Specific Requirements for the Synthesis of Superheavy Elements: A Close Look at the Work of Yuri T. Oganessian, the World's Leading Researcher of Superheavy Elements

Is the Synthesization of Superheavy Elements an Endeavor Too Expensive to Justify in the "Pursuit of Knowledge"?

IB Chemistry HL

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Research Question:

In regards to their significance and real-life application(s), is the synthesis of superheavy elements (SHEs) worth the financial and other costs?

Introduction:

Personal Engagement:

Superheavy Elements were chosen as the focus of my investigation because I have a strong fascination for the periodic table of elements. For instance, I appreciate its structural precision such as how the elements in a group/family share the same number of valence electrons (electrons in their outermost electron shell), or how all the elements in a period have the same number of electron shells. Superheavy elements are the nuclei-heavy elements at the latter end of the periodic table and drew my interest because they are considered the key to proving long-held nuclear theories such as the existence of the "island of stability" and are likely to inform scientists of the ultimate limits of the periodic table.

While browsing the web, I encountered Mathias Schädel's *Chemistry of the Superheavy Elements,* a short paper which details information about SHEs such as their position/location in the periodic table of elements (and their relativistic effects), their nuclear synthesis and decay, their chemical nature, and provides a summarized introduction of specific SHEs.[1] In the conclusion of his paper, Schädel credits the exploration of SHEs as the very beginning steps "to challenge most advanced fully relativistic theoretical model calculations and to map the architecture of the periodic table at its farthest reach."[2] He emphasizes the potential that future developments of SHEs may have in the scientific world and their possible applications outside the scientific community. Thus, I researched SHEs in regards to its future potential.

Relevance:

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[1] Mathias Schädel, *Chemistry of the Superheavy Elements*, (royalsocietypublishing.org, 2015), 1.

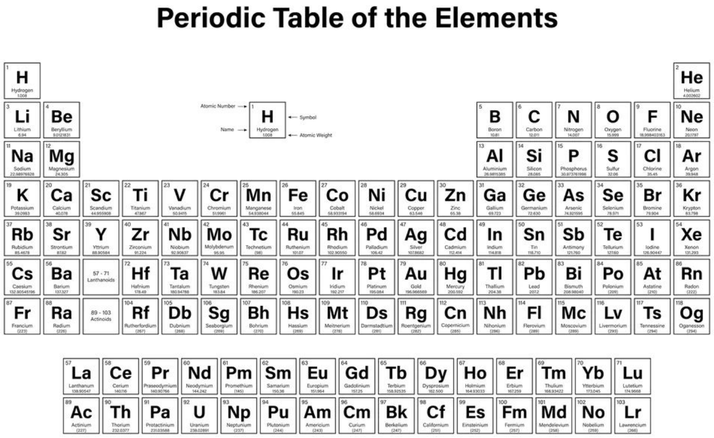
[2] Ibid, 11.

The United Nations General Assembly named this past year (2019) the International Year of the Periodic Table.[3] Thus, this couldn't be a better time to undergo an in-depth exploration of SHEs; man made elements that challenge our current understanding of the universe because of their mysterious nature.

Environmental and Ethical Concerns:

Superheavy elements are human-synthesized and do not appear to be found naturally so their radioactive decay will not be a threat to the natural environment. Furthermore, scientists are also safe from the radiation emitted during SHE decay since they are created in very controlled settings (where the radiation will not come in contact with any humans).

Background:



[4]

Heavy Elements: Z = 93 - 103 // Superheavy Elements: Z = 104 - 118...and so on

> "The dreams of medieval alchemists have nearly come true in the modern era of accelerators and nuclear reactions."[5]

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[3] Laura Howes, *Exploring the Superheavy Elements at the End of the Periodic Table*, (Chemical and Engineering News, 2019).
[4] Mark Blackovich, *The Periodic Table: From Its Classic Design to Use in Popular Culture*, (The Conversation, 2017).
[5] Oganessian, Yuri Ts., and Krzysztof P. Rykaczewski, *A Beachhead on the Island of Stability*, (Physics Today, August 2015), 33.

