Photonuclear Reaction Yields and Excitation Functions

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ABSTRACT

A new collaboration between the New Mexico Institute of Mining and Technology, Idaho State University, and Idaho National Laboratory builds the domestic workforce in isotope production and related science and technologies by conducting research and education programs related to photonuclear reactions. Workforce development was identified by the Department of Energy's Office of Science in the Reaching a New Energy Sciences Workforce (RENEW) program that seeks to engage underrepresented university students in isotope production activities. This collaboration includes coursework development, student training, and isotope production research utilizing photonuclear reactions at electron linear accelerators. Bremsstrahlung-weighted excitation functions and cross-sections will be measured and the use of nanomaterials to exploit kinematic recoil reactions will be investigated. Students will be hosted at Idaho National Laboratory where mentors will provide opportunities to explore careers in nuclear science and technology. This presentation regards the ongoing progress of the research and education objectives performed for the Office of Science Isotopes Program under award number D000-22-2765.

BACKGROUND AND INTRODUCTION

Scientific discoveries that occurred during World War II accelerated research and development into atomic energy and isotope production. That research continued for peaceful purposes following the war under the establishment of the Atomic Energy Commission (AEC) [1-4]. The AEC aided in transferring military control and knowledge to civilian researchers [4]. This allowed civilian scientists to leverage useful wartime infrastructure, including nuclear reactors. Part of the civilian scientific exploration resulted in developing new methods and uses of stable and radioactive isotopes. Notable early isotope uses included tracking the movement of phosphorus from phytoplankton to inorganic debris, diagnosing thyroid function, detecting tumors, and advancing national security [2, 5-7]. Under the AEC, over 20,000 shipments of more than 60 different isotopes were delivered to medical and research facilities from 1946 to 1951 from the largest supplier of radioisotopes, Oak Ridge National Laboratory [1, 8]. In the 1960's research continued with new applications developed including isotopes that provided electrical-generating units on the moon [1]. However, concerns over the AEC having agency over the regulation and production of isotopes and atomic energy led to the division of scope and the formation of the Nuclear Regulatory Commission and the Energy Research and Development Administration (ERDA) in 1974 [9]. The ERDA was ultimately renamed to the Department of Energy (DOE) in 1977 [2, 9]. Isotope production and supply grew until the mid-1980s in the United States (US) under the DOE [10]. Due to declining budgets and the implementation of a full-cost recovery system to the isotope program in the 1990s, research and development significantly declined as did the career pathway into the industry. These setbacks led the US to fall behind efforts that grew in other parts of the world [11, 12]. In response, in 2006 a working group was established whose mission was to prioritize investments in order to increase the US competitive edge in nuclear science [11]. In 2009, the DOE requested the establishment of an isotope subcommittee under the Nuclear Science Advisory Committee (NSAC) that would be responsible for two main directives: 1) identify and prioritize research opportunities using isotopes, and 2) recommend a long-term strategic plan for the Isotope Development and Production for Research and Applications Program [13]. The 2009 isotope subcommittee's inaugural recommendations included supporting "a sustained research program … to enhance the capabilities of the isotope program in the production and supply of isotopes generated from reactors, accelerators, and separators", and investing "in workforce development in a multipronged approach, reaching out to students, post-doctoral fellows, and faculty through professional training, curriculum development, and meeting/workshop participation" [13]. A half dozen years later, in 2015, the isotope subcommittee created a new long-range plan that included isotope production research using electron linear accelerators as a "unique potential source of isotopes" and reiterated the need for "investments in workforce development to educate and train the next generation of nuclear scientists …" [14].

To advance efforts into developing and strengthening the workforce in science and technology including nuclear science and isotope production, the DOE Office of Science established the Reaching a New Energy Sciences Workforce (RENEW) initiative in 2022. The RENEW initiative provides research opportunities and training to students and postdoctoral researchers from historically underrepresented institutions including Historically Black Colleges and Universities, Hispanic-Serving Institutions, and Asian American and Pacific Islander Serving Institutions[15, 16]. The RENEW initiative exposes students to careers in science and technology in the hopes of diversifying the talent pool and ultimately growing and enhancing the workforce in science, technology, engineering, and mathematics.

