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Group Project
Unnatural Elements

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Abstract

Although the modern periodic table extends all the way up to $Z = 118$, this has not always been the case. Since the early 20th century, scientists have been slowly expanding the periodic table with heavier and heavier elements that are not naturally occurring. In order to facilitate expansion to this new realm of the periodic table, the development of innovative accelerator technologies has been required. Using these, unnatural elements with ever more unexpected qualities have been synthesised and explored. The periodic table has had to alter with the discovery of each element and thus the periodic system of elements itself has been forced to adapt in novel and exciting ways.

Declaration

We declare that this project and report is our own work.

Supervisor: Professor P J Woods, FRSE Date: 06/02/2023

Contents

1 Background

"The most remarkable discovery in all of astronomy is that the stars are made of atoms of the same kind as those on the earth."
Richard P. Feynman

This constancy of our minds and the night sky is a wonderful concept to consider. But a very particular question springs forth only naturally. To put it bluntly, when it comes to elements, is that it? In a great feat of 19th-Century scientific ambition, the dream of Dimitri Mendeleev was realised fully as the periodic table of elements. Defined entirely by a chemical structure that was in the nascency of being explored, the entire known universe was mapped out by a great grid of elements. This pattern would describe the precious gemstones of antiquity, the industrial metals that fuelled the creation of the Modern Age and the anatomy of the animal kingdom. Mendeleev's gaps in the periodic table were extracted from rare-earth ores and isolated from the air. In a rather unexpected turn however, additions to his periodic table would increasingly come in the form of artificially created elements, synthesised in laboratory environments and not present in the natural world.

An Unnatural element is defined as an element which was originally isolated in a lab rather then found in nature. This broad definition can refer to elements that vary greatly in atomic number and method of production, varying from technetium, with $Z = 43$, which is embedded within the transition metal block, to the hyper-heavy oganesson $Z = 118$[1]. This paper, however, will focus on the Trans-Uranium Elements $Z > 92$ with specific interest in the Super Heavy Elements (SHE) $Z > 104$, where the majority of current research is being conducted. This paper will provide a review on the development of experimental methods used to produce and isolate these new synthetic elements. It will then take in the chemical properties of these SHE and analyse the current theoretical models used to determine them. A case study of oganesson is used to highlight some of the key findings of these models. In particular, the differences between oganesson and lighter elements are presented and commented upon. This course of discussion will lead to a review of the structure of the current periodic table, and even a question as to whether it is fit for service at all. The world of super heavy nuclei (SHN) appears to be a bizarre one indeed, with many traditional tools and models within physics proving unsuitable in these contexts. The key frontiers of research that are attempting to understand these atoms of many hundred nucleons have been considered and outlined.

Since all unnatural elements share a common origin in some form of induced synthesis, many of them prove highly unstable. Despite the short half-lives of many elements explored across this report, chemical and industrial uses can be found for many synthesised elements. The instability of many synthetic elements can in fact be flipped on its head in terms of usefulness, when utilised as alpha and beta sources, leading to applications in the fields of medicine, health and safety, spectroscopy and power production among others. The discovery of plutonium alone led to an atomic revolution, with a rather more morbid tone applied to geopolitics since its discovery. Its military and energy applications still hold great relevance in the present day.

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[1] For the readers convenience a periodic table has been provided in the appendix as figure 20.

Much of the groundwork laid for the techniques to synthesise new elements, as well as the inclination to search for them, stemmed from the discovery of the radioactive decay of uranium in 1896 by Henri Becquerel [1]. This detection would lead to a scientific footrace to understand a new natural phenomenon. In the following years, the work of Ernest Rutherford provided proof that both alpha and beta decay could lead to the transmutation of atoms into differing atomic elements. The radioactive displacement law would then be proposed in 1913, laying clear mathematical guidelines to the effects of decay modes [1]. It states that an alpha emission lowers the atomic number by two of it's parent nucleus and that a beta minus emission raises the atomic number by one. The continuous spectrum of particles emitted in these beta decay emissions would lead Enrico Fermi in 1933 to suggest the presence of a third particle present in these processes. In a paper (published in 1934) titled "Tentativo di una teoria dei raggi β", the theories established of quantum mechanics were applied to matter. Under the proposition that matter could be annihilated and created, Fermi suggested the third neutral particle (a neutrino) was created in beta decay [2]. In 1934, Friedrich and Irene-Juliot Curie, announced both the discovery of beta positive decay and a method of inducing radioactivity in stable elements [3]. The transmutation of atoms into higher elements therefore became a process that could be induced. As such, it was theorised it would be possible to synthesise elements heavier than uranium.

In 1934, Fermi would attempt to do this using a low energy beam of neutrons and a uranium target. As part of his experiment, he would observe a product that did not correspond to the known half-lives of uranium, winning a Nobel Prize in 1938 for his efforts. This claim would not last long however. In fact, in the same year that Fermi was awarded a Nobel, the process of nuclear fission would be provided, which would provide the mechanism to describe the process that Fermi observed [4]. The process of creating unnatural elements would prove to be a much more challenging one. In order to synthesise an entirely new element, a high energy beam of neutrons was required to avoid inducing fission. Thus, a particle accelerator capable of accelerating to high energies was necessary to be constructed.

The next advance in the world of unnatural elements, the creation of this proposed particle accelerator, would develop on the other side of the world. The man responsible was Ernest Lawrence, the youngest ever professor at the University of Berkeley in California. In 1933, he would patent 'the Cyclotron' ,a circular particle accelerator that, after successful early tests and later a Nobel prize, was proven to be effective at creating a focused beam of high energy, charged particles. In 1931, the Berkeley Radiation Laboratory was founded by Lawrence, centred around this cyclotron technology. In 1939, the group, now headed by Edwin McMillan, used a 60 inch cyclotron to investigate the separation of the fission products of uranium-238. This yielded an unusual beta radioactivity occurring only after the decay of the known ^{239}U isotope. Initially, this was written off as resulting from an unknown fission product. A rigorous chemical investigation later in 1940 showed this product to be chemically similar to uranium, such that it could not be formed from fission [5]. Neptunium had been discovered, plutonium followed soon after and led to a total of 6 elements being discovered in the period of a decade at Berkeley using similar methods [6].

Due to the increasing costs of targets, along with the shorter half-lives associated with the new elements synthesised, the team at Berkeley were unable to further confirm new products by this process of chemical analysis. A different technique was required. In 1959, Berkeley pioneered a 'Double Recoil Technique' designed to capture all of the products associated with the subsequent alpha emissions from the induced product. This was improved upon by a competing Russian Research group using a jet of helium gas to separate any products produced from the target. The Joint Institute for Nuclear Research (JINR), located in Dubna, would use this process to confirm the discovery nobelium (Z=102). In general, this verification method was found to be fifteen times more efficient at collecting products then previously employed experimental methods for discovering earlier elements [7]. This proved sufficient to produce elements all the way up to dubnium (Z=105). All intermediate elements in terms of atomic number were synthesised across the competing teams at Berkeley and Dubna.

However, as even heavier elements were synthesised, it was found that the products were being vaporised before they could be measured. This was due to the fact that, as the Z number increased, so did the excitation energies of the produced heavy ions. A team led by Yuri Oganessian developed a new reaction, known as cold fusion. Targets of lead or bismuth chosen for their almost closed nuclear shells were bombarded with heavy ion beams. This process produced heavy elements with low excitation energies and was hence given the name 'cold' fusion. Particle accelerators capable of accelerating heavier beams were required for the cold fusion mechanism. This was first tested by Oganessian in 1974 and returned a much higher yield then expected [8].

Due to the high fissility of products made by cold fusion, very few products would survive to be detected by the sensitive detectors. The GSI centre for heavy ion research in Darmstadt, West Germany would be the first institution to resolve this issue and hence the next institution to be closely associated with the story of unnatural elements. The team at GSI were able to apply a velocity filter that would remove undeflected particles from the detectors [9]. This reduced the detection of undeflected particles incident on the detector by an order of magnitude of ten to sixteen [10]. This breakthrough permitted the GSI centre to be able to announce the observation of bohrium ,Z=107, in 1981. Bohrium was to be followed by five further elements announced via cold fusion methods at GSI over a period of 15 years . As the atomic of the products increased, however, the cross-sections of the products were observed to decrease. This reduced probability of reaction meant that experiments at GSI began to run much longer with far fewer atoms of the targeted synthesised element observed [10]. The heaviest element to be produced by cold fusion is nihonium (Z=113) at the RIKEN institute in Japan in 2004. Heavier elements thus far have been not been confirmed by these methods to a statistically significant level.

At this stage, far more than just science was at stake in the world of unnatural elements. The prestige of an element discovery, heightened by the dynamics of the Cold War, engendered a highly competitive atmosphere between the three institutions of Berkeley, Dubna and GSI. As such, it was considered diplomatically advisable for an independent judiciary body to be formed to attempt to clear the way for international cooperation. Following a number of years of consultation across the global scientific populace, the Joint Working Group (JWG) was founded in 1985 by the International Union for Applied Physics (IUPAP) and the International Union for Applied Chemistry (IUPAC). The JWG was given the jurisdiction to assign credit and naming rights for the discovery of new elements. In

1989, it would go a step further and set out a criterion of necessary experimental observations that would need to be satisfied in order for a new element to be synthesised. These criteria would influence the design of all following heavy nuclei synthesis experiments [11].

But regardless of debates over nomenclature and procedure, it was clear to the international community that it would not be possible to synthesise new elements using cold fusion methods. The hot fusion methods that were, once again, developed by Yuri Oganessian, would prove the process used to find the elements $Z = 114-118$. A key development allowing hot fusion to become viable once more is the use of the double magic number calcium-48 as an ion beam. The high stability and neutron excess of the isotope allow for many successive beta decays [12].

The process associated with the confirmation of elements began to change. After the discovery of an element, chemical analysis of the synthetic products had proved to be the next step. However, with the latest experiments producing synthetic elements numbering in the single digits, this required elements to be studied an 'atom at a time' [13]. Many of the superheavy elements have not been chemically analysed. The current heaviest element to be studied in this manner is flerovium $Z = 114$. The majority of SHE are proton rich systems and would be expected to decay by electron capture or β^+ decay, however, experimentally they have largely been observed to decay by an alpha emission mechanism [14]. There is a significant amount of research being conducted in the field to explain this discrepancy, and more generally the bizarre behaviour shown by of the superheavy elements.

