Report of the NSAC Subcommittee on

Comparison of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility

Sub Committee Members:

James Beene	Oak Ridge National Laboratory
Peter Bond	Brookhaven National Laboratory (Chair)
Steven Koonin	California Institute of Technology
Curtis Meyer	Carnegie Mellon University
Jack Sandweiss	Yale University
James Symons	Lawrence Berkeley National Laboratory
Michael Wiescher	University of Notre Dame
Stan Woosley	University of California at Santa Cruz

February 23, 2004

Table of Contents

Executive Summary

NSAC charged this subcommittee with comparing the opportunities and capabilities of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility in Germany, given the previously identified scientific opportunities. The charge focused on science associated with studies of rare isotopes, but also asked about the other opportunities available at GSI.

We reaffirm a very strong science case associated with study of rare isotopes. Such studies span a wide range of topics in nuclear structure, nuclear astrophysics, fundamental symmetries and applications. RIA and the GSI future facility were designed for quite different purposes and each has unique capabilities.

RIA optimizes the science associated with the study of rare isotopes by using a variety of methods to maximize their yields: projectile fragmentation, projectile and target fission and target fragmentation and spallation. It provides the capability to then study the nuclei in-flight, at rest or to re-accelerate them. RIA will provide yields of any element at intensities that are unmatched by any facility, present or currently planned.

The GSI future facility will provide very high velocity beams of unstable isotopes and will be able to store and cool those beams for reactions with internal targets, lasers and collinear electron beams. Beyond its narrower and more specialized reach in rare isotope studies, the GSI project encompasses a broad variety of science disciplines including relativistic heavy ions, plasma physics, anti-proton physics and atomic physics. These latter forefront opportunities at GSI will attract U.S. researchers, who might propose to invest in specific experimental equipment there.

While both facilities will produce rare isotopes by fast beam fragmentation and there is collaboration between the U.S. and European communities on R&D issues, we find that this overlap in capabilities is less than it would appear. It is clear that the RIA rare-isotope research capability is more extensive than GSI. The question of whether an upgrade of GSI would duplicate the rare isotope capability at RIA is answered firmly in the negative.

The user communities for RIA and GSI, including those devoted to rare isotopes, are both large and distinct; neither facility could accommodate the full user base. Both facilities would impact several areas of local national importance, particularly training personnel needed in a number of important societal areas dependent upon nuclear physics.

Introduction

The substantial world-wide excitement and interest in the study of unstable ("rare") isotopes is evidenced by the number of facilities, existing, being built or proposed, in Canada, Japan, the U.S. and Germany. While these facilities have similar goals in studies of nuclear structure far from stability, astrophysical reactions of importance and fundamental symmetries, their capabilities are quite different. This document responds to a charge from NSAC (Appendix A) to compare the two most recently proposed facilities that have the broadest reach: the Rare Isotope Accelerator (RIA) and the GSI accelerator complex project. Both facilities have received strong endorsements from relevant planning committees, NSAC, NUPECC and the OECD Forum and they have been viewed positively by funding agencies. RIA has been recently categorized by the Secretary of Energy in his 20-year facilities plan as tied for third priority among the 28 important new facilities chosen for the plan and the GSI project has been reviewed favorably by the German government.

The questions posed by the NSAC charge can be summarized as:

1) What are the rare isotope capabilities that are unique to each facility?
2) What are the rare isotope scientific opportunities offered by each facility?
3) Are there U.S. nuclear physics programs or national considerations that are relevant to the two facilities?
4) What are the relative costs and benefits of U.S. investments in the two facilities, including possible upgrades that extend the scientific reach of GSI?

The committee initially gathered information from the GSI and RIA web sites. The GSI plan is in a Conceptual Design Report. As RIA is not yet at that stage we sought guidance from RIA proponents to find the most relevant information. We were aided by a recent joint RIA-GSI document comparing the projected performance of the facilities. (Appendix B). Clarifying questions were then sent to proponents of both facilities (Appendix C) and the committee profited from the candor of the responses. Finally, a meeting with presentations from the proponents of RIA and the GSI Director was held at Brookhaven National Laboratory (agenda Appendix D).

A direct comparison of the RIA and GSI facilities is complicated in that the GSI project is proposed as a multi-faceted facility whereas RIA is focused exclusively on rare isotope studies. As specified in the charge our focus will be on the rare isotope aspects of these facilities, but we include brief discussions of the other science capabilities at GSI and how they might impact other areas of U.S. science.

Facilities

Since both proposed facilities have been through various technical reviews and the focus of our charge is on the science, not technical feasibility, we will only sketch the projected facilities, accept the stated performance goals while recognizing some needed R&D, and compare their relevant capabilities.

The focus of RIA is the science enabled by the production of rare isotopes. The heart of the RIA facility is a 400MeV/A linac that will accelerate all masses up to U with beam power up to 400kW. Isotopes can be produced in a variety of ways: projectile fragmentation, projectile and target fission and target fragmentation and spallation. Isotope separation is obtained by an Isotope Separator on Line (ISOL) or fast beam fragment separation. The fast beams can be used directly or subsequently stopped in gas so that isotopes can be studied at rest. A second, very important feature of RIA is the ability to re-accelerate isotopes, produced by ISOL or stopped fast beams, and study them further via reactions on stable targets.

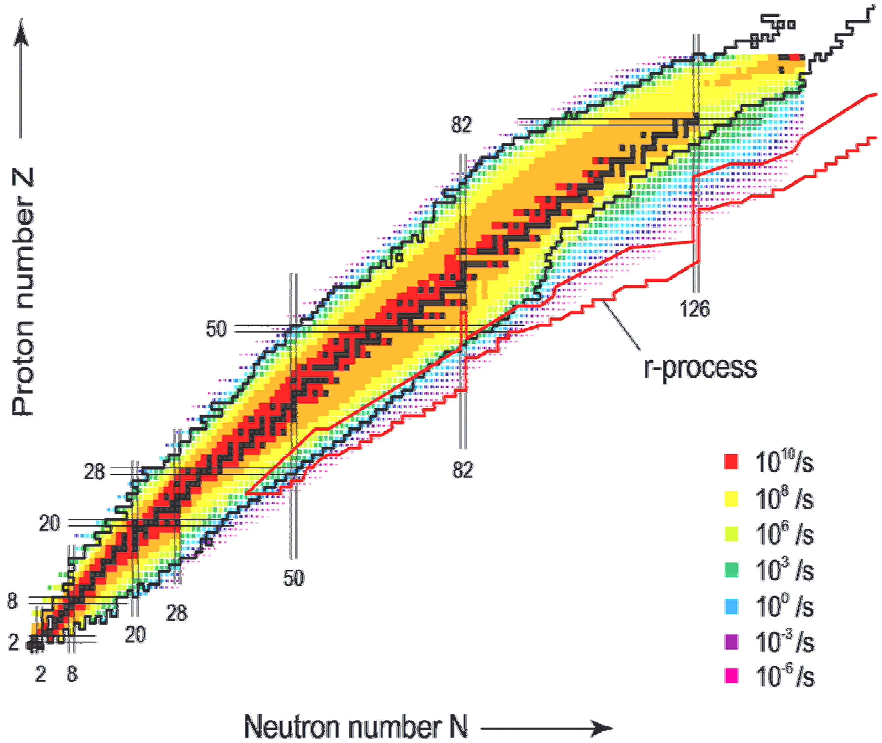
The GSI plan is to improve its existing facility and augment it with additional synchrotrons and storage and cooler rings to dramatically enhance its current capability in a number of research areas. For the study of rare isotopes it would have a primary beam of roughly 2GeV/A and 100 kW (both species dependent) that would enhance its current production rate by several orders of magnitude. Utilizing the panoply of new facilities would allow simultaneous operation (albeit with reduced performance) for study of a) rare isotopes produced via fragmentation, b) electron-rare nucleus scattering, c) fixed target relativistic heavy ion collisions from 1 to ~40 GeV/A, d) antiproton interactions from 1-30 GeV, e) plasma physics with terawatt beam pulses, and f) atomic physics.

A number of the capabilities of the GSI project will draw interest and participation from U.S. researchers, but the only overlap with RIA is the production of rare isotopes via fast beams. As detailed in the rest of the report this overlap requires some analysis to delineate the significant differences, but RIA will produce significantly higher yields of isotopes and achieve a greater reach away from stable nuclei while the GSI storage rings and some of its experimental equipment will allow specialized rare isotope experiments that cannot be done at RIA.

One metric for differentiating the capabilities of RIA and GSI is the range of isotopes each can produce. Figure 1 shows the fast fragmentation yield plots as given by the two facilities. Obviously there are regions where both facilities can carry out experiments on the same isotopes, but there are also significant differences. For example, the current estimates of the r-process are shown as solid lines on the neutron rich side (red on the GSI plot, black on the RIA plot). Note that GSI will be able to produce only some of the isotopes along the r-process path while RIA will produce nearly the whole range of nuclei. What is not so obvious from the plot is that RIA will produce at least 10-100 times more intensity for any given isotope, even in the overlap region. Also not obvious are the advantages each facility has for specific experiments. These will be outlined in the science sections below.

Figure 1

GSI yields



RIA yields

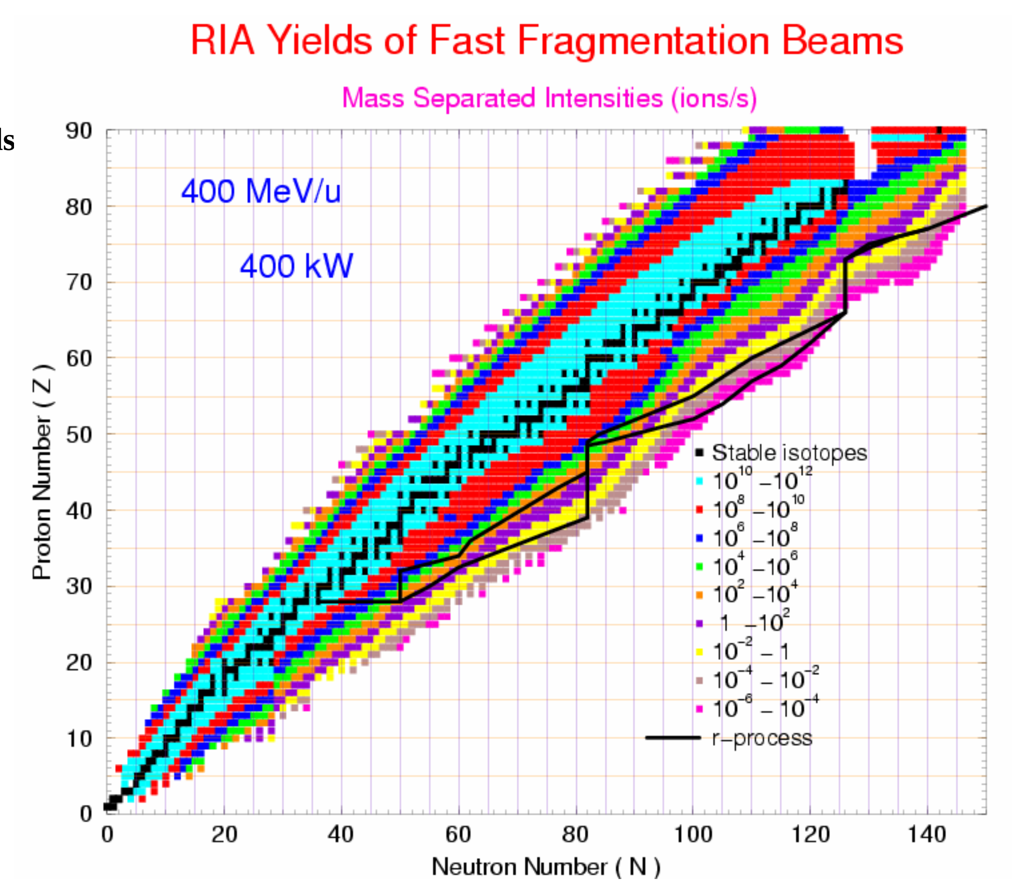
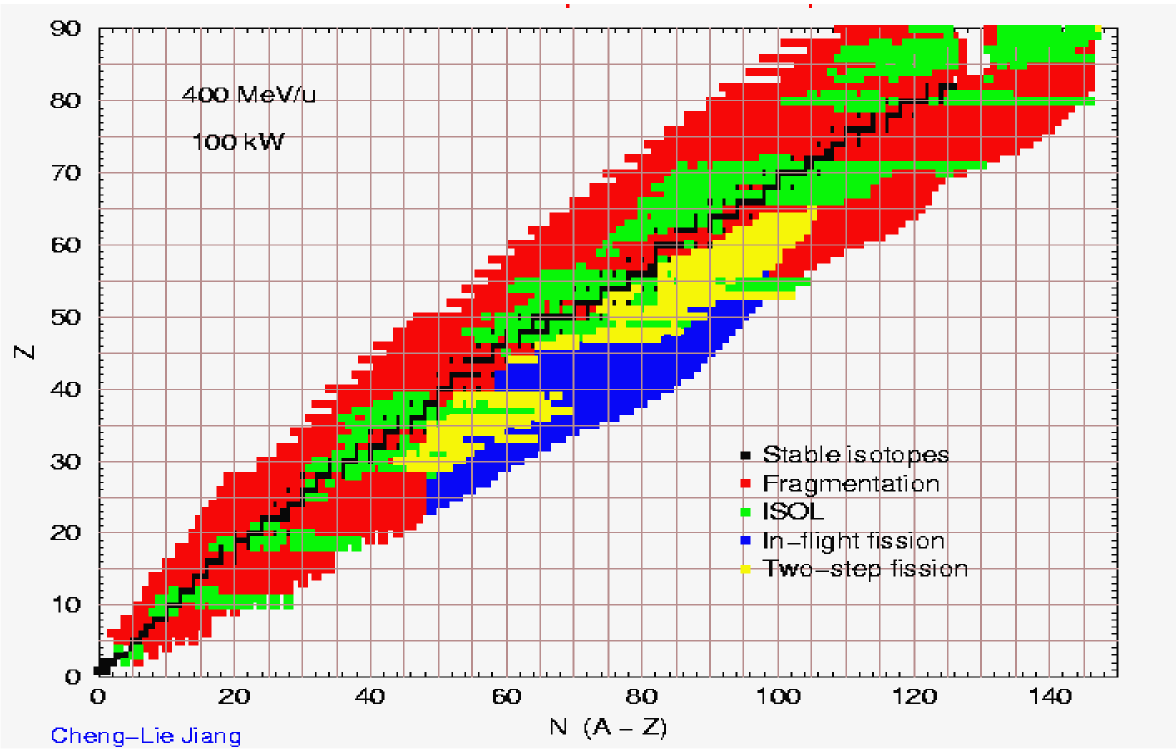


