Review Article

www.bombaytechnologist.in

BOMBAY TECHNOLOGIST

ISSN: 0067-9925

Superheavy Elements – Elements 119 and 120

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Abstract

The periodic table currently consists of 118 elements, with many of those near the end of the periodic table (actinides and trans-actinides) discovered over the last century. Elements Nh, Mc, Ts, and Og were the latest elements officially added to the periodic table in 2016. Elements 119 and 120 are next in line of the elements to be synthesized, with scientists working on experiments for the past decade to synthesize them. Many of their properties have been predicted using various models and theories, but the elements remain yet to be synthesized. Discovering E119 and E120 would mark the beginning of the 8th period of elements. This review paper aims to present an overview of how these 'Super heavy' elements are synthesized, what challenges scientists face in producing them, and the differences in properties they exhibit. It also aims to show the complications in synthesizing E119 and E120 and the solutions being presented and applied to overcome them.

Keywords: element 119, element 120, superheavy elements, nuclear reaction, relativistic effects

1. Introduction

Dmitri Mendeleev first put forth the periodic table in the 1860s based on arranging elements periodically by their atomic mass number. He classified the then 63 known elements into groups based on their properties. More than 150 years later, there exist a total of 118 elements in the modern periodic table. Out of the 118, 24 do not occur in nature and have been artificially made, 10 are very rare in nature and have to be produced synthetically as well [1]. The first man-made element was Technetium, and its isotopes were first formed by bombarding Molybdenum with neutrons and deuterons [2]. Uranium was the heaviest element known to man till the 1930s. Elements beyond Uranium were synthesized mainly after the 2nd world war after the discovery of nuclear fission by, chemists O. Hahn and F. S. Strassmann, and were classified as actinides, as proposed by Dr. Seaborg. All the actinides were discovered by the 1960s by bombardment of heavy nuclei with lighter elements/neutrons or protons. The final Actinide synthesized was Lawrencium (Z = 103), and all the elements synthesized after actinides were termed 'superheavy elements,' based on the suggestion of Dr. John Wheeler [3]. Rutherfordium (Z = 104), the 1st SHE was synthesized in 1960 [4]. Ever since then, all the elements up to 118, Oganesson have been synthesized by compound nucleus formation and modern reactors. Discoveries of these elements in the late 20th century fuelled the search for the 'Island of stability' and brought up the concept of relativistic effects leading to anomalous behaviour of these heavy elements. We will delve deeper into both these topics in the next section of this article.

2. Superheavy Elements and the 'Island of Stability'

2.1. Superheavy Elements

Superheavy elements (also known as trans-actinide elements) are those elements of the periodic table with an atomic number greater than 103. They are radioactive and man-made with very short half-lives (for example, $^{269}Sg_{106}$ has a half-life of 14 minutes); thus, no sample of them has been collected in a macroscopic amount yet [5]. Synthesis of these elements pushes nuclear science to its very limits, with only limited samples of SHEs being produced till now. For elements with Z >92 (Z = Atomic number), fission barrier which prevents the spontaneous fission of a heavy nucleus into two fragments, rapidly decreases with an increase in Z. This is due to an increase in the Coulomb repulsion (repulsive force between tightly packed protons) inside the nucleus. This dramatically increases the odds of spontaneous fission, reducing the stability of the heavier nuclei [6]. SHEs are formed via nuclear reactions, where particle accelerators are used to bombard a lighter element as a projectile in the form of a beam towards a heavier element having the target nucleus. The two nuclei react to form the required element, with their atomic numbers adding up to that of the target element [7]. This method of 'nuclear transmutation' is how all the current SHEs have been formed. Projectile elements used are usually neutron-rich isotopes of light elements [17].

