RARE-ISOTOPE (HEAVY ION) ACCELERATORS

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Abstract

A review of new projects worldwide involving rare-isotope accelerators is presented with emphasis on designs employing superconducting rf accelerating structures. Reasons why rare-isotope accelerators play such a significant role for future research and development (R&D) provide the impetus for moving forward aggressively. This aggressive movement affects many scientific disciplines, including that of accelerator physics and accelerator engineering. Areas of superconducting rf (SRF) R&D that would have big impacts on performance, maintainability, reliability, availability and cost of a rare-isotope research facility are discussed in terms of facility implications.

INTRODUCTION

Study of the fundamental properties of space and time is an extremely exciting area of investigation requiring innovative tools, and the ability to determine specific properties of matter and to understand how this matter interacts with its surroundings. What comprises matter as we know it, what are the fundamental constituents and how are these constituents interconnected? Questions such as these lead to more fundamental questions related to the history of the universe: what happened after its initial formation (and how and why), what are existing symmetries and their impacts, what is "dark matter", what theories best predict the present situation, and is there a grand unification scheme to explain known phenomena while predicting what remains to be discovered.

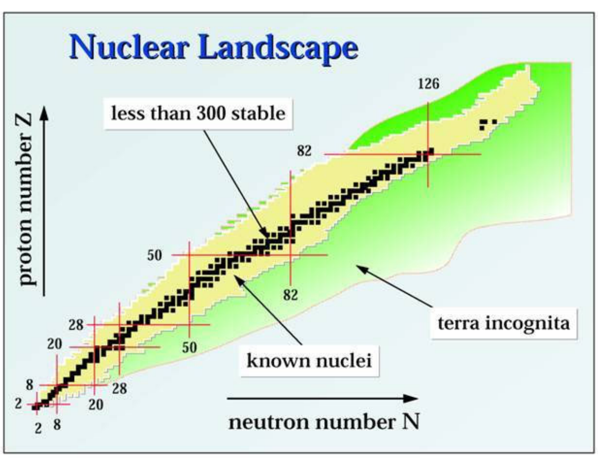

Figure 1: Known and predicted nuclei relative to proton (Z) and neutron (N) number. Shown are regions for the almost 300 known stable nuclei, the almost 2500 known unstable nuclei, and the expected 3500 other unstable nuclei, "terra incognita". Magic Z and N numbers for closed shells of the nuclear shell model are highlighted.

Figure 1 [1] shows the nuclear landscape as predicted by theory and known from present isotope information. Particle accelerators will continue to play a key role in unraveling details of matter, fundamental forces and related symmetries. Astronomical measurements and astrophysics studies will continue to be key components of the inter-related investigations with nuclear physics. Covering the microscopic to macroscopic scale research are the nuclear physics accelerators and the astronomy telescopes.

Some interesting facts, theories, puzzles and questions that drive interests in rare-isotope studies are listed below, in very simple terms:

- Properties such as mass, lifetime and decay of nuclei far from stability limits are required for studies of fundamental symmetries and of stellar phenomena.
- Need basic understandings of compressed hadronic matter and associated high-density plasma states. For example, what is the equation of state for neutron-rich matter?
- Is there a stable heavy element region above Z=107?
- Present premise is that a small degree of symmetry violation during the first instant of the universe led to an observed matter bias. Are there anti-matter areas?
- Do nuclei halos or skins imply shell model quenching? Magic Z and N numbers are no longer valid close to the drip lines. For example, ^{29}F exists but doubly magic ^{28}O (Z = 8 and N = 20) does not. Adding one proton to ^{24}O binds up to six neutrons for ^{31}F. Doubly magic ^{78}Ni (Z = 28, N = 50) exists.
- ^{11}Li (halo body) and ^{208}Pb have similar nuclear radii.
- Quark mass is less than 2% of nucleon mass. The rest of nucleon mass is associated with gluons and energy. Quarks do not exist in isolation in our world. Although not directly bearing on this area, some data collected might be of minor use in quark research.
- The domain for nuclei is bounded by the neutron (n) and proton (p) drip lines, and the spontaneous fission border. Z and N are unbalanced with respect to isospin and Coulomb forces. Nuclei are radioactive at the limit of nuclear binding. Close to the n drip line, binding energy of the last n decreases until the nucleus spontaneously emits a n. Similarly, close to the p drip line, binding energy of the last p decreases until the nucleus becomes unbound. An upper limit for the Coulomb force acting between protons leads to spontaneous fission for heavy nuclei.
- Star movements indicate that we see only less than 5% of the universe mass. Is the rest "dark matter"?
- Cosmic evolution depends on the laws of physics and chemical interactions. First stars (within 1B years of the 'big bang') from the primordial mixture were composed of H to Li. During the next 14B years,

stars exploded and reformed. Some speculate that our sun has gone through four such transitions.