Figure 2 shows the production mechanism that maximizes the yield of rare isotopes for re-acceleration at RIA with the caveat that the lifetime be greater than about 10 milliseconds for fast beams and about 1 second for ISOL beams.

Figure 2



From this picture it is clear that production via fast beams, which includes fragmentation and in-flight fission (red and blue in the diagram), will be a dominating factor in optimally producing rare isotopes. However there are significant regions crucial for the science of RIA in which other means of production are optimal (yellow and green). Since the majority of the isotopes are optimally produced by fast beam methods, GSI has the potential to produce them, albeit, with lower intensity and a considerably more restricted reach. Moreover, the GSI project does not include reaccelerated beams. As part of the charge we were asked whether further upgrades to GSI were possible to accommodate this capability. We heard clearly from GSI management that because of the nature of the accelerator systems chosen to implement their broad range of science in support of their extensive user community, reacceleration could not be justified and will not be pursued.

What are the strengths of each facility ?

- **RIA strength**: The choice of a linac driver means that much larger primary beam currents can be produced at RIA than at GSI where synchrotrons are used. While the fragmentation cross section is modestly higher at the GSI energy, the yield of rare isotopes produced with fast beams at RIA is 10 to 100 times greater than at GSI. The increased intensity of rare isotopes gives two advantages: the ability to reach nuclei further from stability, and the possibility to utilize a wider variety of experimental techniques. The ISOL production mechanism at RIA and the ability to reaccelerate isotopes produced via any method are available only at RIA.

- **GSI strength**: The storage rings are unique. GSI's fragment separation capability will likely to be superior to RIA's, particularly for the heaviest ions. These capabilities will allow certain specialized experiments to be done better at GSI. GSI will have the ability to do electron scattering on rare nuclei.

The scientific benefits associated with each facility and their differences are detailed in the following sections.

Nuclear Structure

Scientists pursuing the study of nuclear structure seek a comprehensive understanding of the properties of the atomic nucleus: at the heart of such understanding should be a theory capable of predicting the properties of any nucleus to a few-percent accuracy. With such a theory in hand, not only would a prime scientific goal have been reached, but we would also have a tool that could supply critical nuclear structure information needed to better understand and predict astrophysical phenomena and other phenomena where "applied" nuclear structure is key. We are still far from this goal, but significant advances are being made.

The ab initio work on few-nucleon systems, based on the bare nucleon-nucleon interaction augmented by a three-body force, already allows accurate calculations of the energy levels of nuclei with $A \leq 12$. For heavier nuclei, various shell model methods utilizing sophisticated truncation schemes have been very successful. The effective interactions developed in shell model studies can be used to understand the forces employed by the mean-field methods applied to heavy nuclei based on the density functional theory. It is hoped that an exploration of connections between these models will offer a path toward a unified description of the nucleus. This is an ambitious program, but practitioners of the field feel that there are good reasons for optimism, including an influx of promising new ideas and the tremendous increase in computational power coupled with the development of new algorithms that this has engendered. It is important to realize however that this optimism, in part, results from an anticipated resurgence of the experimental study of nuclear structure that will be catalyzed by the construction of next generation radioactive ion beam accelerator facilities like RIA and the GSI project.

The microscopic framework that has been developed to guide our understanding of all but the lightest nuclei rests on a foundation that nuclear behavior can be approximated by the motion of nucleons in an average field, with residual two and three body interactions between them. The mean field generates the shell structure that pervades our present understanding of nuclear structure, while the residual interactions generate collectivity and correlations. There are already suggestions that both concepts may have to be altered radically in nuclei far from the valley of stability. The unified description of the nucleus that we seek must account naturally for changes in nuclear properties as the number of neutrons and protons is varied to the extreme values produced at the new generation of unstable beam facilities. While these facilities will certainly increase the number of nuclei that can be studied, the total number of nuclei is less important than the qualitative difference made by the ability to choose the right nucleus, or the optimum reaction partners, to isolate or amplify particular phenomena. Initial forays into the realm of unstable nuclei have already provided glimpses of such exciting physics as the formation of halo nuclei and the quenching of shell structure with the emergence of new magic numbers. Further study with new facilities should uncover new phenomena and enable enlightening simplifications of nuclear behavior. We believe that experiments at these next-generation facilities will provide a vital stimulus to theoretical development, and provide the benchmarks against which these theories will be tested.

While both facilities will provide capabilities to study “stopped” (~keV) nuclei and make direct use of fast beams derived from fragmentation, RIA will provide intensities that are up to 100 times larger. Measurements with stopped nuclei will include decay and laser studies of nuclear lifetimes, charge radii and electromagnetic moments, as well as high precision (~10 keV for 0.01 ions/s) mass measurements employing ion traps. The isotopes derived from direct fast beam fragmentation will be used to establish the limits of nuclear existence, to carry out stripping and knock-out reaction studies that probe single particle states, and to carry out Coulomb excitation measurements of the strengths of ground-state electromagnetic transitions.

The fast fragmentation beams will also provide data on strength distributions of giant resonances and soft collective modes in nuclei with extreme N/Z ratios. Results on the Gamow-Teller strength distributions will be important to both astrophysics and nuclear structure, while study of the spin-dipole mode may provide a direct measure of the thickness of neutron skins. The higher intensities at RIA will translate directly into greater reach in these experiments. A typical estimate predicts that RIA will be able to extend detailed knowledge of the neutron drip line from the present Z=8 to approximately Z=30, with some data extending to Z~40. The GSI Future Facility would reach about 10 units lower in Z. In general at a fixed Z, RIA will provide beams with a neutron number two units larger than GSI at any specified intensity level.

Fragmentation beams also will be used to extend our limited knowledge of the nuclear equation of state (EOS) to nuclear matter with appreciable neutron-to-proton asymmetry. Here RIA will cover the region up to about 2 times normal nuclear density and GSI will extend that reach up to about 4 times normal density.

The ability of RIA to provide high-quality reaccelerated beams of unstable nuclei at energies up to ~10 MeV/A will extend the entire range of nuclear structure measurements that have been carried out with stable beams to beams of unstable nuclei. Examples will include multiple Coulomb excitation studies, precision measurements of single-particle and pair transfer reactions to probe the location and distribution of single particle strength and pairing, and an extension of high-spin studies into new and exotic regions. The high-intensity reaccelerated beams will be used to probe the existence of new, more neutron-rich superheavy systems and to map the fission-barrier mass surface. Though many of these experiments will be similar in principle to those carried out at stable-beam facilities, the actual experimental requirements will be quite different and extremely challenging. Development of the tools necessary to carry them out will stretch the ingenuity of the community.

The unique capabilities of the GSI Future Facility will be those opened up by the availability of stored and cooled unstable beams. Storage rings make possible broad-range measurements of large numbers of masses at moderate precision (~50 keV). Colliding-beam eA studies of nuclear charge distributions will also be possible for species produced at relatively high intensity ($>10^6$ ions/s). The availability of thin internal targets of hydrogen and helium isotopes will facilitate hadron scattering studies of radial mass distributions in nuclei, and may allow us to extend our knowledge of isoscalar giant modes into the regime of neutron-rich unstable nuclei via inverse alpha scattering.

To illustrate these points more quantitatively, we will consider the experimental attack on two specific issues. The first concerns how shell structure changes with neutron or proton excess, while the second considers how nuclei change as a function of neutron number over a wide range of isotopes.

Consider the four nuclei ^{48}Ni, ^{78}Ni, ^{100}Sn and ^{132}Sn. According to the "magic numbers" that have been established for nuclei near stability each of these should be a double-closed shell nucleus, and hence critical to the question of evolution of shell structure. The intensities of beams of these nuclei projected to be available at RIA in units of ions/s are 0.6, 300, 40 and 3×10^{10} (*note* ^{132}Sn is many orders of magnitude higher); the relative intensity advantage over the same beams at the future GSI facility is estimated to be a factor of 60, 40, 20 and 300 respectively. Study of the energy levels of single particle states in the vicinity of these nuclei is best carried out with single-particle transfer reactions at energies on the order 10 MeV/A. Intensities of reaccelerated beams at RIA will be sufficient to carry out these experiments on all important nuclei in the vicinity of ^{132}Sn in tractable experiments requiring on the order of one week per nucleus or less. Systematic transfer studies in the vicinity of ^{78}Ni will also probably be possible at RIA, but the intensities of beams near ^{48}Ni and ^{100}Sn will be too low for such experiments. In these regions information on ground state wave functions can be obtained from knock-out reactions, and further spectroscopic information obtained, for example, from Coulomb excitation with fast beams and by taking advantage of the occurrence of isomers in nuclei near the closed shells.

An interesting suggestion for spectroscopic study of low-lying low-spin states of weakly produced nuclei is gamma spectroscopy following excitation and decay of the giant dipole resonance (GDR) studied at high energy. The cross section for GDR excitation is very large (~barns) for relativistic beams, and the GDR strength function is very well localized in excitation energy so that only one or two nuclei neighboring the projectile are populated by the subsequent neutron evaporation. At GSI energies the probability for excitation and decay of a projectile through this particular channel can exceed 5%, a factor of 3 to 4 larger than that for a comparable experiment at RIA, partially compensating for the RIA intensity advantage in this particular case.

We now consider measurements of a few selected nuclear properties along isotope chains at constant Z. As an example, consider the Ni isotopes. The nuclei of interest range from the potential double-closed shell nucleus at A=48 on the neutron deficient side to the as yet undetermined drip line nucleus on the neutron-rich side, encompassing the range where the r-process path is expected to cross the Ni isotopes somewhere between A=76 and A=83. The projected production rates at RIA range from 0.6 ions/s at A=48 to $\sim 10^{-5}$ ions/s at A=85, which the best available mass models predicts to lie at the drip line. The rate predictions for GSI are smaller by factors of ~30 and ~40 at these two extremes. The expected RIA intensity implies that the drip line predictions could be tested there in experiments of tractable length, while it is much less likely that GSI could reach the dripline. Mass measurements to an accuracy of better than ~ 50 keV/c^2 could be made with Penning traps in experiments lasting on the order of one week at RIA from A=48 on the neutron deficient side and out to about A=81 on the neutron-rich side; the limit of similar experiments at GSI would be two or three neutron numbers closer to stability.

The development of neutron “skins” in neutron-rich nuclei is interesting in itself, and offers a tool for exploring the properties of very neutron rich matter. The neutron skin thickness in stable Ni nuclei ranges up to 0.1 fm. Typical model predictions for skin thickness at the neutron drip line (A=85) approach 0.5 fm. It has been suggested that systematic measurements of neutron skin thickness can be made from measurements of both isospin components of spin dipole resonance strength. Such measurements require intensities of $\sim 10^4$ ion/s and can be made at RIA out to about A=75. Systematic information on matter radii can be carried much farther (A~86) by inverse proton scattering or total reaction cross section measurements; coupled with measurements or extrapolation of charge radii, neutron skin thickness can be obtained. The limits at GSI are roughly two neutrons less (A~84), but the ability to do electron scattering measurements in the storage ring at GSI means that very detailed information on the charge distribution can be obtained for nuclei nearer stability (out to A~71 or 72).

