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The Status and Ambitions of the US Heavy Element Program

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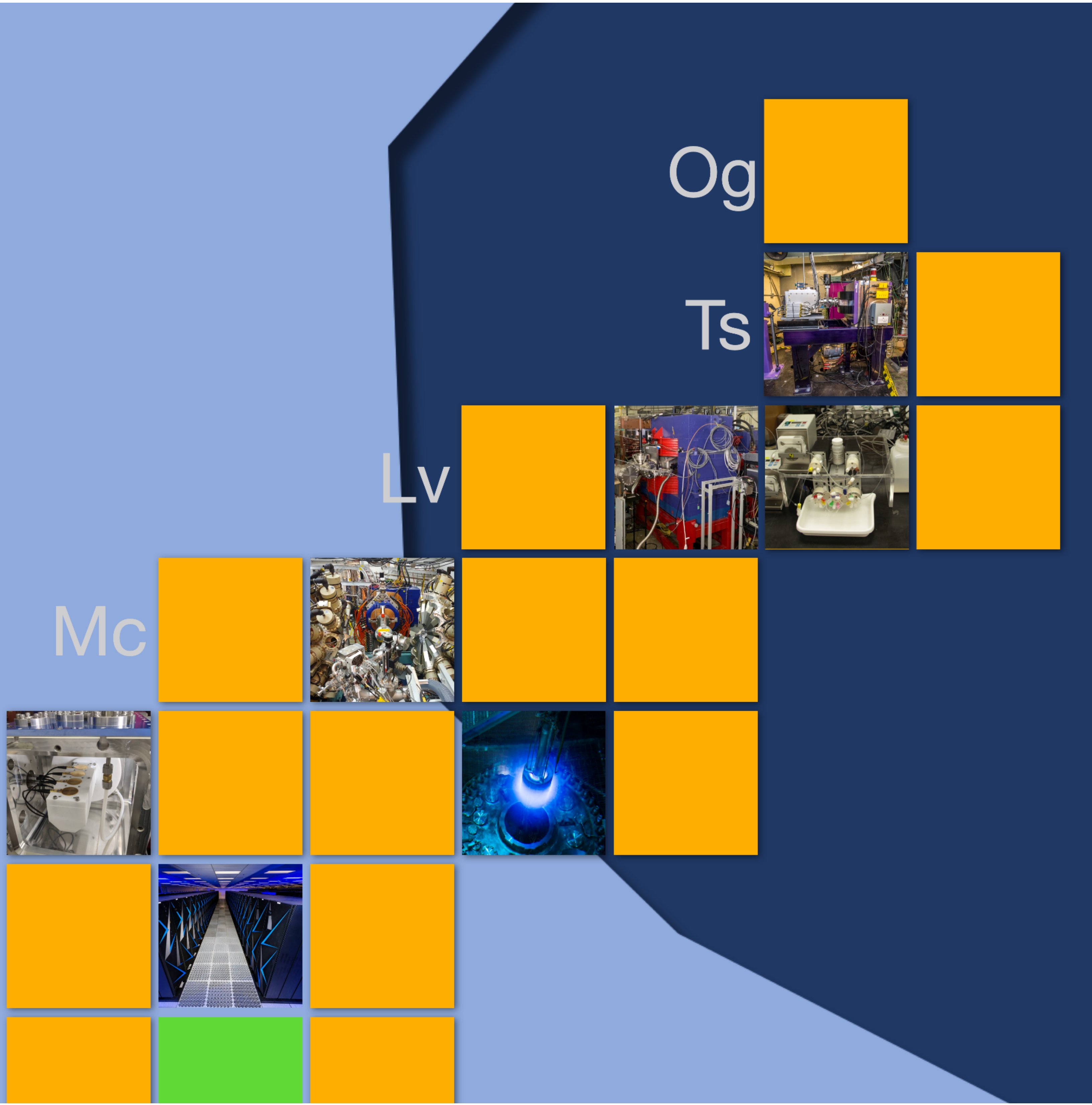

The Status and Ambitions of the US Heavy Element Program

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List of Acronyms and Abbreviations

AGFA	Argonne Gas Filled Analyzer
AGGIE	Al Ghiorso's Gas-filled Ion Equipment
ANL	Argonne National Laboratory
ATLAS	Argonne Tandem Linac Accelerator System
BGS	Berkeley Gas-filled Separator
BNL	Brookhaven National Laboratory
CAFE2	China Accelerator Facility for Superheavy Elements
CATS	Center for Accelerator Target Science
DOE	Department of Energy
ECR	Electron Cyclotron Resonance
FAIR	Facility for Antiproton and Ion Research
FIONA	For the Identification of Nuclide *A* (mass)
FRIB	Facility for Rare Isotope Beams
GANIL	Grand Accélérateur National d'Ions Lourds (Large Heavy Ion National Accelerator)
GARIS	Gas-filled Recoil Ion Separator
GREAT-NS	underGraduate Research Educational Academic Traineeships in Nuclear Science
GRETA	Gamma Ray Energy Tracking Array
GSI	GSI Helmholtzzentrum für Schwerionenforschung GmbH
HFIR	High Flux Isotope Reactor
HIRFL	Heavy Ion Research Facility
HPGe	High Purity Germanium
IMP	Institute of Modern Physics
IUPAC	International Union of Pure and Applied Chemistry
IUPAP	International Union of Pure and Applied Physics
JINR	Joint Institute for Nuclear Research
JYFL	Physics Laboratory at the University of Jyväskylä, Finland
LBNL	Lawrence Berkeley National Laboratory
LECM	Low Energy Community Meeting
LLNL	Lawrence Livermore National Laboratory
MARA	Mass Analyzing Recoil Apparatus
MARS (Separator)	Momentum Acromat Recoil Separator
MARS (Ion Source)	Mixed Axial and Radial field System
MNT	Multinucleon Transfer reactions
MR-TOF	Multi-Reflection Time-of-Flight
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
OSU	Oregon State University

RRC	RIKEN Ring Cyclotron
REDC	Radiochemical Engineering Development Center
RIBF	Radioactive Isotope Beam Factory
SASSYER	Small Angle Separator System at Yale for Evaporation Residues
SHANS	Spectrometer for Heavy Atoms and Nuclear Structure
SHE	SuperHeavy Element (Z>103)
SHEF	SuperHeavy Element Factory
SHIP	Separator for Heavy Ion reaction Products
SIPRC	Stable Isotope Production and Research Center
SRILAC	Superconducting RIKEN Linear ACcelerator
TASCA	TransActinide Separator and Chemistry Apparatus
TAMU	Texas A&M University
TUNL	Triangle Universities Nuclear Laboratory
UNM	University of New Mexico
UM	University of Michigan
USHEWG	US Heavy Element Working Group
UTK	University of Tennessee, Knoxville
VENUS	Versatile ECR ion source for NUclear Science

Executive Summary

The aim of this whitepaper is to highlight the current capabilities and priorities of the US Heavy Element community and to provide the framework for a coordinated advancement of nuclear science from these studies. This is an organized effort to reflect on what has been achieved in the field given the recommendations and initiatives of the 2015 NSAC Long Range Plan, and on what can be realized in the next decade given current and possibly expanded investments.

Current investments have positioned the US community to be among the world leaders in studies of the nuclear and chemical properties of the heaviest elements. These include studies of reaction mechanisms, moving us ever closer to the “island of stability”, in spectroscopy, allowing us to better understand nuclear structure at these extreme proton numbers, in chemical behavior, looking to determine how these elements should be placed on the Periodic Table, in performing the first measurements where isotopes are directly identified by their mass numbers, and in laying the foundation for a potential US-led new element discovery experiment.

At present, the highest priority of the US Heavy Element community is to capitalize on the current investments by supporting the operations of US facilities at optimal values. These facilities include the Argonne Tandem Linac Accelerator System at Argonne National Laboratory and other Department of Energy facilities such as the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory, which has a dedicated superheavy element program, as well as university laboratories, including Texas A&M University.

The High Flux Isotope Reactor at Oak Ridge National Laboratory is crucial to providing the radioactive isotopes required for heavy element science targets. This facility should be supported to provide the actinide materials that are essential for US-based science. Production of stable, rare isotopes for beam material, including ^{48}Ca, ^{50}Ti, ^{54}Cr and ^{58}Fe, at the Stable Isotope Production and Research Center is critical to continued research in heavy element science and should be a priority.

The continued development of targets for heavy element science and retaining US-based expertise is critical for the heavy element community. This is an area that is currently under pressure. For example, the target laboratory at Argonne National Laboratory serves a broad community and is currently under threat due to loss of critical personnel. The skills needed to make targets for nuclear science and develop new targetry methods need to be supported long term at Argonne, Oak Ridge and Lawrence Livermore National Laboratories as well as maintaining the programs at Oregon State University and San José State University as vital pipelines for training students.

Advances in theory are the foundation to understand how nuclei behave and to predict those behaviors in new circumstances. Progress in these studies will necessitate continued and new investment and access to high-performance computing.

The future health of the heavy element field is dependent on the continuous support of talented early-career professionals at all levels. It is critical that opportunities continue to be created for the next generation to become established in heavy element research so that we can ensure the field is attracting and retaining the best minds for continued success. It is also clear that to ensure diversity of ideas, perspectives and techniques, we need to recruit diverse personnel that are trained at the best facilities. The heavy element community is in support of continued investment to programs with initiatives in diversity, equity, and inclusion.

Looking to the next decade of research, support needs to maintain and grow US leadership in heavy element science. Specifically, new investments in state-of-the-art instrumentation will be essential to scientific development of the field and in expanding scientific knowledge. Advances in the next generation of electron cyclotron resonance ion sources, multi-reflection time-of-flight devices, laser spectroscopy, trapping methods and next generation alpha and gamma spectroscopy systems should be prioritized.

1. Introduction

Identifying and understanding the limits of the atomic nucleus and the boundaries of the nuclear landscape provides the motivation for the majority of experimental and theoretical efforts in low energy nuclear science. The most recent NSAC Long Range Plan in 2015 articulated this question explicitly as one of the primary open topics in our field [LRP2015]. This question can be explored in multiple ways. While efforts are underway to study the extremes of isospin and push exploration towards the proton and neutron drip lines leveraging rare isotope beam (RIB) facilities such as FRIB, equally important answers lie in the studies performed at the top of the nuclidic chart, in the regime of the heaviest elements. Heavy element science is on the edge of new, exciting discoveries about the nature of matter at the extremes.