- Fusion is energetically viable to create the isotopes up to iron. How were heavier elements produced? As shown in Fig. 1, there are almost 300 stable isotopes, almost 2500 unstable isotopes known today and about 3500 other unstable isotopes predicted on the basis of binding energy of the strong nuclear force. Violent explosions of stars led to the elements heavier than iron. Nuclear astrophysics and explosive nucleosynthesis suppositions for heavy element creation include slow n capture (s-process) for Fig.1 central regime, rapid n capture (r-process) for nuclei to the right side (close to neutron drip line) of Fig.1 and rapid p capture (rp-process) for the left side (close to proton drip line) of Fig.1. Exploding red giants, neutron star merging and supernova are possible sources for the r-process while x-ray bursters from accreting neutron stars, and nova explosions of accreting white dwarfs are possible sources for the rp-process. Another process for populating the lower central region is electron capture, followed by pyconuclear fusion, and then by further electron capture and neutron emission.
- Bulk properties and crust processes (deformation and heating) of neutron stars require basic nuclear properties of the unmeasured rare isotopes.

Recent publications [2-8] on rare-isotope accelerators provide interesting and informative discussions on technology status and needs, experimental programs, and justifications for major new rare-isotope R&D facilities. Justifications for siting several rare-isotope R&D facilities worldwide are found in Ref. 9-13 and at websites [14-16]. Figure 2 [17] shows the worldwide effort underway in rare-isotope R&D, including the proposed RIA facility in the US.

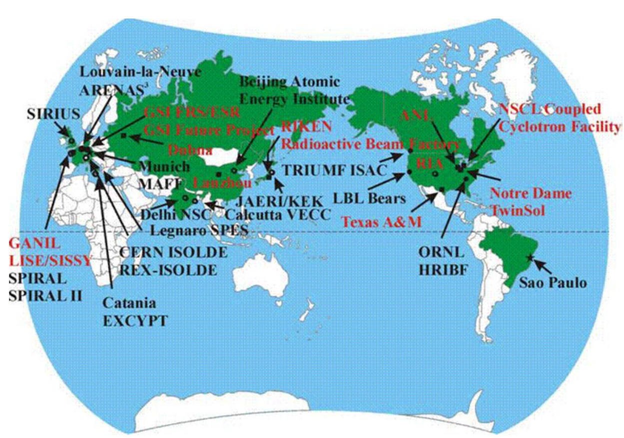

Figure 2: Worldwide efforts underway with ISOL and in-flight separation facilities for rare-isotope R&D. Shown are operating, planned and under-construction facilities. Dark black print indicates ISOL facilities.

The following discussion will only highlight a few of the rare-isotope facilities that are in the planning or initial phases, and only those that have connections with SRF cavities in one way or another. In order to represent fairly each major world region by portraying no more than two facilities, activities such as REX-ISOLDE [18-20] and EURISOL [21-23] will not be discussed.

SELECTED RARE-ISOTOPE ACCELERATOR FACILITIES WORLDWIDE

Rare-isotope facilities employ two major techniques to provide beams suitable for analyzing exotic nuclei. One is the in-flight technique (suitable for high-energy beams, short-lived isotopes and fast, clean, chemical-independent separation of the elements) and the other is the Isotope Separation On-Line (ISOL) technique (suitable for longer-lived isotopes, and for high beam intensity and quality). A high-energy ion beam impinges on a thin high-Z target, producing from the nuclear interactions a copious supply of fragments that will be analyzed. When using a thick target, adequate spacing in the target allows for efficient release of the fragments. The nuclear products of these interactions are collected by various schemes for either in-flight analysis or ISOL analysis.

ISAC II at TRIUMF

TRIUMF uses their 500 MeV cyclotron as the 100 μA source of high-energy protons that strike a thick target producing exotic nuclei collected in their ISOL, as shown in Fig. 3. Presently ISAC [24-27], a 50-kW ISOL facility, is operating with plans underway for a post-accelerator upgrade called ISAC II [24, 25] using SRF cavities. Web sites [28, 29] provide recent status of the upgrade project.

