# NATIONAL NUCLEAR SECURITY AND OTHER APPLICATIONS OF RARE ISOTOPES

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*Abstract*

The proposed Rare Isotope Accelerator will produce large quantities of short-lived isotopes in beams suitable for experiments in low energy nuclear physics and nuclear astrophysics. The full suite of particles available offers the opportunity for advances in other scientific fields and applied technologies, including national security, medical technology, material science, and nuclear energy.

## INTRODUCTION

For several years, the Office of Science of the Department of Energy has been working on plans for a facility to produce beams of short-lived isotopes for experiments in low energy nuclear physics and nuclear astrophysics. The justification for this facility, called either a Rare Isotope Accelerator (RIA) or the Facility for Rare Ion Beams (FRIB), comes from the world-class fundamental science that could be performed there. The range of science is very broad—stretching from how the elements above iron were created in the Universe to exploring the nuclear force in systems far from stability. A RIA is needed to explore this science as (1) facilities using stable particles are able to produce only about 10 percent of all bound nuclei and (2) experiments with highly radioactive targets are quite difficult due to high backgrounds, safety concerns and the short half-lives of the target nuclei. While the main arguments for RIA concern this wealth of science, we discuss in this paper how a RIA would be an important tool for several interesting applications—especially in the area of national nuclear security.

## THE NATIONAL NUCLEAR SECURITY MISSION

### *Stewardship of the Nuclear Weapons Stockpile*

Ever since the end of underground testing, the reliability and safety of the nation's nuclear stockpile has rested on a program known as Stockpile Stewardship. The premise of this approach is that testing can be replaced with world-class science, detailed engineering investigations and high fidelity 3-D simulations. This requires that there be a vital and dynamic science community engaged in questions relevant to nuclear weapons.

There are several stewardship goals in which RIA would play a central role: 1) In order to measure the neutron flux in environments with extremely high instantaneous fluxes, it is essential to measure the cross sections and reaction rates on unstable nuclei—one of the strengths of a RIA; 2) Experiments at RIA would be able to fill major holes in nuclear databases and 3) RIA would be the training ground for low energy nuclear physicists and nuclear chemists for the National Nuclear Security Administration (NNSA) laboratories.

The problem of measuring neutron fluxes is of particular concern to the Stewardship Program. Extremely high instantaneous fluxes are found in only a few phenomena: a) inside stars where it is impossible at present to do experiments; b) in the future, near an ignited capsule at the National Ignition Facility where experiments are in the planning stage and c) in underground nuclear tests that are no longer conducted. Even though there are no experiments underway at the moment, a challenge in stewardship is to improve the accuracy of the interpretation of the archived test data. In those experiments, certain isotopes were used as probes of the neutron intensity. Isotopes were loaded in the device and samples of the debris were subjected to radiochemical analyses after the test. The amounts of isotopes produced during the experiment were then used to calculate what the neutron fluxes had been. A goal of Stewardship is both to improve the accuracy of the calculations and reduce the uncertainty in the determination of the neuron flux.

This goal has remained difficult to achieve because many important pieces of physics have not been measured. When the original isotope is exposed to a very intense neutron flux, some of the nuclei undergo reactions changing them into other atoms. Those "daughter" nuclei are in turn exposed to the neutrons and they evolve into yet other states. The measured isotopic abundances are determined well after this complex chain of production, destruction and transmutation has completed. Unfortunately, most of the cross sections and reaction rates on the unstable intermediate nuclei have never been measured. Thus, there is a degree of uncertainty in the calibration of these isotope probes.


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An example of this problem is to consider $^{90}Zr$ as the original probe and the radiochemical measurements of the ratios of $^{89}Zr/^{90}Zr$ and $^{88}Zr/^{89}Zr$ as the results of the experiment. In the simplest possible network there are only 5 nuclear states and 8 nuclear transitions between those states to consider. Yet, almost none of the neutron cross sections causing those transitions has ever been measured. A study of the sensitivity of the values of the final isotopic ratios to the values of these unmeasured cross sections reveals that ratios are not sensitive to some of these cross sections. However, there are one or two that have a large, direct impact on the final results. This demonstrates the importance of measuring those cross sections even though the nuclear states involved have very short half-lives, making the experiments (without a RIA) almost impossible.

To make matters worse, the real world is not limited to just 5 nuclear levels. In fact, there are some 14 nuclear levels in this region of the periodic table and roughly 39 transitions that could occur. Less than 8 of the relevant cross sections have been measured. It should also be noted that this dearth of experimental data is just for one of the many different isotopic probes that were employed. Thus, experiments at a RIA would allow many of the important cross sections to be measured.

Because the physics of nuclear weapons and of the interior of stars is quite similar, it should come as no surprise that the cross sections of interest to the Stewardship program are also of interest to the nuclear astrophysics/ nuclear nucleosynthesis academic communities. Thus, there are at least two motivations for every measurement and there should be broad participation in the experimental program.

