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Domestic Stable Isotope Enrichment Initiative at Oak Ridge National Laboratory (ORNL)

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During World War II, the race to build an atomic weapon was based partly on the development of enrichment capabilities to bring the content of U-235 from its natural abundance to that consistent with the needs of a nuclear weapon. One of the options that was proposed and pursued was to use electromagnetic enrichment whereby the heavier isotope's trajectory was not as sharp as the lighter isotope when accelerated through and bent by a magnetic field. A large facility was constructed at Oak Ridge to engage in this technical option while other options were pursued elsewhere.

The end of the war also brought most of the enrichment capability at Oak Ridge offline, in part due to the use of gaseous diffusion for the bulk of uranium enrichment from that time onward. Some of the enrichment capability was maintained at Oak Ridge and the calutrons remaining were used to generate a stockpile of enriched stable isotopes that were used for a variety of applications. In fact, there was one bank of calutrons that was reserved for enriching actinides with adequate controls for separating long lived radioactive materials. This stockpile of enriched isotopes exceeded demand for many years with a few exceptions, primarily enriched isotopes that were used to produce radioactive isotopes in high purity. While it developed that some elements were suitable for a newer technology of centrifugation or distillation for enrichment, many can only be enriched by electromagnetic separation.

The US inventory of enriched stable isotopes, housed at Oak Ridge National Laboratory (ORNL) and distributed through NIDC's Isotope Business Office, is being depleted over time since production using the US Calutrons was halted in 1998. Responding to recommendations from several scientific committees including the Nuclear Science Advisory Committee, the DOE Office of Nuclear Physics has initiated a number of R&D efforts over the last several years with the goal of establishing a modernized domestic capability to produce enriched stable isotopes. The first R&D project involved the design, acquisition, building and testing of a nominal 10 mA electromagnetic isotope separator (EMIS) in a laboratory at ORNL. The EMIS consists of an ion source capable of volatilizing and ionizing feed material for a large range of elements, magnetic ion optics to separate ions of different mass-to-charge ratio and focus the separated ion beams, and an isotope collection system composed of graphite-lined, water-cooled collection pockets. This R&D EMIS, commissioned in late 2011 (see pictures below), has the capability to produce small quantities (μg 's to mg 's) of highly enriched stable isotopes from calcium to lead. Generally, isotopes of the lighter elements are enriched using different methods.



Pictures of the ORNL R&D EMIS. Experimental enrichment trials have been conducted and efforts to increase ion current (throughput) are ongoing.

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Domestic Stable Isotope Enrichment Initiative at ORNL (continued)

An initial test of the R&D EMIS included enrichment of the 7 stable isotopes of molybdenum using a natural abundance MoO₃ feedstock. A picture of the separated ion beams of molybdenum entering the collection pockets is shown below. Over time, a quantity of separated isotopes accumulates in the graphite collection pockets. These pockets are burned and the recovered enriched isotope can potentially be transferred to the stable isotope sales inventory. The results of this particular trial run included recovery of a few mg's of material for each isotope. Assays for the ⁹⁶Mo and ¹⁰⁰Mo isotopes from the single pass material collected during the experiment were greater than 98% for each isotope. Efforts to increase ion current (throughput) while maximizing single pass enrichment are ongoing. Recently, another ORNL R&D project was funded to upgrade the R&D EMIS with an ion source capable of up to 100 mA of ion current measured at the collector. The potential to further increase throughput for selected isotopes using pre-enriched feedstock material obtained from other enrichment techniques such as gas centrifugation is also under investigation.

The isotope program is working to ensure that supplies of critical isotopes for commercial and research applications are available. Private industry has also been active in securing new sources of enriched stable isotopes. One of the most important uses for them is to produce radioisotopes for medical applications. Enriched Thallium-203 is used to produce Thallium-201, a heart imaging isotope. Zinc-68 is used to produce Gallium-67 which is used for infection and cancer imaging.

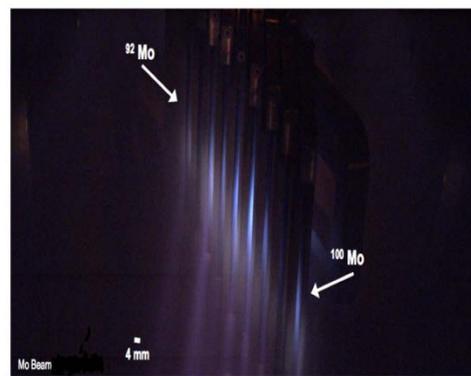
Newer applications require Nickel-64 for Copper-64 production, Zinc-68 for Copper-67 production, enriched strontium isotopes for Yttrium-86 production, and Tungsten-186 for Tungsten-188 production. New technical approaches to producing Molybdenum-99 and Technetium-99m will require large quantities of Mo-100 and Mo-98, depending on the approach. These quantities will be beyond the capabilities of the current system, but have generated a lot of interest in bulk technology.