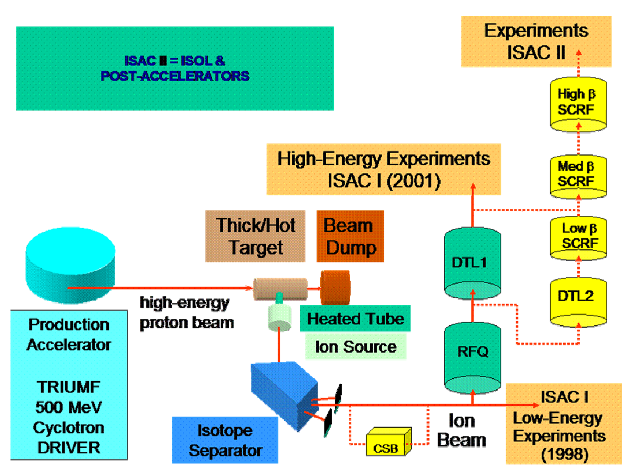

Figure 3: Schematic layout of the planned Canadian ISAC II facility at TRIUMF. Shown is the operating ISAC facility (experimental program started 2001) with ISOL, RFQ and DTL1, and the planned upgrade to ISAC II (expected completion 2010) involving three different beta quarter-wave SRF cavities.

ISAC I post accelerates beams to 1.5 MeV/u for atomic mass (u) up to 30 using a 35.4 MHz RFQ and a 106 MHz IH-DTL. ISAC II is under construction to further post accelerate rare-isotope beams to 6.5 MeV/u for masses up to 150 with a mass to charge ratio up to A/q = 7. ISAC II utilizes new accelerating structures including a new IH-DTL and three groups of quarter-wave resonators [25], totaling 48 SRF cavities. RF frequencies range from 70.7 MHz for the 8 'low' β (β = 0.042) cavities, 106 MHz for the 20 'medium' β (β = 0.057, 0.071) cavities to 141 MHz for the 20 'high' β (β = 0.104) cavities. TRIUMF is collaborating with INFN-Legnaro, ANL and CERN on the SRF cavities.

RIBF at RIKEN

The Rare-Isotope Beam facility (RIBF) [30-32] shown in Fig. 4 is an upgrade project to the RIKEN Accelerator Research Facility in Japan. Adding to the existing heavy ion facility is a new driver accelerator comprised of three coupled cyclotrons fRC, IRC and SRC, the last being a superconducting K2500 ring cyclotron. Beams from the existing RIKEN Ring Cyclotron (RRC) are accelerated to 400 MeV/u for light ions and 350 MeV/u for heavy ions. These 100 kW ion beams impinge on a rare-isotope production target followed by the larger acceptance BigRIPS for projectile fragment separation. The upgrade project is scheduled for completion in 2006 with the new RIBF Experimental Building becoming operational in 2007.

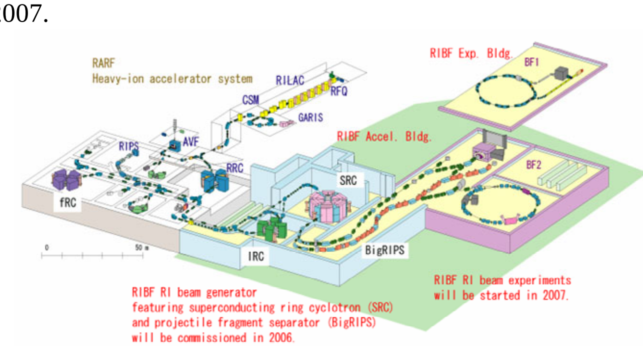

Figure 4: RIBF at RIKEN showing existing K540 RRC injector cyclotron for the new facility. Three new cyclotrons (K520 fRC, K980 IRC and K2500 SRC) will accelerate the RRC beam to 400 MeV/u for most ions, decreasing to 350 MeV/u for uranium. Rare-isotope beams from the high Z target will pass through the projectile fragment separator BigRIPS for analysis prior to entering the experimental building.

The 100 kW RIBF will have a larger isotope reach than TRIUMF, will have more intensity for most isotopes but will suffer in comparison by not having an ISOL plus post accelerator. Planned for the future is an ISOL plus post accelerator that will have some similarities to the TRIUMF facility.