One way of doing this is using 'cold-fusion,' using which elements 107-112 have been synthesized. This method uses $^{208}Pb_{82}$ or $^{209}Bi_{83}$ as the target elements since they have large binding energies, being bombarded with different isotopes of Z >16 with energies just greater than their Coulomb barrier, so that the nuclear reaction can take place. This results in the formation of nuclei with excitation energies (12-15 MeV) lower than those formed by using target elements with much greater Z [1]. However, this method does not work for the compound nucleus formation of heavier elements as increasing the Z of the projectile leads to an increase in Coulomb repulsion and results in a decrease in the evaporation-residue cross-section, decreasing the probability of forming the element. (The evaporation-residue cross section (denoted by σ_{ER}) corresponding to the sequence of events – capture, compound nucleus formation, survival against fission – is essential in the synthesis of SHEs. σ_{ER} is a measure of the probability of whether an element will be formed or not. When the reaction between the 2 elements occurs, there are various ways in which the target nucleus stabilizes itself like spontaneous fission, α or β decay, or in this case the formation of a compound nucleus. A higher σ_{ER} shows us that the formation of a compound nucleus has a higher probability of occurring). Along with this, there is a lack of neutrons in both the target and projectile for the formation of the required element [4].

To solve this, SHEs 112-118 were synthesized by 'hot-fusion', where $^{48}Ca_{20}$ beams were used as a projectile with the appropriate heavy actinide elements such as Pu, Am, Cm, Bk, and Cf with excitation energies of 40-50 MeV depending on the reaction [12]. $^{48}Ca_{20}$ is a rare isotope of Ca (0.187% natural abundance) and is commonly used as a projectile for the synthesis of many SHEs due to it being a neutron-rich, doubly magic (Z=20, N=28) stable isotope of Ca [6]. Its increased stability due to it being doubly magic leads to it having a very high binding energy, making it a great isotope for compound nucleus formation. Using these methods, more than 50 isotopes of SHEs have been synthesized over the last few decades [9]. Only a few specialized places in the world, including the University of California, Berkeley and Lawrence Berkeley National Laboratory, USA (one in partnership with Lawrence Livermore National Laboratory); the Joint Institute for Nuclear Research (JINR), Russia; GSI Darmstadt, Germany; and RIKEN, Japan are responsible for the production of SHEs [3].

Quantum Mechanics are currently used to describe the electronic structures of most elements. It is based on the Schrodinger Equation, which gives us a wave function for the system under consideration, and based on this equation we can predict dynamics, reactions, interaction with electromagnetic spectra, and other behavioral properties of these elements. However, these calculations are non-relativistic i.e., they do not consider the deviations from physics caused by Einstein’s theory of relativity in the Schrodinger equation [8]. These relativistic effects are significant for understanding the properties and chemistry of SHEs. These relativistic effects are caused due to the electrons in the inner s-orbitals in the vicinity of the nucleus acquiring very high speeds, approaching the speed of light [10]. This is where we have to consider relativity, as it states that there will be an increase in the mass of the electron as its velocity approaches the speed of light [8]. It results in the inner orbitals (mainly the s orbitals) being much closer to the nucleus, thus having contracted mean radii and different periodic properties. This direct mass-velocity effect is negligible for electrons with large angular momentum in the d and f orbitals, but the contraction of inner s and p shells increases the shielding of the nuclear charge leading to an expansion and energy destabilization of d and f orbitals [11]. Thus, modern relativistic theories such as the Dirac-Coulomb, Dirac-Slater, Dirac-Fock, CCSD, Douglas-Kroll theories, and many others are used for predicting atomic properties of SHEs such as electron density, electron affinity, ionization potential, polarizability, etc.

2.2. Island of Stability

In 1933, shortly after Chadwick discovered the neutron, Walter Elsasser noted that with certain numbers of nucleons (2, 8, 20, 28, 50, 82, and 126), the nucleus was far more stable. These were termed as 'magic numbers,' and this rule was found to apply to both protons and neutrons, with isotopes having magic numbers in both neutrons and protons being termed as 'doubly magic.’ [5]. When we plot a chart with Z along the y-axis and neutrons along the x-axis, we observe a 'peninsula of stability' for naturally occurring stable isotopes of elements [3].