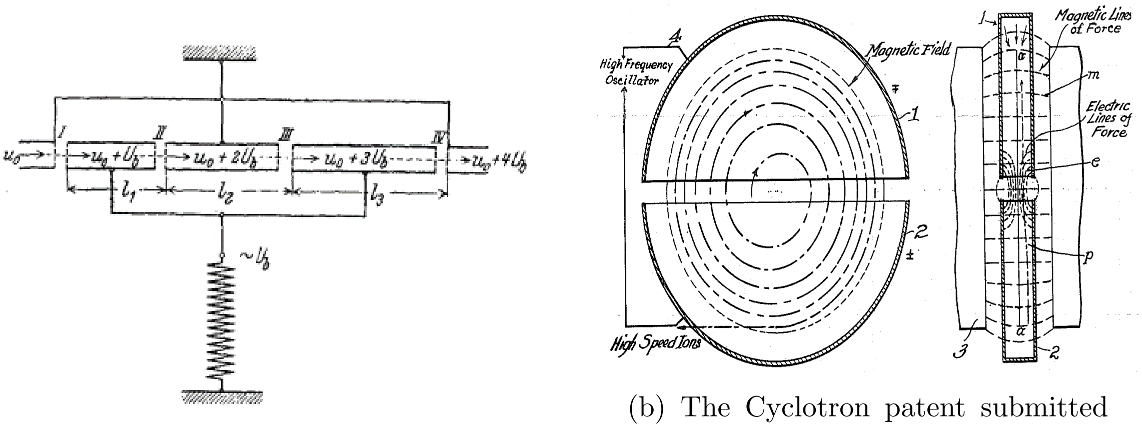
First, however, the world of the cyclotron at Berkeley is to be re-encountered and explored in greater detail. This report will describe the breakthroughs made in the field of unnatural elements chronologically. The story is brought back to the paper first written by Fermi, and the initial experimental configurations and observations.

2 Early Experimental Developments in Synthesising Unnatural Elements

The initial tools for elemental synthesis were provided by two sources. Fermi's landmark 1933 paper, that linked quantum mechanics to beta decay, along with the discovery of the neutron by James Chadwick a year earlier [2, 15]. The combination of these two discoveries provided a model of beta decay that was finally accurate enough to make experimental synthesis physically viable for the first time. The theory of this mechanism was straightforward, under which a neutron-rich uranium isotope was bombarded with neutrons inducing a beta decay into the desired element 93. As outlined qualitatively, this method would be stymied by the process of nuclear fission, discovered in 1938. The only way to avoid splitting the atom would be to accelerate the incident beam of neutrons to high energies. This was not technology that was contemporaneously available.

2.1 Development of the cyclotron

The first obstacle to overcome to produce a successful particle accelerator, was the ability to produce the high enough voltages necessary to produce the high energy beams



(a) The linear accelerator schematic that inspired Lawerence to use alternating electrodes to accelerate a particle beam. Figure taken from ref [17].

(b) The Cyclotron patent submitted by Lawerence in 1932 taken from ref [16], when seen side by side the the thought process of Lawerence is clear to see.

Figure 1: The schematics that led to the development of the cyclotron.

[16]. Due to the financial limitations of producing transformers and rectifiers capable of handling such high voltages, a new method was necessary. Ernest O Lawrence, while reading a German electrical engineering paper by Wideröe, found schematics (see Figure 1a) [17], for a proposed linear accelerator. This accelerator would comprise of sequential cylindrical electrodes of alternating polarity such that, when a positively charged ion such as a deuteron or proton entered the drift tube, it would be accelerated forwards. Once the ion reached the end of the electrode, the voltage would have switched directions, due to the opposite polarity. The ions would then be accelerated across the gap to the next electrode. For the accelerating ion to remain synchronous as it accelerates, the distance between the gaps must be $1/2$ an RF cycle, or more generally, (n + $1/2$) cycles, where n is an integer. This would require the electrodes to become longer to maintain the synchronicity [16].

Lawrence set a goal of making an accelerator capable of accelerating ions to energies in the order of MeV. It was calculated that, to achieve this, a linear accelerator would need to be at least 10 metres long. The production cost of a vacuumed tube that was several metres long was deemed to be unjustifiably high, and too otherwise impractical for laboratory use [16]. Instead, a circular spiral accelerator was proposed. Using a uniform magnetic field and two semi-circular shaped electrodes named Dees, it would still be possible to accelerate the particle across the gap between the shells. This would maintain the particles' frequency of orbiting at what is now known as the cyclotron frequency [16].

This method would prove so successful that the first working cyclotron was soon created. Even with a 5 inch diameter, the cyclotron could accelerate a proton beam to 80 Kev using an input voltage of less than 1,000 Volts to the Dee [18]. This prompted the construction of larger cyclotrons by Ernest O Lawrence and his team at Berkeley. After narrowly missing out on the discovery of Radio elements announced by Curie-Joliot in 1934, the team moved onto the investigation of heavier nuclear elements. In 1939 the construction of a 60 inch diameter cyclotron was completed. This contained a 220-ton magnet capable of accelerating a beam of deuterons by 16 MeV and up-to a distance of 153 cm. This would allow Berkley to conduct bombardment experiments at longer distances then other groups[19]. This was the particle accelerator used in the discovery of elements 93 to 101 and was a major contributor to the Berkeley research group's dominance in the field of synthetic elements [6].

2.2 Discovery of plutonium-238

In the discussion of synthetic elements, particularly among those isolated in this time frame, the element that is impossible to ignore is plutonium. Currently the synthetic element with the most practical applications, whether it be economical or military its discovery shaped and influences global politics to the present day. Due to these many uses; plutonium became the first synthetic element to be mass produced and thus serves as a good example for the methodology of using chemical analysis to determine whether or not a new element has been produced.

Using Berkely's 60 inch cyclotron, a 16MeV deuteron beam bombarded a uranium-238 sample in the form of U_3O_8 [20]. Triuranium octoxide was used as the target as it is one of the most kinetically and thermodynamic-ally stable yellowcakes of uranium and thus, also one of the most easily available forms of uranium in 1940. The deuterons were directed to bombard alternating thin layers of foil and target, producing neptunium-238 and 2 neutrons (see equation 1). The neptunium was then chemically purified and then analysed using an ionisation chamber connected to an FP-54 tube and a Lauristen electroscope. This apparatus measured direct currents of 10^{-17} Amperes or 60 electrons per second [5]. The data was used to trace out an aluminium absorption curve that had an upper energy limit of 1 Mev, compared to the upper energy limit of 0.5 Mev observed from the aluminium absorption curve for neptunium-239 (which had been previously synthesised from bombarding uranium-238 with neutrons [5, 20].) The rate of beta and gamma emission was plotted and the half-life of neptunium was determined to be 2.1 days under these methods [20].

$$^{238}\mathrm{U} + {}^{2}\mathrm{H} \rightarrow {}^{238}\mathrm{Np} + 2n \rightarrow {}^{238}\mathrm{Pu} \tag{1}$$

This process showed a growth of alpha emissions with a range of up to 2.3cm and a new product determined to have a half-life of 90 years [20]. This did not and could not resemble any isotopes of uranium and neptunium that had previously been explored. The most abundant and well-known alpha emitting isotope in 1941 was thorium-232 and thus it was necessary to chemically distinguish the radioactivity from a rare earth metal. It was found that the radioactivity precipitated in a 4+ valence state as either a fluoride or an iodate using thorium as a carrier material,. This was very similar to the structure of a rare earth metal [20]. However, when using an extremely strong oxidising agent like a persulfate ion on a higher oxidised state of plutonium then 4+ was found that did not precipitate as a fluoride.This was unlike thorium or any known rare earth metal. The unknown product that had been synthesised was instead, chemically similar to elements 92 and 93. This gave the necessary proof that a new actinide element had been produced [20]. The later discovery of the highly fissile ^{239}Pu isotope, in December of the same year, would, as a nature of its well-known applications in weapon testing, make significant waves. All information on the discovery of element 94 was censored from wider circulation until April 1946, well after the conclusion of the Second World War and the Manhattan Project. [6].

2.3 Obtaining proof via mapping decay emissions

For the early synthesis of synthetic elements with relatively long half-lives, the products produced via neutron bombardment proved stable enough and in large enough quantities, such that it was possible to identify new elements using chemical techniques. This was often through oxidation, as explored in the case of plutonium. However, as the number of particles being produced greatly reduced, starting to number in the single digits, it was no longer possible to analyse the products produced directly. The process of analysing elements through their decay emissions was formed. Under this process, rather than the atoms produced directly in the first reaction being measured, it was the daughter or granddaughter particles produced by decay that were analysed. If it could be proven that a decay chain led to a particle with a known emission energy and half-life, this was deemed sufficient proof for the discovery of a new element.

Emission energies of new isotopes of synthetic elements were carefully measured and tabled, to construct extended decay chains beyond what was found in nature. The first example of Berkeley discovering a new synthetic element via the confirmation of a decay chain, would occurred with the discovery of einsteinium $Z = 99$. Einsteinium was produced as the result of beta decay from fermium, $Z = 100$, a previously known element that had been discovered by the detonation of a thermonuclear bomb in 1955 (see figure 2).

