the antineutrino sinteracting with the detector (i.e., due to the strong energy dependence of the cross section, there is a 1.8-MeV threshold and higher energy antineutrinos have a larger cross section in antineutrino detectors [Str03]). In addition to this bias,  $\beta$ -decay feeding directly to the ground state in the daughter nucleus can be either overestimated or underestimated, if measured at all, in the current nuclear data, and this can result in either an increase or decrease in the antineutrino energy emitted during  $\beta$  decay.



**Figure 11:** Calculated <sup>142</sup>Cs antineutrino energy spectrum for MTAS data (black) compared with the expected antineutrino energy from the latest ENSDF data (cyan). Notice the large increase of antineutrinos with energy below the inverse  $\beta$ -decay detection threshold of 1.8 MeV when compared to the ENSDF data [Ras16].

Beyond the reactor antineutrino anomaly, there is also an anomalous spectral shoulder in all of the measured reactor antineutrino energy spectra [An17, Ahn12, Abe14]. This shoulder shows an excess of counts around antineutrino energies ranging from 5 to 7 MeV. The source of this shoulder is not known [Hay15, Son16]. Since the reactor antineutrino shoulder is at higher energy, there is a possibility that forbidden  $\beta$  transitions in many fission products with large  $\beta$ -decay Q values, e.g., in the regions from As to Mo and Sn to Ce, sum to create the bump; this is supported by a recent shell-model study [Hay18]. FRIB will be the place to study the exotic  $\beta$  decays required to understand the reactor antineutrino shoulder.

An efficient way to measure complete  $\beta$ -decay feedings accurately is to use a segmented total absorption spectrometer (TAS). TAS measurements have near 100% total  $\gamma$ -ray efficiency, which makes it possible to detect high-multiplicity decays

from levels populated during  $\beta$  decay [Sim13, Kar16, Mon13]. There are several recent examples of total absorption spectroscopy with fission products [Alg10, Zak15, Ras16, Ras17, Fij17]; the results in general have greatly modified the  $\beta$ -feeding patterns. Many of the TAS measurements will benefit from initial surveys with discrete neutron and  $\gamma$ -ray spectroscopy, which enable a more reliable deconvolution of the absolute  $\beta$ -decay feeding.

FRIB will be capable of producing all of the important nuclei that contribute to the reactor antineutrino anomaly and reactor antineutrino shoulder. By employing total absorption spectroscopy and discrete  $\gamma$ -ray and neutron spectroscopy as a component of the FDS, it will be possible to constrain the decay data sufficiently to confirm or disprove the reactor antineutrino anomaly and high-energy shoulder. This effort will simultaneously provide much of the decay data needed to determine the decay heat in neutron-rich nuclei (discussed in Section 2.4).

#### 2.3.2 β-decay input to permanent EDM searches

The present charge conjugation-parity (CP) or time-reversal (T) symmetry violation included in the Standard Model, i.e., through a phase in the CKM matrix, is insufficient to account for the matter-antimatter asymmetry of the universe [Din03]. Therefore, new sources of CP violation beyond the Standard Model must be found. One promising avenue is to search for a permanent electric dipole moment (EDM), which would be a signature for CP or T violation [Eng13].

The best EDM limit set to date is for the spherical nucleus <sup>199</sup>Hg [Gra16]. Such limits set invaluable constraints on extensions of the Standard Model. Furthermore, many-body effects of nuclei may enhance CP violation [Fla85]. In particular, octupole deformation (reflection asymmetry, pear-like shape), which generates closely spaced parity doublets connected by E1 transitions, can lead to a larger CP-violating Schiff moment, which can then induce a larger atomic EDM [Aue96]. In fact, nuclei with octupole deformation may enhance the sensitivity to sources of CP or T violation by factors of 100-1000 over more spherical nuclei like <sup>199</sup>Hg [Spe97, Dob05, Eng13]. Consequently, the nuclear octupole deformation must be known, which can be measured with multi-step Coulomb excitation (see recent example with <sup>220</sup>Rn and <sup>224</sup>Ra [Gaf13]). However, multi-step Coulomb-excitation studies are nominally dependent upon spectroscopic input (spins, parties, branching ratios, multipolarities, lifetimes), which are often supplied from radioactive decay studies. *The FDS will provide the spectroscopic input required for EDM searches, and it will scout the landscape for new candidates with even greater octupole deformation, further enhancing the sensitivity to an EDM.* 

"Heavy radioactive atoms hold promise in the search for an electric dipole moment, one of the crucial probes for physics beyond the Standard Model. This is expected to have a very weak signal, but an enhancement of order 100-1000 (or more) is possible in nuclei that have pearlike shapes, such as  $^{225}Ra$ . One of the near-term goals of the field is to identify the best candidates for enhancement and characterize their structure." – [NSAC15]

#### Searches and Characterization of EDM Candidates

Observation of a permanent EDM would indicate CP or T violation and physics beyond the Standard Model. Atomic nuclei with large octupole deformation provide enhanced sensitivity to sources of CP or T violation [Spe97, Dob05, Eng13].