Scientists have artificially created 26 elements and hundreds of isotopes. Of these man-made elements, 15 are recognized as superheavy elements. Some of the main contributors to the synthesis and discovery of this recent SHEs are RIKEN Nishina Centre for Accelerator-based Science in Wako, Japan, the Joint Institute for Nuclear Research in Dunba, Russia, the Lawrence Livermore National Laboratory, and the Oak Ridge National Laboratory. According to Jefferson Lab, all 15 SHEs serve no purposes outside of basic scientific research because only minimal to a few atoms of each have been produced and their half-lives are so short.[6]

> "All currently known superheavy nuclei are radioactive; they have been synthesized in nuclear reactions by scientists" (*Superheavy Elements: Oganesson and Beyond*).

One common characteristic of superheavy elements is that their nuclei are very radioactive meaning they are extremely unstable. Their instability derives from their atoms having an excess of internal energy that upsets the band of stability. The band of stability refers to the stability of elements determined by the ratio of the number of neutrons to the number of protons in the elements' nucleus (*N:P*). For elements with an atomic mass of about 20 or less, the elements are stable around a ratio of 1:1. As the element's atomic mass reaches 20 and goes beyond, the ratio will increase until around 1.5:1 for the very heavy elements. To clarify, all elements up to $Z = 92$ with the exception of technetium ($Z = 43$) have isotopes that are stable and have neutron to proton ratios between 1 and 1.5.

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[6] Jefferson Lab, *The Periodic Table of Elements*, (JLab Science Education).

As a result of being very unstable, SHEs undergo decay rapidly. For example, $^{294}_{176}$Og, $Z = 118$, has an initial half-life of 0.7ms.[7] Although SHEs decay at a rapid rate, scientists can be sure they have detected one based on the characteristic pattern of the atom's decay (will often decay into an unknown isotope of a known isotope, and each isotope has a unique decay pattern). However, this method of atomic number identification only applies to SHEs 107 - 112. For experiments synthesizing superheavy element 113 or any subsequent SHEs, they "suffer a disadvantage that their nuclear decay is not 'genetically' linked by unequivocal α–α-decay sequences to the region of known nuclei—a prerequisite used for unique identifications."[8] Thus, scientists have turned to identifying characteristic K-X rays.[9]

> "Since the discovery of nuclear fission in 1938,... researchers have artificially created 26 new elements and hundreds of isotopes, all by using nuclear reactions to modify the properties of existing nuclei."[10]

Particle accelerators (pictured below) are used to synthesize new elements (including all SHEs) because they are able to project an element with enough speed/power to overcome the repulsion between nuclei (sometimes they project the ions almost as fast as a tenth of the speed of light $\approx 3 \times 10^7$ m/s). In turn, the collision between two positively charged nuclei allows the possibility of a new element being created. As scientists continue to discover their way down the periodic table, the synthesis of each new element requires "greater projectile charge and mass, higher beam intensity, and longer irradiation time to fuse the colliding nuclei."[11] Increasing the projectile charge is crucial in synthesizing these heavier elements, however, with each increase of the projectile atomic number, the probability of creating fusion-evaporation residues in regard

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[7] Oganessian and Rykaczewski, *A Beachhead on the Island of Stability*, 37.
[8] Schädel, *Chemistry of the Superheavy Elements*, 4.
[9] Ibid, 4.
[10] Oganessian and Rykaczewski, *A Beachhead on the Island of Stability*, 33.
[11] Ibid, 34.

to the cross section for each nuclear reaction channel.[12] In other words, the opportunity of identifying new heavier elements becomes more and more difficult.


[13]

> "Current experimental results are consistent with the existence of an extended island of superheavy nuclei that are more resistant to radioactive decay and have much longer half-lives than somewhat lighter isotopes…"[14]

One of the main purposes of synthesizing super heavy elements is to confirm the existence of the island of stability. The island of stability is the prediction of synthesizing superheavy elements that have a "magic number" of protons and neutrons that allows them to have half-lives many magnitudes longer than others. While there are many speculations regarding its existence, evidence points towards the magic number of neutrons being $N = 184$. Scientists have created models that predict that the half-lives of these superheavy elements to be up to millions of years, or even close to earth's age (≈ 4.5 billion years).[15] (If) and once the "magic number" of N:P is found, only then can scientists hope to find applications for SHEs outside of being for research interests.

> "...the future development of JINR in accordance with the goals outlined in the present Seven-year plan will further demonstrate convincingly to the world the attractive force of scientific knowledge."[16]

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[12] Ibid, 34.
[13] Ibid, 35.
[14] Ibid, 33.
[15] Ibid, 33.
[16] Joint Institute For Nuclear Research, *Seven-Year Plan for the Development of JINR 2017 - 2023*, (2017), 3.