These few comparisons are intended only for illustration; there are many more measurements on the Ni isotopes that would provide important nuclear structure data, including the systematic transfer reaction measurements in the vicinity of ^{78}Ni, which can be done with reaccelerated beams at RIA, along with knock out reaction and Coulomb excitation studies among others.

What are the strengths of each facility ?

- **RIA strength**: RIA’s generally higher intensity of unstable nuclei, especially at the limits of existence, will provide it with across the board advantages even in the capabilities it shares with GSI. The flexibility of the RIA concept allows the choice of production methods to be optimized for particular rare isotope species that will, for example, have a major impact on studies of very heavy elements. The re-accelerated beam capability at RIA, which is unique to that facility, will enable the application of a wide range of classical nuclear structure studies to nuclei with extreme N/Z ratios that will be a focus of the nuclear structure program.

- **GSI strength**: GSI has unique capabilities of stored and cooled unstable beams that make possible broad-range measurements of large numbers of masses at moderate precision (~50 keV). Colliding-beam eA studies of nuclear charge distributions will also be possible for species produced at relatively high intensity (>10^6 ions/s). The availability of thin internal targets of hydrogen and helium isotopes will facilitate hadron scattering studies of the radial distributions of mass in nuclei, and may allow an extension of knowledge of isoscalar giant modes into the regime of neutron-rich unstable nuclei.

In summary, RIA has significant advantages over the GSI future facility for advancing the study of nuclear structure physics by providing substantially higher yields of nuclei, particularly in the unexplored regions farthest from stability. The ability to select an optimum production method for particular rare isotope species, and a re-accelerated beam capability is critically important to a large part of the nuclear structure program. GSI does, however, add important and complementary capability in nuclear structure experiments that can take advantage of stored and cooled beams.

Astrophysics

It is the purpose of RIA, and one of the purposes of the GSI project, to explore nuclear matter at its extremes, in particular at the extremities of neutron to proton ratio, and also at the limits of nuclear mass and density. Such extremes find a natural application in astrophysics, where nuclei of all sorts and lifetimes experience a transitory existence in the cosmos and where the universe's grandest nucleus – the neutron star – is central to many interesting phenomena.

Stars live a long time, so nuclear reactions determining their structure involve nuclei along the valley of beta-stability. Most of these reactions either occur at well known rates or are accessible using stable beams (a possible exception is $^{12}C(\alpha,\gamma)^{16}O$ which can be studied by the beta-delayed alpha emission of ^{16}N). The general hypothesis that the elements of nature, other than the lightest few, have been created as a byproduct of stellar evolution is not contested. Experiments at RIA and GSI will focus mainly on the study of nuclear reaction and decay processes in stellar explosions such as a supernova shock fronts or thermonuclear explosions in accreting binary systems. These experiments will lead to a more quantitative theory of nucleosynthesis and a better understanding of the behavior of matter in extreme environments.

In principle either RIA or GSI would:

- Improve our understanding of the origin of specific elements and the ratios in which certain sets of isotopes are made.

- Calibrate a *diagnostic tool,* the theory of stellar nucleosynthesis, that can tell us about the nature of cosmic explosions of all sorts and the history of stellar evolution in our galaxy and others.

- Refine key nuclear uncertainties that directly affect astronomical observables such as the light curves of Type I X-ray bursts.

- Enable a better understanding of the operation of core-collapse supernovae where weak interactions and the super-nuclear equation of state play a key role.

- Lead to a more physical description of the structure of neutron stars, especially their crusts.

In the following sections we discuss these applications in greater detail and compare the capabilities of RIA and the future GSI facility in astrophysics. There are areas where each excels and a large area where they overlap, but broadly speaking, the higher beam intensity at RIA and the ability to harvest large quantities of radioactive isotopes on line give it an advantage in most astrophysical applications.

Physics of the r-process

The r-process is responsible for producing roughly half of the elements heavier than iron. Nuclear systematics tell us that the process must have occurred on an explosive time scale, probably of order a few seconds, and at a very high neutron density. The presumed path of the r-process in the periodic chart is based on extrapolating nuclear models into regions of highly uncertain binding energy and half life. To complicate matters further, even after 45 years of study, the actual astrophysical site of the r-process is uncertain, and this allows considerable latitude in the important characteristic parameters -temperature, density, time scale, neutron density. It is currently thought that either the neutrino-powered winds from young neutron stars or the mergers of binary neutron stars might provide the necessary conditions, but other scenarios such as supernova powered jets are not ruled out. It is clear from astronomical observations that r-process nuclei were already being made when some of earliest stars formed, so it is not a “secondary” process, like the slow neutron capture that makes the other half of the elements heavier than iron.

The most important nuclear physics for the r-process are the binding energies and lifetimes of nuclei along the r-process path, especially at the so called ``waiting points” where the flow stagnates, producing the major abundances. Because the most important flows occur through links where (n,γ) is balanced by (γ,n), the actual (n,γ) cross sections are not so critical, so long as they are not too small. Several reactions involving light isotopes ($A < 12$) interacting with alpha particles and neutrons are important for setting the neutron to seed ratio for the r-process, but the most important of these, $^{9}Be(\alpha,n)^{12}C$, is reasonably well known. There is however considerable uncertainty concerning neutron capture processes on light neutron-rich halo isotopes that may open new reaction branches. Some important secondary scientific goals are the cross sections for fission recycling at the end of the r-process, for neutrinos interacting with nuclei at the waiting points, and for beta-delayed neutron emission as the neutron-rich progenitors decay back to the valley of beta-stability. Neutron capture reactions may play a significant role during the late phase of the r-process when equilibrium is not maintained. This requires knowledge of neutron capture rates on neutron-rich nuclei.

The experimental study of the r-process requires probing a wide range of isotopes along and near the r-process path. The first approach will be the study of r-process isotopes near closed shells, but shell quenching could shift the focus of the search. Many nuclei are made by the r-process and we need to know the properties of all of them – or at least their progenitors – in order to compute their abundances.

Current nuclear uncertainties are affecting the yields of various isotopes especially in the vicinity of shell closures, particularly around A = 120. A better knowledge of the binding energies and lifetimes along the r-process path would also constrain both the path and its time scale more rigidly. A better understanding of the r-process nucleosynthesis would also improve the reliability of radioactive cosmochronology, for example U-Th dating.

What are the strengths of each facility?

- **RIA strength**: The higher intensities allow more sensitive and higher quality structure and life-time measurements, identification and study of halo effects, and shell quenching signatures. In particular, determinations of half-life and the probability for β-delayed neutron emission are very intensity dependent. RIA also provides deeper access (on average by 2-3 neutrons compared to GSI) into the neutron rich regions of the nuclide chart. The proposed (d,p) transfer studies to probe (n,γ) reaction rates can also be performed without major difficulty over a wide energy range. Because of the fast beam option, (γ,n) Coulomb break-up experiments are also possible, but face similar uncertainties as at GSI.

- **GSI strength**: The storage ring allows global mass measurement for many masses at the same time. This is a good technique for testing mass models and promises to provide mass information with uncertainties less than 100 keV/c^2. The fast beam capability allows measurements of Coulomb break-up, but the method may only be useful for light isotope systems because of the complexity in structure and gamma-decay pattern of the resonance states.

In summary, the higher beam intensity at RIA allows both deeper penetration into the region of unexplored neutron-rich nuclei and better statistics for the less extreme cases. The ability to reaccelerate some isotopes and harvest others also facilitates important secondary r-process science, e.g., the measurement of cross sections.

Of some importance to astrophysics is a facility for studying neutron induced reactions on unstable nuclei. In some cases the targets are sufficiently long lived that they can be harvested and studied off line, but in others, particularly in the astrophysical r-process, the lifetimes can be very short. RIA needs to determine what capabilities will be present for studying neutron-induced reactions. The National Nuclear Security Administration may contribute to such a facility (see below under stockpile stewardship) but it is not clear that the range of energies and lifetimes they are interested in overlap what is needed for astrophysics.

The rp-process in Type I x-ray bursts.

A Type I X-ray burst occurs when a critical mass of hydrogen and helium accumulates on the surface of a neutron star. An unstable nuclear runaway develops, in part because of degeneracy, but also because the strong gravity keeps the layer thin (about 10 m) compared with the radius of the neutron star. The nuclear energy is carried to the surface by a combination of diffusion and convection, and the star glows brightly in X-rays for about a minute. The observed light curves of these explosions have been studied for years and are known, from current modeling, to depend sensitively on the assumed nuclear physics. Precision analysis of the light curves of X-ray bursts is expected to yield information on how the nuclear burning spreads over the surface of the neutron star and therefore on the rotation rate and magnetic field strength. Current evidence suggests that many X-ray bursters have been spun up by accretion almost to the point of break up and may in fact be stabilized by gravitational radiation. The light curve also constrains the gravitational potential – hence mass and radius – of the neutron star.

The nuclear flow is carried from the light elements up to above iron by a series of (p,γ) and, at high temperature, (α,p) reactions and weak decay, known collectively as the "rp-process". Like the r-process, the rp-process has waiting points where (γ,p) – or proton emission of drip-line nuclei - balances (p,γ) and so mass excess and lifetimes are again the most crucial physics. Important waiting points occur at the “alpha-nuclei” – ^{56}Ni, ^{60}Zn, ^{64}Ge, ^{68}Se, and ^{72}Kr – whose abundances “bleed out” by a combination of proton capture and weak decay, through the nuclei one and two protons above them in the periodic chart.

There are also indications that the rate of proton capture and weak flows between A = 28 and 40 may affect the light curve. Many nuclei in this range of masses and proton excess (essentially $14 < Z = N < 50$ to the proton drip line) have uncertain masses, positron emission and electron capture rates, isomeric structure, and proton capture cross sections. The latter might be probed by Coulomb dissociation techniques for near drip line nuclei. The temperature of the rp-process is predicted to range between 0.5 to 2.0 x 10^9 K; hence the relevant center-of-mass energies for the protons in (p,γ) reactions is about 1 MeV. Typical weak lifetimes of interest range from 10 ms to 10 s.

The rp-process starts at about A = 20 and continues up to around A = 120, though individual reactions for breaking out of the CNO cycle – ^{15}O(α,γ), ^{19}Ne(p,γ), ^{14}O(α,p), ^{18}Ne(α,p), and others – are also important. Many of these reactions are presently under investigation at radioactive beam facilities - e.g. Louvain la Neuve, HRIBF, ISAC – but the lack of available beam intensity prevents the measurements in the critical energy range of the thermonuclear runaway (E_{CM}<0.5 MeV). X-ray bursts are generally not thought to be important for galactic nucleosynthesis, but the composition of the ashes of X-ray bursts determine the neutron crust composition (for stars that are producing bursts) and this affects crustal cooling – or heating - by electron capture and pycnonuclear reactions.

What are the strengths of each facility?

- **RIA strength**: The higher intensities allow more sensitive and subsequently higher quality structure measurements. Coulomb dissociation measurements such as 2p-break-up as inverse to 2p-capture are ideally suited for RIA's fast beam component. Capture reactions on neutron deficient isotopes with Z<30 require high intensity together with techniques developed at HRIBF and ISAC. Such measurements might only be possible at RIA. RIA will also provide unique capabilities for β-decay studies and other spectroscopy along the drip line that will be relevant for exploring isomer configurations that could alter the rp-process conditions.

- **GSI strength**: the storage ring approach allows global mass measurement for many masses at the same time. However, the storage ring technique is limited to lifetimes > few ms, therefore very short lived nuclei at or beyond the drip line cannot be measured. Coulomb dissociation will also be possible in the storage ring approach but the lifetime limitations may be a handicap. The fast beam technique at GSI is however well suited for α-break up studies of N=Z nuclei. Also β decay measurements may be very suitable for storage ring experiments with its sensitivity for masses and mass changes. Storage ring experiments may require new developments in detection and timing techniques at "target" stations.

In summary, RIA appears especially favored for studies of the rp-process because of the higher beam intensity and the consequent ability to measure the small (p,γ) cross sections on a broader range of interesting nuclei. (α,p) and (p,γ) cross sections are more important for the rp-process than (n,γ) cross sections are for the r-process.

Nova explosions

Classical Novae explosions are thermonuclear runaways on the surfaces of accreting white dwarf stars. The relevant nuclear physics resembles that of the rp-process in that one is still interested chiefly in (p,γ) reactions and weak decay, but the temperatures are lower, probably $< 0.5 \times 10^9$ K, and the time scales are longer. The nuclei are neither as heavy (A < 41) or as proton-rich. Typical lifetimes of unstable nuclei of interest are seconds and longer. Photodisintegration is not so important and cross sections for (p,γ) are more important.