Precision studies of nuclei such as <sup>221,223</sup>Rn, <sup>221,223</sup>Fr, <sup>225</sup>Ra, and <sup>229</sup>Pa will be targeted with the FDS due to the anticipated Coulomb-excitation program to measure E1, E2, E3 matrix elements with GRETA at ReA-FRIB. The low-lying level schemes of these complicated nuclei are poorly known. Both even-even and odd-mass nuclei in the general region northeast of <sup>208</sup>Pb will be surveyed for large octupole deformation; a search for low-lying 1<sup>-</sup> and 3<sup>-</sup> states in even-even nuclei would provide the simplest place to start. While decay studies will often be limited to relatively low-spin states, such states near the ground state are often the most important for constraining the ground-state deformation needed for setting an EDM magnitude or limit. FRIB will be able to deliver intense fast and stopped beams of these species.

The FDS will need a diverse set of detector subsystems to determine spins, parties, branching ratios, multipolarities, and lifetimes. Such measurements are extremely demanding and will require an efficient, granular, high-resolution  $4\pi \gamma$ -ray array with sensitivity at low energy, granular conversion-electron and charged-particle detectors, fast timing capabilities, and more. The envisioned FDS will enable searches and characterization of EDM candidates.

# 2.4 How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?

The FDS enables several opportunities to contribute more directly to society. A few example topics include nuclear medicine, stockpile stewardship, reactor monitoring, and reactor decay heat. The implementation of "commensal/parasitic beams" at FRIB would be ideal for many of these studies.

Radioactive isotopes that decay through  $\beta$  and  $\alpha$  emission have long been employed in various applications of nuclear physics. Radioisotopes are used in medicine for both diagnostic imaging and radiation therapy; see the review by Nichols [Nic12]. Quantifying the therapeutic benefit and radiation dose delivered to patients from potential medical radioisotopes often requires very accurate data. The FDS will be capable of such high-precision measurements of medical radioisotopes and it will bring resolution to any emergent discrepancies. A recent example involves determining the absolute <sup>82</sup>Sr decay rate [Gro12] where post-acceleration was used to enable ion counting, allowing the absolute decay branching ratios to be determined with high precision.

The radiation emitted from fission products provides vital information used for science-based stockpile stewardship, nuclear forensics, and nuclear nonproliferation. In many cases, the quantity and distribution of fission products is determined through  $\gamma$ -ray spectroscopy, which requires a detailed understanding of the  $\gamma$ -ray cascades and intensities using both total absorption and discrete spectroscopy. Independent and cumulative fission-product yields are also determined using  $\gamma$ -ray spectroscopy. The FDS detector systems, together with the high-intensity beams of neutron-rich isotopes produced at FRIB, will be ideal for performing detailed studies of  $\beta$ -decay and  $\gamma$ -ray emission properties of fission products, especially for the shortest-lived species. Indirect methods to infer neutron-capture cross sections, as discussed earlier in the context of astrophysics, also apply to stockpile stewardship interests. There is also a large overlap in the needs for absolute  $\beta$ -decay feedings with those of decay heat and reactor antineutrino anomaly investigations.

The reactor decay heat problem has been the subject of multiple decay studies of fission fragments with the total absorption method. High-resolution, low-efficiency measurements of  $\beta$  decays are unable to detect numerous weak transitions feeding highly excited states in the daughter nucleus (i.e., the pandemonium effect) [Har77], and their results are hampered by systematic errors. Total absorption studies use very efficient detector systems to measure the  $\beta$  feeding over the entire decay energy window [Val17, Fij17]. The TAS measurements of absolute branching ratios are significantly improving the quality of the data needed for decay heat calculations. For the fission fragments, which are  $\beta$ -delayed neutron precursors, complementary discrete neutron energy measurements are required to complete the task of mapping  $\beta$  feeding. Such studies will continue at FRIB with fragmentation beams, which are insensitive to the chemistry of the separation and provide access to a wider range of isotopes.