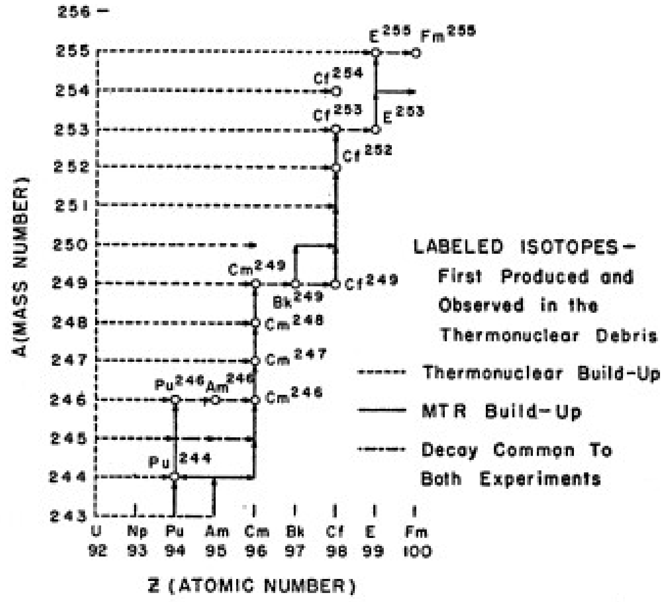


Figure 2: The decay chains constructed by A Ghiorso and the Berkeley Team when analysing the debris of the first Thermonuclear bomb test. Berkeley chemically isolated two new elements from these experiments and proved the ability of heavy element targets to accept multiple neutrons,leading to a chain of successive beta decays. This led to heavier ion beams being used in all subsequent experiments. This figure was taken from [21]

However, the first synthetic elements existence proved due to the construction of a decay chain from its products, was the discovery of nobelium. This discovery was claimed and contested by 3 different laboratory groups, each claiming to have evidence in favour of element 102 being produced in the years of 1957-1971 [22]. This led to 20 different research papers being published each attempting to prove that the alpha decays observed were due to the presence of element 102. The discovery was only officially accredited to Dubna in 1992 by the IUPAC [22].

2.4 The Double Recoil Method

The Berkeley and Dubna research groups both found most success when conducting a double recoil experiment, aiming to identify the daughter particles produced from the alpha decay of the as-yet unknown nobelium. In 1959, Berkeley used a thin target made up of 95% ^{244}Cm and 5% ^{246}Cm which was bombarded by a beam of ^{12}C ions with energies of 60-100 MeV. Afterwards, the reaction recoils were caught and decelerated a in helium gas hemisphere [23]. The particles were deposited using an electric field onto a moving belt passing under a detector foil to catch the secondary alpha recoils and then deposited into a collector, which was split into five sections to account for time delays [23]. Fermium-250 was confirmed to be found in the collector via ion exchange techniques and alpha emissions of 7430 KeV being observed, agreeing with previous experiments [22, 23]. The half-life of the parent particles were claimed to be 3s with an excitation energy upon of 8.3 MeV which agreed with predictions for ^{254}No. However, this was not considered enough to draw conclusive evidence. The Berkeley paper itself published after the claimed discovery would conclude with the notion that [23] "due to the difficulty and the complexity of the conditions ... we cannot be sure that this activity was actually caused by element 102". Later experiments showed it was possible that ^{250}Fe could have been produced directly instead of through the alpha emission of Nobelium. As such, Berkeley would not be credited with the discovery of the element. [7].

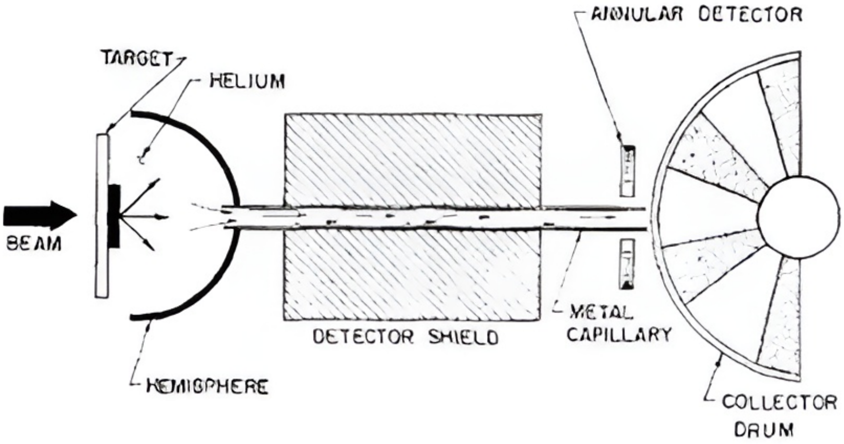


Figure 3: The set up for a helium jet separator similar to what was used at Dubna to discover this figure is taken from ref [24]

That honour would pass to the Dubna laboratory. In 1964, Dubna attempted to reproduce Berkeley's findings conducting two double recoil experiments. With an experimental set-up consisting of a beam of neon-22 ions incident on a thin uranium-238 target, (see equation 2), the products were then swept up in a helium jet (see figure 3). This deposited the products onto a wheel that could be turned to semiconductor alpha particle detectors[7]. They also found evidence for ^{250}Fm being produced via alpha decay, but results showed that the predicted ^{254}No had a much longer half life then the 3s stated by Berkeley. This was then repeated using nitrogen-15 ions and an americium-254 target that agreed that ^{254}No had a longer half-life than the Berkeley team had stated [22]. These results were confirmed in December 1966 by Berkeley. This would not end the dispute however, with both teams claiming the discovery across the next 25 years.

$$^{22}\mathrm{Ne} + {}^{238}\mathrm{U} \rightarrow {}^{254}\mathrm{No} \rightarrow {}^{250}\mathrm{Fm} + \alpha \tag{2}$$

When Dubna tested the efficiency of the double recoil techniques compared to the more traditional electron capture approach, they found that the double recoil experiment collected 15 times more product then equivalent electron capture experiments [7]. This would then become essential in all following heavy element experiments, and alone led to the discovery of elements 102-105. The next major breakthrough would come with the discovery of "cold" fusion, first proposed and tested by Yuri Oganessian at Dubna and pioneered experimentally by the GSI Centre for Heavy Ion Research based in Darmstadt. This breakthrough is discussed further in the following section.

3 The Cold Fusion Years

3.1 Dubna and the Development of Cold Fusion.

One of the most important developments in the field of heavy element research would come in 1974, when the reaction technique of Cold Fusion was developed in the town of Dubna. Dubna is an example of a Naukograd, a term that indicates it was founded in the USSR to be a hub of scientific research. Indeed, Dubna was founded solely to be the location of the Joint Institute for Nuclear Research (JNIR) in 1958 [25]. The laboratory that would put the town of Dubna onto the periodic table is the Flerov Laboratory of Nuclear Reactions (FLNR). It is the FLNR that is involved in the search for super-heavy elements [26].

Before exploring the reaction of cold fusion, it is helpful to understand the techniques that researchers at the FLNR were using prior to its discovery. The final element synthesised at the FLNR before Cold fusion was also named after the town it was discovered in, dubnium [22]. The year was 1968 and the element that would eventually be dubnium was known only by its proton number, 105. The reaction used was a 'Hot Fusion' reaction, whereby a heavy target of ^{243}Am was bombarded by a beam of light ^{22}Ne ions. They would then use a modification of the 'Double Recoil' method, similar to that described for the production of nobelium and fermium in the previous section [7, 23]. The target was placed on a copper mesh which was cooled by water. The target chamber was filled with helium gas, which provided a further cooling effect. This cooling was of the utmost importance, as the beam of neon ions had a maximum energy of 175 MeV, high enough to severely damage an uncooled target. The next step in the process was to collect the fragments of element 105 produced in the reaction. To do this the researchers set up a rotating strip of nickel behind the target, this moved with a constant speed to as to be in effect an 'infinite' detector. This collected the fission fragments as they were produced. Along the strip there were fission detectors, in the form of phosphate glass plates. The researchers put the efficiency of these at 95% [27].

The researchers at the FLNR then had to analyse the results of their experiment. From the apparatus they had, they were able to determine the half-life of their 105 fragments, the cross section of the reaction, as well as being able to posit that the primary decay mode was α-decay [27]. When the discovery of element 105 was assessed by the IUPAC working group however, it was found that the preliminary data gathered by the Dubna team was not sufficient to be able to claim discovery. The researchers were able to produce further papers to strengthen their claim, but equally strong evidence was also produced by the Americans at the Lawrence Berkeley lab, leading to the credit for element 105 being shared between the two groups [22].

As researchers began to probe elements with proton numbers higher than $Z = 107$, they began to encounter issues with the traditional method of Hot Fusion. The main problem was that as the Z number increased, so did the excitation energies of the produced super-heavy ions. This led to the products being vaporised before they could be measured [22].

The solution was proposed by a team at the FLNR, led by Yuri Oganessian. This would become known as Cold Fusion. Later, Oganessian would gain even more fame by refining Hot Fusion and discovering the heaviest elements discovered to date [8]. The theory of Cold Fusion is that targets of lead or bismuth ("magic nuclei", which have high binding energies due to their closed nuclear shells) are bombarded by ions of $Z > 16$, which are themselves near closed shells, such as ^{54}Cr or ^{62}Ni. The result of this is that the produced super-heavy elements have much lower excitation energies than if they had been synthesised through hot fusion. Cold Fusion only started to become a feasible reaction with the development of both accelerator and detector technologies in the early 1960s. The most notable accelerators in this context were the HILAC (later superHILAC) accelerator at Berkeley, the UNILAC accelerator at GSI Darmstadt, and the U-300 and U-400 cyclotrons at Dubna. Prior to the production of these machines, earlier accelerators could only accelerate the lightest ions [28].

The minimum excitation energy of a fusion reaction is given by the sum of the interaction barrier, a modified form of the Coulomb potential taking into account further nuclear effects, and the reaction Q-value, $E^*_{min} = B_{int} + Q$ [29].

The strength of the interaction barrier is given by:

$$B_{int} = \frac{Z_I Z_T e^2}{r_e(A_I^{1/3} + A_T^{1/3})}$$

And the Q value is given by:

$$Q = M_I + M_T - M_P$$

where M represents the mass of the nuclei, where subscript I, T, and P represent incident, target, and product nuclei respectively [29]. r_e is the effective radius, this decreases with the charge of the projectile[30]. The mass values are calculated by a correction to the liquid drop model that takes into account the shape and shell effects of the nucleus [31]. It can be shown that the minimum excitation energy is found when the mass of the ion is around 50 atomic mass units (u), as shown in Figure 4 [32].