Isotopes of the heaviest elements ($Z>92$) exist at the limits of nuclear mass and charge. The current view of the layout of the nuclear chart at the extremes of proton and neutron number are displayed in Figure 1.1. What are the properties of these giants? Which single-particle configurations are important to their stability? What is the nature of their excitation modes, and what theoretical descriptions best capture the physics relevant in these systems? What are the upper limits for the combination of protons and neutrons which can form a bound nuclear system? Is there the potential for an ‘’island of stability’’? How far do its shores extend? Does the periodic table hold or does the high nuclear charge of these elements lead towards its breakdown? In the last decade, substantial progress has been made towards answering these questions. The field of heavy element science is focused on systematically attacking these questions.

Multiple research groups are active across the U.S. and internationally, investigating different aspects of heavy element physics and chemistry, both experimentally and theoretically. Reaction studies aim to provide insight into the reaction mechanisms available to create the heaviest elements and move toward progressively more neutron rich isotopes, including the long sought “island of stability” in the heaviest nuclei. Spectroscopy, both prompt and delayed, provides key insights into the structure of these species and their excitation schemes allowing us to better understand their modes of excitation and the relevant single particle orbitals at the Fermi surface. Chemical studies include efforts to understand the placement of these heaviest elements on the Periodic table by exploring their physical properties and reactivity. Ingredients from all of these areas allow us to look forward to potential new element discovery efforts. And of course, the critical theory effort and the accessibility of enriched isotopic material must proceed concurrently.

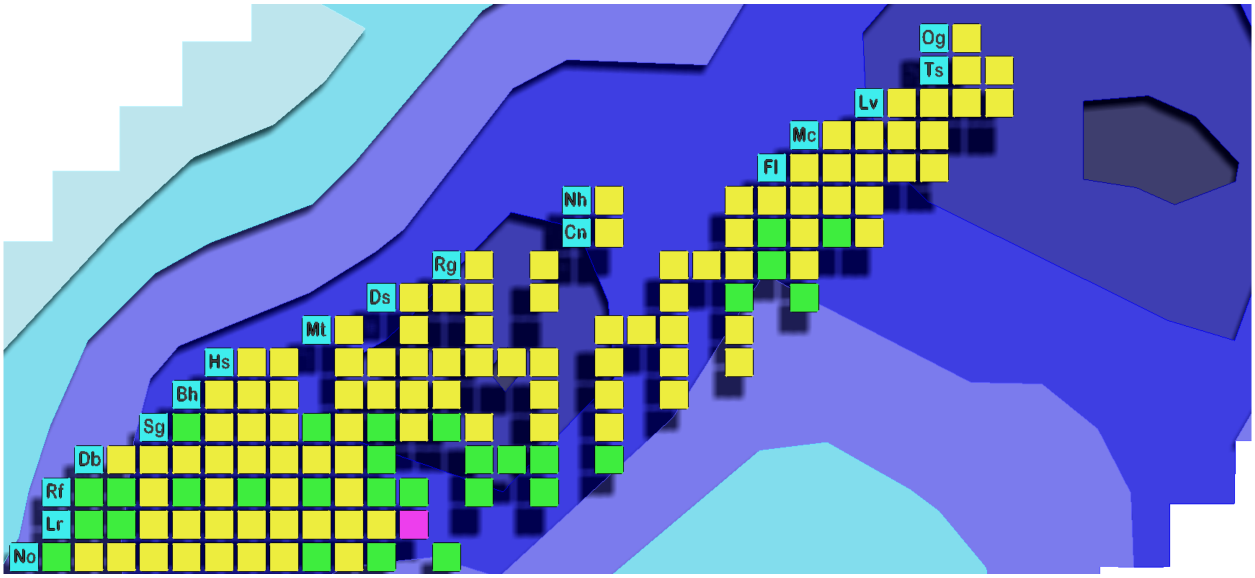

Figure 1.1: Nuclear Chart with the Island of Stability. Known isotopes are shown by their preferred decay mode, either alpha (yellow), beta (magenta) or spontaneous fission (green). These are on a backdrop of predicted shell effects from [Sob01].

2. Nuclear Reaction Studies

It is clear that central to any research program surrounding the heaviest elements is production of these rare species. Production of heavy elements, and in particular superheavy elements (SHE, those with proton numbers Z>103), is of great interest, with respect to both what can be learned about these reaction mechanisms and what can be inferred regarding the structure of these isotopes. Further studies of these nuclear reactions will extend our understanding of the production of these heaviest elements in stars, whether SHE are formed naturally in the universe, and the detailed impacts of shell effects in these heavy systems. All of these additional studies, however, start with the production of these nuclides from nuclear reactions.

Presently there are two techniques that are being pursued for the production of the heaviest elements, namely compound nucleus and multinucleon transfer reactions. To date, compound nucleus reactions have dominated the landscape in heavy element science, but the experimentally available beam and target combinations limit which SHE and SHE isotopes can be produced via this method. Specifically, these reactions produce neutron deficient SHE isotopes, which so far have numbers of neutrons lower than the expected new spherical shell closure at N=184, the expected position of the potential SHE ‘’island of stability’’. As such, alternative methods, like multinucleon transfer reactions, that can produce more neutron rich isotopes are of great interest. In addition, much remains to be learned about the reaction dynamics relevant in these processes. Understanding the subtle and complex aspects of the reaction mechanisms that can produce these elements is critical to future experiments that are aimed at production of new isotopes and new elements (see Section 4).

2.1. Compound Nucleus Reaction Studies

All of the presently known SHE isotopes have been formed in compound nucleus evaporation residue reactions, where a beam of one isotope impinges on a target of another isotope [Hof07, Oga17]. The compound nucleus resulting from complete fusion of the two nuclei then deexcites through the predominant emission of neutrons, in competition with γ rays and fission. There are presently three commonly used methods for SHE production from compound nucleus reactions:

- Cold fusion reactions, where transition metal beams impinge upon targets of lead or bismuth to produce a compound nucleus. This method leads to the most neutron deficient SHE isotopes currently observed and has been used to explore nuclei that decay through electron capture delayed fission or those near the deformed shell at N=152 where K-isomers have been observed. Cold fusion has also been used to produce elements up to Z=113 [Mor07].

- Hot fusion with light beams, where actinide targets are bombarded with light ion beams to produce isotopes that are more neutron rich than those produced in cold fusion reactions. These reactions have been successfully used to produce SHE up to Z=108 and to probe the doubly-magic deformed shell at Z=108, N=162 [Dvo08, Dvo09].

- Hot fusion with ^{48}Ca beams, where actinide targets are irradiated with a ^{48}Ca beam, produce the heaviest and most neutron rich isotopes presently observed. This reaction method has been used to produce elements up to Z=118 and isotopes that are on the edge of a predicted doubly magic closed shell, also known as the famed “island of stability”, around Z=114 and N=184 [Oga17]. In the next five years, there is great interest in using these types of reactions to produce even heavier elements. Specifically, beams of ^{50}Ti or ^{51}V on actinide targets could extend SHE production out to Z=121.

These three methods of compound nucleus reactions have been used extensively to discover and explore the more than 100 known SHE isotopes. Both hot and cold fusion show similar behavior where cross sections decrease with increasing proton number of the compound system, as shown in figure 2.1. Warm fusion with ^{48}Ca beams, however, follows this pattern until the SHE near the predicted doubly magic closed shell, where enhanced cross sections for the production of copernicium (Z=112) through oganesson (Z=118) are observed. Understanding this observed enhancement may aid in discovering new methods for SHE production.

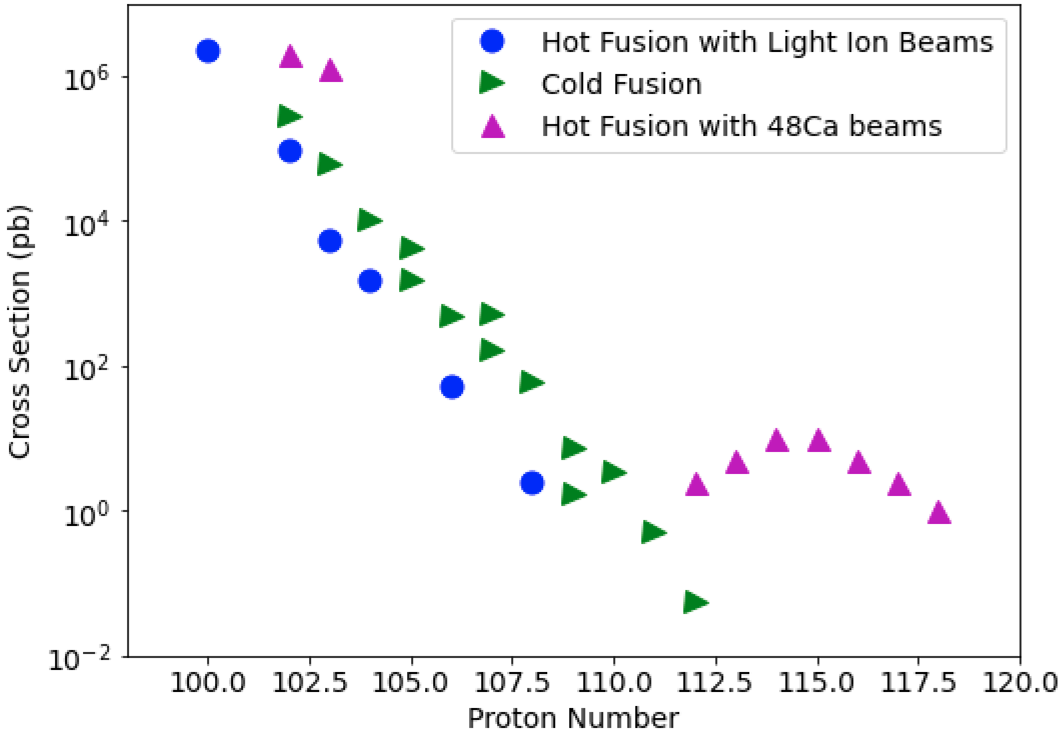

Figure 2.1: Cross sections for the hot fusion with light-ion beams [blue circles], cold fusion [green right-facing arrow] and hot fusion with ^{48}Ca beam [magenta up-facing arrow] production of elements with Z=100-118.