There is a range of open questions concerning the mixing mechanism between accreted material and the white dwarf, a discrepancy between the observed and predicted masses of the ejected material, and the nucleosynthesis (sometimes heavier species are seen than predicted by the models). Some of these issues may reflect observational uncertainties, but the nuclear physics is also problematic. Chiefly it involves (p,γ) reactions on stable and unstable nuclei in the CNO range. In the case of the so-called Ne novae (characterized by pronounced neon abundances in the ejecta) reactions on stable and unstable nuclei in the neon to calcium range are important. In view of the new generation of γ-ray observatories (e.g. INTEGRAL) the production of potentially detectable long-lived radioactive isotopes is of considerable interest. Especially important are reactions producing or depleting ^{22}Na and ^{26}Al, whose gamma-ray decay lines might be detected, and of other short-lived radioactivities whose convection may augment the luminosity.

What are the strengths of each facility?

- **RIA strength**: The higher intensities will allow better studies of Coulomb break-up and transfer, but the main advantage is the use of low energy radioactive beams for capture measurement. Many of these reactions will have been measured at facilities like HRIBF and ISAC, but the higher RIA intensity will allow studies with considerably reduced uncertainty and will also probe weaker contributions like direct capture components and low energy resonances which would dominate the rates at nova conditions.

- **GSI strength**: The fast beam capability of GSI provides excellent opportunities for Coulomb break-up measurements. Measurements with long-lived isomeric states (^{26}Al) might be feasible.

In summary, RIA has the advantage here because it can determine (p,γ) cross sections on the relevant nuclei more accurately.

Supernova diagnostics
The observation of the galactic plane with γ-ray observatories demonstrates the existence of galactic radioactivity from a wide variety of sources such as supernova remnants and the interstellar medium. For example, ^{60}Fe (lifetime about a million years) was discovered a few months ago in the interstellar medium; ^{26}Al, with a similar lifetime was discovered there years ago; and ^{44}Ti, which lives less than a century, has also been observed in the young supernova remnant Cas A. The cross sections for the production and destruction of these radionuclides are uncertain and important. Determining them primarily requires the measurement of proton and alpha capture reactions on neutron deficient unstable nuclei.

What are the strengths of each facility?

- **RIA strength**: Good experimental conditions for low energy p or α capture measurements, but also suited for α-break up studies of T=0, N=Z nuclei in the ^{44}Ti to ^{56}Ni range.

- **GSI strength**: Coulomb dissociation techniques can be applied, but again, since the Q-values of the reactions in question are high, the experimental results will be subject to large uncertainties due to the complex nuclear structure involved. However, it may be interesting in case of α-break up of T=0, N=Z nuclei in the ^{44}Ti to ^{56}Ni range.

RIA's ability to harvest and reaccelerate high intensity beams of long-lived radioactivities gives it an advantage here.

Supernova explosion physics

The physics of how iron core collapse in a massive star leads to a supernova explosion has been studied and debated for over 50 years. Even today, there is no clear consensus on the exact explosion mechanism. The currently favored paradigm is an explosion powered by neutrino transport. Neutrinos diffuse and convect out of a proto-neutron star several tenths of a second old, and deposit a fraction of their energy in the neutrons and protons (not bound nuclei) just above the emission region. This energy deposition inflates a bubble of radiation that drives the explosion. Calculations must be carried out in 2 and 3 dimensions because convection, both within the neutron star and in the bubble, plays a key role in the transport and deposition. Multi-dimensional calculations of neutrino transport have proven to be challenging. The most recent calculations remain ambiguous as to whether the star explodes (though nature obviously has found her way through this ambiguity). Nuclear physics is important to determining the structure of the collapsing core, especially the iron core mass which is sensitive to weak decay rates in the pre-explosive star, and the strength of the prompt shock that emerges from the bounce. It is no longer believed that this prompt shock explodes the star by itself, but it does set up the conditions in which the neutrino mechanism or some other mechanism operates. It is likely that the solution to the "supernova problem" will come from a combination of detailed, multi-dimensional numerical simulation and improved input physics, but there is no clear single bit of nuclear structure that presently determines the success or failure of the model.

More theoretical work is needed to know just how, quantitatively, variation in the weak interaction rates affects the explosion mechanism. Some significant changes since the 1980's have, so far, made little difference, but the studies have been confined to relatively low temperature ($T < 10^{10}$ K) and density ($\rho < 10^{10}$ g cm^{-3}). Electron capture on nuclei with A = 60 – 80 occurs at uncertain rates for these extreme conditions and may be important to setting up the conditions for explosion.

Measurement of the Gamow-Teller strength function for nuclei in this mass range and exploration of the isospin dependence of the nuclear force for densities up to about three times nuclear, Z/A down to at least 0.3, and temperatures up to 100 MeV is important.

What are the strengths of each facility?

- **RIA strength**: Charge exchange reactions with radioactive isotopes will provide improved information about the electron capture rates of relevance for pre-SN collapse phase. RIA would provide a broad opportunity for studying such charge exchange processes for a broad range of nuclei with various probes.

- **GSI strength**: The facility provides excellent conditions for giant resonance studies that would provide a good way for testing the incompressibility of neutron rich nuclear matter. These measurements could be complemented with relativistic heavy ion studies. Charge exchange reaction studies with the fast beam component are also feasible.

In summary, both facilities will make important measurements here. GSI may be able to access higher densities (up to about 4 times normal nuclear vs 2 for RIA). Both will address a comparable range of isospin. RIA may be superior for the (p,n) cross sections needed to constrain the Gamow-Teller strength function.

The "p-process" or "gamma-process"

The p-process is responsible for the production of rare proton-rich stable isotopes (p-nuclei) above the iron group. The favored scenario is photodisintegration in explosive O/Ne-burning in the type II supernova shock-front at temperatures of 2 – 3 x 10^9 K operating for several seconds. The p-nuclei are mostly produced by (γ,n), (γ,p) and (γ,α) reactions on unstable "proton-rich" nuclei. More detailed theoretical and experimental analysis is necessary to determine the most sensitive reactions and the observable characteristics of p-process nucleosynthesis. One open question is the origin of light p-nuclei in the Mo-Ru range. The observed abundances cannot yet be explained by any model.

These photodisintegration reactions could be studied by (p,γ) and (α,γ) reactions on unstable targets A = 150 – 200 via detailed balance. Coulomb dissociation techniques should be well suited for these studies if virtual γ distribution (and flux) can be matched with anticipated Planck distribution in the supernova shock front. Of particular interest are measurements near (γ,n), (γ,α) branching points which could be induced by regions of large deformation or closed shell configurations e.g. near Z=50, N=50 closed shell nuclei.

What are the strengths of each facility?

- **RIA strength**: The higher intensities might allow better studies of Coulomb dissociation such as at GSI, but a major advantage would be the use of low energy radioactive beams for (p,γ) and (α,γ) reactions on unstable targets A = 150 – 200 to determine inverse photodisintegration via detailed balance.

- **GSI strength**: Coulomb dissociation techniques should be well suited for these studies if virtual γ distribution (and flux) can be matched with anticipated Planck distribution in SN shock front. Of particular interest are measurements near (γ,n), (γ,α) branching points which could be induced by regions of large deformation or closed shell configurations e.g. near Z=50, N=50 closed shell nuclei.

In summary, while both facilities are comparable in the application of Coulomb dissociation techniques, RIA seems more versatile since it also offers the possibility of measuring inverse proton and alpha capture reactions, which has emerged as a powerful tool for p-process experiments with stable nuclei.

s-process nucleosynthesis

The s-process involves mainly neutron capture on stable nuclei above Fe up to Bi. The s-process takes place during helium and carbon burning phases of late stellar evolution and is therefore not directly associated with explosive nucleosynthesis scenarios. Nevertheless a detailed understanding of s-process abundances is important for the determination of the r-process abundance distribution that serves as one of the major signatures and tools for testing r-process models and r-process model predictions. There are some interesting aspects for radioactive beam applications for s-process studies, namely, the branching points between β-decay and neutron capture on long-lived radioactive nuclei. Detailed knowledge about the reaction branching will provide opportunity to develop analytical techniques such as an s-process thermometer and a neutron flux-meter. Also neutron capture on long-lived isomers is of interest.

What are the strengths of each facility?

- **RIA strength**: Neutron capture measurements require a high neutron flux and significant quantities of long-lived radioactive targets. The installation of a low energy neutron generator (not part of the RIA proposal) would allow on-line (or nearly on-line) neutron capture measurements at implanted radioactive targets.

- **GSI strength**: The lack of slow radioactive beams and of neutron beams prevents GSI from being a suitable s-process facility.

In summary, neutron capture experiments with radioactive beams are experimentally challenging. Because of its higher beam intensities RIA would have an advantage for measuring (n,γ) reactions on implanted long-lived (>1d) radioactive isotopes were an external neutron beam available; direct (n,γ) studies on short-lived isotopes are not possible with presently available techniques on either facility.

Fundamental Symmetries

Studies of fundamental symmetries often benefit from particular choices of the nuclear systems in which they are performed. Either a specific set of nuclei have properties that make them unique for a particular effect, or often a small effect can be significantly magnified by the proper choice of a nuclear species. Both RIA and GSI will be able to produce a very large number of isotopes, and provide these in quantities ranging from single atoms up to micro-grams. This capability will make it possible to significantly improve experiments that directly probe fundamental symmetries and the standard model. Both RIA and GSI anticipate programs in this area to address compelling questions. Some examples of such experiments are given below.

Atomic parity violating experiments have been carried out in materials where the atomic physics is well understood. The parity-violation arises from effects of Z^0 exchange. Such experiments measure $\sin^2\Theta_W$ at very low momentum transfer. The best values to date come from measurements on Cs and are ultimately limited by our understanding of atomic effects. The size of the parity violation effect increases like Z^3 of the atomic system, and is roughly proportional to the number of neutrons. The proton effect is reduced by a factor of $(1-4\sin^2\Theta_W)$. By measuring the ratio of the difference in two isotopes relative to the effect the uncertainties due to atomic effects cancel out. If measurements are made on isotopes of Fr that are separated in neutron number by about 20, it is in principle possible to improve the current best measurement by about a factor of 3. Of course, these measurements depend on being able to produce sufficient quantities of the two isotopes of Fr and, in this particular experiment, the intensities from RIA give it a clear advantage in their production.

There is cosmological evidence for CP violation stronger than allowed by a phase in the CKM matrix. Electric Dipole Moments (EDM) measurements are the most sensitive probes for this physics and also put stringent limits on the standard model (SM). SM extensions naturally predict enhancements in the electron EDM and an observation of a non-zero EDM at the level possible for the next generation of experiments would be direct evidence of new physics. It is essential that the electron EDM, the neutron EDM and nuclear EDM all be measured since they provide complementary sensitivity to the underlying models. For example, the neutron EDM is believed to be sensitive to both the quark EDM and the quark color electric dipole moment (CEDM), while the nuclear EDM, which is sensitive to the P-odd, T-odd component of the nucleon-nucleon interaction, is primarily sensitive to the CEDM. There is also a recent indication that an EDM search in octupole deformed nuclei would have the best sensitivity to the CP violating θ term in QCD, while the electron EDM would have no sensitivity to this term. Isotopes produced in both RIA and GSI could be used to significantly improve the limits on these EDM measurements.

The EDM of the electron is normally measured in atomic systems. The T- and P-odd interaction between the electron EDM and the electric field of the nucleus results in an admixture of the ground state of the atom and excited states with opposite parity. This induces an EDM in the atom that can be enhanced by a factor R over that of the electron alone. The EDM signal is enhanced because of relativistic effects in a neutral paramagnetic atom and the enhancement scales as roughly Z^3/α^2. This enhancement factor varies by element, but not within isotopes of a given element. Measurements to date have been carried out in Tl that has R of 585. However, the largest enhancement factor is in Fr, where R is about 1000. Unfortunately, due to its short half-life (the longest lived isotope of Fr has a half-life of about 20 minutes), Fr is very hard to produce in sufficient quantity to carry out these measurements and the accuracy of the measurements depends on the quantity of Fr that can be produced and trapped. There are plans to attempt these measurements at TRIUMF and the situation should greatly improve with the availability of RIA and the GSI project. Any deviation from the currently measured value of zero for the electron EDM would provide direct evidence of new physics beyond the SM.

EDM measurements on nuclei provide the best measure of the CP-violating term in QCD, while the electron EDM has no sensitivity to this. The best measurements to date come from ^{199}Hg and ^{129}Xe. P- and T-odd effects in the radium atom should be greatly enhanced because of the octupole deformation. This deformation leads to a collectivity effect as well as to near parity doublets that enhance the moment. The enhancement in ^{225}Ra over ^{199}Hg is a factor of about 375, and other species may provide even larger factors. A program of measurements using these isotopes is likely to eventually provide substantial improvements over the current best measurements. RIA is expected to produce a Curie of ^{225}Ra, while GSI production is likely to be down by several orders of magnitude.