Studies of fission fragments with fast-fragmentation and stopped beams will require a full suite of detectors. The experiments will include implantation detectors, with the capability to measure fast decays, neutron counting, discrete neutron spectroscopy, and total absorption spectroscopy for decay strength distribution measurements. Precision high-resolution  $\gamma$ -ray spectroscopy will also be needed to disentangle the TAS data and provide information on the relative population of ground and isomeric states in fission. In selected cases, when forbidden decays play an important role, direct measurements of electrons will be of particular value for reactor antineutrino research.

#### **Decay Heat Release in Nuclear Reactors**

Roughly 10% of the overall energy generated in a nuclear power reactor comes from the decay chains of neutron-rich nuclei, i.e., fission products from nuclear fuel composed of <sup>235</sup>U, <sup>238</sup>U, <sup>239</sup>Pu and <sup>241</sup>Pu. These delayed decays are the only source of energy after a planned or accidental reactor shutdown; heating the nuclear fuel assembly in a Loss-of-Cooling-Accident (LOCA) can create dramatic consequences as occurred during the 2011 Fukushima disaster. Precise data on neutron-rich decay chains are important for the operation of nuclear power plants, the transportation and storage of spent fuel, and the design of new generation reactors.

Recent results from TAS experiments [Ras16, Fij17] demonstrate that our knowledge on decay heat released in fission products is limited, Figure 12. The largest change in the decay heat was found for the decay of a short-lived nucleus, <sup>142</sup>Cs(1.7s), previously assessed as having only third-ranking priority for decay-heat investigations [NEA07].



**Figure 12:** Change in the decay heat (electromagnetic component) for fission of  $^{235}$ U due to new total absorption data with a few select isotopes [Fij17].

FRIB will produce all short-lived neutron-rich nuclei involved in the nuclear fuel cycle. The effect of neutron emission followed by  $\gamma$ -ray transitions will be a leading interest for FDS investigations. Total absorption spectroscopy combined with discrete neutron and  $\gamma$ -ray spectroscopy will establish the full pattern and modes of decay heat release.

The efforts to determine the decay heat in neutron-rich nuclei will simultaneously provide the antineutrino energy distribution important for solving the reactor antineutrino anomaly and high energy shoulder effect. Both anomalies are considered to support the possible existence of a new fourth (sterile) neutrino generation.

# 3. The FRIB Decay Station (FDS)

The construction of the FDS will enable full access to the physics opportunities outlined in the previous section of this whitepaper. The performance of the FDS hardware and its reach for scientific output depends on the combined efficiency and sensitivity of the instrumentation.

The FDS will require an infrastructure composed of modular multi-detector systems with the ability to measure nuclear decays and the resulting delayed emissions. It requires detection of charged particles, photons, and neutrons. At the core of the FDS is a system to stop the incoming exotic ions and detect subsequent charged-particle decay emissions. Additional detector arrays will surround this system to measure emitted photons, neutrons, or both. The exact configuration of the charged-particle, photon, and neutron detection arrays will be dependent on the specific science goals of each experiment and it will be adaptable to optimize tradeoffs between energy resolution, time resolution, efficiency, and background.

The FDS will include three new devices: (1) a large-volume HPGe array, "DEGA", (2) a neutron time-of-flight (TOF) array, "NEXT", and (3) a silicon-scintillator hybrid implant detector, "XSiS". These three workhorse devices constitute 78% of the total budget but represent a major advance over past generation detectors. They will be characterized by high resolution and efficiency, good background suppression, and granularity. For example, the efficiencies of DEGA, NEXT, and XSiS at 1 MeV will be factors of approximately 2, 6, and 2 larger, respectively, than past generation detectors. Combined efficiencies for  $\beta n\gamma$  and  $\beta 2n2\gamma$  can be larger by factors of approximately 10 and 50, respectively. The energy resolution of NEXT will increase by up to a factor of 6 over the previous generation. These gains will increase the scientific output, reduce the rate requirements for many of the spectroscopic techniques, and extend the scientific reach towards the drip line. The remaining detectors largely exist and require relatively minor upgrades for compatibility with the new detector systems and FRIB beams.

We propose a novel approach to enable execution of multiple measurements in quick succession (or simultaneously) when particular detector systems cannot be combined, by placing two such systems along the beam trajectory and using removable implantation detectors to choose the stopping point at the first (discrete spectroscopy) or second (total absorption / counting spectroscopy) location together with manipulating the focal length of the last stage of the fragment separator beamline. Simultaneous measurements may be possible by allowing an adjustable amount of beam, e.g., 10%, through the charged-particle detectors. Such a combination of instrumentation and measurements will provide a unique and powerful opportunity for consistent and thorough decay measurements. The FDS with a two-focal point solution can be seen in Figure 13 for two different configurations.