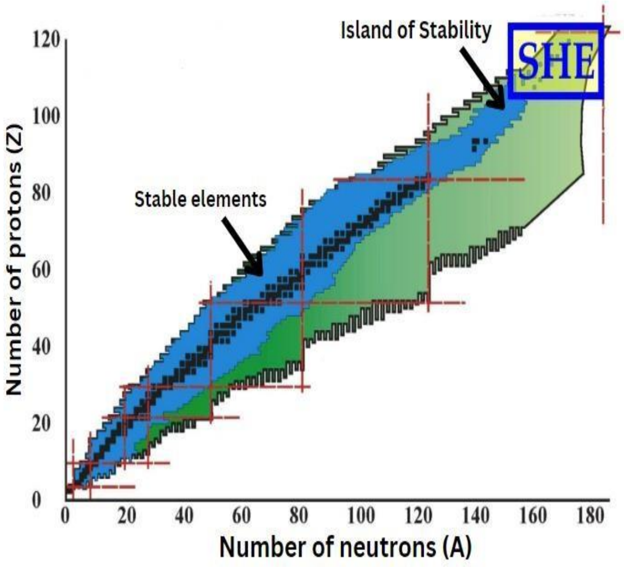

Figure 1: The sought-after island of stability [13].

This peninsula shows a massive drop in stable compounds after Bi_{83}, with there being a small island of stable elements for U and Th, and another decline once again [3]. It is theorized based on various models that isotopes of SHEs with Z >114 will show another island of stability in this sea of instability due to magic numbers. The island is theorized to start from $^{298}Fl_{114}$ due to N=184 and Z=114 expected to be doubly magic. Along with this, isotopes of elements 120,122, and 126 (having the magic number of protons) are theorized to be a part of this island of stability [9]. These elements are predicted to be stable against spontaneous fission and undergo alpha decay. Finding isotopes of elements in this region might lead to real-life applications of SHEs, as there are currently none due to their high radioactivity and incredibly short half-lives [12]. This is one of the prime reasons for the search for newer elements and studying the differences in their properties caused by relativistic effects.

3. Element 119

3.1. Synthesis of element 119

The method of using a $^{48}Ca_{20}$ to synthesize elements using ‘hot-fusion’ is not viable past Og, as the elements having atomic numbers greater than 98 (those after Cf) are very difficult to produce in sufficient quantities for reactions[13]. Regardless, the synthesis of E119 was attempted using this method at Berkley in 1985 by bombarding $^{254}Es_{99}$ with $^{48}Ca_{20}$. However, no traces of E119 were detected [14]. As stated earlier, the evaporation-residue cross section (σ_{ER}) is a measure of the probability of whether an element will be formed or not. The evaporation-residue cross-section for elements with Z > 118 is very low, meaning the probability of a compound nucleus forming is very low, making the reaction very difficult [15]. After confirmation of the four elements in 2016, focus was shifted back to the synthesis of E119. $^{50}Ti_{22}$ + $^{249}Bk_{97}$ is the currently proposed method of synthesis of E119, and this experiment was run for four months with a beam of E=281.5 MeV in 2011 in TASCA, Germany. Unfortunately, no traces of E119 were found, with the detected σ_{ER} being very low at 65fb [13]. Thus it is apparent that $^{50}Ti_{22}$ is not as effective of a projectile as $^{48}Ca_{20}$, but this is still one of the more promising methods of synthesis of E119 if we can successfully increase the σ_{ER} of the reaction [13]. The researchers at RIKEN, Japan have tried using $^{51}V_{23}$ as a projectile to undergo compound nucleus formation with $^{248}Cm_{96}$ with an expected σ_{ER} of ~10fb. (fb = femtobarn, the units of σ_{ER}) Since upgrading their equipment in 2020, they have been running the experiment 100 days a year. However, no signs of E119 have been observed yet [16]. Regardless, there have been several attempts at predicting the properties of E119 using different models.

3.2. Predicted properties of element 119

Element 119 will be the first element in the 8th period of the modern periodic table, and will belong to Group 1, along with other alkali metals. It is predicted to have the 8s orbital, and many of its properties have been predicted using different theories and models, which treat relativity and electron correlation at the highest possible level [18]. A lot of properties like polarizability, electronegativity, IE, etc. show a trend reversal after Cs due to relativistic effects displayed by Fr and E119. Atomic radius, however, still increases down the group with that of 119^+ expected to be around 202 pm [19]. Its ionization enthalpy is assumed to increase after Fr, in agreement with the increase from Cs to Fr as a consequence of relativistic effects. Using CCSD(T) (Coupled cluster) theory, the static dipole polarizability (α) of E119 is expected to be much lower than any of its homologues, closest to that of Na [18, 20]. Group 1 elements are some of the most electropositive elements in the periodic table, with Cs having the least electronegativity of the entire periodic table. However, due to relativistic effects electropositivity decreases after Cs to Fr and onwards, with E119 predicted to have the same electronegativity as Na [21]. Similarly, the electron affinity's (EA) trend of decreasing till Cs is reversed with the EA of Fr being higher by 20 MeV than Cs, with E119 having the highest of the alkali metals of approximately 662.5 meV [22]. E119 would also have a higher covalent nature as compared to its lighter homologues when bonded to elements, for example, Fluorine, opposite to non-relativistic predictions of it having the most ionic bonds possible [23]. Adsorption enthalpies (ΔH_{ads}) of alkali metals on noble metals such as Au are predicted to become less negative for Fr and E119 compared to the rest of its group [21].