$0^+ \rightarrow 0^+$ super allowed decay studies have yielded a very high-precision test of the CVC hypothesis, the most precise value of the weak vector coupling constant and the most precise value of V_{ud} , which in turn yields the most precise unitary test of the CKM matrix. The extraction of V_{ud} from these decays rests upon calculations of isospin breaking corrections. These corrections could be put on a more secure footing by measuring superallowed decays in heavier nuclei where the corrections are much larger. Progress in this area is currently being pursued at existing facilities and will advance significantly before either RIA or the GSI future facility become available. However, the more detailed nuclear spectroscopy of excited low-spin states required to unravel isospin mixing to low-lying states in these nuclei will require reaccelerated beams available at RIA. Precision measurements on the most exotic of these nuclei might also require the higher intensities available at RIA and the GSI project.

The GSI storage ring also makes possible a number of Quantum Electrodynamic tests involving highly ionized heavy ions. Measurements on Hydrogen-like Uranium provide an environment in which QED can be tested in strong electromagnetic fields. Precision measurements of electron binding energies are best suited to deduce characteristic QED phenomena in intense fields. Comparison of predicted with experimentally determined level energies of strongly bound electrons provides a critical test of QED in strong fields. In the case of hydrogen-like uranium the Lamb shift has been measured to an accuracy of 13 eV. A measurement to an accuracy of 1eV and below would be one of the most important tests of QED in strong fields. Other important measurements can also be carried out. Without the storage ring, RIA will be at a severe disadvantage in this area of physics.

As described later in the document, the antiprotons available at GSI will make possible a host of experiments that will not be possible at RIA. There will be 2 orders of magnitude more cooled antiprotons than have been available at CERN. This will allow important extensions of existing programs on anti-hydrogen and make possible experimental investigations of the gravitational interaction of antimatter.

These topics are natural extensions of existing programs that will benefit from the availability of new isotopes and ions that can be provided by both RIA and the GSI project. Other opportunities exist such as searches for currents outside the standard V-A form of the charged weak interaction and time reversal studies. These will benefit from both availability of materials, and advances in trapping, lasers and other technology.

What are the strengths of each facility?

- **RIA strength**: the higher intensities and multiple separation techniques will give RIA a clear advantage over GSI because larger quantities of isotopes will be available. These enhancements will be very important for the atomic Parity violation and EDM measurements.

- **GSI strength**: GSI will clearly be competitive in experiments that are limited by experimental challenges other than intensity. The storage ring will make it possible to carry out QED studies on highly ionized ions, and probe QED in the strong field regime. The planned antiproton facility and the host of fundamental experiments on antimatter that will be possible are unique to GSI.

In summary, the facilities are quite complementary. RIA's advantage in higher yields of rare isotopes is balanced by GSI's unique capabilities with storage rings and antiprotons.

Applications

Both RIA and GSI list a number of applications that they envision their facilities providing. While plausible, and perhaps even likely, these applications are not the driving force behind these facilities and thus we do not focus on them, other than areas most evident in the RIA proposal: the production of medical isotopes and measurements related to stockpile stewardship.

Stockpile Stewardship

Documents from the NNSA outline strong interest in utilizing RIA for studies related to stockpile stewardship. In the era of nuclear testing, information about device performance came from radiochemistry studies. In particular, foils of various stable isotopes (a total of some 40 different ones were used at one time or another) were placed near the device. Elemental and isotopic analysis of the post-test debris would then yield information about the neutron exposure of these samples, and hence the device performance. Such radiochemical measurements were one of the principal methods for determining device yield.

Cross sections for various neutron-induced processes on stable and unstable nuclei are required to model the nuclear reaction networks that produce the observable debris. Unfortunately, few of these cross sections are known precisely, so most are estimated using reaction models such as the Hauser-Feshbach description of the compound nucleus. RIA measurements of such cross sections would improve modeling capabilities both directly (by better determining some of the specific cross sections needed) and indirectly (by better calibrating semi-empirical extrapolations and interpolations of nuclear properties). In that way, they will improve our confidence in the interpretation of historical test data through the detailed modeling of the ASCI program.

To carry out some of the measurements NNSA proposes to make targets of some short-lived isotopes and bombard them with neutrons produced by an accelerator. Space to accommodate these latter activities is part of the RIA plan, but the facilities to generate the neutrons are not part of the RIA proposal and presumably would be funded and built by NNSA.

The radiochemical diagnostics that would be improved by RIA are most indicative of the performance of the secondary parts of explosive devices. They would be therefore valuable, but not crucial, to Stockpile Stewardship, as the greatest uncertainties with weapons yields are associated with primaries, which have a separate and complementary suite of diagnostics. Radiochemical methods will also play a role in diagnosing NIF capsules, although again there will be more direct techniques employed.

NNSA personnel have given plausible technical and social/political reasons why their rare-isotope activities would be best carried out at RIA, rather than GSI.

Medical Isotopes
Radioactive isotopes are used routinely for thousands of medical procedures every day and RIA has discussed the production of medical isotopes as a possible application. While it is certainly true that RIA would be able to produce a wide variety of isotopes the situation is not as compelling as is described. In the U.S. the DOE currently funds the government's medical radioisotope R&D program with the two major U.S. accelerator facilities at LANL and BNL (BLIP). Medical radioisotopes are also produced at reactors. The situation at LANL is complicated in that they have not irradiated any targets since 1999. Rather they have been importing irradiated targets from other facilities in Russia and South Africa, and doing the chemical processing at LANL.

DOE maintains a list of isotopes to be produced by these facilities. The list changes slightly from year to year in response to commercial demand and researcher proposals, but the number of isotopes that have been developed and could be produced is much larger than the DOE list. However, in recent years the funding for production of research isotopes has decreased. The isotopes expected to be produced for the commercial sector at BLIP this year are ^{82}Sr, and ^{68}Ge. Small quantities of ^{7}Be, ^{67}Cu, ^{73}As, ^{95m}Tc and ^{65}Zn for research will also be produced, however, BLIP cannot produce much this year because funding limits running time to only 9 weeks. LANL has been building a new facility, the Isotope Production Facility (IPF), that is almost ready for operation parasitically with the LANSCE accelerator. When it starts they expect to expand their list to ^{7}Be, ^{67}Cu, ^{109}Cd and ^{22}Na with the latter two, ^{109}Cd and ^{22}Na, for commercial users. There is a designed product overlap between BLIP and IPF in order to improve availability throughout the year.

We note that TRIUMF in Canada also produces medical isotopes through a different mode of operation. A commercial firm, MDS Nordion Inc., uses a target station at

TRIUMF and leases space from TRIUMF to operate 3 small cyclotrons that it owns. With these facilities Nordion is the major producer of accelerator isotopes for the US. Their list of available isotopes includes ^{57}Co, ^{67}Ga, ^{103}Pd, ^{111}In, ^{123}I, ^{82}Sr, ^{201}Tl. These are all commercial scale, high volume products. Nordion and other commercial producers do not service the research market, as it is too small to be profitable.

It is important to note that most (>90%) of the accelerator produced medically useful isotopes can be produced with up to 30 MeV protons. Approximately 97% can be produced with 70 MeV. The cost to run RIA makes it less likely that this will be a significant application area and we note that the concepts put forward for this capability are very sketchy, especially with regard to cost-effectiveness. Thus, for RIA to have a significant program in medical isotopes a much stronger case will have to be made.

Other Research Opportunities at GSI

The following research areas are largely a focus at GSI, but not at RIA. They are briefly described as they do have an impact on other areas of U.S. science.

Antiprotons

The proposed GSI program on antiprotons is best described as an extension of the antiproton programs carried out at the CERN LEAR facility in the 80s and 90s with an increase of energy to explore the charm sector. This program includes a spectroscopy program that will focus on charmed states that are not easily made at an e+e- machine, such as CLEO, and will extend work begun at Fermilab to higher energy with higher luminosity. Such work will be complementary to the planned CLEO-c program. The program also proposes to search for charmed hybrid mesons, an activity that complements the planned searches for light-quark hybrid mesons at CEBAF following its planned 12 GeV upgrade. The recent significant advances in spectroscopy were made when several different production mechanisms were available: antiproton annihilations, central production and pion peripheral production. There is also a proposed effort to study in-medium hadron properties using antiprotons to produce the desired states. Given both the complementary nature of much of this program, and the aspects that are unique to an antiproton facility, this program at GSI is likely to be of interest to U.S. researchers.

Relativistic Heavy Ions

The proposed GSI program on nuclear matter properties utilizing relativistic heavy-ion beams is not an aspect of the RIA proposal. Programs in the late 1980's through much of the 1990's at the Brookhaven AGS and the CERN SPS mapped out many of the features of the matter produced in fixed-target relativistic heavy-ion collisions in the region from 10 GeV/A to 160 GeV/A. However, the experiments at the AGS and the lowest energies at SPS did not complete a systematic study of the energy, collision species, identified particle fluxes, flow phenomena, HBT radii, etc. There are many facets of these collisions which have not been studied and which promise interesting physics. The GSI accelerators will permit fixed target experiments with beams of ions up to Uranium with energies ranging from 1GeV/A to about 40 GeV/A. This is a regime that we know, from the earlier experiments at the AGS and SPS, produces the highest baryon density. It is an interesting regime and in a sense complementary to the high temperature, low baryon density regime that is probed at RHIC and will be studied in the heavy ion phase of the LHC.

The energy at GSI is well above the strange particle threshold and copious production of strangeness will occur. Theorists have predicted that hypernuclei with large strangeness might exist and be metastable because Pauli blocking prevents fast decay. These objects could be searched for at the GSI facility. The high-density regime also raises the possibility to study the color superconducting phases of high baryon density quark matter that have recently been predicted although this will be difficult, perhaps not even feasible, because the system temperature in these collisions is too high. On the other hand, the exact range of applicability of these new ideas is not well understood and experimental studies would cast some light on the subject and might even reveal surprises.

Measurement of leptons and direct photons produced in the collisions are also of interest. The lepton pair measurements would permit the study of the modification of resonance parameters (e.g. ρ mass and width) due to the surrounding dense nuclear medium. Another interesting possibility is that the critical point in the phase diagram of hadronic matter would occur in the range accessed by the GSI facility. Observation of this critical point would be a major step in verifying our understanding of the thermodynamics and statistical mechanics of hadronic matter. In large systems the critical point is characterized by very large fluctuations. Presumably, the heavy ion systems to be studied are large enough so that such distinct fluctuations would be observable.

While the majority of U.S. heavy ion physicists would continue to do their research at the highest energies available, at RHIC and perhaps at the LHC, there may well be some who would wish to pursue the opportunities made available at the new GSI facility.

Plasma Physics
The DOE and GSI have a signed agreement to do cooperative research on inertial fusion. Thus this is clearly a U.S. community that would utilize this aspect of the multi-faceted GSI facility.

Atomic Physics
A strong and diverse program in fundamental atomic physics is planned at GSI to investigate a variety of topics including relativistic atomic collision dynamics in the strongest electromagnetic fields, and tests of Quantum Electrodynamics in strong fields. Many of the planned experiments make use of the large Doppler shifts of atomic transitions in high velocity ion beams. Activity in this area has diminished in the United States in recent years, in part because of the lack of available facilities following the closure of the LBNL Bevalac. The availability at GSI of very high-energy primary and stored beams is most advantageous and will be a cost effective option for US scientists interested in pursuing these interesting problems.

While fundamental atomic physics studies will likely be concentrated at GSI, applied atomic physics is a ubiquitous and essential part of the proposed scientific programs for both facilities. Some examples include energy loss processes in gases, collinear laser spectroscopy, and tests of fundamental symmetries. Detailed understanding of energy loss processes is essential both for production of secondary beams at RIA following stopping in a gas cell and for the high energy density program at GSI. Radii of unstable isotopes can be measured using collinear laser spectroscopy. As discussed above in this report tests of fundamental symmetries involving the use of atoms will be undertaken at both facilities. These tests are essentially high precision atomic physics experiments using atoms of unstable nuclei. For example, neutral atom traps have already been used in pioneering experiments measuring beta-neutrino correlations, and trapped polarized atoms may be used in searches for nuclear electric dipole moments. Further refinement of these techniques will take place at both facilities.

Training

An important aspect for all fields of science is the education and training of new researchers for the future development in the field. Equally important is how people with this training apply the science, techniques and methods to other areas of human endeavor. It is of course customary, for communities of scientists to argue that a) their field is important and b) survival of their field requires the funding of a particular costly project. However, the case here has a special focus.

There is a broad spectrum of applications that rely on expertise in traditional nuclear physics and nuclear physics techniques. Numerous industrial applications ranging from material analysis to oil exploration techniques with radioactive probes traditionally have absorbed a large number of young nuclear physicists. Medical physics is a continually growing field with its widespread use of radiation in diagnostics and radiation treatment. That field relies to considerable extent on training in accelerator and radiation techniques as well as in the use and development of arrays of x- or γ-radiation detectors similar to typical low energy instrumentation. Other areas where low energy nuclear physics training is important include stockpile stewardship and a broad and expanding range of homeland security related applications. All these areas rely on expertise in low energy nuclear physics and low energy physics instrumentation.