The decay modes and lifetimes of SHE produced in compound nucleus reactions have been widely investigated, allowing for theories in this region to be refined. For many of the isotopes, studies have begun to probe deeper and demonstrate the unique properties of the heaviest isotopes. *K*-isomers have been discovered around the deformed *N*=152 shell, unique decay modes, such as electron capture delayed fission, are seen in the most neutron deficient isotopes, spectroscopy studies have begun to probe the ordering of single particle states. Additionally, chemistry has begun investigating if these heavy elements still follow Periodic Table trends and we have reached the edge of the predicted doubly magic closed shell near *N*=184 and *Z*=114. In the future, we will continue to push the bounds of what can be learned from the production of just a few atoms of a SHE and further our understanding of both atomic and nuclear properties at the edge of the chart.

Beyond the systematics of these classes of compound nucleus reaction cross sections, it is also possible to consider the reaction kinematics in a stepwise fashion. Each compound nucleus reaction can be considered as a capture with a given cross section for the target to capture a beam particle, a fusion of the two nuclei with a given probability to proceed to the formation of a compound nucleus, and then the resulting reaction product that survives the de-excitation of the compound system, which also has a given probability. Understanding these individual processes can better inform new directions in the search for heavy elements. One way to probe the impact of these three processes is to perform systematic studies comparing how cross sections are impacted by small changes in the reaction mechanism. For example, we can probe these mechanisms by investigating cross sections where two different reactions produce the same compound nucleus [Dra08] by studying the impact on the cross section of adding two protons or two neutrons to the projectile or target [Oga17, Nel08, Nel09] or directly investigating capture cross sections. Continuing these studies will enhance our understanding of SHE production and potentially lead to improved ways to produce SHE.

2.2. Multinucleon Transfer Reaction Studies

While compound nucleus reactions have dominated SHE studies to date, these reactions produce relatively neutron deficient isotopes. An exciting development in the production of heavy nuclei is the use of multinucleon transfer (MNT) reactions to synthesize new neutron rich heavy isotopes. Examples of this work are found in references [Lov19, Des19, Des20, Wan21, Eve22, Bao21, Hei22, Kar17]. To date, research into MNT reactions has focused on using stable beams to make new neutron rich heavy isotopes in the actinide region. In experiments at the GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI) and Lawrence Berkeley National Laboratory (LBNL), several studies investigating MNT reactions have already been performed [Lov19]. neutron rich nuclides up to fermium and mendelevium have been produced with observed cross sections of ~0.1 microbarn [Kra15] and theoretical predictions from [Zag10, Hei22], shown in Fig 2.2, indicate the MNT could successfully produce new neutron rich isotopes of SHE with $Z<110$ at cross sections of up to several picobarns or more.

One obstacle in the use of MNT is that the higher excitation energies lead to broader distributions of the trans-target nuclei. This then causes the produced, highly excited nuclei to preferably undergo spontaneous fission. However, it is desirable to find a possible path towards the production of new neutron rich SHE, therefore, these MNT cross sections need to continue to be studied. Additionally, the use of radioactive beams to produce new neutron rich nuclei has not yet been thoroughly investigated. With the advent of facilities such as the Facility for Radioactive Ion Beams (FRIB) and the N=126 factory at Argonne National Laboratory (ANL), where high beam intensities of radioactive beams are possible, the investigation of MNT should be extended to radioactive beams.

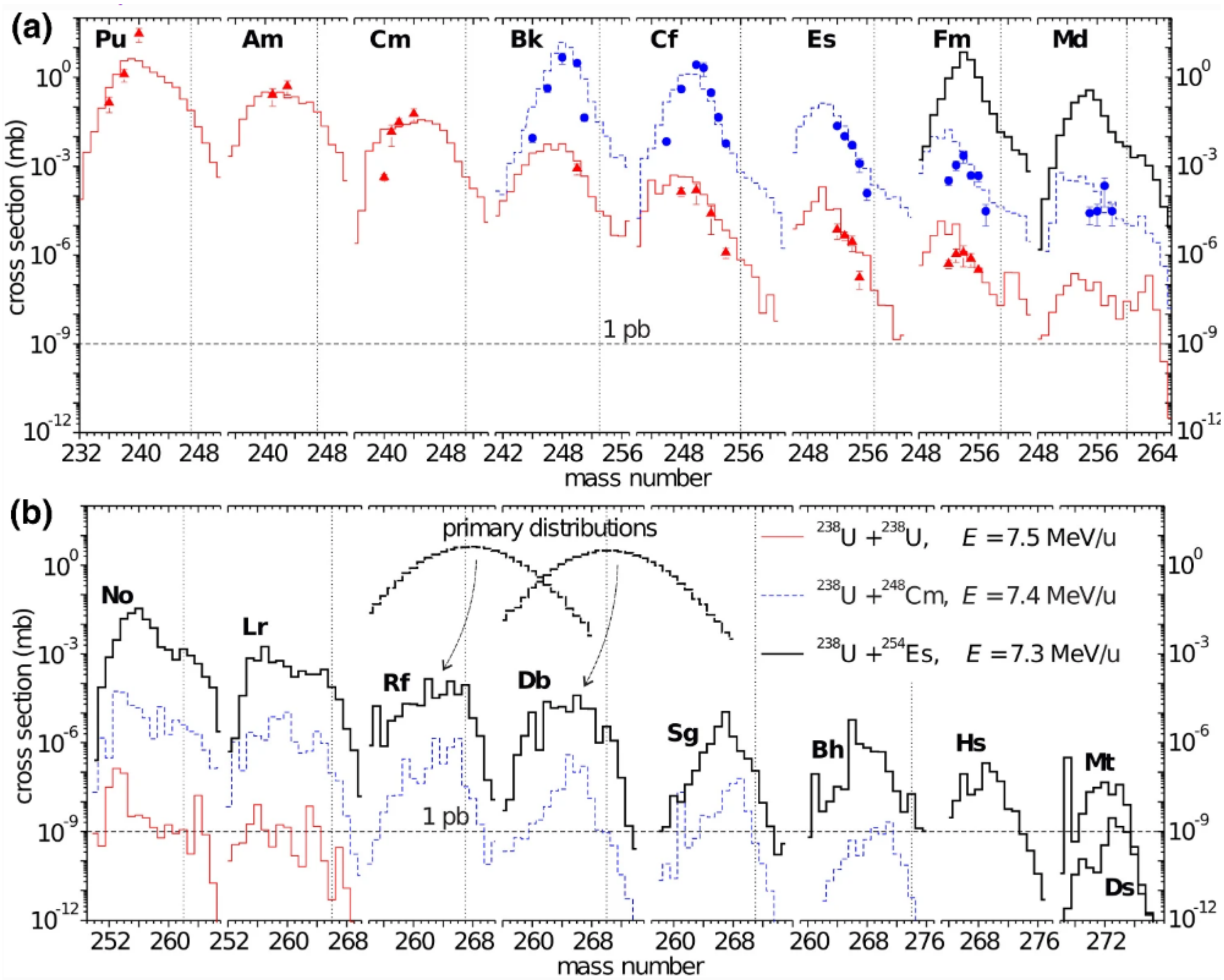

Figure 2.2: Theoretical isotopic distribution of above-target products obtained from collisions on actinides as compared to experimental data from [Hei22].

3. Spectroscopy of Superheavy Nuclei

Experiments on the heaviest nuclei address the fundamental question of the limits of maximum nuclear mass and charge. Initial discovery experiments provide first nuclear structure information on basic properties, such as the lifetime and ground state decay modes, but such results are usually quite limited since only a few SHE are produced during an experiment and represent only the first step in understanding the structure of these systems.

Prompt and delayed spectroscopy of heavy elements ($92<Z<104$) and SHE is fundamental to developing a comprehensive picture of their structure. Detection of de-exciting γ radiation at the target position, as these isotopes are produced, allows an exploration of their excitation spectra. However, this remains challenging as the maximum rates of current γ-ray spectrometers limit the beam intensity that can be used. It is in part for this reason that many such studies focus on transfermium nuclei. Heavy element isotopes are produced with higher cross sections than

SHE, but can nonetheless provide key information on the relevant single particle configurations which correspond to excited states in these lighter systems, but still sit at the Fermi surface of SHE.

Complementary to prompt spectroscopy, delayed α and γ spectroscopy, which involves studying both isomeric and ground state decay properties of heavy isotopes after separation through a spectrometer, does not suffer from the same limitations in beam intensity. These measurements provide different insight, relying on the existence of isomeric excited states, or primarily providing information in the daughter nuclides.

The subsections below discuss in more detail the current state of the art of spectroscopic studies in heavy and superheavy elements, and provide an outlook for these classes of experiments.

3.1. α-γ and α-decay fine-structure spectroscopy along decay chains of SHE

Increasingly sophisticated experimental efforts now aim to perform spectroscopy directly on the heaviest of nuclei. For instance, a recent experiment at GSI, led by the Lund University group, used a high efficiency, high resolution, focal plane setup for α-γ decay spectroscopy of nuclei along the α-decay chains of $^{288\text{-}290}$Fl (Z=114) [Såm21]. The results indicate that there are at least two parallel α-decay sequences starting from at least two different states of ^{289}Fl and that close-lying levels in nuclei along these chains have quite different spin-parity assignments. Further, observed α-electron and α-photon coincidences, as well as the α-decay fine structure along the decay chains, suggest a change in the ground state spin assignment between ^{285}Cn and ^{281}Ds. These results show that a wealth of nuclear structure information, sufficient to challenge theory, can be gleaned even from such low statistics direct experiments. In the United States (US), an array of High Purity Germanium (HPGe) detectors has been coupled to the FIONA (For the Identification Of Nuclide *A*) spectrometer at the LBNL 88-Inch Cyclotron facility. The expected γ-detection efficiency is on the order of 60% for 150 keV γ rays. This will allow for α-γ spectroscopy to be performed on mass separated and identified isotopes of SHE. A similar setup also exists at the focal plane of the Argonne Gas Filled Analyzer (AGFA) at ANL. These studies will further elucidate the structure of the nuclei at the top of the nuclear chart.