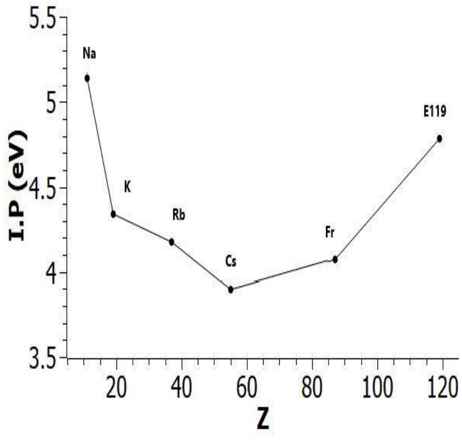

Fig 2: Ionization potentials of alkali metals showing a trend reversal after Fr [18, 22].

Element	I.P (eV)	E.A (meV)	α (a.u)
Na	5.139	549.9	162.7
K	4.341	506.8	290.6
Rb	4.177	490.8	318.8
Cs	3.894	474.6	401.0
Fr	4.073	491.3	311.5
E119	4.783	662.5	169.7

Table 1: Ionization potential (based on CCSD(T) calculations), electron affinity (based on IHFSCC calculations), and polarizability (CCSD(T)) values of group 1 elements [18, 22].

The possible isotopes of E119 are expected to be between $265 \leq A \leq 316$, with its most stable isotopes predicted to be between $^{291-298}$119. Isotopes $^{271-291}$119 and $^{305-316}$119 would undergo spontaneous fission, while the rest of its isotopes are predicted to undergo α-decay and show different α chains for different isotopes. They will decay into lighter elements and undergo fission after the appropriate α chain comes to an end [24, 25].

4. Element 120

4.1. Synthesis of element 120

Similarly to E119, element 120 cannot be synthesized by 'hot-fusion' of $^{48}Ca_{20}$ with Fm_{100} due to Fm only being synthesized in extremely small quantities, not enough for nuclear reactions. Thus, heavier projectiles need to be used. Four different reactions have been proposed for E120 [5]. The first time an attempt was made to synthesize E120 was at Dubna using $^{58}Fe_{26}$ and $^{244}Pu_{94}$ in 2009. However, this reaction was unsuccessful, not leading to the formation of any E120 isotopes and having a very low σ_{ER} of 0.4 fb [26]. After this, in 2010 there were attempts to synthesize E120 at GSI, Germany using a $^{54}Cr_{24}$ beam and $^{248}Cm_{96}$ target. This reaction was expected to have 5 times the probability of forming E120 compared to the one attempted at Dubna due to it being asymmetric and having less Coulomb repulsion resulting in a greater σ $_{ER}$ of 0.1-1 pb [27]. An isotope of ^{302}120 undergoing 3 neutron emissions forming ^{299}120, with α-decay and SFs was observed. However, alongside this, there were some anomalies and uncertainties with half-lives of some of the decay chain products, with later experiments unfortunately unable to replicate this data. An initial nucleus starting the decay chain could not be confirmed, and the possibility of background events could not be excluded. Thus, even if E120 was synthesized here, it could not be successfully confirmed [5]. However, this experiment was encouraging and gave hope for the synthesis of elements with Z>118. In 2011/2012 another attempt was made to make E120 using a $^{50}Ti_{22}$ beam with a $^{249}Cf_{98}$ target. The experiment was run over 4 months with the Cf decaying into Bk, which was used for experiments for synthesizing E119 as seen above. This experiment was also unsuccessful, with the σ $_{ER}$ being 200 pb [13]. This reaction is considered to be the most promising one to date. There are still attempts planned to synthesize E120 using $^{50}Ti_{22}$ and $^{249}Cf_{98}$ at Dubna, and $^{248}Cm_{96}$ + $^{54}Cr_{24}$ at RIKEN and Dubna [12].