The NNSA is quite interested in the data that would emerge from RIA experiments. To that end, the NNSA is already providing support to University groups developing techniques for experiments there through the Stewardship Science academic Alliance program. The NNSA expects that scientists at its laboratories would help any site chosen for RIA to develop the best scientific experimental program. In fact as early as 2003, the Deputy Administrator for Defense Programs wrote to the DOE Director of the Office of Science expressing NNSA's interest in RIA. That interest remains strong today.

Even when the decision has been made to construct a RIA or FRIB, there are significant experimental challenges to measure Stewardship Science relevant cross sections. These challenges include the harvesting of the proper isotopes, techniques to do the radiochemical separations and to construct the appropriate high purity targets, the transportation of the target material to a co-located neutron source for irradiation, the very existence (design) of the co-located neutron source and the details of the measurement techniques that have to deal with extraordinarily high background rates. While this paper cannot do justice to the impressive work that has been done to address these problems, it is worth mentioning that some truly ingenious approaches have been developed.

Depending on the specific layout of a RIA, there are several places where isotopes of interest could be harvested. In some cases, the harvesting could be carried out in a parasitic fashion. In other cases, beam time would have to be devoted to collecting a particular sample. As is well known, the amount that can be collected of a given isotope is a competition between the production rate and the decay rate. This competition indicates that for a particular production rate there is a maximum amount of a given isotope that can be collected. Above that value, the isotope decays away as fast as new atoms are created. If the production rate is $10^{11}$ particles per second, $10^{16}$ atoms (~2 Curies) can be collected in 3 days of an isotope with a half-life of 1 day. If the half -life of the isotope is 1 year, 8 x $10^{16}$ atoms (50 mCuries) can be collected in 10 days.

In order to separate the isotopes of interest and create pure targets, there will have to be a fully equipped radiochemistry laboratory on site at a RIA. Current estimates are that the facility will have to be able to handle up to 1 kCurie of activity.

The need to expose targets of short-lived isotopes to neutron beams to measure cross sections for both Stewardship Science and nuclear astrophysics implies that a neutron source spanning the energy range from about 10 keV up to 20 MeV be located on the RIA site. A great deal of work has been done on preliminary designs for such a facility. It is modular so that beams of different energy neutrons can be developed as funding allows.

It is impressive to examine the various experimental designs that could be used once RIA exists. Many are being employed at other facilities now. A partial list of these would include DANCE, GRETINA, GEANIE, the Surrogate approach etc. It is also clear that when this facility becomes a reality, there will be impressive new approaches developed.

## *Test Readiness Program*

The U.S. Congress has mandated that the nation be prepared to resume underground nuclear testing should the President so order. While there is only a miniscule chance that the U.S. would go down that path, it is clear that the challenges facing experimenters at RIA are very similar to those that would be encountered by scientists trying to analyze a nuclear test. These challenges include the radiochemistry of extremely radioactive samples, separation techniques etc.



 

Of even more importance is the fact that the Test Readiness program requires trained low energy nuclear physicists and radiochemists. RIA would be the training for those scientists.

## HOMELAND SECURITY

In the unthinkable event that a nuclear device is exploded as an act of terrorism or war, the political leaders of the country need to know what kind of nuclear device it was and where it came from. It is crucial that the uncertainties associated with answering those questions be as small as possible. Since the answers will be inferred from the isotopes collected after the incident, it is essential that the knowledge base of the relevant cross sections be as accurate as possible. RIA could be of enormous help in determining those cross sections.

## NUCLEAR ENERGY

A major initiative of the Office of Nuclear Energy is the Global Nuclear Energy Partnership—GNEP. This is an add-on to the Advanced Fuel Cycle Initiative and is studying technology options to produce reactor designs to transmute long-lived radioisotopes into shorter-lived ones. This would reduce both the long-term storage problems and would impact proliferation concerns.

The GNEP effort would profit from a RIA in two ways. First, there is a need for highly accurate cross sections on the nuclei involved in the reactor fuel burning processes. These cross sections could affect the specific designs of the advanced reactors. Second, if the GNEP is successful and the nations of the world move towards a greater reliance on nuclear reactors, there will be a genuine need for trained nuclear physicists and nuclear radiochemists at those reactors. Once again, RIA will be the perfect training ground.

## MEDICAL APPLICATIONS

RIA will be an excellent facility at which to make research quantities of radioactive isotopes tailor-made to address particular medical problems. It also could be a place to explore the effectiveness of different techniques to produce medically interesting species. It has been proposed, for example, that isotopes could be found that would enable systemic therapy – sources could be localized within the cells of a tumor with the radiation confined to cellular dimensions.

It is clear, however, that a RIA would not become a factory producing medical isotopes. Should a particular isotope prove to be very important in therapy, the logical choice would be to construct a facility tuned to its production.

## CONCLUSION

In addition to a broad program of world-class science, a Rare Isotope Beam Facility holds the promise of contributing to a range of important applications. These include Stockpile Stewardship, Homeland Security, Nuclear Energy, and Medicine. There is every reason to invest in such a facility as soon as possible.

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