3.2. Transfermium nuclei

While SHE can be directly produced and investigated, the low cross sections, and thus the time required for a spectroscopic measurement, can be prohibitive. Thus, it is advantageous to take a more indirect approach to understanding the behavior of SHE. Detailed spectroscopic studies of deformed nuclei in the vicinity $Z\approx100$ and $N\approx152$ (transfermium nuclei) are far easier to perform due to the larger production cross sections of isotopes in this region. A clearer understanding of both these nuclei and their SHE relatives can be gained simultaneously. Identification and characterization of rotational bands in the transfermium isotopes are built on some of the same single particle orbits which lie close to the Fermi surface of the spherical

SHE. One can also learn about the pairing, shapes (including high order multipoles which may play a significant role in this mass region), elementary excitation modes, and the robustness of fission barriers at high angular momentum for these very heavy nuclei. Investigation of these nuclei using can help us better understand the structure of the heaviest SHE.

3.2.1. Isomer spectroscopy

The axially symmetric deformation of transfermium nuclei results in behavior that involves interplay between collective and single particle degrees of freedom. For example, the total projection of the angular momentum on the symmetry axis is a good quantum number, denoted *K*. Several possible configurations near the Fermi surface in the transfermium nuclei involve high-*K* values. Such a high-*K* state may be a long lived isomer if all the decay pathways to the ground state involve large changes in *K*. There has been an intense effort by ANL and LBNL, among others around the world, to find such isomers and to study the decay of these states [Dav15, Ris13, Cla10]. This provides a way to populate and study low lying nuclear excitations, with selectivity complementary to prompt spectroscopy. In particular, it is often possible to identify rotational bands, the properties of which can help define the active orbitals near the Fermi surface and hence constrain the nuclear potential. This can then be used to predict properties of SHE.

3.2.2. Prompt γ-ray spectroscopy

It is possible to correlate the implant decay events used to identify heavy nuclei with the γ rays emitted soon after the compound nucleus is formed, by using the timing information from data acquisition systems. Large arrays of HPGe detectors can surround the target position and detect these “prompt” γ rays. In the US, the current state-of-the-art system is Digital Gammasphere, in combination with the AGFA. In the future, combining AGFA with the Gamma Ray Energy Tracking Array (GRETA), with its superior efficiency, will provide even greater sensitivity.. The current setup has been used to perform sensitive prompt in-beam spectroscopy on several nuclei including odd-*Z* ^{251}Md and ^{255}Lr and even-even ^{254}No and ^{254}Rf [Dav15]. The technique enables identification of rotational bands in these deformed nuclei up to high angular momentum. By identifying such bands in odd-*A* systems and measuring their properties, such as the signature splitting and B(M1)/B(E2) ratios, we are able to firmly assign single-quasiparticle configurations to the band head and investigate properties such as the nuclear shape. Searching for backbending in the observed rotational sequences is also of great interest, since there are predictions of high-j low-Ω orbits originating from above the spherical shell closures in SHE, intruding close to the Fermi surface in these deformed nuclei. If one requires that an implantation event is followed by the decay of an isomer, this technique can be extended to investigate the properties of rotational bands based on multi-quasiparticle states, which will give information on the configurations of the excitations involved, and the roles of collectivity and pairing. Rotational bands built above two- and four-quasiparticle isomers in ^{254}No were recently identified using this technique by a collaboration working at ANL.

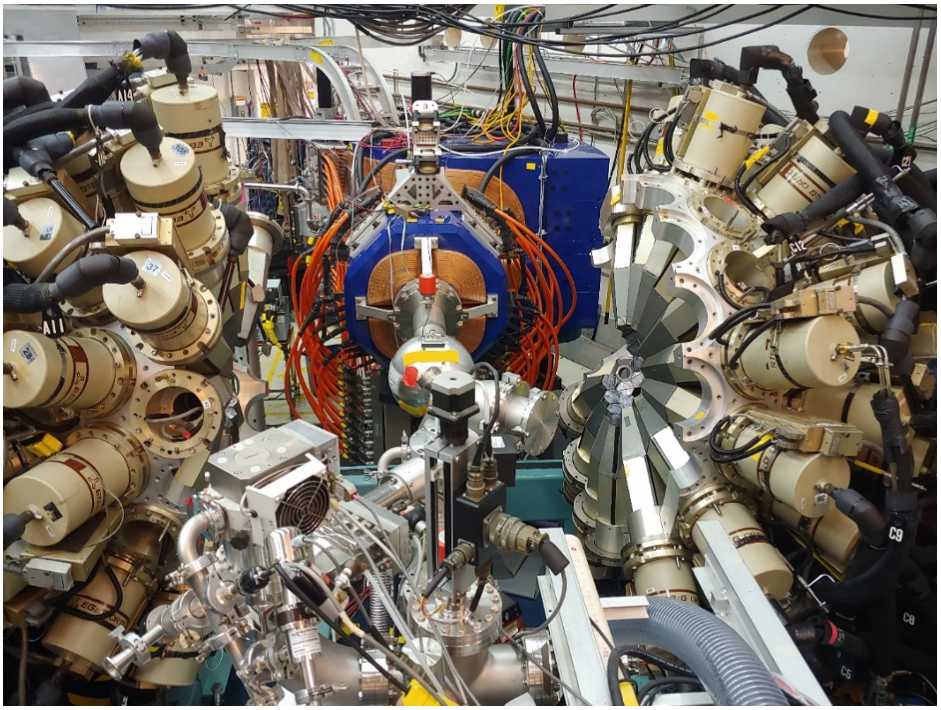

Figure 3.1: Looking downstream along the beamline into AGFA at ANL. Gammasphere is open in this image, but closes around the spherical target chamber, providing a sensitive setup for prompt γ-ray spectroscopy of transfermium isotopes. Figure taken from https://www.anl.gov/phy/argonne-gasfilled-analyzer.

4. New Element Discovery

Extending the Periodic Table of Elements remains a compelling scientific endeavor and one that continually grabs the attention of the public. The recent discovery of new elements nihonium, moscovium, tennessine, and oganesson prompted more than 200,000 submissions of suggested names to the relevant committees from the International Union of Pure and Applied Chemistry (IUPAC) and the International Union of Pure and Applied Physics (IUPAP). Whether the most massive elements continue to obey the organizing principle of the Periodic Table, which sorts the lighter elements into the familiar groups with recognizable recurring patterns of chemical reactivity, remains a central question in chemistry. Whereas determining the limits of nuclear mass and charge lies in the domain of nuclear physics. Attempts to synthesize elements beyond oganesson (Z=118), with Z=119 and Z=120 will push the limits of current technology due to the expected very low production cross sections (below the 100 femtobarn level) and short half lives (likely of order a few microseconds) for these elements. These experiments will require dedication of significant beam times at world class accelerators, stable operation of high current ion sources, production and handling of radioactive targets, efficient and well characterized ion separators, and modern detection systems including fast digital electronics for the observation of short lived radioactivities. The experiments also require experienced teams of scientists, postdoctoral associates and graduate students to staff long experimental campaigns.

The successful campaigns at the Joint Institute for Nuclear Research (JINR) in Dubna, which resulted in discovery of isotopes of several new elements with Z=113-118, used reactions induced with ^{48}Ca beams on a variety of actinide targets [Oga22B3]. This approach was found to have favorable production cross sections of around one picobarn. The doubly magic nature of the ^{48}Ca beam, and the fact that the ^{48}Ca-induced reactions tend to make the most neutron rich isotopes (closest to the expected superheavy "island of stability"), are features that have been suggested as being responsible for the favorable reaction cross sections. However, the approach of using ^{48}Ca beams on a variety of targets has essentially come to an end since necessary actinide targets for Z=119 and Z=120 discovery experiments will require tens-of-milligram quantities of einsteinium (Z=99) and fermium (Z=100). Currently, these can only be produced in microgram and picogram quantities, respectively. The approach to making new elements in the future will necessitate the use of beams other than ^{48}Ca (such as ^{50}Ti) on suitable actinide targets (such as ^{249}Cf). The use of a ^{50}Ti beam to make SHE is predicted to result in lower cross sections than if a ^{48}Ca beam were feasible, as shown in Figure 4.1. However the production of a new element with Z=120, using the ^{50}Ti+^{249}Cf reaction, is predicted to have a cross section of ~40 femtobarns. This is within reach of US facilities.

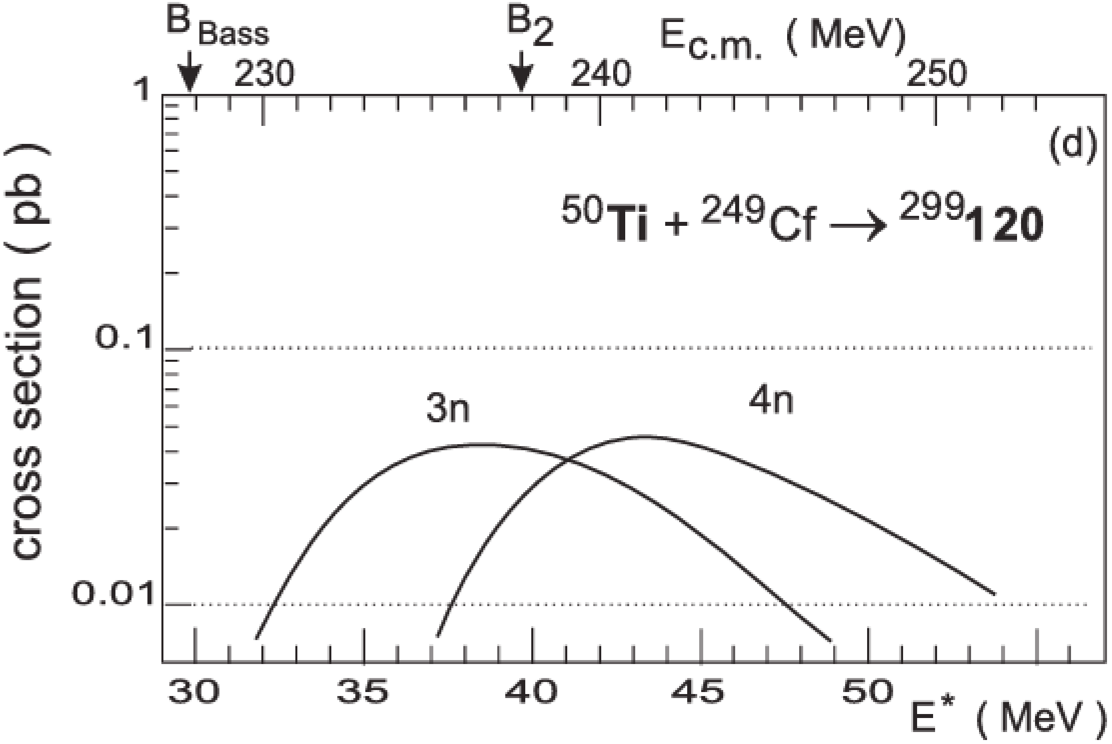

Figure 4.1: Theoretical excitation function for 50Ti induced synthesis of element 120 from [Zag08].