**Figure 13:** Two example FDS configurations are shown: (*left*) DEGA - 3Hen, (*right*) NEXT-DEGA-MTAS. Both configurations make use of two focal points for discrete and total absorption / counting spectroscopy.

#### 3.1 Overview of detector subsystems

The performance requirements of the individual detector subsystems are tailored to the physics requirements outlined in the previous section of this whitepaper. These subsystems largely fall under three categories (listed below) and must be designed or upgraded under a common FDS framework to ensure maximum efficiency, performance, and compatibility:

- Implant and charged-particle detectors
- γ-ray detectors
- Neutron detectors

No single type of implantation detector is optimal for all experiments. Detector requirements for any particular experiment may favor high efficiency, energy resolution, or timing resolution. Beam rates are expected to be much higher at FRIB than those typically found at NSCL due to higher primary beam currents and a higher momentum acceptance for fragments transmitted to the end station. Energy-loss and time-of-flight techniques will be used to identify individual isotopes delivered to the implantation detector. The rate and range of implants in the detector determines its size and segmentation. It must also measure subsequent charged-particle decays. The design of this element of the array is particularly challenging because of the necessity to deal with implant and decay energies that range from GeV down to keV, respectively. Implantation detectors will include silicon double-sided strip detectors (SiDSSDs), segmented scintillator-based detectors (XScint), germanium double-sided strip detectors (GeDSSDs), and time projection chambers (TPCs). These detectors are optimal for  $\beta$  decay and  $\beta$ -delayed charged particle spectroscopy,  $\beta$ -decay lifetime measurements of very neutron-rich nuclei, fast timing and neutron time of flight measurements, and correlated charged-particle decay, respectively.

An ensemble of  $\gamma$ -ray and neutron detection systems capable of discrete spectroscopy, fast timing, and total absorption spectroscopy will be implemented as part of the FDS. They will surround a core implantation detector that is optimally matched to the performance requirements. For  $\gamma$ -ray detection, these include large-volume HPGe (high-resolution discrete spectroscopy), Lanthanum and Cerium Bromide (fast timing and good energy resolution), and Sodium Iodide (highefficiency, total absorption spectroscopy) detectors. For neutron detection, these will include segmented n-TOF (highresolution discrete spectroscopy) and large-volume <sup>3</sup>He neutron (high-efficiency counter) arrays. These detector systems are optimal for characterization of excited states and  $\beta$ -delayed absolute branching ratios.

A summary of the individual detector systems, organized by one of the three categories above, is provided in Table 2. Many of the required detectors either exist or require relatively minor upgrades for FRIB compatibility. The new systems DEGA, NEXT, and XSiS constitute the majority of the total budget and will be described in more detail.

Subsystems	Detection type	Path	Comment
SiDSSD - XSiS	implant & charged particles	new	Good resolution for proton and $\alpha$ spectroscopy
XScint - XSiS	implant & charged particles	new	Fast segmented scintillator
GeDSSD	implant & charged particles	exists	High resolution detection of X-rays and conversion electrons.
ТРС	implant & charged particles	exists	Correlated charged-particle detection
HPGe Clovers - DEGA	γ rays	new	High-resolution, large-volume (4 crystals x 7 cm x 8 cm), and tapered
BGO Shields - DEGA	γ rays	new	Recessed Compton-suppression coverage for high efficiency configuration
HPGe PCs - DEGA	γ rays	new	Large-face and very high resolution at low and medium energies
LaBr <sub>3</sub>	γ rays	upgrade	Fast timing and good resolution
NaI(TI) – MTAS / SUN	γ rays / neutrons	upgrade	Segmented total absorption
<sup>3</sup> Hen	neutrons	upgrade	Highly segmented and efficient neutron counter
n TOF - NEXT	neutrons	new	Good resolution, large solid-angle and efficiency, granular, discrete neutron spectrometer (pairs with XScint for TOF)

#### Table 2: Overview of major detector subsystems of the FRIB Decay Station.

### **DEGA – DEcay Germanium Array**



Figure 14: The DEGA HPGe  $\gamma$ -ray array (72 crystals), showing large-volume clovers and very high-resolution PCs (Compton shields not shown).