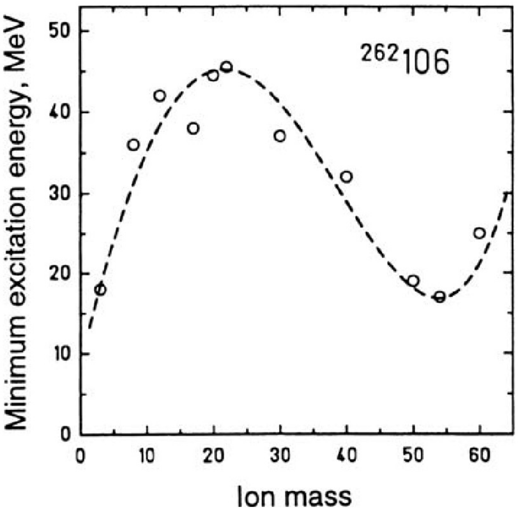


Figure 4: A graph of the minimum excitation energy when element 106 is formed against the mass of the ion beam. A similar trend is observed in all heavy ion production reactions. [28]

In one of the first attempts at Cold Fusion, the JINR researchers collided beams of argon-40 ions with a lead target. Oganessian expected to produce ^{244}Fm by losing 4 neutrons and that any fermium produced would have a half-life of 4ms. When the element was produced using cold fusion, only two neutrons were released, and the half-life was 1.1 seconds [32]. This gave the team a much larger yield than they had expected [8]. Further studies on the reaction of titanium-50 with lead to produce atoms of element 104 further solidified the position of cold fusion. It was found that the half life of element 104 was also significantly increased using cold fusion. This gave researchers confidence that the technique could be used for further reactions using heavier beam ions to search for even heavier elements at the end of the periodic table [29].

3.2 GSI and the Application of Cold Fusion:

Though cold fusion was first put into practice in 1974, it would take six years before the first new element to be discovered by the technique was officially discovered. Furthermore, it would not be in Dubna, the birthplace of cold fusion, but in Darmstadt, West Germany. The lab that utilised cold fusion to discover element 107, later dubbed bohrium, was the GSI centre for Heavy Ion Research. They would go on to use cold fusion to dominate the field of super-heavy element discovery from 1981 to 1996 [33].

The JNIR did try to use the reaction they had invented to discover super-heavy elements. As early as 1975, they attempted to synthesise element 106 by the reaction of lead and chromium-52 ions. While they were successful in producing the element, they were unable to produce sufficient evidence to claim discovery and the credit went to the Berkeley lab, who discovered seaborgium using Hot Fusion [22, 34]. The main thing holding back cold fusion as a means of super-heavy element production was the sophistication and sensitivity of contemporary detectors. While the beams of incident ions had fluxes in the order of 10^{12} particles per second, the high fissility of the products led to very few events being detected, even after a day of running. Cold fusion was especially sensitive to fissility, as fissility depends on the product of the beam and target Z numbers. For many years, until the proof of synthesis of fermium by Oganessian, this fissility had led physicists to believe that cold fusion was impossible. The detectors that nuclear physicists used had to advance to meet the demands of this new reaction [28].

The development that would give the GSI such an advantage over their peers for nearly a decade and a half was the addition of a velocity filter to their detector set-up. The specific velocity separator in question was SHIP, the Separator for Heavy Ion Reaction Products.

A Velocity Filter is a modern development of a much older piece of technology, the Wien Filter. This concept was first developed by Willy Wien in 1897, predating the discovery of the nucleus by 16 years. Wien used his device to show that by applying a magnetic field to a Cathode Ray (beam of Electrons) he could negate the effect of an electric field on the beam. As science progressed, the basic concept of the Wien Filter was developed into uses as a Mass Separator and, in the case of SHIP, a Velocity Filter [9]. This would prove to be a major development over the previous double-recoil method.

A Velocity Filter uses electric and magnetic fields to separate the charged heavy element ions from the other particles present, such as beam ions and other reaction products due the differences in their velocities. There are certain properties of the heavy ions that need to be considered when designing the velocity filter; that the ions move slower than the beam due to conservation of momentum, that the angular and velocity dispersions are different depending on factors such as beam and the process by which the products de-excite, and that the product ions have a wide charge distribution due to the stripping off of electrons in the outer shells [35].

The separator consists of five main components, the target, quadrupole magnets, dipole magnets, Electric Deflection Condensers (sources of electric fields), and the detector area. There are two Electric condensers that provide an electric field, while the magnetic fields are produced by four dipole magnets. The quadrupole magnets act as lenses that focus the incoming particle beam [35].

A schematic of the SHIP system can be found in Figure 5. The lighter beam ions and background particles are deflected by the filter out of the main beam and into a beam stop. SHIP was highly efficient. When it was in use during the discovery of element 107, GSI researchers put the suppression (reduction) of undeflected beam ions at a factor of 10^{16} to 10^{18}, while even beam ions that had been deflected and had a similar velocity to the were suppressed by 10^{10} to 10^{12}. From an initial beam flux of 10^{12} particles per second, SHIP had reduced the incidence of projectile ions reaching the detector to rates of 10-100 per second. Any ions dislodged from the target were even more thoroughly filtered, with a target ion reaching the detector only every 40 minutes [10]. Before the use of a velocity filter at Darmstadt, previous discoveries of heavy elements had simply placed detectors behind the target in some arrangement, without the use of any separation system [29, 34].

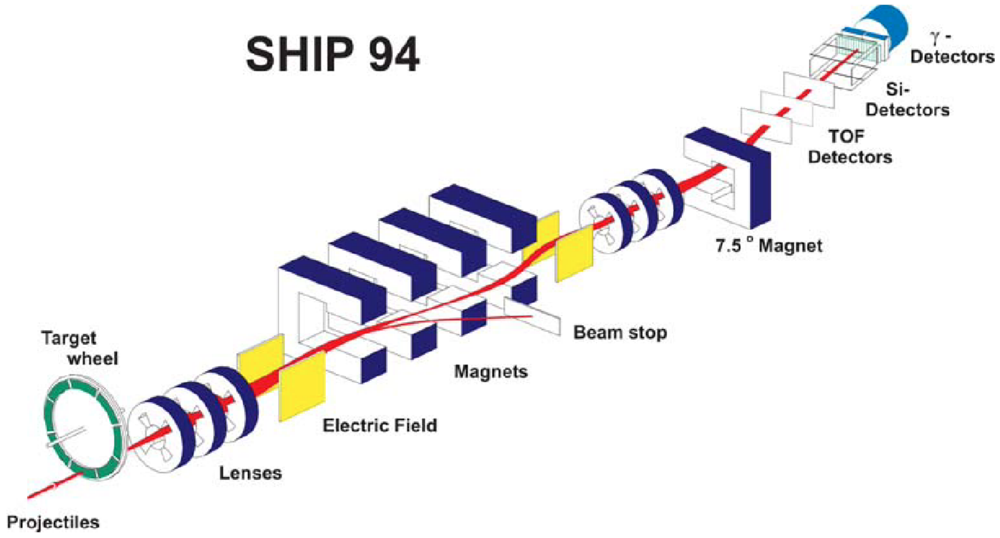


Figure 5: A schematic representation of SHIP. Note the quadrupole magnets acting as lenses and the combination of electric and magnetic fields directing the ion beam into the beam stop. This diagram also includes the additional dipole magnet added during the search for element 110. [28]

The first discovery that made use of SHIP was element 107, bohrium, in 1981. The GSI team used the UNILAC linear accelerator collide a beam of ^{54}Cr ions into a target of ^{209}Bi. UNILAC was able to accelerate the ions up to energies of 5.07 MeV/u [10]. The beam intensity was so high that, to avoid the target melting, it had to be placed on a rotating wheel to avoid prolonged exposure to the beam radiation. To further cool the target, the surface was covered with a film of carbon, microns thick, to aid with radiative cooling. The products then passed through the SHIP velocity filter where events were then detected by 7 surface barrier detectors [10].

By element 110, it was clear that, as the proton number of the target super-heavy elements increased, the cross section of the cold fusion reaction would get smaller. This led to even less events being recorded in longer time periods. Even in the production of element 107, there were never more than 10 events even after running for more than a day [10]. In the case of element 110, the cross-sections were in the order of picobarns. To combat this, the sensitivity of the apparatus had to be further increased. If the experiment had used the same sensitivity as previous attempts, the researchers estimated it would take months of running just to get a single event. The reaction was

$$^{62}\mathrm{Ni} + {}^{208}\mathrm{Pb} \rightarrow 110 + n$$

Once again, the eight lead targets had to be placed on a rotating wheel to avoid melting. To increase the solid angle, and hence the transmission of products to the detector, the distance between the targets and the SHIP velocity detector was decreased. The addition of a further dipole magnet to the SHIP set up to further decrease the background, especially low energy nickel ions from the incident beam which had been scattered but not reacted [36]. Once again the low yield was evident, as after a total of twelve days of running, the GSI recorded only nine events [37].

The final element that, as of the date of writing, the GSI would be credited for discovering is element 112, later named copernicium. It was discovered in February 1996 by the reaction of ^{70}Zn ions incident on a ^{208}Pb target. As before, the ions of element 112 were separated out by the reliable velocity filter SHIP. During the first running of the experiments, which lasted for three weeks, only two decay chains of element 112 were observed. [38] It was later discovered, in the fallout from the Ninov controversy at Berkeley, that the first of these decay chains had been based on fabricated data. After many checks, the GSI team were able to verify that the second decay chain, found over a week later than the spurious first, was indeed legit and the credit for element 112 remained in Germany [39]. This incident shows how desperate researchers were at the time for events, as the low cross sections for cold fusion at this Z number led to experiments running into the time-frame of months where before they had been able to find good results in a matter of days.

3.3 The End of the Cold Fusion Story (so far):

By the discovery of copernicium in 1996, the GSI team were aware that their method of cold fusion, which had seen such success in a 15-year run, was reaching the limits of its usefulness. There was a general acknowledgment that to probe heavier elements they would require a serious upgrade of their facility, as the UNILAC accelerator could not produce beams with a higher duty factor i.e., they could not provide longer more consistent beams with the UNILAC [39, 40]. Furthermore, they would have to run the beam for longer than the weeks spent looking for 112, which is not feasible at the GSI facility [39].

The fundamental limitation for cold fusion as a technique for continuing super-heavy element research is the fact that as the Z number of the desired product increases, the reaction cross section decreases. The final element discovered by cold fusion was element 113 at the RIKEN experiment in Japan. Here they found that the cross section for a reaction was a tiny 31 femtobarns [28]. The practical result of this is that it can take years of running an element to see a result. In the period that RIKEN ran the experiment to produce element 113, from 2003 to 2012, they only recorded decay events three times [8]. For the time being, cold fusion had reached its technical limit. The next developments in the field of super-heavy elements would be from Yuri Oganessian's development of hot fusion with calcium-48 ions. However, this technique could only reach up to element 118. A new approach will have to be taken to push the field further than this, with one likely avenue being the use of heavy ion beams. In the same way that the developers of SHIP looked back to Wien Filters, perhaps the reaction of cold fusion may again come to the forefront of element discovery [28].