There are several facilities around the world that could mount an attempt to search for a new element. The production of elements 119 and 120 were attempted at GSI, but neither were detected at cross section sensitivity levels of 65 and 200 fb, respectively [Khu20]. The only ongoing attempt, at the time of this writing, is currently taking place at the RIKEN Nishina Center for Accelerator-Based Science in Japan. The Japan - US - France collaboration has chosen to focus on the ^{51}V+^{248}Cm reaction to produce element 119. While this may not be the reaction with the largest expected cross section for production, the Japanese have developed a high intensity ^{51}V beam (>3pμA on target) and invested significant effort to develop the technology to allow use of the full beam current on the ^{248}Cm target foils. The ^{248}Cm material is supplied by Oak Ridge National Laboratory (ORNL). Presently no events have been reported and we estimate that the current cross section limit has been pushed below the 10 femtobarn level. JINR in Dubna Russia has a new facility, the SuperHeavy Element Factory (SHEF), which has just come online. SHEF has yet to demonstrate a suitable high intensity beam beyond ^{48}Ca, but they are actively trying to develop such beams. It is also worth noting that the JINR team, like the RIKEN collaboration, is dependent on actinide materials from ORNL for their targets, in particular ^{248}Cm, ^{249}Bk, and $^{249\text{-}251}$Cf. GSI (Germany) plans to continue its SHE work but will only commit significant resources after the Facility for Antiproton and Ion Research (FAIR) comes online, likely in the late-2020s. In the longer term the Grand Accélérateur National d'Ions Lourds (GANIL, France) and the Institute of Modern Physics (IMP, Lanzhou,China) are also developing facilities aiming at studies of SHE, however these are beyond the timescale considered here.

In the US, accelerator facilities including at Texas A&M University (TAMU), ANL, and LBNL all have active and productive heavy element programs. However, the 88-Inch Cyclotron at LBNL is the facility in the US that is presently best suited to attempt a new element search, since the experiment involves long periods (~months) of running of intense beams (~pμA ^{50}Ti), on actinide targets, such as ^{249}Cf, in order to approach the theoretical tens of femtobarn production cross sections. The 88-Inch Cyclotron facility at LBNL has the capabilities, and capacity, to meet those requirements. Additionally, the highly efficient Berkeley Gas-filled Separator (BGS) with its custom built focal plane detector system (along with upgraded digital electronics) have been developed with such an attempt in mind. It is worth pointing out that the effort to optimize the setup for a new element search will also enhance the current US capabilities for a broad variety of studies of the physical and chemical properties of heavy and superheavy isotopes. Lastly, these experiments also depend on the supply of radioactive actinide target materials from the High Flux Isotope Reactor (HFIR) and Radiochemical Engineering Development Center (REDC) teams at ORNL, a part of the Department of Energy (DOE) Isotope Program.

5. Chemical Studies

As the chart of nuclides is extended at the top corner, it is important to recognize that questions abound for each new element that is added to the Periodic Table of the Elements. What happens to the chemical behavior of the heaviest elements due to relativistic effects in their electronic structure? Do the well studied chemical trends of their lighter counterparts break down? Do we need to rethink how to organize the Periodic Table for the heaviest nuclei? To begin to answer these questions it's necessary to pursue chemical studies of heavy and superheavy elements, which are only enabled by combining the nuclear physics facilities required to produce the atoms of interest and sensitive chemistry setups capable of atom-at-a-time measurements.

Advances in the last decade have opened a window for nuclear chemists to probe the chemical behavior of the heaviest elements with only a few atoms at their disposal. Internationally, efforts have been made to study the chemical properties of flerovium (Z = 114) [Yak16, Aks16] and nihonium (Z = 113) [Yak21], to produce the first carbonyl complex of seaborgium (Z = 106) [Eve14], to measure the first ionization potential of lawrencium (Z = 103) [Sat15], and to perform the first measurement of an electronic excited state in nobelium ($Z = 102$) [Chh18]. In the US, the first direct mass number determination of a superheavy element was performed [Gat18], and new ideas for chemical experiments are being developed.

The Cyclotron Institute at TAMU has been working to increase the sensitivity of its accelerator based experiments from multiple angles. The former Small Angle Separator System at Yale for Evaporation Residue (SASSYER) [Res03], a gas filled separator, was moved from Yale University to TAMU and rechristened as the AGGIE (Al Ghiorso's Gas-filled Ion Equipment) gas filled separator; this provides a much higher efficiency for the purification of fusion evaporation products than the Momentum Acromat Recoil Separator (MARS) which is a vacuum spectrometer that was used previously [Fol12]. This new separator will allow for chemical experiments to be conducted on SHE. TAMU is developing a silicon detector coated with a self assembled monolayer of an organic compound; this effectively converts the functionalized detector surface into a chromatography column. Proof-of-principle experiments have shown a difference in adsorption between erbium, astatine, and iridium. This work is complemented by "offline" developmental work in a traditional chemical laboratory.

At Lawrence Livermore National Laboratory (LLNL) a new continuous gas-liquid interface was developed for transfering accelerator based products from the gas phase to the aqueous phase. A microfluidic contactor system as well as novel organic ligands for studying flerovium and copernicium for the first time in the aqueous phase, have also been developed. A novel flow through position sensitive liquid scintillation system has been tested for integration with the automated microfluidic chemistry system. This detection system has the capability to unambiguously detect transactinide ($Z \geq 104$) activities. The system developed, by LLNL, requires deployment at an accelerator facility, but simulations indicate a 28% efficiency throughout the entire production to detection per atom of ^{285}Cn produced, with a total throughput time of under 20 seconds, in its current state.

At the LBNL 88-Inch Cyclotron facility, a new technique has been developed utilizing the FIONA device [Kwa21]. With FIONA, ions of SHE are trapped, reactive gasses are then added to the trap such that a chemical reaction can occur, and then the reaction products are sent through a mass analyzer, such that they can be identified by their mass-to-charge ratio. This now allows researchers to remove any ambiguity as to what is produced in chemical reactions with heavy elements.These studies can readily be performed on the actinide elements and, with future upgrades, continued work would even be feasible for transactinide species. Sample data showing the production and direct-identification of holmium-oxide molecules with FIONA is shown in Figure 5.1.

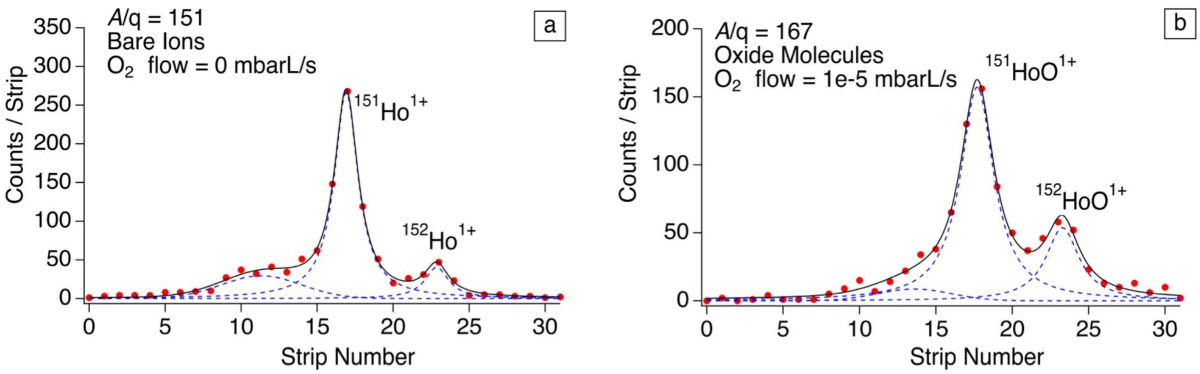

Figure 5.1: LBNL Data taken at the FIONA focal plane, where ions of holmium isotopes were reacted with oxygen (O_2) gas to produce holmium-oxide molecules. The production of each was confirmed with mass-to-charge-ratio measurements. *(a) Observed counts of* ${}^{151\text{-}152}Ho^{1+}$ in the absence of O_2 gas. *(b) The counts of oxide molecules* ${}^{151\text{-}152}HoO^{1+}$ *produced when a flow rate of 1e-5 mbarL/s* O_2 *gas was added to the system. Figure adapted from data in [Kwa21].*

Continued investigation of the chemical properties of the heavier actinide and transactinide elements should remain a focus over the next decade. The continued development of new techniques to understand the chemistry of these elements, and the impact on the Periodic Table, remains a priority in heavy element nuclear science.

6. The Next Generation of Experimentation

The US is a world leader in innovation and those talents are always being harnessed to increase our scientific knowledge. Over the next decade, there are multiple areas of research where using our expertise to build new equipment will greatly expand the breadth of scientific studies that can be performed. Some of these include, but are not limited to, high precision mass measurements, laser spectroscopy and searching for unique decay modes in SHE.

Masses of the known isotopes are an important test of our theoretical understanding of the heaviest systems. The recently commissioned FIONA mass analyzer at LBNL has the capability to determine masses of heavy isotopes to within one mass unit. This was sufficient to perform the first mass measurements of the SHE discovered with ${}^{48}Ca$ beams on actinide targets [Gat18] and will continue to investigate masses of isotopes that can only be produced at atom-per-day scales. FIONA does not allow for precision mass measurements. Masses of the majority of the SHE are determined by precisely measuring the masses of isotopes in the Z=102-104 region, then extrapolating masses of the heavier isotopes based on their known α decay energies down to isotopes whose masses were precisely measured. This process is imprecise and prone to errors if the known α decays are not from ground state to ground state. Until recently, techniques for precisely measuring masses required hundreds or thousands of atoms per measurement, thus limiting their uses to elements with $Z \leq 104$ [Blo13]. Recently, multi-reflection time-of-flight (MR-TOF) apparatuses have been shown to be ideal for performing high precision mass measurements using just a handful of SHE atoms [Sch21]. Building US-based expertise in this region and extending these measurements to the SHE should be a priority in the next decade.