An efficient, high-resolution, granular array of Compton-suppressed HPGe detectors will be an essential component of the FDS. The DEcay Germanium Array (**DEGA**) will be used primarily to detect  $\beta$ and isomer-delayed  $\gamma$ -ray transitions with high energy resolution in exotic nuclei produced at FRIB. It will be used in conjunction with other detectors such as implantation detectors, neutron detectors, and scintillator arrays. Compton suppression will not only improve the peak-to-total (P/T) of the  $\gamma$ -ray spectrum, but it will also suppress correlated background in γ-γ coincidence measurements that arise from Compton cross scattering.

Large-volume and tapered (22.5°) clover detectors, which house 4 crystals (7 cm diameter x 8 cm length each) per cryostat and can be closely packed, are a good compromise between cost and performance. They also have excellent energy resolution (FWHM < 2.5 keV at 1.33 MeV) and "back catchers" for extra coverage by recessed BGO Comptonsuppression shields, which will provide excellent peak-to-total ( $\geq$ 50% at 1 MeV). Simulations indicate that the larger

crystals, as compared to the old 5x8-cm style clovers, will alone improve the P/T by ~20% at 1 MeV. The addition of back catchers will further improve the P/T by as much as 10%; this becomes more substantial for higher energies. New recessed shields are required for high-efficiency configurations of any clover type. In order to enhance the sensitivity of such an array at low energies, thin-windowed, p-type point-contact detectors (PCs) are required (~9 cm diameter); a newly implemented technology that provides outstanding energy resolution (FWHM  $\leq 0.6$  keV at 100 keV) and efficiency at low energy. Sensitivity in this energy range is important for studies of isomers (e.g., seniority isomers), X-rays, and decays in heavy-

and odd-mass isotopes. Simulations for the entire array (72 crystals) indicate photopeak efficiencies of up to 23(2)% at 1 MeV and 65(7)% at 100 keV; there are "push-in" configurations that can take the array to even higher efficiencies but at the expense of granularity. These efficiencies are nearly double that achievable with the old 5x8-cm style clovers. The symmetry and granularity of the spherical HPGe array (72 crystals) is ideal for angular correlations and medium-to-large multiplicities. It is also ideal for matching to  $2\pi$  configurations of other detector arrays; e.g., the neutron TOF array NEXT.

"The detection of  $\gamma$ -ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science." - [NSAC02]



**Figure 15:** Point/small contact (PC) HPGe resolution, cf. BEGe & SAGE versus Coax resolution [MIR].

# NEXT – NEutron (Xn) Tracking array



**Figure 16:** The NEXT TOF neutron array in  $2\pi$  and  $4\pi$  configurations and the energy resolution improvement over the past generation array.

"Single- and even multiple-neutron emission are expected to characterize nuclei at the neutron drip line, while  $\beta$ -delayed neutron decay is prevalent among neutron-excess nuclei before the drip line is reached. Both forms of radioactivity only occur among nuclei far from stability." – [NSAC15]





The next-generation neutron spectroscopy array will comprise layers of fast plastic scintillator detectors arranged in a hemispherical configuration and read out by position-sensitive light sensors. **The NEutron (Xn) Tracking array (NEXT)** will achieve a dramatic gain in neutron energy resolution over the energy range of 0.1-10 MeV as compared to the previous generation, e.g., VANDLE [Pet16]. This will be possible by improving both the timing resolution and the neutron interaction localization through the use of thinner, 0.5-cm thick, layers of fast plastic instead of the thicker 3-cm VANDLE bars. In addition, new generation materials enable neutron- $\gamma$  discrimination for background suppression. The hemisphere will be located opposite to a  $\gamma$ -ray detector array. Each neutron detector module will be approximately 10" x 3" x 3". The array can be operated in multiple time-of-flight configurations between 50 cm and 100 cm depending on the goal of experiment. This modularity will enable high-precision neutron energy distribution using long (100 cm) TOF base or detailed studies of multineutron emission in a more compact geometry (50 cm). At 50- and 100-cm TOF, the energy resolution at 1 MeV is expected to be 66 and 33 keV, respectively, which is a factor of 3 and 6 better than VANDLE. The  $2\pi$  and  $4\pi$  efficiencies of NEXT at 1 MeV are expected to be 29 and 57%, respectively, which are factors of 3 and 6 better than VANDLE.

NEXT will require compatibility with fast implantation systems. Addition of <sup>6</sup>Li glass detectors or other new-generation materials will improve low energy (< 100 keV) neutron detection. Gamma-ray detectors are essential components of the new neutron array for complete measurement of decay cascades. Therefore, this array will nominally be operated in a hybrid configuration, where part of the solid angle is covered by high-efficiency  $\gamma$ -ray detectors, e.g., DEGA.