International Accelerator Facility at GSI

An upgrade to the very successful GSI facility is shown in Fig. 5. The existing facility consists of the UNIversal Linear ACcelerator (UNILAC), the heavy (Schwer) Ion Synchrotron SIS18, FRagment Separator (FRS) and the Experimental Storage Ring (ESR). To add to the facilities research capabilities, it is planned [13] to use the existing UNILAC/SIS18 as an injector to feed a co-located pair of superconducting synchrotrons SIS100 (100Tm) and SIS200 (200 Tm) each of 1100 m circumference, a High Energy Storage Ring (HESR), a collector ring (CR), a New Experiment Storage Ring (NESR), and Superconducting FRagment Separator (Super-FRS). The SIS100 accelerates beams from protons to uranium while the slower cycling SIS200 can be used as a stretcher ring.

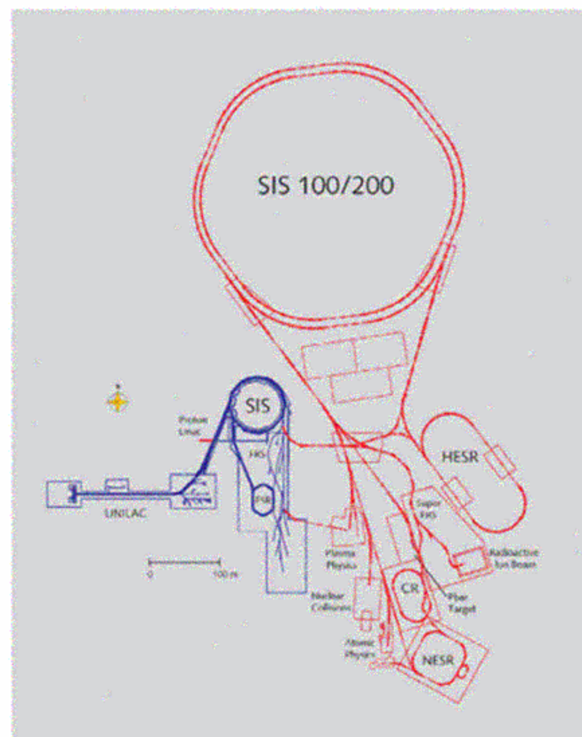

Figure 5: Upgrade project for GSI showing existing UNILAC and SIS18 that will serve as injector for the new facility. The co-located synchrotrons SIS100 and SIS200 will raise the beams to 1.5 GeV/u.

The pulsed GSI facility [33, 34] will have increased intensities for all rare-isotope beams in use at GSI today, as well as an extended reach to many other isotopes of interest. It has the highest energy reach of new facilities under consideration today.

Under consideration in collaboration with RIKEN is an ISOL plus post accelerator with some similarities to the TRIUMF facility for the future.

SPIRAL 2 at GANIL

SPIRAL has been using beams from GANIL for ISOL studies of rare isotopes [35]. Upgrade [36] to increase the range and mass of rare isotopes available involves a driver to accelerate 5 mA D^+ to 20 MeV/u and up to 14.5 MeV/u for 1 mA of A/q = 3 ions into a fissionable target. Fission in the target is the source of the radioactive ions to be studied. Recent beam calculations [37, 38] show good performance of the array of independently driven SRF cavities shown schematically in Fig. 6. The 30 resonators are arranged in two modules of six β = 0.07, 88 MHz quarter-wave resonators followed by three modules of six β = 0.14, 166 MHz half-wave resonators.

The ion source for SPIRAL 2 will be based on advances made on the new generation of ECR sources. High frequencies and high confinement fields will be necessary to obtain the beam currents of interest.

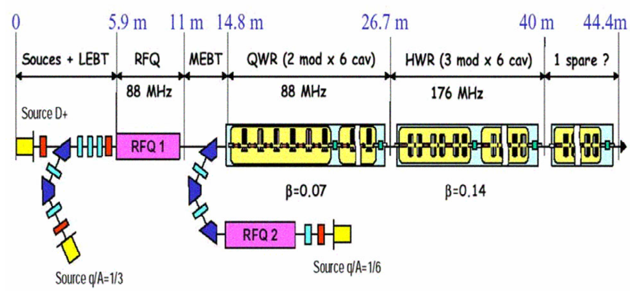

Figure 6: Schematic layout of SPIRAL 2 showing the 2 quarter-wave modules with 6 cavities each and the 3 half-wave modules with 6 cavities each.