Understanding how the uniquely high proton numbers of SHE impact the energies and ordering of the atomic orbitals, and how this changes the chemistry of SHE, is an important topic in chemistry. Most experiments have thus far only observed if a SHE is more like one lighter homologue or another. However, the exact energies of atomic orbitals, and thus more detailed information on expected chemical behavior, can be obtained by probing these energies with laser spectroscopy. Currently Resonance Ionization Spectroscopy has been performed on nobelium, Z=102. This process is highly inefficient and requires hundreds or even thousands of atoms,which limits the number of SHE that can be investigated with this technique [Chh18]. The development of new technology, where ions or atoms are trapped and resonantly excited, will push far beyond the current limit of Z=102 for precision measurements of atomic properties.

Our current understanding of SHE decay is limited to directly observing α- or spontaneous fission decay, and inferring electron capture decay based on the decay properties of the daughter of an isotope. However, theoreticians have shown the models predict other decay paths for SHE, such as heavy particle radioactivities (HPR). This decay mode, in which a particle of ^{14}C, ^{20}O, ^{23}F, $^{22,24\text{-}26}$Ne, ^{28,30}Mg, ^{32,34}Si etc is emitted from the parent nucleus has been observed in parent nuclei with Z=87-96 [Poe11]. Recent theoretical studies have shown the HPR is a potential decay mode with a similar branching ratio as α decay in ^{286}Nh, $^{285\text{-}286}$Cn and ^{282,283}Rg [Roy22], all isotopes on the edge of accessibility with current facilities. Efforts should be made to search for this unique decay mode in SHE.

7. Materials for SHE Research

SHE can only be produced in nuclear reactions with cross sections from nanobarns to femtobarns. As these production cross sections are small, efficient production of SHE requires high currents of neutron rich, medium mass ion beams to collide with targets composed of elements from lead to californium. At facilities such as LBNL, ANL or TAMU, beam intensities of up to two-particle microamperes are achievable. These beam currents correspond to SHE production rate of atoms-per-minute for nanobarn-level cross sections to atoms-per-year for isotopes made with cross sections of a femtobarn. Providing material for both the rare isotope beams and the targets is essential for heavy element science.

7.1. Rare Isotope Production

Due to their low production rates, SHE are ideally produced using high intensity beams that run over long campaigns of weeks or months at a time. Specifically, beams of rare, stable isotopes such as ^{48}Ca, ^{50}Ti, ^{54}Cr and ^{58}Fe are needed as projectiles for SHE experiments. The material required to produce these beams is a function of the efficiency of the ion sources and particle accelerators used and the running time of the experiment. As discussed in Section 4, a month-long experiment will, therefore, require approximately 250 mg of isotopes, such as ^{48}Ca, or upwards of 3.5 g of material for metal beams. Presently, supply of the highly enriched separated isotopes that are crucial for investigating SHE is limited. The new Stable Isotope

Production and Research Center (SIPRC) at ORNL can produce these, and other isotopes required for national security. The construction, commissioning and long term operation of such a facility should be highly supported within the heavy element community.

In addition to the isotopes required for beam production, the majority of studies of SHE require exotic target material. With only 20-23 protons coming from the beam species such as ^{48}Ca or ^{51}V, production of the heaviest elements require actinide targets with thicknesses of order 500-800 μg/cm^2 across target wheels with areas of several cm^2 (see Fig 6.1). This corresponds to 15-30 mg of actinide material that is required for each target. The radioactive materials required for targets have depended on the availability of isotopes from the HFIR/REDC teams at ORNL, a part of the DOE Isotope Program. This is sufficient material to create the targets that are essential for understanding the physics and chemistry of the heaviest elements. Maintaining this capability is crucial to the continued investigation of the heaviest elements around the world.

7.2. Target Production

The production of SHE requires targets that consist of a thin, uniform layer of isotopically enriched material from lead (Z = 82) to californium (Z = 98). Since all but two of these elements are radioactive, SHE targetry generally requires specialized radiochemical equipment to prepare and manipulate the radioisotopes into the needed thin-film target form. In general, targets for heavy element research have a few overarching qualities: (1) generally free-standing thin films (often on the order of 500 μg/cm^2 ≈ 100 – 1000 nm thick, depending on the material's density), (2) ideally composed of a single, isotopically enriched sample to limit background from concurrent nuclear reactions, (3) usually too thin to be self-supporting and requires a target backing to provide structure and support, and (4) designed to be placed in specific experimental setups.

Figure 6.1: ^{209}Bi target produced via vapor deposition

For SHE production studies, a key feature to these targets is their survivability in beam. Given the picobarn to femtobarn production cross sections for the heavier transactinides, the best way to increase production of SHEs is to increase beam current. With the advent of modern ECR ion source technology [Lyn10], typical beam fluxes can be in the particle microamp range ($>1.0 \times 10^{13}$ pps). To help dissipate the beam power deposited on these thin films, targets are almost always mounted on a rotating wheel (see figure 6.1), which continuously moves the target material into and out of the ion beam path. This allows the film time to cool and increases in-beam survivability.

The targets used for SHE studies are generally produced via molecular plating, electrodeposition or vapor deposition onto a target backing. Electrodeposition has the target material suspended or dissolved in a solvent, which is then driven to precipitate onto the target backing using an electrical potential. This method has the distinct advantage of having high plating efficiency (> 90% typically), which is needed when working with rare and radioactive samples such as the heavier actinides. As all of the known actinides are radioactive, these materials are typically handled in gloveboxes or even hot cells, depending on the properties of the given isotope. Currently, facilities at ORNL, LLNL, ANL, and LBNL have the capabilities to make actinide targets in gloveboxes. Indeed, ORNL being the site of HFIR, is able to work with the shortest lived isotopes to make targets inside of their hot cells.

The other approach to target production is with vapor deposition under vacuum [Sil20]. A sample is heated beyond its vapor point under vacuum, the resulting vapor plume is cooled and collected as a uniform thin film. Common heating techniques that drive this evaporation include resistive heating in a tantalum or tungsten crucible or impinging an electron beam (e-beam) onto the sample. The ^{209}Bi target in figure 6.1 was produced via vapor deposition. Recently, the Oregon State University (OSU) group has pioneered the use of vapor deposition to make targets (^{233}U, ^{237}Np and ^{239}Pu) of high specific activity (10^7 Bq) actinides. Actinide oxides are converted to fluorides, in simple reactions such as $UO_2 + 4HF = UF_4 + 2H_2O$ [Sil2020]. The use of vapor deposition can allow the target maker to produce deposits of unusual shapes. The Oregon State group makes vapor deposited targets of actinides for various groups in the US [LLNL, ANL, University of Michigan (UM), the Triangle Universities Nuclear Laboratory (TUNL) and University of New Mexico (UNM)].

Currently in the broader low energy nuclear science community, there is a critical need for well-made targets. Presently, with the closure of several target production and characterization laboratories, coupled with an aging pool of target makers, the demand for well-made targets has only increased in the last decade [Sil20, Gre18]. For example, the Center for Accelerator Target Science (CATS) at ANL has recently had a retirement and an additional vacancy that has impacted their ability to maintain operations. When combined with the specialized equipment and procedures needed for heavy element research, the US-based SHE community is in real risk of losing valuable and necessary capabilities. To help correct this trend, an independent targetry lab at San José State University (SJSU) was recently established to produce both stable and radioactive targets using the techniques described above. It is crucial that we continue to train incoming students and scientists to work in these environments and to maintain the capabilities to perform this work inside of the United States.

8. Theoretical Studies

Theory has an important role in heavy element research [Naz18, Giu19]. An extensive knowledge of reaction mechanisms is essential for planning experiments to produce SHE. There has also been a resurgence of interest in the theory of nuclear fission [Ben20], motivated in part by the recognition that it may have an important role for the origin of the heavy elements in the universe.

To study the heaviest elements that can be produced in laboratory settings, one needs theoretical guidance for choosing appropriate target and projectile combinations together with the optimal bombarding energy that would maximize the yields. The most promising route to make superheavy nuclei is through heavy ion collisions that leads to an equilibrated compound nuclei that then decays without undergoing fission to smaller nuclei. There are many aspects to estimating the probabilities in this reaction chain, much related to competing fission processes such as quasifission, fusion-fission, and the spontaneous fission of the super heavy ground state. All require theoretical input, both in reaction theory and in the static theory of the fission barriers.

Fission theory has benefited enormously from calculational tools based on density-functional theory and its time-dependent generalization. Of the quantities that are important for a theory of cross sections and lifetimes, a quantitative knowledge of the shape and size of the fission barrier is essential. Ultimately the barriers and other perturbations on nuclear energetics are due to shell effects and are very significant in determining the outcome of a fission event [Ram12]. There are now newer techniques based on a full treatment of the nucleon interaction that might be more accurate than density-functional theory, and thus more reliable [Str19]. These new methods have been very successful in the theory of nuclear binding energies, and it would be worthwhile to gather the resources to apply them to the fission landscape.

The other aspect of fission theory is the dynamics that carries the nucleus from a mildly-deformed initial shape to the highly-deformed shapes that lead directly to scission. There has been great progress using time-dependent mean-field theory to describe these shape changes [Str19], but much remains unknown. Competing with time-dependent mean-field theory is another approach, also quite successful, that puts statistical degrees of freedom at the forefront [Sim18]. Again, we need to develop the computational tools to bring both approaches under the same theoretical umbrella and come to a real understanding of the dynamics. There are many kinds of experiments that could shed light on questions of dynamics, if only we had the fully microscopic calculational tools. For example, the mechanisms that generate angular momentum in fission fragments are still not well understood, and yet the angular momentum of the fragments is an important ingredient in modeling the properties of the neutrons and γrays they emit. Recent experimental results suggesting the absence of correlation between fragment spins have rekindled interest in the theoretical description of angular momentum generating mechanisms. At present, there are two competing points of view about how the angular momentum is generated [Bul20, Wil21]. It may be due to spin modes acting prior to scission, but there are also arguments supported by the mean-field theories that the nuclear shape itself is responsible. These calculations are the subject of ongoing state-of-the-art research. Another observable that is far from understood is the odd-even staggering of the proton numbers in the fission fragment distributions. So far neither the mean-field nor statistical approaches have been helpful. The principal source of fission-fragment angular momentum data is obtained through the γ-rays they emit. Both prompt γ-rays and those issued from isomeric states in the fragments have been used to this end. The advent of new facilities and detector arrays presents a timely opportunity to further constrain theoretical calculations of fission fragment spins using new γ-ray data over a broad range of fissioning nuclei.