4 How to verify new elements

The confirmed discovery of an element is an achievement highly desired by research teams around the world. As such, rules must be put in place to assure the legitimacy of claims made and to provide a due process for prospective teams attempting to add to the periodic table. Historically, the lack of a clear procedure has led to scientific inconsistencies associated with elements reported, along with one notable case of deliberately falsified results. The history of this verification process, specifically in relation to the clearer standards laid out in recent years, will be explored in this section.

In 1991 the Transfermium Working Group (TWG) was set up to determine criteria for assigning priority [11]. At this point only elements up to 109 had been discovered which was in the middle of GSI laboratory's succession of discoveries.

In order to update the criteria established by TWG on how new elements are verified, the a new JWG was established in 2016 by two groups, the IUPAP and the IUPAC. There are six members in the JWG, with two nuclear physicists and one nuclear chemist chosen by each union to comprise the verification committee [41].

The Joint Working Parties (JWP) would then be created to make decisions on claims for new elements. The JWP analyses results and data to determine if they meet the updated criteria for new claims.

Although there are a number of different methods to determine if a new element has been produced, there is a clear pattern among discoveries in this century. The last 18 elements were all determined using physical methods, suggesting that any new additions will also have to be identified in a similar manner [41]. Specifically, the analysis of decay chains (genetic relation) is currently the most widely-used tool for identification of new elements. In the use of this technique and otherwise, there are a number of clear criteria that must be reached to confirm the discovery of a new element.

The definition of a new element given in the TWG report [11] is: 'Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number Z not identified before, existing for at least 10^{-14}s'.

As genetic relation is the most used method for identifying new element, the criteria needed to use this method will now be examined in greater detail.

4.1 Technical Criteria for genetic relation

The first step in the identification of an element using genetic relation is to identify what is being produced. Every fusion reaction produces some amount of unwanted product along with the desired output, in this case the newly synthesised element. Some form of separator must be used in order to identify and analyse the reaction products. Examples of these devices include gas-filled separators, velocity separators, favoured by the GSI laboratory in Darmstadt, and energy filters [41], such as VASSILISSA used by FLNR prior to 2015 shown in Figure 6.

The arrangement of a genetic relation experiment should consist of the procedures outlined.

The evaporation residues of the complete fusion reaction will pass a time-of-flight detector before being placed into a series of position-sensitive silicon detectors [41]. These detectors are placed specifically around the evaporation residue as α-particles and fission fragments can go in both the forward and backward direction. As such, the placement of these detectors is sufficient to fully specify the energy of the α-particles [41]. Position-sensitive detectors are also able to reduce the effective background rate in order to track decay chains over a long period [41]. Other methods can also be used to reduce the effective background rate.

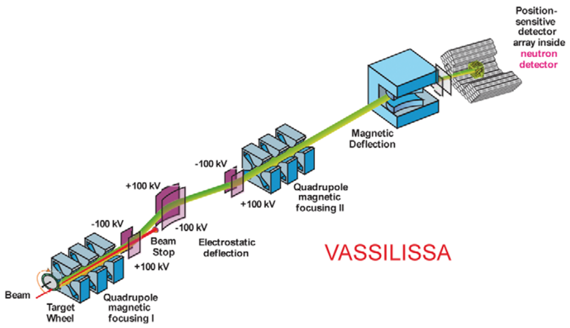


Figure 6: Diagram of VASSILISSA energy filter used by FLNR [42].

At the end of this experimental analysis, the research teams must outline any potential factors that may have affected their results. This has to be accompanied with some form of statistical significance analysis considering whether the claim initially made can be considered to be valid in context of the results presented . This is standard scientific practise and ensures the reproducibility of the results presented.

When publishing results the key information needed so the JWG can have independent scientists confirm the results is any steps taken during the experiment that would be of significance to their claim as well as what criteria has been met and how successfully they met the criteria [41]. As for any scientific experiment the main criteria is that it needs to be reproducible.

4.2 Physical Criteria for genetic relation

Decay chains can be used to identify new elements by establishing a relation between radioactive decays of unknown nuclei into known nuclei. This process, however, is not always entirely simple.

There can exist cases where multiple teams claim to find an element at a similar time, with each using decay chains to determine the new element. For these examples, certain aspects of the decay chain need to be considered in order to establish priority.

The key to understanding which set of results is more likely to lead to an accepted discovery is found within the analysis of α energies. The fluctuation pattern of these energies is a useful tool to help analyse the validity of a set of results obtained via genetic relation. A small spread of α-energies would be a good indication when assigning the decay of a nucleus [41] as this would indicate an accurate assignment. However, the reverse is not necessarily true. For odd-odd and odd-A nuclei, α-energies are expected to have a broader distribution due to their nuclear structure [41]. Thus, while analysing fluctuation distributions can prove a useful rubric, in general cases, any genetic relation experiments need to be repeated at higher yields in order to comment authoritatively on any experimental claim.

Here a distinction is established between even-even nuclei and nuclei of any other structure.

For decay chains between ground states of even-even nuclei, observing one decay chain will be adequate for allocating priority. This is because even-even nuclei decay chains are the least complicated to analyse the results of [41]. As decay chains for odd-A and odd-odd nuclei are more complicated due to their decay routes, one or more decay chains may be required to assign priority. In order to assign priority without confirmation, daughter decays of the new element must have been identified in previous experiments [41]. In the final case, decay chains ending via spontaneous fusion in a region of unknown nuclei cannot be solely used to determine a new element.

These rules can be applied in the search for as yet unknown heavy elements, which are likely to be verified via genetic relations. For elements 119 and 120, the decay chains are thought to start with a number of unknown α-decays, afterwards proceeding to α-decay via known decay chains ending at a known nucleus [41]. Two exceptions to this theorised decay process are found in the isotopes ^{299}119 and ^{300}119. Any decay chain resulting in a known nucleus from these isotopes is thus far unknown [41]. However due to the unknown nuclear structure of 119 and 120, certain aspects may complicate the decay properties and obfuscate the search for isotopes using known chains.

4.3 Claims of discovery for element Z=118

Most elements which have been found have stood up to all the necessary criteria in order to definitively say that a new element has been created. A notable exception to this, which would later provoke a desire for more exacting guidelines, involved a set of results for which the element that was claimed to have been synthesised could not be confirmed or reproduced by other teams. The incident would prove instructive in regards to the dangers of making confident claims about the existence of nuclei with fleeting half-lives and precious little evidence of their existence.

In 1999 at Berkeley, a research team were trying to find element $Z = 118$ through the bombardment of a lead target with a beam of krypton nuclei. Supposedly, three instances were observed where 118 decayed into 116 and then 114 and decayed down to 106 [43]. A diagram of the supposed decay was drawn by Victor Ninov as seen in Figure 7 after finding data for 118 decay. Upon a review by other people in the team, the claims of these three events seemed to be legitimate. However when groups at GSI and RIKEN both failed to reproduce these results alarms were raised. However, in the field of nuclear physics, it can often take years for an element to be produced, so there was still a chance that GSI and RIKEN could confirm the results in the future [43]. When Berkeley repeated the experiment in 2000, no evidence of 118 was found. However, after updating equipment, a decay event involving 118 was reported in 2001 [43]. Multiple review teams were made to analyse the 1999 experiment and its data, but none of the teams managed to find the decay chains presented by Berkeley in the raw data [44]. Due to this the findings were retracted.

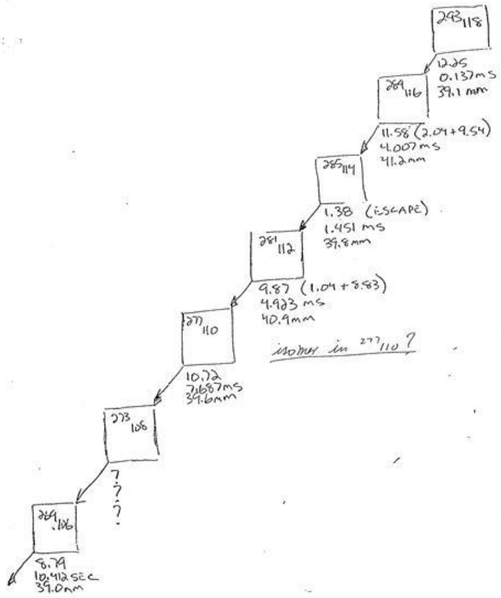


Figure 7: Decay chain that Victor Ninov drew after finding decay data for element Z=118 [45].

The next frontier of element discovery, however, which would require further elemental verification, would not come from the laboratories of Berkeley or GSI. By the turn of the century, the majority of the elements produced in the following twenty years would come from the Dubna laboratory with pioneering hot fusion methods, as explored in this following section.

5 Hot Fusion

The synthesis of super heavy-ion elements via hot fusion involves the bombardment of lighter ion elements differing more greatly in atomic number (though manifesting higher excitation levels) with unstable neutron rich transactinide elements, projecting the lighter calcium-48 to the heavier ion target element. This section explores experimental advancements used by JINR using hot fusion.

5.1 Calcium-48 reinvigorates Hot Fusion

After the realisation that Cold Fusion was running out of usefulness as a discovery tool in the search for new elements, the hunt was on for a new reaction that would keep the chain going. Once again, Yuri Oganessian would be the one to make the breakthrough [12]. In the late 90s he had the idea to use ions of calcium-48 as the beam ions incident on heavy targets ranging from ^{238}U to ^{249}Cf, also known as heavy actinide elements [46]. ^{48}Ca was the perfect ion; both its proton number (20) and neutron number (28) are "magic" – the most stable quantities possible. This stability gives heavy elements formed by ^{48}Ca a relatively low excitation energy of around 30 MeV. Furthermore, the high ratio of neutrons to protons found in this ion (^{48}Ca has less protons than many of the heavier beam ions often employed in cold fusion) leads to much less Coulomb repulsion in the produced nuclei [12, 46]. For example in the production of element 114, the use of ^{48}Ca in a reaction with ^{244}Pu gave a Coulomb repulsion around 40% lower than that caused by the production of 114 by colliding lead targets with ^{76}Ge beams [46]. The combination of low excitation energy and low Coulomb repulsion in reactions involving ^{48}Ca means that the cross sections for superheavy formation were in the order of picobarns [46], orders of magnitude higher than the femtobarn sized cross sections recorded in the heaviest cold fusion reactions [28].