RIA in the US

Figure 7 shows a schematic [9-11] of the Rare-Isotope Accelerator (RIA) concept that combines advantages of projectile fragmentation and target fragmentation. Design work on the RIA proposal continues at two institutions in the US, using colleagues within the various communities interested in rare-isotope R&D. Accelerator designs from MSU and ANL are similar in overall general performance and characteristics, but differ in a few details. For example, the ANL design has a one-bend folded linac driver while the MSU linac has no bends. Both designs are feasible, i.e. the beam 6D phase space as calculated by each team easily meets the stringent requirements for reliable long-term operations.

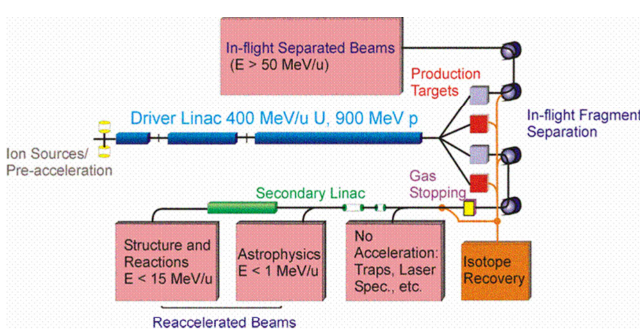

Figure 7: Schematic layout of RIA facility. A 400 kW 400 MeV/u driver linac provides ion beams to several targets from which rare isotopes are collected for in-flight studies or ISOL plus post acceleration studies.

The RIA driver linac provides 400 kW ion beams up to 400 MeV/u for uranium and 900 MeV protons. Rare isotopes for in-flight analysis or ISOL plus post acceleration are provided from a set of production targets. Details of SRF cavities for RIA and design considerations are found elsewhere [39-47].

The scientific reach of RIA [10, 17, 48] is shown for initial 100 kW beams in Fig. 8 along with indications of the various stellar processes producing isotopes. RIA intensities for most of the isotopes are a factor of 100 higher than for the GSI upgrade (varies from a factor of 5 for the heaviest isotopes and greater than a factor of 1000 for the lightest). RIA reaches almost all of the isotopes of R&D interest for a better understanding of many of the scientific issues outstanding today.

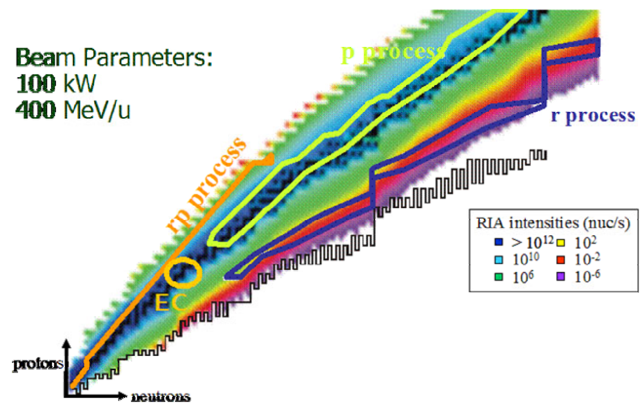

Figure 8: The scientific reach for RIA based on 100 kW of up to 400 MeV/u U beams. Similar data for RIKEN RIBF, SPIRAL 2 and the GSI Upgrade show reduced intensities as compared to RIA.

SUMMARY AND CONCLUSIONS

Scientific justification for new high-intensity rare-isotope research is extremely strong. Various countries either have initiated planning efforts or have started construction for facilities that will extend the isotope reach as well as the beam intensity. These facilities have many interesting engineering development areas other than the accelerator, including those of targets, fragment catchers, fragment separators, fragment transport and experimental apparatus.

Construction and commissioning of the new accelerator facilities for investigating rare-isotope properties will have significant impacts on SRF technology and its applications. The biggest impacts will be on high quality niobium, understanding surfaces and impurities, cleaning techniques, cavity advances and infrastructure support. Within the cavity development area, advances in quarter-wave cavities, half-wave cavities (spoke, cylindrical, ladder, multi-gap), elliptical cavities, tuners, couplers, cryostats and high-field operation (reliable, ease, repeatable, maintainable) will lead to an understanding of important issues and related performance improvements.

R&D areas that can significantly affect performance of SRF cavities include cavity design, materials and joining, manufacturing techniques, "stacking factor" and cryostats, low-level rf control, turn-on and transient response, tuners fast and slow, microphonics, Q-slope, and field emission.

The SRF community has been collaborating for many years in these areas with great success: success that will continue for the benefit of future rare-isotope facilities.

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