To address all these theoretical developments necessitates a sustained theoretical and computational effort that requires a renewed investment in personnel and computational resources.

9. International Context for the U.S. based SHE Studies

The US SHE scientific community is aware of and involved in the ongoing SHE science programs around the world. The US scientific program is complementary to many of these efforts, and will lead and participate as resources allow. However, collaboration between the US and international communities will enable more rapid progress in this field. This has been amply demonstrated during the last 30 years.

Outside of the US, there are several facilities conducting research aiming to investigate properties of SHE, each with their own specializations and focuses. The Radioactive Isotope Beam Factory (RIBF) at the RIKEN laboratory (Wako, Japan) now has two independent facilities capable of performing research on SHE [Sak22]. The new Superconducting RIKEN Linear Accelerator (SRILAC) accelerator and Gas-filled Recoil Ion Separator (GARIS) III are being used to search for the new element 119 in collaboration with scientists from ORNL and the University of Tennessee, Knoxville (UTK). In addition, the RIKEN Ring Cyclotron (RRC) has been adapted to lower beam energies and is available for SHE studies part time. The RRC will focus on mass measurements of very heavy nuclei using a well-developed MR-TOF device [Sch21].

GSI (Darmstadt, Germany) has two separators that can be used for SHE investigations: the gas-filled Transactinide Separator and Chemistry Apparatus (TASCA) [Sem08] and Separator for Heavy Ion reaction Products (SHIP) [Mün79], a velocity filter. Groups at GSI focus on investigating the chemistry of SHE through gas-phase chromatography [Yak16], explore the electron energies using laser spectroscopy [Chh18], or perform high precision mass measurements in a penning trap [Blo13].

The accelerator facility at the Physics Laboratory at the University of Jyväskylä (JYFL, Jyväskylä, Finland) utilizes the gas-filled RITU separator [Sar11] and the Mass Analysing Recoil Apparatus (MARA) [Sar08], a vacuum-mode separator, for their SHE investigations. There, the nuclear structure of SHE is probed using a combination of JUROGAM3 [Pak20] and the Sage Spectrometer [Pak14]. These studies are important additions to our understanding of the production, chemistry and nuclear structure of the heaviest elements.

In Lanzhou, China, the Spectrometer for Heavy Atoms and Nuclear Structure (SHANS) is coupled to a HPGe detector array at the Heavy Ion Research Facility (HIRFL) and a new device, SHANS2 is being installed at the China Accelerator Facility for Superheavy Elements (CAFE2). These two devices are being used to search for new superheavy element isotopes, investigate the nuclear structure of the actinide elements and synthesize new neutron deficient isotopes.

In Dubna, Russia the new SHEF at JINR was recently constructed and commissioned [Oga22]. Beams of ^{48}Ca of more than six particle microamperes have been already used in physics experiments at this new facility. With intense ^{48}Ca beams, SHEF has produced tens of decay chains of copernicium, flerovium and moscovium isotopes, and improved decay data for more than 20 super heavy nuclei [Oga22, Oga22B, Oga22C].

The Heavy Element research group at the GANIL (Caen, France) is focused on spectroscopic study of the very heavy elements located beyond Z=100 which leads to information relevant for the microscopic understanding of the superheavy elements [Isa22, Tez22, Lop22] .

10. Supporting the Next Generation of Researchers: A Focus on Diversity, Equity, and Inclusion

It is always of utmost importance to ensure that there is a new generation of scientists both excited about and capable of continuing heavy element research. Worldwide and in the US the community needs to prepare to pass on the reins to a younger cohort. It is also clear that to ensure diversity of ideas, perspectives and techniques, we need to recruit diverse personnel. We all have an important role to play in enhancing Diversity, Equity, and Inclusion (DEI) in our community, both domestically and internationally. In the US, pointed efforts have already begun to recruit undergraduate students from underrepresented minority groups into traineeship programs to increase their interest in nuclear science. The goal of these programs is to inspire these students to pursue graduate degrees and then eventually employment in the field of nuclear science. In the past couple of years, students from these programs have already become involved and invested in heavy element research. This is an immense opportunity to develop a more diverse workforce. Continuing to support and expand DEI programs needs to be a top priority for nuclear science researchers. The continued development of a diverse generation of nuclear scientists, through the underGraduate Research Educational Academic Traineeships in Nuclear Science (GREAT-NS) at LBNL and expansion of these programs to more national laboratories and universities, is of high importance.

11. Future Prospects

The US community continues to be among the leaders in Heavy Element research. The availability of stable isotopes and actinide materials from ORNL coupled with the availability of beam time at facilities such as the LBNL 88-inch Cyclotron, the Cyclotron Institute at TAMU, and the Argonne Tandem Linac Accelerator System (ATLAS) at ANL make it possible to perform impactful studies within the US. Additionally, the recent formation of a US Heavy Element Working Group (USHEWG) has sparked renewed collaboration within the US community to best take advantage of the available resources. These revitalized partnerships will lead to a more-focused and deliberate research program that can target the field's biggest questions. Looking towards the near future, this community is prepared to lead efforts in:

- Producing the first SHE with beams beyond ^{48}Ca, including a potential search for element 120 at LBNL.
- Detailed spectroscopic studies of isotopes around Z>100, with both in-beam and decay techniques utilizing arrays of HPGe detectors such as Gammasphere and the *X*-array at ANL or the FIONA decay station at LBNL.
- Studies to investigate nuclear reaction mechanisms that can be performed at TAMU and FRIB. Of particular interest will be to better understand the potential of MNT in creating new neutron rich SHE isotopes.
- Studies of the chemical properties of the heaviest elements, where the complementary experimental approaches available from LBNL, TAMU, and LLNL can work in concert to provide a comprehensive picture.
- Theoretical work to better understand the mechanisms leading towards fission and to search for new methods to produce neutron rich SHE.
- Ion source development at LBNL to create the next generation Mixed Axial and Radial field System (MARS) ion source to improve both the beam intensity and the available ion charge states, offering significantly better performance and new opportunities for researchers.
- Building new experimental apparatuses that will usher in the next generation of US SHE research, such as high precision mass measurements and ion traps for laser spectroscopy.

Progress in each of these efforts will be critical components in the greater, world wide endeavor to further the field of SHE research.

The US program in accelerator-based heavy element nuclear physics and chemistry is benefitting from its position at the forefront of research internationally while also pursuing ideas that are not being considered elsewhere. We support efforts to encourage greater collaboration between these US laboratories, along with efforts to encourage students to study heavy element nuclear physics and chemistry. This training, which touches on nuclear physics, nuclear structure, chemistry, radiochemistry, accelerator science, and high precision measurements, also increases the pipeline of trained personnel for careers in areas of national need. The USHEWG should continue meeting during the Low Energy Community Meeting (LECM) each year to work on developing priorities for SHE research within the US community and to increase collaboration opportunities between the US laboratories and institutions. A priority must be placed on increased participation of students and postdoctoral researchers in experiments being performed throughout the US.

12. Recommendations

The aim of this whitepaper is to highlight the current capabilities and priorities of the US Heavy Element community and to provide the framework for a coordinated advancement of nuclear science from these studies. This is an organized effort to reflect on what has been achieved in the field given the recommendations and initiatives of the 2015 NSAC Long Range Plan, and on what can be realized in the next decade given current and possibly expanded investments.

Current investments have positioned the US community to be among the world leaders in studies of the nuclear and chemical properties of the heaviest elements. These include studies of reaction mechanisms, moving us ever closer to the “island of stability”, in spectroscopy, allowing us to better understand nuclear structure at these extreme proton numbers, in chemical behavior, looking to determine how these elements should be placed on the Periodic Table, in performing the first measurements where isotopes are directly identified by their mass numbers, and in laying the foundation for a potential US-led new element discovery experiment.

At present, the highest priority of the US Heavy Element community is to capitalize on the current investments by supporting the operations of US facilities at optimal values. These facilities include the Argonne Tandem Linac Accelerator System at Argonne National Laboratory and other Department of Energy facilities such as the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory, which has a dedicated superheavy element program, as well as university laboratories, including Texas A&M University.

The High Flux Isotope Reactor at Oak Ridge National Laboratory is crucial to providing the radioactive isotopes required for heavy element science targets. This facility should be supported to provide the actinide materials that are essential for US-based science. Production of stable-rare isotopes for beam material, including ^{48}Ca, ^{50}Ti, ^{54}Cr and ^{58}Fe, at the Stable Isotope Production and Research Center is critical to continued research in heavy element science and should be a priority.

The continued development of targets for heavy element science and retaining US-based expertise is critical for the heavy element community. This is an area that is currently under pressure. For example, the target laboratory at Argonne National Laboratory serves a broad community and is currently under threat due to loss of critical personnel. The skills needed to make targets for nuclear science and develop new tagetry methods need to be supported long-term at Argonne, Oak Ridge and Lawrence Livermore National Laboratories as well as maintaining the programs at Oregon State University and San José State University as vital pipelines for training students.

Advances in theory are the foundation to understand how nuclei behave and to predict those behaviors in new circumstances. Progress in these studies will necessitate continued and new investment and access to high-performance computing.

The future health of the heavy element field is dependent on the continuous support of talented early career professionals at all levels. It is critical that opportunities continue to be created for the next generation to become established in heavy element research so that we can ensure the field is attracting and retaining the best minds for continued success. It is also clear that to ensure diversity of ideas, perspectives and techniques, we need to recruit diverse personnel that are trained at the best facilities. The heavy element community is in support of continued investment to programs with initiatives in diversity, equity, and inclusion.

Looking to the next decade of research, support needs to maintain and grow US leadership in heavy element science. Specifically, new investments in state-of-the-art instrumentation will be essential to scientific development of the field and in expanding scientific knowledge. Advances in the next generation of electron cyclotron resonance ion sources, multi-reflection time-of-flight devices, laser spectroscopy, trapping methods and next generation alpha and gamma spectroscopy systems should be prioritized.

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References

[Aks17] N.V. Aksenov, et al., Eur. Phys. J. A 53, 158 (2017), https://doi.org/10.1140/epja/i2017-12348-8.

[Bao21] X.J. Bao, Phys. Rev. C 104, 034604 (2021), https://doi.org/10.1103/PhysRevC.104.034604.

[Ben20] M. Bender, et al., J. Phys. G, Nucl. Part. Phys. 47, 113002 (2020), (2020),https://doi.org/10.1088/1361-6471/abab4f.