5.2 The Dubna Gas Filled Separator

Alongside their development of the calcium-48 hot fusion reaction, the next thing that Oganessian and his team at the JNIR needed was a device to separate the superheavy elements they produced from the rest of the beam, especially important as their cyclotron produced a beam intensity of up to 10^{13} ions per second. Their solution was the Dubna Gas-Filled Recoil Separator (DGFRS) [46]. This employed a similar concept to the SHIP separator at the GSI, in that both use an adaptation of a Wien Filter to use magnetic and electric fields to deflect the beam ions to separate them [47]. As its name suggests however, the DGFRS differs from the design of SHIP in that it is filled with gas, in this case low pressure hydrogen ~ 130 Pa [12, 47].

The first gas filled separator was developed in 1958, at Oak Ridge National Laboratory, Tennessee [48]. Since then many gas-filled separators had been developed, notably the GARIS separator at RIKEN, made famous by the discovery of nihonium [47, 49]. Where the DGFRS stood apart from the rest, however, was in its use of hydrogen when its competitors used helium. This gave the DGFRS an advantage in separation efficiency [47]. For example, in the production of element 114 in the reaction $^{244}\text{Pu}+^{48}\text{Ca} \rightarrow {}^{292}114$, the collection efficiency was found to be 41% [47]. This was one of the higher efficiencies at Dubna, but the DGFRS kept up a high average range of efficiencies between $30-40\%$ for the production of elements 112 to 118 in the time it was in use [46].

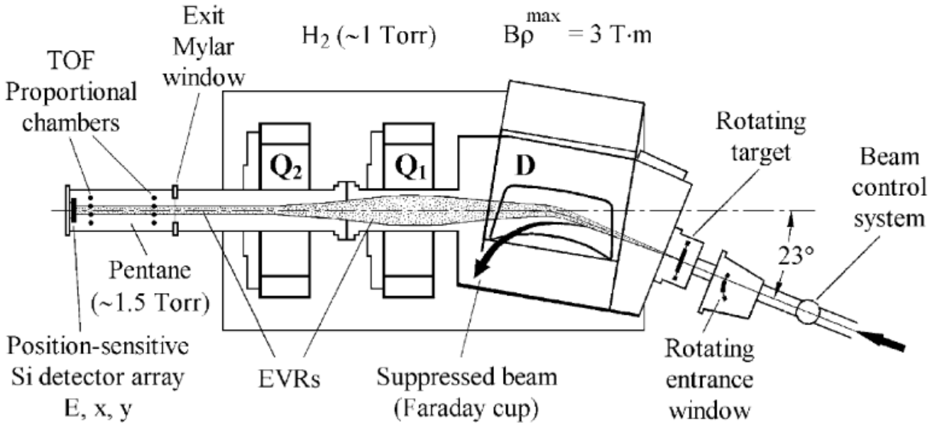


Figure 8: A schematic of the DGFRS, quadrupole magnets are labelled as Q, the dipole magnet is labelled D [47].

On the technical side, the DGFRS is similar in construction to SHIP in Darmstadt. As shown in Figure 8, the main construction of the DGFRS is a dipole magnet, which separates the heavy ions, followed by two quadrupole magnets that focus the ions into α-detectors [12]. When the heavy ions pass through a low-pressure gas, such as the hydrogen in the DGFRS, they change electronic state through collisions with the gas. These collisions occur about 100-1000 times per 1 m of travel [50]. These interactions with the gas lead to the average charge and velocity dispersion of the ions being greatly reduced [47, 50]. These quantities, alongside the mass of the ion, contribute to the magnetic rigidity of the ions. Rigidity is defined as: [47]

$$B\rho = \frac{Am_0v}{q}$$

Where ρ is the curvature of the ions in the separator, m_0 is the atomic mass unit, and v, q, and B are the velocity, charge and Magnetic field strength respectively. When the hydrogen is added, the new distribution of charge and dispersion gives the equation for rigidity a new form: [47]

$$B\rho = 0.02267\frac{A}{Z^{1/3}}(Tm)$$

By adding the hydrogen gas, the curvature radius of the ions in the magnetic field is mainly due to atomic mass with a small factor due to atomic number [47]. Since the produced ions are much higher mass than the beam ions, the DGFRS is highly effective. The suppression factors of the ^{48}Ca beam ions, and nuclei fragments from the target were about 10^{15}–10^{17} and 10^4–10^6 respectively [46]. This device, combined with Oganessian's calcium-48 reaction, would see the JNIR dominate modern discoveries of superheavy elements.

5.3 The Heaviest Elements Yet

Yuri Oganessian and his team found themselves in a fortunate position at the turn of the century; having decided that reactions involving calcium-48 were the correct direction to proceed, they were fortunate to have the element in ready supply. Calcium-48 is rare, it makes up only around 0.187% of naturally occurring calcium [51]. In order to use this isotope in their experiments, the JNIR first had to upgrade their cyclotron, the U-400, to accommodate this new beam particle [51]. This cyclotron, in conjunction with the DGFRS would be the backbone of the JNIR experimental set up for the production of elements 114 to 118 [52]. Indeed, the reaction procedure for these elements would remain steadily consistent throughout. A beam of ^{48}Ca ions would be incident, often at intensities of about 4×10^{12} ions per second, at a heavy actinide element target [51]. For example, elements of Z numbers 114, 116, and 117 were produced by ^{48}Ca ions incident on plutonium-242, curium-248, and berkelium-249 targets respectively [51, 53]. The other elements at produced in Dubna during this time were produced in much the same manner [53]. Element 117, now given the name tennessine after the Oak Ridge laboratory in Tennessee where many of the heavy actinide targets were synthesised is the final super heavy element to date. Found after its heavier cousin oganession in 2009, tennessine represented the limit to what ^{48}Ca reactions could achieve [53, 54].

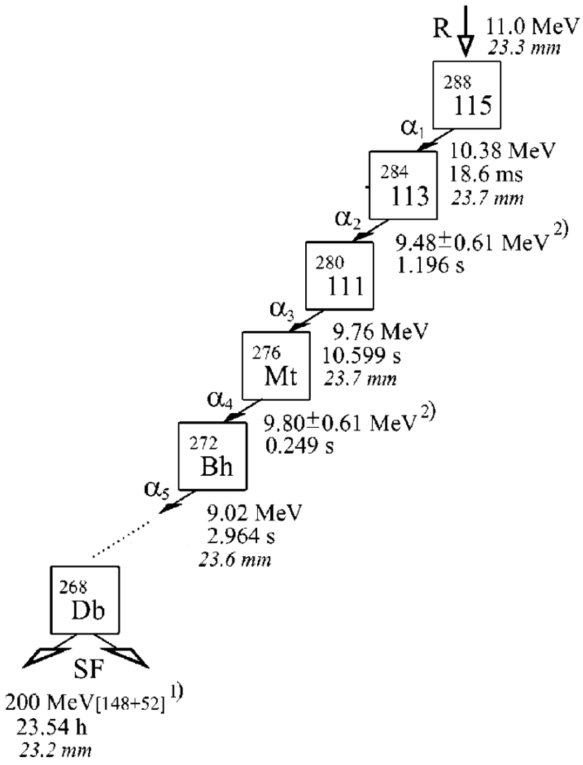


Figure 9: An example α-decay chain of element 115; note the long half-lives in the order of seconds. Figure adapted from [52]

One important discovery made during the process of producing the superheavy ions at Dubna was in the creation of many new, neutron rich, isotopes of other superheavy elements. In the process of analysing the α-decay chains of element 114, the researchers noted that they produced isotopes of superheavy elements that were substantially more stable than any found previously [51]. This pattern continued as heavier elements were synthesised and then their decay chains analysed. For instance in the decay of ^{117}Ts there were 11 completely new isotopes discovered [53]. It was noted that in particular it was the decay chains of superheavies with odd Z numbers that produced isotopes with the highest stabilities [52]. An example of one such chain from the decay of element 115 is shown in Figure 9. The reason for this stability is that the decay of the odd-Z nuclei produce isotopes with an excess of neutrons. This lowers the Coulomb repulsion in these isotopes, greatly increasing their stability and therefore their half-life [52]. The main implication for this behaviour is that the produced isotopes have such long half-lives that it becomes feasible to study the chemistry of these superheavy elements [53]. As will be described in the next sections, it is in the area of chemistry that the study of superheavy elements has some of its' most profound implications.

6 Properties of Super Heavy Elements

With the knowledge of how these superheavy elements have been synthesised both historically and in modern times, this paper can now move on to discussing and explaining the physical properties of these elements. This will hopefully prove to justify the massive undertaking in terms of resources, effort, and expenditure that has been expended in the discovery of these elements.

Superheavy elements typically refer to the elements with $Z \geq 104$, also known as the transactinides [55]. These elements are known to be all radioactive and have all been synthesised artificially via fusion reactions inside laboratories. These superheavy elements can be divided into two currently disjointed categories, these being the: 'lower superheavy region' and the 'upper superheavy region' [56]. The lower superheavy region consists of the lighter elements in the region of $Z \leq 113$ which were discovered using cold fusion reactions [57]. Conversely, the upper superheavy region consists of elements between $114 \leq Z \leq 118$ synthesised using hot fusion reactions [14].

As mentioned previously, these two regions are currently considered to be disjointed. This is because no known nuclear decay chains have been experimentally observed which are able to connect two isotopes from both the upper and lower superheavy region. Finding a decay chain that links these two regions is a current goal for scientists in this field. A connection across these regions would allow for a direct mass and charge identification for super heavy isotopes. This would a mark a significant improvement, as the mass and charge for products of hot fusion reactions are currently measured indirectly [54, 58, 59].