Similarly, there are several experimental projects that are examining fundamental physical phenomenon that require large quantities of enriched isotopes. One of them is the quest to determine the makeup of neutrinos that are generated by the stars. Discussions revolve around the need for nearly a ton of an enriched isotope to be able to detect these neutrinos.

Maintaining and expanding a capability to enrich stable isotopes is essential for a variety of applications in the commercial, medical and research arenas. The program at ORNL is addressing the technology that provides the greatest flexibility in enrichment technology.

Recent and Upcoming Publications:

- 1) B.J. Egle, K.J. Hart, W.S. Aaron, "Stable Isotope Enrichment Capabilities", International Nuclear Target Development Society Conference, Mainz, Germany, August, 2012. (Proceedings to be published in *Radiochemistry and Nuclear Chemistry*)
- 2) K.J. Hart, B.J. Egle, W.S. Aaron, "Enrichment of Stable Isotopes Using an Electromagnetic Isotope Separator", 245th American Chemical Society National Meeting, "Isotope Production: Past, Present, Future: Symposium in Honor of Michael J. Welch", New Orleans, LA, April 2013.
- 3) K.J. Hart, B.J. Egle, W.S. Aaron, "Preparative Scale Mass Spectrometry: A Modernized Electromagnetic Isotope Separator", 61st ASMS Conference on Mass Spectrometry and Allied Topics, Minneapolis, MN, June 2013.



Picture of the isotope collection pockets during a molybdenum separation. Separated ion beams are focused into the graphite lined collection pockets.

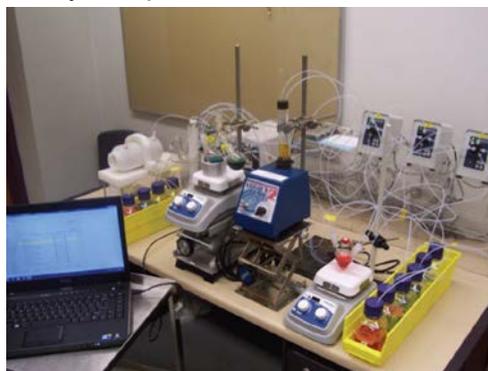
Increasing the Supply of Astatine-211

Dennis Phillips

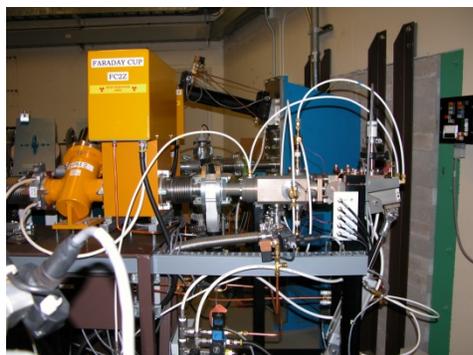
The first recommendation of the Nuclear Sciences Advisory Committee's Sub-Committee on Isotopes (in *Compelling Research Opportunities using Isotopes, Final Report*, published April 23, 2009, page 2) is to invest in new production technologies for alpha-emitting radioisotopes. There is significant promise of such radionuclides for effective therapies in the treatment of cancers using targeted alpha-therapy. A review article entitled *Chemical and Radiochemical Considerations in Radiolabeling with α -Emitting Radionuclides* (Curr. Radiopharm. 2011 Jul; 4(3):214-47, D. Scott Wilbur), and the many references there-in, describes work being done in the development of therapeutic radiopharmaceuticals based upon alpha-emitting radionuclides. In the previous issue of the NIDC Newsletter (April 2013), we described on-going research into the production of ^{225}Ac using accelerated protons on thorium-232 targets. Actinium-225 has demonstrated potential (along with its generator-produced decay daughter ^{213}Bi) to treat a variety of tumor types. The recent FDA approval of Bayer Health Care's Xofigo ($^{223}\text{RaCl}_2$) for the treatment of men with advanced prostate cancer that is castrate resistant and who also have symptomatic bone metastases and no known visceral metastatic disease is indicative of the promise of alpha-emitting radiopharmaceuticals.