# XSiS (SiDSSD + XScint)



**Figure 17:** An implementation of an adaptable segmented silicon (SiDSSD) and fast scintillator (XScint) hybrid array. The placement of this array at the center of DEGA is also illustrated.

Silicon double-sided strip detectors (SiDSSDs) have traditionally been the workhorse for experiments with fragmentation beams because of their good energy resolution for charged particles (20-50 keV FWHM), adequate timing characteristics, and compatibility with most  $\gamma$ -ray detector arrays [Pri03]. SiDSSDs will be particularly well suited for experiments targeting isotopes on the proton-rich side of stability because the  $\beta$ -delayed charged particles can be studied with these same detectors. The stopping power of silicon is low, necessitating several 1-mm thick layers to stop the heavy ions of interest and the electrical segmentation pitch must be 0.5 to 1 mm to handle the implantation rates and subsequent decays. In addition, a large dynamic range is required to handle both high-energy implants and low-energy decays in order to maintain good energy resolution for each case. However, for the n-rich side of stability, a fast position-sensitive inorganic scintillator (XScint) is required for neutron TOF measurements with NEXT. In fact, there are merits to both types of detectors for both sides of stability. A preliminary design of the **XScint-SiDSSD hybrid array (XSiS)** layout is shown in Figure 17. This detector is expected to achieve an implant- $\beta$  efficiency of up to 75%, which is nearly a factor of 2 larger than the previous generation implant detector, NSCL-BCS [Pri03].

The XSiS detector design could also enable parallel measurements with a downstream total absorption/counting spectrometer by allowing an adjustable amount of beam through, e.g., 10%. This would be a completely new capability for the FDS that is not provided in a previous generation equivalent of this detector.

#### **3.2 Locations**

The FDS and its mechanical infrastructure must be modular, flexible, and robust so that it can service multiple locations in an efficient, dependable, and reproducible manner. The two nominal locations of the FDS are illustrated in Figure 18 for access to fast-fragmentation and stopped beams. Satellite systems are also expected to travel to the reaccelerated beam line and to the focal points of recoil separators. The FDS infrastructure will include mobile platforms (see Figure 13 for preconceptual design) that will expedite relocation.



**Figure 18:** The nominal fast- and stopped-beam locations of the FDS. Satellite systems will travel to other locations such as the reaccelerated beam line for absolute branching ratio measurements (implant counting) or use with recoil separators.

#### **3.3 Funding Profile**

The total estimated cost range of the FDS is \$24-30M, which is based on a combination of budgetary quotes and actual costs from prior projects. Due to the inherent modular design, the FDS can be staged (e.g., three even portions of \$8-10M). This can be achieved by first developing the FDS mechanical infrastructure and then using equipment from existing, past-generation arrays until it can be replaced by new systems, increasing the resolution and combined efficiencies (by factors of approximately 10 for  $\beta$ n $\gamma$  and 50 for  $\beta$ 2n2 $\gamma$ ) along the way; this will increase the scientific output, reduce the rate requirements for many of the spectroscopic techniques, and extend the scientific reach towards the drip line. The majority of the cost, i.e., 74%, is due to the new HPGe (DEGA) and n-TOF (NEXT)  $4\pi$  arrays. The remaining cost covers the new XSiS detector, upgrades to existing detectors for FRIB compatibility, R&D, and project engineering and management. Under a restricted budget scenario,  $2\pi$  versions of the new DEGA and NEXT arrays should be considered as a bare-minimum configuration of the FDS. This would reduce the total budget by \$7-9M to yield a new total budget of \$17-21M. However, this would reduce the science output of both discovery and precision studies for both proton-rich and neutron-rich nuclei. The FRIB Decay Station Working Group and members of the community recommend the nominal  $4\pi$  configurations of DEGA and NEXT as essential to achieve the full discovery potential.

	Cost Range (\$M)	Comments
XSiS $(q^+/q^-)$	1	Segmented silicon-scintillator hybrid array
DEGA (γ)	10-12	Compton-suppressed large-volume HPGe
NEXT (n)	8-10	Segmented TOF neutron array
Upgrades	2-3	Re-purpose existing detectors and misc. expenses
SUBTOTAL	21-26	
R&D + PED	3-4	R&D and project management + engineering
TOTAL	24-30	

#### Table 3: Cost range of the FRIB Decay Station.

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