As of now, currently the heaviest element that has been able to be chemically studied is flerovium. Flerovium has a half life in the order of seconds, which is long enough to enable chemical reactions [60]. In order to conduct chemical studies on elements with such short half lives, 'atom at a time' studies must be conducted which allow for the basic chemical properties of these super heavy elements to be tested. The nature of these studies, what they consist of and how they are conducted is outlined further in this section. In the case of flerovium, several atoms can be studied per day, giving researchers ample data for their studies [13].

A majority of the known superheavy nuclei are proton rich systems As a result, a naive expectation would be that their primary decay mode is via the weak interaction, with either β^+ decay or e^- capture. This, however, is not what has been experimentally observed with the modes of decay being either alpha decay or spontaneous fission, which is in line with theoretical expectations [14]. As there is no current method for synthesising neutron rich superheavy isotopes on earth, all predictions about said systems are made from models that involve large extrapolations [54].

6.1 Nuclear Structure

Although the nuclear density distribution provides information on the bulk property of nuclei, direct experimental information on the nucleonic distribution of superheavy nuclei is very difficult to observe due to their vanishingly small half lives. As such, models must be used to predict the structure of most superheavy nuclei. Example of such models are UNEDF1 and SV-min, which provide reliable predictions for very heavy nuclei (i.e.: $Z \approx 90 - 102$) [61]. and hence can be expected to provide reliable predictions for super heavy nuclei (although experimental evidence will be needed to prove this). As of now, experimental studies on the nuclear charge radii and quadripole moments using laser spectroscopy has been conducted in nuclei up to nobelium [62].

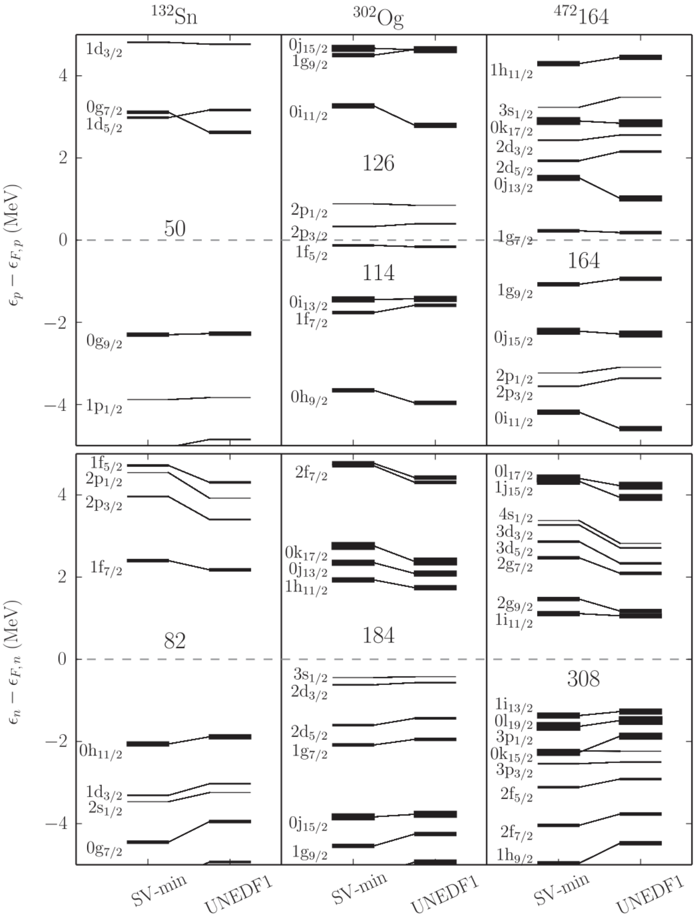


Figure 10: The proton (top) and neutron (bottom) Hartree-Fock single particle energies relative to the Fermi level, ϵ_f predicted with SV-min and UNEDF1 for ^{132}Sn (left), ^{302}Og (middle) and ^{472}164 (right). Adapted from [54].

When analysing the predicted shapes of the nucleonic density functions (DFT) for super heavy nuclei, exotic geometries (such as tori, bubbles rings, etc) can be observed [54]. These exotic shapes appear as a result of the two competing forces in the nucleus (the short range strong force attraction and long range Coulomb repulsion) being unequal. The competition between these two forces in the nucleus is known as Coulomb frustration. Due to shell effects, however, there is a limit on the existence of exotic nuclei geometries. This results in less exotic nuclear structures, such as semi-bubbles as can be seen in certain isotopes of oganesson, which are stable configurations [63].

Modern studies for the shell structures of super heavy nuclei have shown that they vary when compared to the shell structures for lighter nuclei, with the pattern of single particle systems changing drastically in super heavy systems [54, 64].

In figure 10, the predicted single particle energies for ^{132}Sn, ^{302}Og and the nuclei ^{472}164 calculated using the UNEDF1 and SV-min models are shown. When observing the energy gaps for the neutrons, the magic gap for ^{132}Sn is $\approx$ 4 MeV. On the other hand, the gap for ^{302}Og at $N = 184$ is approximately half that of ^{132}Sn. The same phenomenon can be observed to an even more noticeable degree when looking at the energy spectrum for protons, where isolated shell gaps seem to be non-existent [65]. From this, we can see that the shell structure of superheavy nuclei is dependent on the Coulomb frustration, causing magic shell gaps to appear to disappear. This phenomenon, known as shell diffusion, eventually leads to the nucleon density function (NLF) approaching the Fermi gas limit for the outer nucleons [66].

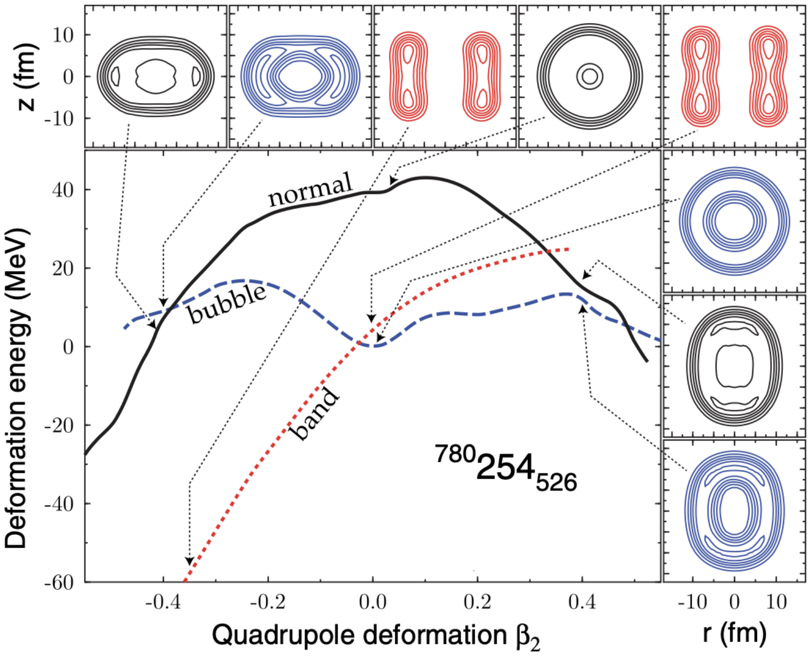


Figure 11: Figure shows the nuclear configurations along side the associated density distributions for the hypothetical $^{780}254_{526}$. The three typologies considered are normal density distribution (black), bubble density distribution (blue) and band distribution (red) and are represented by a contour plot. Adapted from [54].

At the current moment, most models predict that shell stabilised regions for super heavy nuclei can be found at $Z \approx 112 - 116$ and $N \approx 172 - 184$ [64]. Additional regions that are shell stabilised for the neutrons can be found at $N = 258$, $N = 308$ and $N = 410$ [67]. Species with such a large amount of neutrons are categorized as ‘hyper heavy nuclei’.

As the size of nuclei increases, the amount that coulomb pressure influences increases. This therefore leads to a smaller nuclear density at the center of the nucleus, which enables the existence of exotic typologies, such as bubbles or band like toroids, as the mass of the nuclei increases beyond $Z > 120$ [68]. Examples of such nuclear geometries can be seen in the contour plots of figure 11.

6.2 Relativistic effects and Electronic Structure

Atoms are multi-bodied quantum systems, with very complicated behaviour governed by the Schroedinger equation. The reader is to be reminded of the difficulty of describing the hydrogen atom in quantum mechanical courses and then doubly reminded that all of the unnatural elements considered throughout this report consist of atoms that contain many more electrons and much heavier nuclei. As such, approximative methods are frequently utilised to lessen the computational strain of modelling so many particles.

One such simplified example is associated with so-called Hartree-Fock methods. These "methods" consist of a number of assumptions made about the Schroedinger equation. Under these assumptions, in which the wave functions of the atomic orbitals are treated as if they were independent of one another, a minimum value of the energy associated with the energy of the atom can be postulated [69]. These methods are widespread throughout elemental chemistry and are critical in determining the electronic properties of superheavy elements.

When treating electrons as particles, a naive assumption could be made that electron in the valence shells are not affected by relativistic effects due to their velocities not being comparable to the speed of light [70]. However, using quantum theory, a more accurate interpretation can be found as even electron in the valence shell that may be considered slow, still contain a large part of their electron density near the nucleus where perturbations due to relativistic effects are at a maximum. S orbital electrons in particular are greatly affected by relativistic perturbations, as their wave functions are mostly located near the nucleus, resulting in the tails of their wave functions being drawn in and contracting compared to S orbital wave functions for lighter species [71]. These relativistic phenomenons therefore affect the entire electron cloud of super heavy elements and result in the electronic configurations of super heavy elements being different to their lighter counterparts.

There are three main relativistic effects that result in perturbations of the valence wave functions of super heavy elements. The first relativistic effects regards the stability of the atom and the 1s electron state. From the Sommerfield fine structure formula, which describes the discrete spectrum of a fermion with a point like nucleus, we find that the ground state energy of an electron in the 1s state approaches zero as $Z \rightarrow {}^{1}\!/_{\alpha}$, which is ~ 137 and that energy eigenstates beyond this limit become imaginary, known as the 1s catastrophe. When extending this phenomenon to multi-body systems, the nuclear charge becomes screened by the filled shells [54]. Although this does shift the critical nuclear charge at which point the eigenenergies become imaginary, its effect is negligible as the critical charge still remains as $Z \approx 137$. Another factor which affects the critical charge in a non-negligible manner is the fact that the size of the nucleus is finite. This shifts the critical charge where the 1s catastrophe will occurs to $Z \approx 169$ [72].