The *Seven-Year Plan for the Development of JINR 2017 - 2023* details the numerous developments the Joint Institute Nuclear Research plans to execute between the years 2017 - 2023. The full-scale realization of the Dunba Radioactive Ion Beams (DRIBS-III) alone will cost an estimated $102,500,000 USD and includes the development of new physical set-ups for chemical investigations in the SHE factory, reconstruction of supporting systems of the experimental hall of U400R, the modernization of the U400R cyclotron, among others developments such as the construction of new and development of set-ups in regards to the U400R and U400M cyclotrons, and monetary support for experiments.[17] These are all improvements to facilities and machines that aid in the (experimental) synthesization of superheavy elements, and does not take into account the financial costs of the human labor (i.e. of scientists) to run the machines and observe and analyze its findings, as well as, the cost to run the cyclotrons themselves or the expensive samples of the necessary projectile and target element particles.

Methodology: The three following procedures are described by *A Beachhead on the Island of Stability* by Yuri Ts. Oganessian and Krzysztof P. Rykaczewski. (1) The hot-fusion reaction which results in the synthesis of the superheavy element isotope of $^{293}117$ by the Joint Institute of Nuclear Research (Dunba, Russia) in their Flerov Laboratory of Nuclear Reactions Accelerator of heavy ions. (2) Details the procedure of GSI's velocity filter referred to as SHIP in identifying and separating the ions of interest . (3) TOF detector and the implantation counter in spotting the heaviest nuclei and allowing for observation.

Summary of Experiment:

(1) Flerov Laboratory of Nuclear Reactions Accelerator (of heavy ions):[18]

1. The Joint Institute of Nuclear Research's Accelerator of heavy ions was used to fuse a $^{48}{}_{20}$Ca (a $^{48}{}_{20}$Ca beam) with a berkelium-249 ($^{249}{}_{97}$Bk) target.
    a. A hot-fusion reaction occurs between the $^{48}{}_{20}$Ca and the $^{249}{}_{97}$Bk target.

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[17] Ibid, 12 - 13.

[18] Oganessian and Rykaczewski, *A Beachhead on the Island of Stability*, 33 - 35.

The collision between the ${}^{48}_{20}\mathrm{Ca}$ projectile and the ${}^{249}_{97}\mathrm{Bk}$ target creates various reaction products

(2) Ion Separator:[19] The various reaction products then enter the ion separator that identifies and separates the fusion-evaporated residues. Using a combination of magnetic and electrical fields, the machine is able to select the ions of interest and guide them to the detectors.

2. All particles produced from the hot-fusion reaction and the primary beam enter the ion separator.
3. Ion separator identifies the slower moving particles and only allows particles of a particular velocity to pass through. Unwanted particles
    a. The fusion-evaporated residues move slower because they are four to six times heavier than the other projectiles.

(3) Spotting the Heaviest Nuclei:[20]

4. Heavy nuclei set off the time of flight detector creating a valid time of flight signal.
5. Following the signal (seconds/milliseconds after) an alpha particle was detected at the same position.
6. If the alpha particle's energy is close to the predicted one for a superheavy nucleus, a signal is triggered to block the primary beam with a beam.
7. The alpha particle's decays can be observed/recorded.
8. When a final decay is detected, a spontaneous fission signal triggers the beam to unblock the primary beam.

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[19] Ibid 35 - 36.

[20] Ibid 36 - 37.

Data:

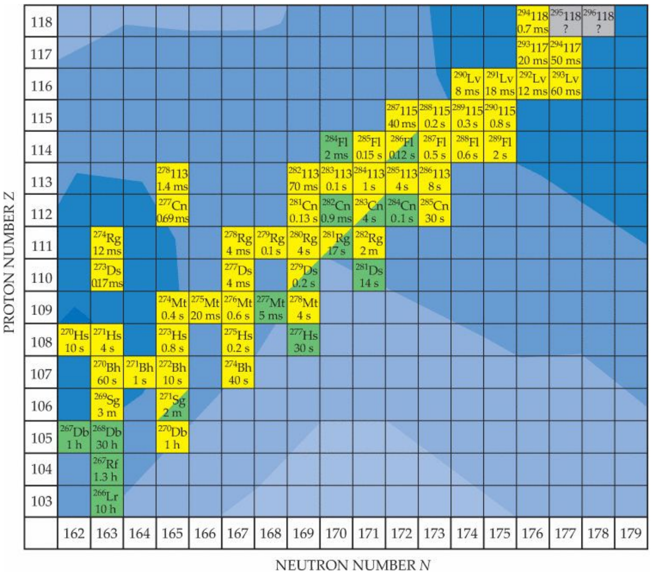

Figure 6. The top of the nuclear landscape, with the heaviest identified nuclei and their half-lives and decay modes—yellow for alpha decay and green for spontaneous fission. The contoured color background indicates the predicted stability of nuclei—the darker the color, the more stable the nucleus. A Russia–US team is currently focusing on new isotopes ^{295}118 and ^{296}118 (gray squares) using a calcium-48 beam and an isotopically mixed californium target. (Background contour plot courtesy of the GSI Helmholtz Centre for Heavy Ion Research.)[21]

The figure above illustrates the half-lives of different superheavy elements in relation to their number of protons and neutrons.

Data Processing:

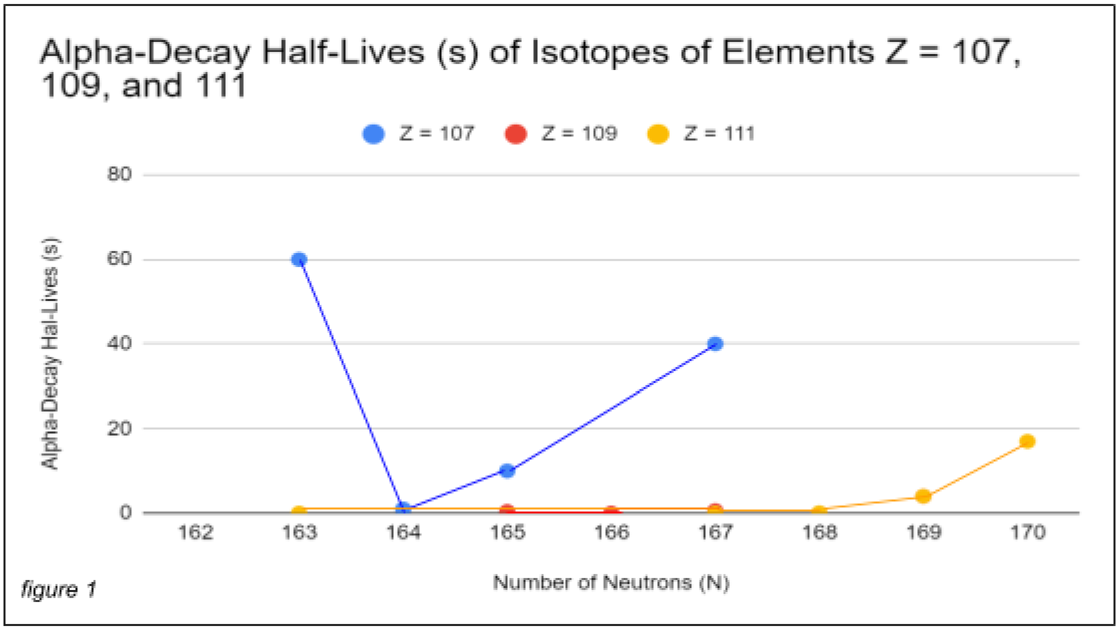

figure 1

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[21] Ibid, 37.