In response to the RENEW initiative and the recommendations laid out by the NSAC isotopes subcommittee, the authors have collaborated to develop a research and training program in isotope production for students at the New Mexico Institute of Mining and Technology (NMT) and Idaho State University (ISU). Students will take courses in nuclear science, engage in photonuclear isotope production experiments using electron linear accelerators, and have the opportunity to experience summer internships at Idaho National Laboratory (INL).

EDUCATION AND RESEARCH

The research and education program will study many of the radioisotopes listed in the 2015 NSAC Isotope subcommittee report "Meeting Isotope Needs and Capturing Opportunities for the Future: The 2015 Long Range Plan for the DOE-NP Isotope Program". The focus will demonstrate the feasibility of using electron linear accelerators (LINAC) for photonuclear isotope production. Isotope production using LINACs has many advantages over nuclear reactors including generating a lower volume of nuclear waste that is also less hazardous. The waste is less hazardous because the power source does not require fission. Additionally, LINACS do not have a nuclear weapons proliferation risk.[17]

The program will focus on three main objectives: 1) Measure (γ, α), (γ, p), (γ, n), and (γ, np), reaction yields as a function of bremsstrahlung end-point energy for select isotopes where results will address gaps in the International Atomic Energy Agency Photonuclear Data Library, 2) Create Figures-of-Merit that elucidate photonuclear production for select isotopes using enriched and natural targets, and 3) investigate using nanomaterials for kinematic recoil separations where the post-emission daughter nuclide is captured in a material chemically different from the target. Objective 3 has the potential to produce high specific activity results from (γ, n) reactions where the daughter isotope is more difficult to efficiently separate from the parent nuclide. These objectives will be addressed through research and experiments that students will participate in as well as other numerous tasks from developing target holders, modeling reactions and interferences, setting up experiment equipment, gamma spectroscopy, and analyzing data, among others.

The core of this program is to educate students in photonuclear isotope production. In that regard, the project is anticipating sponsoring 15 graduate and 15 undergraduate students from NMT and ISU over its 5-year duration. The NMT is a Hispanic-serving institution with over 40% of the undergraduate students identifying as Hispanic, while ISU's College of Science and Engineering has a nuclear-focus and opportunities to work at an on-campus ISU Accelerator Center (IAC). Students will gain knowledge through traditional courses that include nuclear physics, nuclear instrumentation, and radiation safety. Additionally, students will have the opportunity to attend INL for summer internships.

STUDENT MENOTORSHIPS AT IDAHO NATIONAL LABORATORY

Students in this research and training program will have the opportunity to be paired with an INL mentor for summer internships. The mentor will collaborate with the student on a nuclear science project and provide an overview of working life at INL.

This summer, students will work on one of five projects. In one mentorship the student will have the option of working on one of two projects. In one project the student would investigate neutron interrogation methods using either pulsed fast thermal or associated particle imaging neutron activation analysis. The other option is to aid in improving detection sensitivity to characteristic gamma rays through coincidence and anticoincidence methods. Another student will have the opportunity to improve upon a xenon-iodine separation method. The student will build and test a gas manifold using radioactive and non-radioactive samples. In a third project, the student will aid in a photonuclear isotope production experiment at the IAC. Prior to sample irradiation the student will determine, through radiation transport modeling, the expected activity at various bremsstrahlung end-point energies. The student will help prepare the sample for irradiation, participate in experiment setup at the IAC, and aid in gamma spectroscopy following irradiation. A fourth student will become familiar with and support the positron annihilation spectroscopy program at INL's Materials and Fuels Complex. The student will aid in gamma spectroscopy, data analysis, and improve the design of a sample chamber. Finally, the fifth student will have the option to work on a number of projects related to x-ray imaging and tomography including data analysis, segmentation, and image rendering.

Throughout the summer, the students will attend tours of INL facilities to learn more about research occurring at the laboratory. In addition, an intern poster session hosted by the Research Excellence Programs will be held for students to highlight and present their work. Finally, students will interact with other interns joining INL from all parts of the country to discover the research and experiences of others at the laboratory.