Astatine-211 is an interesting alpha-emitting radionuclide with significant potential for alpha therapy applications. It has a favorable half-life (7.21 h), emits two alpha particles in its decay chain (5.87 MeV by direct alpha emission at 41.8%, and 7.45 MeV at 58.2% from its ^{211}Po daughter), and has imageable gamma emissions at about 80 keV. Since astatine is in the halogen family it can be used in traditional organic synthesis mechanisms (both electrophilic and nucleophilic reactions) to directly label targeting molecules for therapeutic applications. Widespread application of ^{211}At to targeted therapy of cancer will require multiple sites for production of ^{211}At , and development of new therapeutic radiopharmaceuticals that use it. The most effective production route to ^{211}At is the bombardment of 100% naturally occurring ^{209}Bi with accelerated alpha-particles in a cyclotron to induce the $^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$ nuclear reaction. Due to the short half-life of ^{211}At , it will be necessary to establish a network of cyclotrons with the capability to do the irradiations. Another requirement is the availability of a robust, reproducible processing technology, ideally applicable in any facility to produce astatine-211 in the radiochemical form and purity usable in the radiopharmacy.

Since 2009, the IDPRA program, administered out of the DOE Office of Nuclear Physics in the Office of Science, has made on-going investments at multiple distributed institutions where research and development work on ^{211}At production and application is being done. These investments have focused on the development of targetry, process chemistries and automatable technologies based upon the $^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$ production route. Progress is being made that shows promise to, hopefully in the near future, establish in the U.S. a reliable supply of ^{211}At sufficient to advance preclinical clinical studies into approved applications of targeted alpha therapy using this isotope.



Bismuth Target Station¹



Jaw Open with Target Displayed

At-211 Semi-Automated Process

¹All photos authorized by the lead PI.

Abstracts presented at the 245th American Chemical Society National Meeting and Exposition, New Orleans, Louisiana, USA, April 7 – 11

Goscinski, N. C., Stableski, Jordan, Medvedev, Dmitri, Mausner, Leonard F., Srivastava, Suresh C., and Smith, Suzanne V. (2013), "Radiochemistry of Yttrium-86 (⁸⁶Y) Produced at the Brookhaven Linac Isotope Producer (BLIP)."

Medvedev D. G., Engle J. W., Nortier, F. M., Smith, S. V., and Mausner, L. F. (2013), "Theoretical Approach to the Production of ⁴⁴Ti (T1/2=59.1 years) using High Energy Protons: Expanding ⁴⁴Sc Availability."

O'Hara, Matthew J., Carter, Jennifer C., Murray, Nathaniel J., Shoner, Steven C., and Link, Jeanne M. (2013), "Development of a System to Purify the Long-Lived Positron Emitter Zr-89 from Irradiated Yttrium Target."

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Engle J. W., Weidner, J., Mashnik, S. G., Ballard, B. D., Fassbender, M. E., Bitteker, L. J., Couture, A., Ullmann, J. L., John, K. D., Birnbaum, E. R., and Nortier, F. M. (2013). "Cross Sections for Proton Induced Reactions on Thorium at 800 MeV."

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Weidner, J. W., Ballard, B. D., Engle, J. W. (Presenter), Hudston, L., Mashnik, S. G., John, K. D., Birnbaum, E. R., and Nortier, F. M. (2013). "Nuclear Data for ²²⁷Ac Production Below 200 MeV by Proton Bombardment of Thorium."

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Engle, Jonathan W., Weidner, John W., Mashnik, Stephan G., Ballard, Beau D., Fassbender, Michael E., Hudston, Lisa, Bach, Hong T., Ullmann, John L., Botteler, Leo, Couture, Aaron, Birnbaum, Eva R., John, Kevin D., and Nortier, Francois M. (2013), "Production of Ac-226 and Ac-227 from Proton Irradiations of Thorium below 200 MeV."

Medvedev, D. G., Mausner, L. F., Cullen C., Denton D., Cosgrove, J., and Mirzadeh, S. (2013), "Production of milliCurrie Amounts of Ac-225 from Th-232 Foils with High Energy Protons: Initial Stage of Collaborative Project within the DOE Isotope Program."

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Srivastava, S. C., Strauss, H. W., Narula, J., Virmani, R., Kolodgie, F. D., Mueller, D. W., Stevenson, N. R., and Gonzales, G. R., "Theragnostic Potential of Sn-117m for the Molecular Targeting and Therapy of Vulnerable Plaque."