The scientific focus of the two most recently established nuclear physics research facilities, CEBAF and RHIC, does not emphasize training in aspects of low energy nuclear physics. The shift of university based nuclear physics programs towards the use of these higher energy facilities has led to a decline in graduate student recruitment in low energy nuclear physics. The development of exciting rare isotope programs and in particular the development of major rare isotope beam facilities such as RIA would provide a major incentive for attracting new talent into the area. The construction of such a facility would provide new incentives to university physics departments and deans to recognize the importance and relevance of low energy nuclear physics for the various fields of science and for society. It would stimulate the hiring of new faculty members and researchers and provide a new training ground for the next generation of applied nuclear physicists.

As noted above low energy nuclear physics – by which we mean nuclear physics in the keV and MeV range – is a critical component of stockpile stewardship, nuclear medicine, nuclear reactor design and safety, hazardous waste disposal, and homeland security. Without RIA on the horizon (10 to 15 years from today), an entire generation of young U.S. nuclear physicists may be lost as the center of gravity of this field shifts even more toward Europe. This could have future ramifications for the US that extend well beyond the immediate scientific opportunities of RIA itself.

International Collaborations/User Communities

Given the large cost of the GSI and RIA facilities the issue of international cooperation is an obvious one. In addition to experimental collaborations RIA and GSI have a number of collaborative R&D activities ongoing and there are other international aspects in place. GSI and RIA are collaborating on various aspects of fragment separators, on high resolution magnetic spectrographs, on trapping of nuclei, on gas stopping of fast nuclei, on improving the predictions for yields of nuclei produced by fragmentation and on high power liquid lithium targets. There is a large international collaboration to test and evaluate the full-scale RIA fast gas catcher at GSI at the RIA beam energies and a joint experiment with 85 MeV/A uranium beams at SIS18 to provide quantitative data on charge states vs. foil thickness for RIA driver stripper foils. In addition, RIA is collaborating with a group at Frankfurt on the RFQ for the linac driver and GSI is working closely with JINR in Russia on warm magnets and Brookhaven National Laboratory on superconducting magnet design and operation.

The current user community at GSI is about 1100 and growing with about 50% interested in rare isotope research. The current RIA community is about 500 users with a projected user base of about 1000 researchers. We asked the GSI management whether they would be able to accommodate the U.S. community also. While they welcomed U.S. participation in experiments they stated they could not accommodate the whole U.S. community on a regular basis.

Costs and Benefits of U.S. Investments

Part of the charge was to address the costs and benefits of U.S. investments in the two facilities, including possible upgrades that might extend the scientific reach of GSI beyond the current proposal. In the preceding text we have detailed the unique capabilities and some of the many scientific opportunities to be provided by both RIA and the GSI project. Both facilities have extensive user communities (essentially non-overlapping) and provide training needed in a variety of important areas where low-energy nuclear physics is vital. However, the costs are high.

The construction cost of each facility, if estimated in the same way, approaches or exceeds $1B. Furthermore, on the U.S. side, the NSAC Long Range Plan stated that the RIA construction cost would largely have to come from new money added to the nuclear physics budget so that the community may exploit the outstanding scientific opportunities provided by its unique facilities, CEBAF and RHIC. Under these conditions, it is essential to avoid duplication of effort and cut costs where possible. Avoiding duplication will require close cooperation between the U.S. and European communities, and tough decision-making when the experimental equipment is specified. Indeed, in areas of common R&D needs there are already a number of ongoing collaborations.

The most extreme cost-cutting scenario would be for the U.S. not to proceed with RIA. Under this scenario, the U.S. would not have to invest a large amount of money, but the world would lose a unique facility with outstanding scientific opportunities. The Committee knows of no way in which more modest investment in upgrades of US or other overseas facilities could match the capabilities of a dedicated, state-of-the-art facility like RIA. Unless GSI were to radically change the technical specification of its project, and drop its interest in other areas such as anti-protons, high energy density matter and relativistic heavy ions, no amount of investment by the US or others would enable this facility to match the capabilities of RIA. To put it more bluntly, for GSI to match the unique capabilities of RIA in production and acceleration of rare isotope beams, it would have to build a "RIA-like" facility.

The two facilities do have an overlap in the production of rare isotopes via fast beam fragmentation and fission so it is natural, as the charge requests, to explore whether removing the fast beam capability from RIA and relying upon GSI for this particular aspect would produce the science benefit at a lower cost. As described in earlier parts of this report, even in the area of fast beams, each facility has capabilities that the other cannot reproduce. Due to the inherent design differences of the RIA and GSI accelerators (linac vs synchrotrons), RIA's rare isotope yields are much higher than GSI and there is no upgrade at GSI that would change this significantly. The higher yields permit a greater range of isotopes to be reached, e.g. approach closer to drip lines, and also permit important lower cross section measurements to be carried out.

In addition, RIA's capability to reaccelerate isotopes produced via fast beam methods, and subsequently stopped, is not duplicated in the GSI project. GSI management clearly stated that because of the nature of the accelerator systems chosen to implement their broad range of science in support of their extensive user community, reacceleration could not be justified and will not be pursued.

In short, GSI could not replace the RIA fast beam capability given RIA's much higher yields of isotopes and its reacceleration capability. And finally, removing the fast beam capability at RIA would remove a key reason for RIA.

Another large part of RIA is the ISOL capability, which is not part of the GSI proposal. If ISOL were removed the cost savings would be 10-15%, but the scientific reach would be reduced by a much larger fraction. ISOL is the source for the highest intensity secondary beams and will be the best way to produce some key elements for tests of fundamental symmetries, and the only way to produce very high intensity ($>10^{10}$) re-accelerated secondary beams for heavy element research. It is also the workhorse for the production of targets of rare isotopes and is key to some of the applied programs.

The cases delineated above are clearly extreme. The committee did not feel it had the expertise to assess other, more modest scenarios for reducing the cost of RIA.

Finally, we note the U.S. is making, or will make, some contributions to GSI, especially in the science areas where RIA has no capability.

General Comments

We urge the RIA community to revamp its website to allow easier access to relevant, current documents both at the public and expert level. We initially found it too difficult to find the existing, compelling scientific documentation as the information on the web site was too scattered and, in some cases, out of date. Particularly helpful would be a single, current scientific document that has all the details of some previous white papers – something the knowledgeable nuclear physicist can get his or her teeth into.

In various forums there has been some confusion about the differences in rare isotope capabilities of RIA and GSI. In reading various documents it is clear how some of that can happen. Here are some examples of wording. The DOE plan indicates "RIA beam intensities are between 10-100 times greater than facilities existing or planned" (without specifying GSI); GSI states beam intensities are 100-10,000 times greater than that of the current GSI. These are consistent statements, but could cause confusion. In another place GSI states they have a terawatt beam and RIA states in different documents their beam is 100 kW or 400 kW, but RIA has a higher isotope production rate. In fact, the GSI steady state beam is about 100 kW and they reach a peak of a terawatt by compressing the beam to a 50 ns pulse for plasma experiments. We also found cases where we believe RIA proponents have overstated the importance of a specific capability. We hope that this report has clarified some of the confusion about the capabilities of the facilities. It is important for the RIA community to be clear on what RIA's capabilities are.

Summary

There have been numerous previous studies that have made a strong science case associated with the study of rare isotopes and we reaffirm those findings. The RIA and GSI facilities are largely quite distinct in their strengths and are indeed, as the proponents claim, complementary. RIA clearly has a much larger reach as a rare isotope facility, and hence the better facility to address the science associated with rare isotopes. The existence of an upgraded GSI facility does not, by itself, constitute justification for de-scoping the rare isotope capability of RIA as there is only modest overlap in their rare isotope capabilities. However, the rare isotope capability at the future GSI facility is only one part of a remarkably versatile and multifaceted accelerator complex. We expect the U.S. research community to have a strong interest in several of the GSI capabilities.

Appendix A – Charge to the NSAC Subcommittee

November 25, 2003

Email to Peter Bond

Brookhaven National Laboratory

Dear Peter,

As you know, Ray Orbach, Director of the Office of Science at DOE, and Michael Turner, Assistant Director for the Division of Mathematical and Physical Sciences at the NSF, have charged NSAC to provide advice regarding a request by the German government for US support of the new nuclear physics facility at GSI in Germany. The charge stresses that the Agencies need to understand the rare isotope capabilities and scientific opportunities of both the GSI initiative and of RIA,as well as to consider other US nuclear physics and national considerations relating to the use of these two facilities. The charge also asks for a cost-benefit analysis of US investments in the two facilities. The detailed wording of the charge, which I have previously forwarded to you, gives further and more precise instructions. The formal deadline for the final report is January 30, 2004, although I understand that it is possible that a short extension could be considered.

I am writing to formally ask you to serve as the Chair of an NSAC Sub-committee to consider this charge and to report back to NSAC. The work of this sub-committee is both extremely important and timely since decisions regarding future major construction projects for nuclear physics in the US are expected soon and the Report of your Sub-Committee will provide important input into these decisions.

There will be an NSAC Meeting in the Washington, D.C. area at an appropriate time before your Report is due, and I would like to ask you to give a presentation on the findings of your Sub-Committee. The Report itself will need to be sent to me for distribution to NSAC in sufficient time before the NSAC meeting to ensure that the NSAC membership has time to read and think about your Report. I will inform you further of the date and detailed Agenda for the NSAC meeting when it is finalized.

I realize that this task imposes an extra burden on you, especially given the tight time constraint and the difficulty of assessing two such diverse facilities. Nevertheless, I am confident that you and your Sub-committee will succeed in this critical task, which will have repercussions for all of nuclear science for years to come. I just want to take this opportunity to express to you and the sub-committee in advance my real appreciation for what you are doing. I will be available to help you in any way I can and will attend the subcommittee meetings in an ex officio capacity.

Best regards,

Rick Casten
Chair, NSAC

Professor Richard Casten
Chairman
DOE/NSF Nuclear Science Advisory Committee
A.W. Wright Nuclear Structure Laboratory
Yale University
New Haven, CT 06520

Dear Professor Casten:

In its 2002 Long Range Plan, the Nuclear Science Advisory Committee (NSAC) identified the scientific opportunities offered by rare isotope beams. The proposed Rare Isotope Accelerator (RIA) facility was recommended as its highest priority for new major construction to address these opportunities. Recently, the German government has indicated that it is prepared to cover the majority of the costs of construction and operation of a new international nuclear physics facility at the Gesellschaft für Schwerionenforschung (GSI) and has invited foreign countries, including the United States, to consider participation in the development of this facility should it be funded and built. Among the capabilities of the proposed GSI facility are rare isotope beams that may address some of the opportunities identified by NSAC.

Given the international character of science and the costs of major scientific facilities today, it is important to optimize research capabilities globally with the resources available. In this context, agencies need to better understand what rare isotope beam capabilities are needed to exploit the scientific opportunities identified previously: 1) what are the capabilities that are unique to each facility, 2) what are the scientific opportunities each facility will offer, and 3) whether there are other U.S. nuclear physics program or national considerations that are relevant to these two facilities.

This letter requests NSAC to provide a comparison of the respective opportunities each facility would offer. The NSAC assessment should include an evaluation of the relative costs and benefits, both for the global scientific effort and U.S. national interest, of U.S. investments in the RIA facility and in the GSI facility, including the possibility of extensions or upgrades that extend the scientific reach of the GSI proposal. It is requested that your report be submitted by January 30, 2004.

We appreciate NSAC's willingness to take on this important task and look forward to receiving your report.

Sincerely,

Raymond L. Orbach
Director
Office of Science

Michael S. Turner
Assistant Director
Directorate for Mathematical and Physical Science

Appendix B – Joint RIA-GSI Document

Research with rare isotopes at the Rare Isotope Accelerator and the future International Accelerator Facility for Beams of Ions and Antiprotons at GSI

In this document we compare two proposed facilities for rare isotope research, namely RIA and the future project at GSI. The most important distinction between the two projects is that they have completely different overarching goals. The future facility at GSI intends to cover a broad range of scientific topics including rare isotope, relativistic heavy ion, anti proton, atomic and plasma physics. RIA focuses on and is optimized for most aspects of the physics of rare isotopes. In the area of research with rare isotopes, the two facilities are complementary. Details of how this complementarity maps into the science are presented in an appendix.

The future facility at GSI is a multidisciplinary physics laboratory that will serve a large, diverse community of scientists. It will have substantial programs in the fundamental study of quantum chromodynamics using anti-protons; the study of dense, heated nuclear matter using relativistic heavy ions, tests of quantum electrodynamics with highly stripped atoms; and study of the characteristics of dense, hot plasmas driven by heavy-ion beams, and research with beams of rare isotopes. Figure 1 shows the layout of the proposed facility. For research with rare isotopes, the new facility will produce fast beams of rare isotopes by in-flight separation using the Super-FRS. These isotopes are produced by heavy projectiles, up to uranium, accelerated up to 2 GeV/nucleon. The maximum intensities of the projectile beams will be 1-3 x 10^{12} per second depending on the energy, mass and charge state. The separated, fast, rare isotopes can be studied directly following the Super-FRS or captured in storage rings to react with internal targets or collided with electron beams.