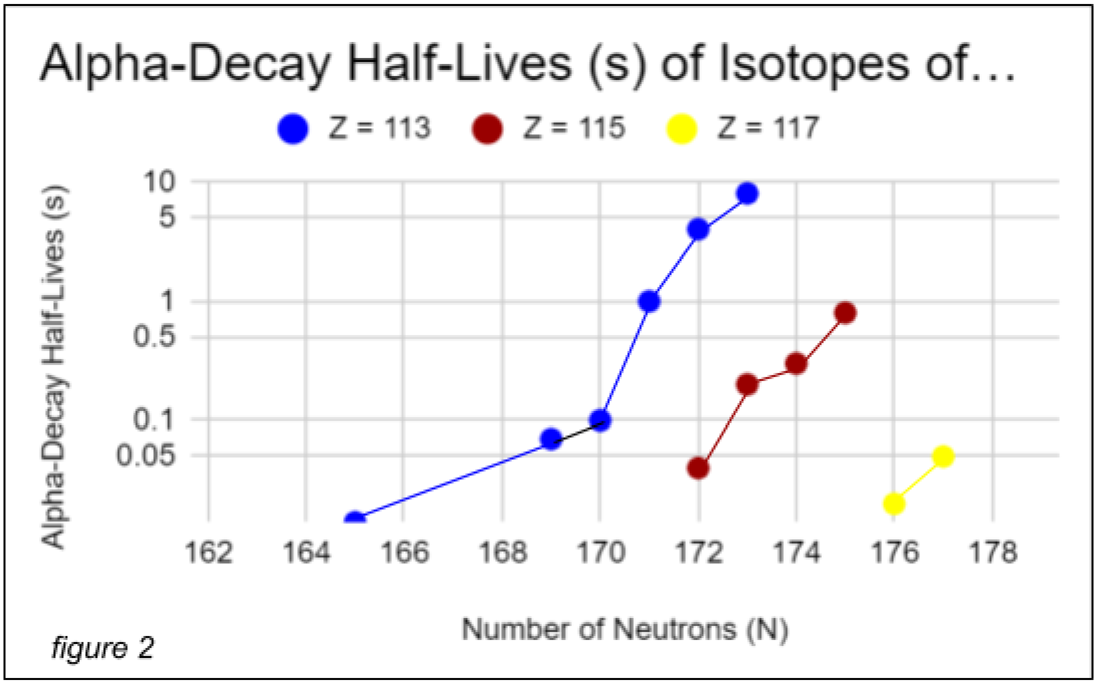

figure 2

figure 1 and *figure 2* rearrange the data in *A Beachhead on the Island of Stability's Figure 6.*[22] *The Top*. In this format, it is easier to identify that the half-lives of superheavy elements increase as they approach $N = 184$, supporting the long-held theory of the island of stability. Although there is a significant drop between the alpha-decay half-lives of elements in *figure 1* and *figure 2*, with each addition of a neutron, the heavier isotopes of elements Z = 113, 115, and 117 show progression towards longer half-lives. Together, these three figures illustrate the information (comparing alpha-decay half-lives to the isotopes of superheavy elements) that helps confirm scientists' current understanding of the nuclear structure of the heaviest atoms (as well as sustains scientists hold on the theory of the island of stability).

Data Uncertainty:

One possible area for error is that only a limited number of cross-sections of fusion-evaporated residues have been created and a small sample size undermines the validity of the study as one or two outliers can completely shift the data to be inaccurate. For instance, note the isotope ^{277}Cn in *Figure 6. The Top*. With an insignificant data pool, it cannot be confidently confirmed whether or not this data point for this isotope of element Z = 112 is indeed a mistake (outlier) or is an accurate representation of the alpha-decay half-life of this element's isotope.

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[22] Ibid, 37.

Conclusion:

In recent years, there have been many major advancements and ground-breaking discoveries in the chemistry-physics world of superheavy elements. Element Z = 118, named Oganesson after the world's leading nuclear physicist Oganessian, is the latest addition to the end of the periodic table of elements, leaving scientists hungry to synthesize element Z = 119 (and Z = 120) which will mark the beginning of a new row in the periodic table.

Although many scientists and individuals outside the nuclear scientific community celebrate these new discoveries and advancements, it appears that the primary motivation of such actions is to quench a scientific thirst. This is not to say that a desire for knowledge and the drive to delve into the task of evaluating the unknown is a negative thing, but rather it serves as a subtle PSA about needing to take more accountability for the direction extreme amounts of time, effort, and money are put towards.

The Joint Institute for Nuclear Research alone has established a seven year plan that estimates total costs to be over one-hundred million USD just for facility developments, improvements and reconstructions. This $100,000,000+ does not include paying the salaries of the workers it will employ, nor can it take into account the costs of the developments, improvements, and reconstructions of other superheavy element-related facilities outside of JINR.

The synthesization of superheavy elements is an endeavor challenging the limits of the periodic table of elements and is helping to shed light on the validity behind the long-held theory of superheavy nuclei (with the "magic number/ratio" of protons and neutrons) that have strongly enhanced stability against radioactive decay. However, while millions of dollars are poured into nuclear research that has a narrow window of success, if any, the Huffington Post explains that for just $600, an HIV patient in a developing country can receive three years of treatment, or for just $115, Doctors Without Borders can give infection-fighting antibiotics to 40 children, among other serious problems that impact people on a larger international scale.

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