4.2. Predicted properties of element 120

Just like E119, several properties of E120 can be predicted using modern, relativistic models. It is expected to be a part of Group 2, the alkaline earth elements of the periodic table [28]. Therefore, it will have an 8s^2 electronic configuration. Using relativistic models, the ionization potential of E120 is predicted to be greater than its lighter homologue Ra, which also shows relativistic effects and has a higher IP than other elements in group 2 [28]. E120 shows much weaker bonds with common elements like Na, H, C, and F and longer bond lengths. Bond energies increase down the group, reaching a maximum for Ba and then subsequently decreasing from Ra as a result of relativistic effects. This means that it will be comparatively inert, and behave a bit more like noble gases as compared to alkaline earth metals [29]. The static dipole polarizability (α) of element E120 (163 a.u.) is lower than that of any element in group 2, due to the contraction of the 8s orbital based on the RCCSD(T) + Gaunt model. The low polarization observed in E120 is due to the outer electron of E120$^-$ polarizing the neutral atoms, and a very weak bond is formed due to strong electron correlation effects, giving E120 a very low predicted electron affinity of 0.021 eV [28]. The -ΔH$_{ads}$ of E120 is expected to be lower than its homologues for its adsorption on Teflon and noble metal surfaces [30]. Thus, we see a reversal in the properties of alkali earth metals after Ra due to relativistic effects.

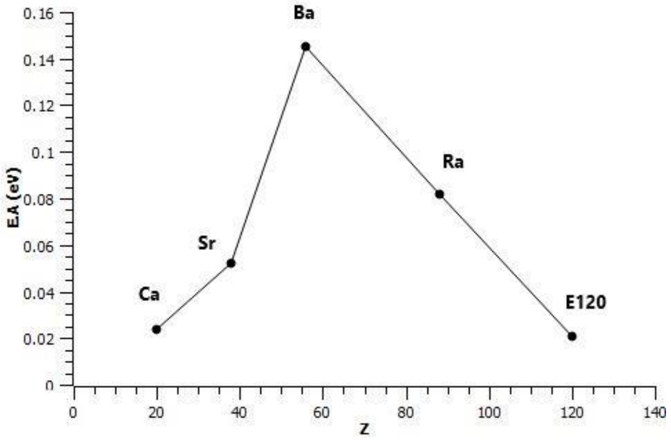

Figure 3: Electron affinities of alkali earth metals, showing a trend reversal after Ra [28].

Element	I.P (eV)	E.A (eV)	α (a.u)
Ca	6.115	0.024	160.8
Sr	5.691	0.052	197.2
Ba	5.212	0.145	272.7
Ra	5.278	0.082	242.8
E120	5.851	0.021	162.6

Table 2: Ionization potential, electron affinity, and polarizability values of group 2 elements using CCSD(T) calculations [28].

Most isotopes of E120 are also predicted to lie in the range of 265≤A≤316. The nuclei $^{290-304}$120 are expected to have the longest half-lives and be the most stable of the isotopes. $^{290-304}$E120 are expected to show chains of α-decay, with E120 decaying into different lighter elements for different isotopes which then undergo spontaneous fission [31].

5. Conclusion

The synthesis of new elements will always be a relevant topic in nuclear chemistry and physics as it helps us understand their properties and come up with better models and theories to predict their behaviour. The current difficulties for the synthesis of E119 and E120 are finding the right two isotopes to undergo compound nucleus formation and a very low reaction residue cross-sectional area. Several ab-initio properties of both these elements have been predicted, but confirming these by experimentation remains a long shot. Regardless, discoveries of these elements would help us better locate the island of stability and understand relativistic effects prevalent in SHEs. There are many possibilities of how the elements part of the island of stability may behave. We may see the 1st signs of stable SHEs, with perhaps applications such as nuclear fuels. We may see elements denser than Osmium, with their half-lives being perhaps the order of a few days. We are yet to reach this island of stability, as well as the 8th row of the periodic table, however the current attempts at producing them are still promising, and we might see reports of the discoveries of E119 and E120 in the next few years.

6. References

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