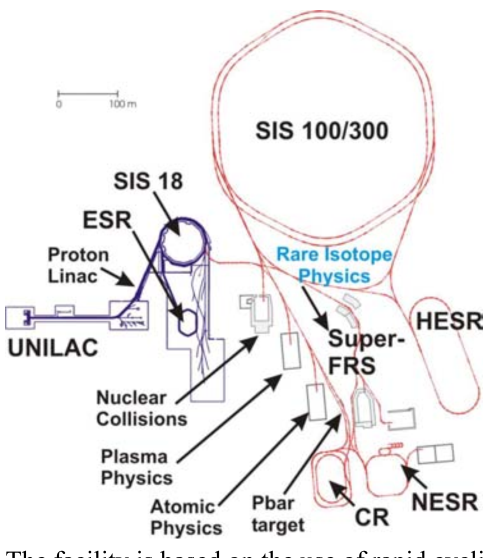


Figure 1: Schematic layout of the future facility at GSI. The facility is based on the use of rapid cycling synchrotrons and the existing UNILAC and SIS accelerators shown in blue. The new accelerator and experimental layout are shown in red. The High Energy Storage Ring (HESR) will perform experiments with cooled antiprotons. The Collector Ring (CR) and New Experimental Storage Ring (NESR) will collect anti-protons and rare isotopes. The cooled exotic nuclei will collide with electrons in the eA-collider.

RIA is a dedicated rare isotope research facility with an emphasis on providing the full range of required rare isotope energies at unprecedented intensities. Capabilities to address the other diverse areas of physics proposed for the GSI future project are provided, in part, by U.S. facilities such as the AGS/RHIC, CEBAF and FNAL and are not discussed here. The RIA concept is to build a heavy ion, superconducting LINAC to accelerate all elements up to uranium to 400 MeV/nucleon and with beam power up to 400 kW. LINAC technology was chosen because it provides the highest intensity primary beams (up to 10^{15}/s), and hence the highest intensity secondary beams. A schematic layout of the RIA concept is shown in figure 2. Rare isotopes at rest in the laboratory will be produced by conventional ISOL target fragmentation, or fission techniques and, in addition, by projectile fragmentation/fission and stopping in a gas cell. Upon extraction, these stopped isotopes can be used at rest for experiments, or re-accelerated, providing precision beams of rare isotopes for reaction, structure, or astrophysical experiments. The fast beams of rare isotopes, which are produced by projectile fragmentation/fission, can also be used directly after in-flight separation. Thus, RIA combines the advantages of the conventional thick-target ISOL techniques and the transmission-target projectile fragmentation/fission techniques.

Figure 3 illustrates the different physics topics addressed by the two facilities and their overlap. For rare isotope research, the differences and similarities of the two facilities are

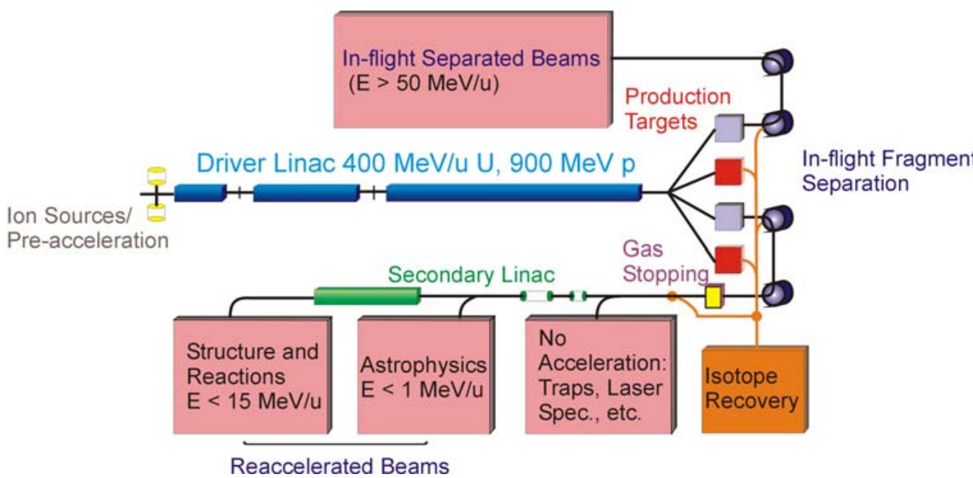


Figure 2: Schematic layout of the RIA facility. The RIA concept relies on a high-intensity superconducting linear accelerator. Rare isotopes are produced by in-flight separation or ISOL techniques in the production target area. Rare isotope beams are available at all energies up to the top energy of the LINAC.

indicated. Unique to RIA are reaccelerated beams and the ISOL capability for stopped and reaccelerated beams. These are required for many applications such as stockpile stewardship research. Unique to GSI is the opportunity to efficiently use storage rings and perform electron scattering on rare isotopes. Both facilities can produce rare isotopes by the projectile fragmentation method. Hence there is some overlap in the science done with fast rare isotope beams. There is also some overlap in the new technique of gas stopping of fast rare isotopes; a new technology that is being developed at both facilities in a highly collaborative effort.

It should be clear from Figure 3 that GSI will not be able to address as much of the wide range of science with rare isotopes as RIA due to the division of emphasis, lower projectile intensities and the lack of reaccelerated beams. On the other hand, there are areas of science beyond rare isotopes that RIA will not directly address, which will be studied at GSI.

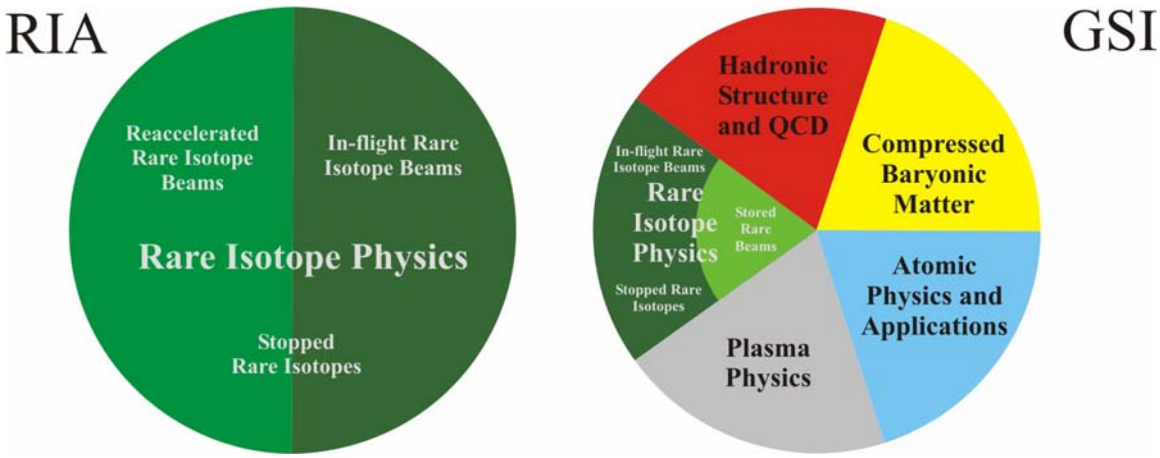


Figure 3: Pie charts showing the scientific focus of the two facilities compared in this document. GSI has a broad focus, while RIA is dedicated to research with rare isotopes.

The RIA concept relies on an accelerator scheme that is more efficient to deliver the highest projectile intensities. For many rare isotopes relatively close to the valley of stability the highest yields will be produced by the ISOL method and thus will be available for reacceleration or for collection and use as targets or other applications. This capability will be unique to RIA. RIA will have the very intense (10^{15} ions per second) light ion beams needed for ISOL production.

GSI and RIA have in-flight separated rare-isotope beams and it is possible to compare the capabilities of the two facilities. However, it may be misleading to merely present the relative rare isotope yields of the two facilities since the energy, purity, and intended use make a significant difference. RIA will have higher rare-isotope beam intensities. GSI has other advantages including more clean separation and the possibility to efficiently capture ions in a storage ring. If one does consider raw production rates for in-flight separated beams, very roughly, the 400-kW beams at RIA (compared to 60 kW at GSI) imply that it will produce 10 to 50 times more rare isotopes from in-flight fragmentation for low- and medium mass (A<150) nuclei and, due to charge state losses, a factor of 5 more for the heaviest fragments (A>200). For fission fragments, RIA will have a roughly one order of magnitude advantage.

The GSI future facility is optimized for the use of storage rings. In-flight separated ions can be efficiently injected, stored and cooled in storage rings due to the capability to produce pulsed primary beams from the SIS 100 synchrotron and hence pulsed rare isotope beams. The use of storage rings opens a number of unique experiments. It will be possible to perform decay and reaction studies with bare exotic nuclei and electron-ion collisions to study the charge radii and electromagnetic response of rare isotopes. Mass measurements of typically 50-100 keV resolution can be made over a wide range.

In conclusion, the two facilities are unique, and one project clearly cannot be substituted by the other. However, this does not rule out collaborations. There are areas where common research and development are beneficial. Collaboration on a variety of issues, such as gas catcher technology, large aperture, radiation resistant superconducting magnets, fragment separator design, beam dumps, remote handling, and beam diagnostics would be beneficial and may result in cost savings for both facilities.

Appendix: Research with rare isotopes at various energies

Beams of rare isotopes must be produced over a wide range of energies, from a few keV to hundreds of MeV to effectively address the intellectual challenges of the field. Often different facets of the science require different energies, yet it is also the case that experiments with rare isotope beams of different energies will complement each other. The following are examples of the science that is addressed in the various energy regimes. They do not form a complete list, but illustrate the complementarity of the various techniques.

Non-accelerated Beams – Available at RIA and to some extent at GSI

The conventional ISOL target fragmentation method and the currently developed method of stopping rare isotopes in a gas cell will allow the study of rare isotopes at rest. The high intensity of rare isotopes of Rn and Fr produced at RIA will probe the standard model to levels of accuracy that are higher than presently possible. The CP-violating electric dipole moment (EDM) and the Weinberg angle at low q^2 can be measured by stopping the isotopes in ion and atom traps. Ion traps can also be used to measure nuclear masses with high accuracy. In addition to the particular isotope of interest many more rare isotopes are produced in the ISOL targets. Some of these longer-lived isotopes are important for science-based stockpile stewardship measurements. They can be extracted and used to measure neutron capture cross-sections and reaction rates.

Low Energy Beams (< 1 MeV/nucleon) – Available at RIA

Nuclear reactions of proton- and neutron-rich nuclei are responsible for stellar explosions such as novae, X-ray bursts and supernovae. At the energies that are important for these astrophysical processes, the cross sections are very small and intense high quality beams of rare isotopes are essential. RIA will produce these beams for many of the crucial nuclei relevant for the rp-process and will allow the measurement of the actual reaction rates for the first time. It may not be possible to measure all the relevant direct capture processes, but a few measurements are absolutely essential to calibrating and testing other indirect techniques. It may not be possible to fully understand the chemical history of the Universe without these measurements.

Medium Energy Beams (< 12 MeV/nucleon) – Available at RIA

This is the regime of classical nuclear structure studies. RIA will be able to expand this research to nuclei with extreme neutron to proton ratios that are presently not accessible. The dependence of the effective interaction and features of nucleonic correlations as a function of neutron-to-proton ratio are key questions to be answered. The change of shell structure in neutron- or proton-rich nuclei can be studied in detail with high-intensity medium-energy beams of rare isotopes. The creation of new neutron-rich super-heavy elements also requires these beams. RIA will provide intense beams of neutron-rich rare isotopes that can be used to explore new regions of super-heavy elements.

High Energy Beams (>100 MeV/nucleon) – Available at both GSI and RIA

The direct use of the fragmentation beams will offer the unique opportunity to extend the knowledge of known nuclei far beyond the current limits. The high energy allows thick secondary targets to be used and hence factors of 1000 to 10,000 increase in sensitivity. The current knowledge of the neutron drip line at Z = 8 (oxygen) will be pushed to at least manganese (Z=25) and the drip line may be reached up to Z=40. The storage capability at GSI will enable a survey of mass and lifetime measurements over a wide range of yet to be discovered nuclei. Coulomb excitation and stripping reactions will also yield indications of changes of the shell structure in a region that is crucial for the astrophysical r-process. Reactions with high-energy rare isotopes can also be used to study the isospin dependence of the equation of state by compressing neutron-rich matter. They also allow the weak interaction strength, which is critical to understanding many astrophysical processes, to be studied in nuclear reactions.