RECENT EXPERIMENTS

In March of 2024, several program students along with members of the collaboration team participated in photonuclear isotope production experiments at the IAC. The students prepared sample foils, listed in Table 1, separately or stacked with bremsstrahlung flux monitor foils depending on the irradiation strategy developed through collaboration between the student and the university project team member. The stacked foil samples were enclosed in an aluminum jacket and inserted into the center penetration of the aluminum sample holder for irradiation, shown in Figure 1(a). The aluminum sample holder was placed behind a tungsten bremsstrahlung converter and aluminum beam-stop, all positioned as shown in Figure 1(b), at the accelerator-end of a 25 MeV L-band LINAC for irradiation. Samples were irradiated at various bremsstrahlung end-point energies for a variety of durations depending on the irradiation strategy. The production isotope of interest and potential uses are listed in Table 1. Directly following irradiation, students performed gamma spectroscopy on irradiated samples.

(a)

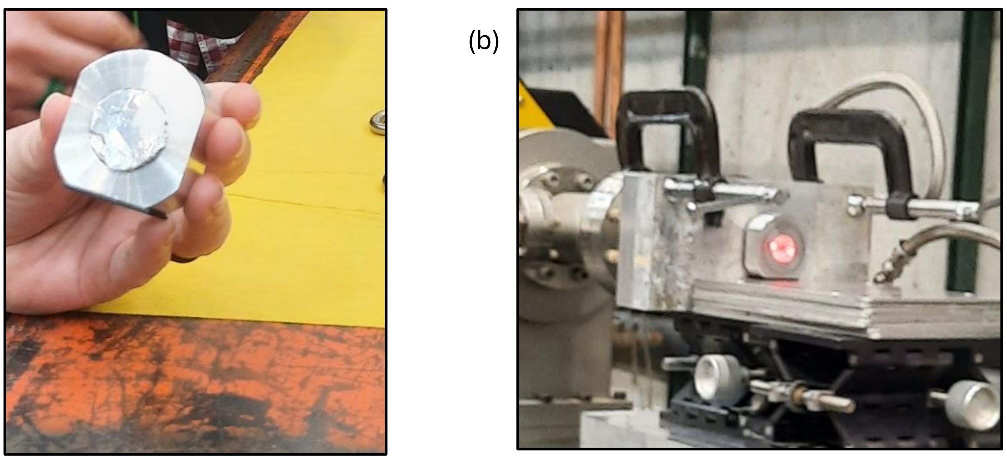

Figure 1. Aluminum sample holder with sample foils stacked and enclosed in an aluminum jacket (a). The samples and holder are positioned at the electron accelerator-end for irradiation (b).

Table 1. List of targets and the photonuclear reaction channels that produce the isotope of interest. Isotope applications are also listed.

Sample	Reactions	Production Isotope	Isotope Use
hafnium	$^{178}Hf(\gamma,p)$, $^{179}Hf(\gamma,np)$	^{177m}Lu	cancer imaging & treatment
tin	$^{118}Sn(\gamma,p)$ $^{117}In \rightarrow \beta^-$	^{117m}Sn	cancer imaging & treatment
zirconium	$^{94}Zr(\gamma,\alpha)$, $^{92}Zr(\gamma,2p)$	^{90}Sr	beta voltaic battery
zirconium	$^{91}Zr(\gamma, p)$, $^{92}Zr(\gamma,np)$	^{90}Y	cancer treatment
gallium	$^{71}Ga(\gamma,\alpha)$	^{67}Cu	cancer treatment
vanadium	$^{51}V(\gamma,\alpha)$	^{47}Sc	cancer diagnosis and therapy

CONCLUSIONS

Applications of isotopes are widespread and include molecular studies, food preservation, radiopharmaceuticals, and nuclear security. In an effort to preserve knowledge in and train the next generation of isotope scientists an education and training program is advancing with support from the RENEW initiative. Collaborators from NMT, ISU, and INL are mentoring students and teaching techniques and methods to produce isotopes through photonuclear reactions. Students are learning through nuclear science classes, seminars, experimentation, and mentorships at INL. This summer five students are joining staff at INL to collaborate on nuclear science projects through the INL internship program. Finally, analysis of irradiated samples is ongoing, and results will be presented by students at conferences in the future.

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