[Ben14] J.Y. Benitez, et al, Rev. of Sci. Instru. **85**, 02A961 (2014), https://doi.org/10.1063/1.4854896.

[Blo13] M. Block, Int. J. Mass Spectrom. 349–350, 94 (2013), http://dx.doi.org/10.1016/j.ijms.2013.02.013.

[Bul20] A. Bulgac, S. Jin, and I. Stetcu, Front. Phys. 8, 63 (2020), https://doi.org/10.3389/fphy.2020.00063.

[Chh18] P. Chhetri, et al., Phys. Rev. Lett. 120, 263003 (2018), https://link.aps.org/doi/10.1103/PhysRevLett.120.263003.

[Cla10] R.M. Clark, et al., Phys. Lett. B 690, 19 (2010), https://doi.org/10.1016/j.physletb.2010.04.079.

[Dav15] H.M. David, et al., Phys. Rev. Lett. 115, 132502 (2015), https://doi.org/10.1103/PhysRevLett.115.132502.

[Des19] V.V. Desai, et al., Phys. Rev. C 99, 044604 (2019), https://doi.org/10.1103/PhysRevC.99.044604.

[Des20] V.V. Desai, et al., Phys. Rev. C 101, 034612 (2020), https://doi.org/10.1103/PhysRevC.101.034612.

[Dra08] I. Dragojević, et al., Phys. Rev. C 78, 024605 (2008), http://dx.doi.org/10.1103/PhysRevC.78.024605.

[Dvo08] J. Dvorak, et al., Phys. Rev. Lett. 100, 132503 (2008), http://dx.doi.org/10.1103/PhysRevLett.100.132503.

[Dvo09] J. Dvorak, et al., Phys. Rev. C 79, 037602 (2009), http://dx.doi.org/10.1103/PhysRevC.79.037602.

[Eve14] J. Even, et al., Science 345, 1491 (2014), https://doi.org/10.1126/science.1255720.

[Eve22] J. Even, et al., Atoms 10, 59 (2022), https://doi.org/10.3390/atoms10020059.

[Fol12] C.M. Folden III, et al., Nucl. Instrum. Methods A 678, 1 (2012), https://doi.org/10.1016/j.nima.2012.02.035.

[Gat18] J.M. Gates, et al., Phys. Rev. Lett. 121, 222501 (2018), https://link.aps.org/doi/10.1103/PhysRevLett.121.222501.

[Giu19] S. A. Giuliani, et al., Rev. Mod. Phys. 91, 011001 (2019), https://doi.org/10.1103/RevModPhys.91.011001.

[Gre18] J.P. Greene and M. Labib, AIP Conf. Proc. 1962, 030018 (2018), https://doi.org/10.1063/1.5035535.

[Hei22] S. Heinz and H.M. Devaraja, Eur. Phys. J. A 58, 114 (2022), https://doi.org/10.1140/epja/s10050-022-00771-1.

[Hof07] S. Hofmann, et al., Intern. J. of Modern Phys. E 16, 937 (2007), https://doi.org/10.1142/S021830130700640X.

[Isa22] A.V. Isaev, et al., Eur. Phys. J. A 58, (2022), https://doi.org/10.1140/epja/s10050-022-00761-3.

[Kar17] A. Karpov and V. Saiko, Eur. Phys. J. Web of Conferences, 163, 00027, (2017), https://doi.org/10.1051/epjconf/201716300027.

[Khu20] Khuyagbaatar, J., et al., Phys. Rev. C 102, 064602 (2020), https://doi.org/10.1103/PhysRevC.102.064602.

[Kra15] J.V. Kratz, W. Loveland and K.J. Moody, Nucl. Phys. A 944, 117 (2015), https://doi.org/10.1016/j.nuclphysa.2015.06.004.

[Kwa21] J.T. Kwarsick, J.L. Pore, J.M. Gates, K.E. Gregorich, J.K. Gibson, J. Jian, G.K. Pang, and D.K. Shuh, J. Phys. Chem A, 125, 31, 6818 (2021), https://doi.org/10.1021/acs.jpca.1c01961.

[LRP2015] The 2015 Long Range Plan for Nuclear Science, https://science.osti.gov/-/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf.

[Lop22] A. Lopez-Martens, et al., Phys. Rev. C 105, L021306 (2022), https://doi.org/10.1103/PhysRevC.105.L021306.

[Lov19] W. Loveland, Front. Phys., 7, 23 (2019), https://doi.org/10.3389/fphy.2019.00023.

[Lyn10] C.M. Lyneis, D. Leitner, M. Leitner, C. Taylor and S. Abbot, Rev. Sci. Instrum. 81, 02A201 (2010), https://dx.doi.org/10.1063/1.3271135.

[Mor07] K. Morita, et al., J. Phys. Soc. Japan 76, 043201 (2007), https://doi.org/10.1143/JPSJ.76.043201.

[Mün79] G. Münzenberg, W. Faust, S. Hofmann, P. Armbruster, K. Güttner and H. Ewald, Nucl. Instrum. Methods 161, 65 (1979), https://doi.org/10.1016/0029-554X(79)90362-8.

[Naz18] W. Nazarewicz, Nat. Phys. 14, 537 (2018), https://doi.org/10.1038/s41567-018-0163-3.

[Nel08] S.L. Nelson, K.E. Gregorich, I. Dragojevic, M.A. Garcia, J.M. Gates, R. Sudowe and H. Nitsche, Phys. Rev. Lett. 100, 022501 (2008), http://dx.doi.org/10.1103/PhysRevLett.100.022501.

[Nel09] S.L. Nelson, et al., Phys. Rev. C 79, 027605 (2009), https://doi.org/10.1103/PhysRevC.79.027605.

[Oga17] Yu.Ts. Oganessian, A. Sobiczewski and G.M. Ter-Akopian, Physica Scripta 92, 023003 (2017), https://doi.org/10.1088/1402-4896/aa53c1.

[Oga222] Yu.Ts. Oganessian, et al., Nucl. Instrum. Methods A 1033, 166640 (2022), https://doi.org/10.1016/j.nima.2022.166640.

[Oga22B3] Yu.Ts. Oganessian, et al., Phys. Rev. C 106, 024612 (2022), https://doi.org/10.1103/PhysRevC.106.024612.

[Pak14] J. Pakarinen, et al., Eur. Phys. J. A 50, 53 (2014), https://doi.org/10.1140/epja/i2014-14053-6.

[Pak20] J. Pakarinen, et al., Eur. Phys. J. A 56, 149 (2020), https://doi.org/10.1140/epja/s10050-020-00144-6.

[Poe11] D.N. Poenaru, R.A. Gherghescu and W. Greiner, Phys. Rev. Lett. 107, 062503 (2011), https://doi.org/10.1103/PhysRevLett.107.062503.

[Ram12] E.M. Ramirez et al., Science, 337 (2012), https://doi.org/10.1126/science.1225636.
[Res03] J.J. Ressler, et al., Nucl. Instrum. Methods B 204, 141 (2003), https://doi.org/10.1016/S0168-583X(02)01906-7.
[Ris13] J. Rissanen, et al., Phys. Rev. C 88, 044313 (2013), https://doi.org/10.1103/PhysRevC.88.044313.
[Roy22] G. Royer, Q. Ferrier and M. Pineau, Nucl. Phys. A 1021, 122427 (2022), https://doi.org/10.1016/j.nuclphysa.2022.122427.
[Sil20] M.J. Silveira, A. Pica and W. Loveland, Nucl. Instrum. Methods A 982, 164570 (2020), https://doi.org/10.1016/j.nima.2020.164570.
[Sak22] Sakai et al, submitted to Eur. Phys. J. A, 2022.
[Såm21] A. Såmark-Roth, et al., Phys. Rev. Lett. 126, 032503 (2021), https://doi.org/10.1103/PhysRevLett.126.032503.
[Sar08] J. Sarén, et al., Nucl. Instrum. Methods B 266, 4196 (2008), https://doi.org/10.1016/j.nimb.2008.05.027.
[Sar11] J. Sarén, J. Uusitalo, M. Leino and J. Sorri, Nucl. Instrum. Methods A 654, 508 (2011), https://doi.org/10.1016/j.nima.2011.06.068.
[Sat15] T.K. Sato, et al., Nature 520, 209 (2015), https://doi.org/10.1038/nature14342.
[Sch21] P. Schury, et al., Phys. Rev. C 104, L021304 (2021), https://doi.org/10.1103/PhysRevC.104.L021304.
[Sem08] A. Semchenkov, et al., Nucl. Instrum. Methods B 266, 4153 (2008), https://doi.org/10.1016/j.nimb.2008.05.132.
[Sim18] C. Simenel, A.S. Umar, Prog. Part. Nucl. Phys. 103, 19 (2018), https://doi.org/10.1016/j.ppnp.2018.07.002.
[Sob01] A. Sobiczewski, I. Muntain and Z. Patyk, Phys. Rev. C 63, 034306 (2001), https://doi.org/10.1103/PhysRevC.63.034306.
[Str19] S.R. Stroberg, H. Hergert, S.K. Bogner and J.D. Holt, Annu. Rev. Nucl. Part. Sci. 69, 307 (2019), https://doi.org/10.1146/annurev-nucl-101917-021120.
[Tez22] M.S. Tezekbayeva, et al., Eur. Phys. J. A 58, 52 (2022), https://doi.org/10.1140/epja/s10050-022-00707-9.
[Wan21] X. Wang and X. Bao, Nucl. Phys. A 1011, 122196 (2021), https://doi.org/10.1016/j.nuclphysa.2021.122196.
[Wil21] J. N. Wilson et al., Nature 590, 566 (2021), https://doi.org/10.1038/s41586-021-03304-w.
[Yak16] A. Yakushev and R. Eichler, Eur. Phys. J. Web of Conferences 131, 07003 (2016), https://doi.org/10.1051/epjconf/201613107003.
[Yak21] A. Yakushev, et al., Front. Chem. 9, (2021), https://www.frontiersin.org/articles/10.3389/fchem.2021.753738/full.
[Zag08] V. Zagrebaev and W. Greiner, Phys. Rev. C 78, 034610 (2008), http://dx.doi.org/10.1103/PhysRevC.78.034610.
[Zag10] V. Zagrebaev and W. Greiner, Nucl. Phys. A 834, 366c (2010), https://doi.org/10.1016/j.nuclphysa.2010.01.041.