High-energy stored beams (>100 MeV/nucleon) – Available at GSI

Experiments with stored and cooled high-energy exotic nuclei are a unique discovery potential for investigations which require a high phase-space density. Reactions with electrons and light hadrons at energies E > 100 MeV/u in inverse kinematics or in the colliding mode will provide detailed charge and matter distributions of rare isotopes. Moreover, experiments with bare stored exotic nuclei give the opportunity to study the decay and reaction properties under conditions which prevail in hot dense stellar plasmas. Bare and few-electron ions can decay in different ways than the corresponding neutral atoms. The selection of isomeric beams is particularly easy with stored ions for further reaction and structure studies. Relativistic cooled fragment beams offer a new field for coherent resonant excitations

Complementary nature of GSI and RIA

The complementary nature of GSI and RIA allow the science of rare isotopes to be addressed in the most effective way. The major scientific questions to be addressed by RIA and GSI are complex in nature and many can only be solved by a coherent multidisciplinary scientific approach. This point is illustrated by looking at a specific example such as the r-process. The r-process is responsible for the formation of about half of the isotopes heavier than iron in our universe. We are convinced of its existence by a specific signature in the abundances of these heavy elements that can only be explained by a process affected by the shell structure of very neutron rich isotopes. However, no comprehensive model in a realistic astrophysical site is able to reproduce the observed abundances. Obtaining a more detailed understanding requires more sound understanding in nuclear physics, knowledge of the conditions of the site of the process, in 3D modeling hydrodynamic and energy transport, in computational tools, and in observational data.

From nuclear science, the most important information are the masses and lifetimes of the isotopes along the path of the process, some specific neutron capture and dissociation experiments to determine that nuclear structure assumptions are valid, basic neutrino interaction cross-sections, and an improved understanding of the fissility of heavy very neutron-rich isotopes. That input, together with better modeling of the astrophysical event generating the r-process and better observational data to determine the variability of the process, will lead to a solution. It is however clear that results on all 3 fronts (nuclear, modeling, observational) are necessary to reach a conclusion. The time scales on all fronts are similar and any front not progressing will lower the return on the investment in the other fields.

On the side of the nuclear physics input, a general view of the mass surface in this region may be obtained in storage rings experiments such as could be done at the GSI future facility. These measurements however rely on calibration masses in the region and those are best measured with stopped beams in ion traps at RIA, as are specific important masses with very low production rate. The shortest-lived rare isotopes at the limits of the r-process, which will be the most weakly produced, may be difficult to study in traps or storage rings and hence may require the direct in-flight time-of-flight mass measurements possible at RIA.

These measurements must be complemented by half-life measurements performed with stopped beams and neutron capture rates best studied with (d,p) reactions in reverse kinematics with reaccelerated beams. The wider reach of RIA will provide the necessary, more detailed tests of nuclear structure calculations. The difficulty of these studies, which often must be performed with limited quantities of a given rare isotope, will require a decadal r-process program once RIA and GSI are in operation and yield the most information if both complementary facilities can bring their resources to bear on the problem.

Appendix C – Questions Sent to RIA and GSI

Questions for Both RIA and GSI

Critical nuclear structure experiments on the proton-rich side of stability will involve heavy N~Z beams. What are the projected intensities of ^{56}Ni, ^{64}Ge, ^{72}Kr and the N=Z nuclei ftom 80Zr to 100Sn at the two facilities? Can studies of the Wigner energy and two nucleon transfer experiments be carried out? For which nuclei?

> Investigation of the evolution of charge and matter radii and consequently neutron skin thicknesses (in a few cases, halos) for medium-mass and heavy nuclei is given emphasis as a part of the radioactive beam program. How will these measurements be approached at the two facilities? What intensities are required? How far out in neutron number do you think you can go? How long will measurements at the extreme limits take? (Use Ni, Zr, and Sn, Xe and Pb isotopes as representative).
>
> Study of GT and spin-dipole strength distributions are potentially particularly interesting. How will experimental studies of these modes be approached at each facility Does the higher secondary beam energy at GSI help make up for higher RIA beam intensities? What beam intensities are needed for these studies at the neutron-rich limits of Zr, Sn and Pb isotopes? How long will experiments take?

One of the goals of this science is to explore the limits of nuclear stability as far along the nuclear chart as possible. Using the Tachibana-Uno-Yamada-Yamada mass formula what is the highest Z neutron drip-line nucleus that can be made at RIA and GSI (at a rate of 1/week)?

Both facilities will be able to make most proton drip line nuclei. What is the predicted rate of a representative proton drip line nucleus 98Sn at both facilities? What experiments can be done at this rate and how long will they take?

An important goal will be to study how the shell structure of nuclei changes with neutron or proton excess. A key will be to produce selected doubly magic nuclei. What are the predicted rates of 100Sn, 48Ni, 78Ni, 132Sn? What intensities are required to study residual interactions in these nuclei? What experimental approach will be used? What will be the rates (and available energies) of key nuclei in the vicinity of these nuclei, e.g. 130Cd and 134Sn?

There are predictions that new magic numbers will be observed. What are the predicted rates for some of the new doubly magic nuclei, e.g., 22Si, 34Ca, 60Ca and 70Ca?

The evolution of structure with neutron number will require a few systematic studies over a wide range of isotopes. What are the RIA and GSI intensities for Ni, Sn, Dy, and Pb? Indicate the experimental limit for various types of experiments, e.g., ground and excited state moments and lifetimes, (p,d) and other transfer reactions, multiple Coulomb excitation, Coulomb excitation of the first excited states, electron scattering, nucleon knockout, masses. Estimate how much beam time will be required to reach these limits.

What intensity and energy are needed to study nucleon correlations by pair transfer? Give an example where enhanced or reduced pairing might be observed in a very neutron rich nucleus? Estimate how long the experiments will take.

Dynamical symmetries play a major role in understanding nuclear collective motion, both in regions of robust structure and in phase transitional regions. What reactions and what experimental techniques could be used to study the low lying levels, level lifetimes, and gamma ray intensities of nuclei that are candidates for, as an example, the X(5) symmetry, such as 102-106 Mo, 110 Sr, and 152-156 Ce? How long will the experiments take?

One of the major goals will be to produce and study the heaviest nuclei. How will the two facilities produce neutron-rich super-heavy nuclei and study them?

The most extreme test of nuclear models will be drip line nuclei. What representative rates of 22C and 122Zr will be available at the two facilities? What experiments can be done at these rates and how long will they take?

The nucleus 42Mg may have a very large 2 neutron halo. For comparison we will need to study 40Mg also. What will be the rate of these nuclei available at the two facilities? What experiments can be done at these rates and how long will they take?

How will the equation of state of neutron rich matter be studied at RIA and GSI?

Measurement of the fission barrier mass surface is a critical issue. How will the two facilities measure the mass surface and over what range of the nuclear chart.

For the r-process

The r-process path is fairly well known from systematics of the abundances and known shell closures. This path is sketched in many of the RIA and GSI documents. Which isotopes along the path – starting at iron - are accessible to RIA and GSI?

Along that path what range of lifetimes can be measured? Certainly one needs to go, in some cases, to times significantly less than one second. Does this mean that ISOL alone is inadequate to study the r-process? Can lifetimes of 10 ms or less be determined for all nuclei along the path?

What is the error bar in mass expected for mass excess measurements along the r-process path? One document says that GSI can give masses accurate to 50 - 100 keV. Is this true of both GSI and RIA everywhere along the path? 100 keV is not very accurate because, at the r-process temperature, 1 - 2 x 10^9 K, the abundance of the nucleus is proportional to exp(11.6ΔE/T9). 100 keV therefore implies an uncertainty of order "e" in the abundance (and effective) lifetime); 50 keV is therefore greatly to be preferred.

For the rp-process

Probably one needs to access only nuclei A < 120 because that is thought to be the termination of the rp-process. Most important are the mass excesses and lifetimes of nuclei between A = 28 and 66, typically those 1 and 2 protons above the Z = N line. Can all these nuclei be accessed by both RIA and GSI?

For what range of lifetimes. Again one needs to access τ < 100 ms and maybe to 10 ms.

More importantly, what is the expected error in the mass determination? Typical temperatures are T = 0.5 to 1.5 x 10^9, so again 100 keV is large.

If one wants to additionally know the cross sections of these nuclei (less important than lifetime and mass excess) the comparison document says that high beam current is needed because the cross sections are small. But if the temperature is 10^9 K and Z = 14 to 30, the Gamov energy is typically 1 MeV. Are the cross sections that small there? Can both GSI and RIA measure (p,γ) and (α,p) cross sections on Z < N nuclei in this mass range?

Can RIA or GSI help refine the accuracy for the $^{12}C(\alpha,\gamma)$ reaction rate?

General

How many and from where do you expect your users ?

Do you expect the medical applications programs to be self supporting ?

What important questions have we overlooked ? (you might also supply answers)

Questions Specific to RIA:

In various RIA documents the primary beam power is quoted as 100kW or 400 kW, please clarify.

Will the ISOL technique at RIA be good for studying the interaction of nuclei with lifetimes of years to millions of years (22Na, 26Al, 44Ti, 60Fe) with protons and alphas in the MeV range and neutrons in the 10 - 200 keV range?

The RIA documentation appears to show two experimental efforts related to symmetries: producing isotopes of Fr for atomic parity violation experiments, and producing isotopes to study 0+ to 0+ transitions. These are both clearly interesting, but do not appear to constitute a program.
*) What is the actual symmetries program? Is it providing material for experiments, or is there a more systematic program? How much of this program is only possible if RIA is built?
*) With the isotopes for Atomic Parity Violation, how many different experiments really need to be performed? Is it 2, 3 or 5 different isotopes?
*) Time reversal violation in 0+ -> 0+ transitions – what particular measurements are needed?
*) Special Odd-A nuclei to enhance EDM searches, which measurements are needed?

List the most important NNSA-relevant cross-sections that could be measured with RIA. For each, answer the following

a) What is the current precision with which the cross-section is known?

b) How much might the precision be improved through RIA experiments (either by direct/indirect measurement or by improved knowledge of nuclear systematics)?

c) By how much will this improvement better constrain historical test data (separately for primary and secondary) or aid in simulating weapon performance i.e., is it the largest component of the uncertainty budget? Particularly convincing in the latter case would be the demonstration of significant differences in simulation results run across the current range of uncertainty vs. results run across the RIA-reduced range.

With the apparent strong interest by NNSA in research related to stockpile stewardship has NNSA been willing to make a monetary commitment ?

Could utilization of GSI by US researchers reduce the cost of RIA ?

Do you envision any foreign contributions to RIA ?

Questions Specific to GSI:

The primary beam energy has been stated as 1.5GeV and 2 GeV, please clarify

The beam power of the primary beams has been stated as 60kW and 100 kW, please clarify.

Could GSI have an ISOL capability with an upgrade ?

In the joint RIA-GSI document it says (p 5) that the decay and reaction properties could be studied (at GSI only) for the conditions that "prevail in hot, dense stellar plasma". What does this mean? Will the alteration of decay lifetime by changes in the ionization state be studied? Presumably it does *not* mean that targets will exist in the distribution of excited states that are populated in the stellar environment. Please quantify "hot, dense".

The DOE fusion program has a signed agreement with GSI for cooperative work. Has there been US research interest in the other non-rare isotope capabilities of GSI ?

A key part of the nuclear structure program at a next-generation RIB facility will be mapping the location and fragmentation of single particle strengths as a function of neutron excess (or deficiency). Presumably, inverse kinematics single nucleon transfer reactions will play a key role here. High beam-quality re-accelerated heavy beams in the 5 to 10 MeV per nucleon range are an obvious tool for this effort. Will direct reactions using internal targets in the GSI storage ring play a role? Is the high beam energy a problem? An advantage?

In a number of the GSI documents the e-A collider is not mentioned and yet it is described in the CDR. Is it viewed as important ?

The GSI program is a very broad, and ambitious program.
1) What are the timescales for each of its aspects?
2) Do the projects have priorities in the case of insufficient funding?
3) How will running be divided between the various efforts?

There are many exciting antiproton physics opportunities, but all appear to use the same facilities and detector. Won't this cause a scheduling problem for the equipment, particularly given that several of the outlined programs require on the order of 1 year of running ?.
1) Are there scientific priorities for the listed programs?
2) Will there be a single collaboration that carries out all of the physics, or will it be individual groups using a facility maintained by GSI?
3) In the latter case, how will the maintenance of hardware and software be handled to guarantee viable physics output?

Do you envision any U.S. contributions to GSI ?

What is the status of GSI funding ?

Appendix D - Meeting with GSI-RIA representatives

Seminar Room Bldg 515
Brookhaven National Laboratory

MONDAY – January 5, 2004

10:00 executive session

12:00 lunch

1:00 GSI presentation – Walter Henning

2:00 RIA presentation – Don Geesaman

3:00 break

3:15 Questions/interactions

6:00 Executive session

7:00 Dinner -

TUESDAY – January 6, 2004

8:30 Executive Session

9:00 Followup questions for both RIA/GSI

11:00 Executive session