The second relativistic effect regards the contraction of outer shells in superheavy elements as outer sub shells with larger n quantum numbers contract more that their counterparts in sub shells with lower n quantum numbers [73] This contradicts the previous assumption of orthogonality which stated that outer shells would only contract 'due to contractions of inner shells' [74]. These relativistic effects result in the deviation from what would be predicted for heavies species, such as why ${}_{111}$Rg's ground state configuration is different from periodic trends. This would further explain why its atomic size halves compared to other elements in the same group [75]. Another result of this particular relativistic effect is the contraction of the 7s valence shell for ${}_{112}$Cn. This has been shown to cause the property that copernicium is more inert than mercury, which is the lighter element in group 12 [76]. This is another break shown by super and hyper heavy elements from standard periodic trends.

The final main relativistic effect that presents itself is fine structure splitting due to spin-orbit coupling of orbitals with a l quantum number greater than zero [74]. In oganesson, this effects manifests itself by resulting in a splitting of the ^2p orbital of 10.1 eV, which is larger than most other bond dissociation energies. Additionally, in oganesson, the expansion of the $^7p_{3/2}$ orbital (valence orbital) and the contraction of the $8s$ orbital result in an electron affinity of 0.064 eV, which breaks from the trend of its periodic group as it no longer behaves as a noble gas [66, 77]. Additionally, due to these relativistic effects, the electron density of $_{118}$Og becomes smeared which leads to the valence electrons of oganesson acting like a Fermi gas [66] (more detail on this phenomenon will be explained in the following section). Conversely, these relativistic effects result in $_{114}$Fl having a closed shell configuration with an electron affinity of zero, hence making flerovium much more chemically inert than other elements found in its period [78].

6.3 Chemical and Bulk Properties

As mentioned previously, relativistic effects have a non negligible impact on the valence electrons of super heavy elements. This also leads to differences in the chemical and bulk properties of these elements diverging from what would be expected when comparing to periodic trends. As the half-lives of these elements are extremely small compared to lighter elements, novel methods must be implemented to conduct chemical experiments. The current method to measure the volatility of super heavy elements is to couple gas phase chromatography set-ups to the recoil chambers of accelerators [13]. A flow chart detailing the process for conducting chemical reactions on fission products can be found in figure 12. These set ups allow for super heavy species to be separated and transported to a chamber where chemical experiments can be conducted. To test the volatility of these elements, the super heavy elements are made to react with a thin gold surface in order to measure the binding energy of bonds between the superheavy element and gold [79].

At the current time, volatility studies have been conducted on elements as large as Fl, however studies on Cn have also been of interests to scientists due to it's closed shell structure. From these studies, it was found that both elements would bind weakly to the gold surfaces, with binding energies of 52^{+4}_{-3} Kj mol^{-1} for Cn and ≥ 48 Kj mol^{-1} for Fl [76, 80]. These values are in accordance with theoretical studies using the latest models [81]. From the results of these studies, it was concluded that, while both Cn and Fl were both elements that exhibited metallic characteristics, they were considerably less reactive compared to lighter analogues in their respective groups, once again breaking from periodic trends [80].

Another chemical property where relativistic effects can be shown to have a noticeable impact is the available oxidation states of superheavy elements. These states will ultimately limit which molecular structures are available to that species of superheavy element. For the elements Rg, Cn and Ds; mixing between the 7s and 6d orbitals in chemical bonds stabilises higher oxidation states then what would be expected for lighter elements. This results in maximum oxidation states of up to +5 and +4 for Rg and Cn respectively [82, 83]. Conversely, the opposite effect can be seen for the elements Nh and Fl, where mixing of the s and p orbitals in chemical bonds reduces the stability of high oxidation states [84]. Orbital mixing is not the only source for divergence of oxidation states from what would be naively predicted from periodic trends, as spin-orbit splitting of the 7p orbital leads to the maximum oxidation state of Og being restricted to +4. This is in contrast to the maximum oxidation state of its lighter analogue in group 18 Xe, which has been observed to have a maximum oxidation state of +6 [85]. This divergent behaviour of oganesson from that shown by other elements in its group is a general trend for the synthesised element. A more in-depth analysis of Oganesson is to be presented in the following section.

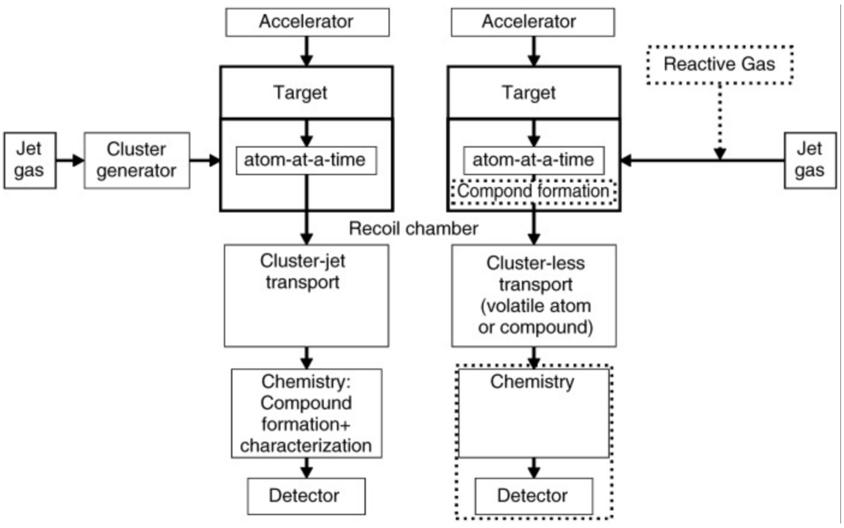


Figure 12: Depicts a flow chart that depicts two methods used to conduct chemical reactions on super heavy fission products. **LEFT**: Products are transported via aerosol (i.e.: cluster) to the chemistry apparatus where compounds are formed. This method is used for studies on compounds of Rf and Bh. **RIGHT**: Compound of fission products are formed in recoil chamber and then the volatile compounds are transported to a chemistry apparatus. This method is used for studies on compounds of Hs and Cn. Figure was adapted from [86]

7 Oganesson

7.1 Oganesson orbital structure

The case study of oganesson is an illustrative example of the possible structures and properties that superheavy, synthesised elements may be able to form and possess. Oganesson is the element associated with $Z = 118$ and is currently the heaviest experimentally verified element of the periodic table. It was first synthesised by the team of Yuri Oganessian at the Dubna Laboratory in 2002. The team used hot fusion methods to isolate oganesson from the collision of a calcium beam with a californium target [87]. Oganesson is highly unstable, with a tiny half-life of just 0.89 ms. As such, its chemical properties cannot be analysed directly and so have been approximated with various methods including Hartree-Fock calculations. As an addition to the periodic table, oganesson would be situated in the group of the periodic table corresponding to the inert gases. However, its theorised properties diverge spectacularly from other elements within the same group. [88]. In fact, oganesson has a number of properties that distinguish it as an extremely unusual element regardless of its position in the periodic table, a number of which will be explored in this subsection.

Oganesson is a superheavy element. Its high atomic number causes the element to possess a number of properties that distinguish it significantly from the behaviour expected of the more familiar elements in the periodic table. This is as a result of a number of relativistic effects. Under the Pauli exclusion principle, multiple fermions (like electrons) are not allowed to occupy the same quantum state. As a result of this, electrons in an atom cannot occupy the same energy levels. With increasing atomic number, the electrons are pushed up to higher and higher energy levels. For a superheavy element such as an oganesson, the electrons associated with the atomic system are given a kinetic energy that is considered significant in a relativistic context. In other words, this means that the electron speed is high enough to approach the limit in which relativistic effects must be considered. This relativistic contribution to the ground state binding energy of oganesson totals 227 KeV, which causes a very large spin-orbit splitting in the atom. This can be compared to a contribution of 40 KeV for Pb which is a significantly smaller quantity. [88]

This large Spin-Orbit separation takes place between the $7p_{1/2}$ and $7p_{3/2}$ shells. A contraction of the vacant 8s orbital is also induced. There are a range of effects associated with this splitting.

The first of these bizarre effects is linked to the energy and interatomic forces associated with an Oganesson atom. The bonding energy of the element is greater than the excitation energy of the atom, meaning that the element is bound only by London or very weak metallic interactions [88]. Furthermore, oganesson has a proton affinity only behind Lead in the known elements [89] and has been shown to have a positive electron affinity [75]. These are certainly not properties that would be considered emblematic of the famously inert Group 18 elements.

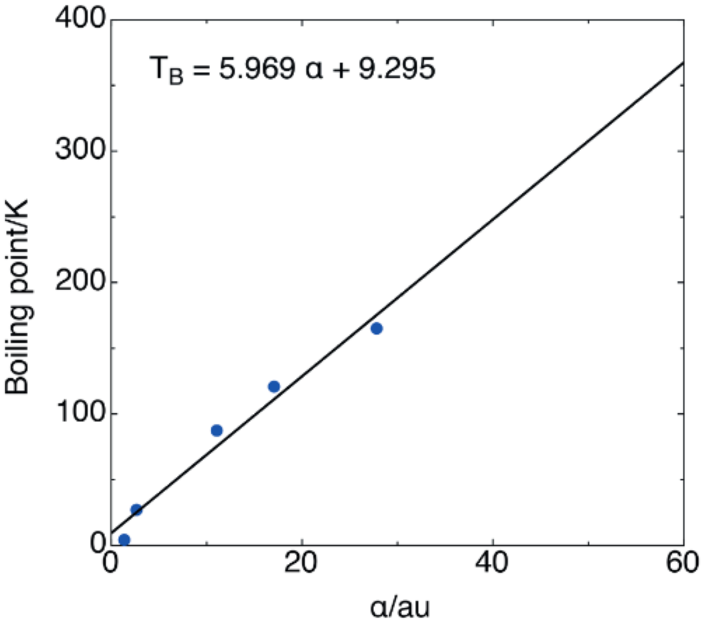


Figure 13: Boiling points of the noble gases He–Xe in kelvin plotted against static polarisabilities in atomic units

Oganesson has been calculated to have an abnormally high static dipole polarisability. This value calculated is almost twice that of Radon, which is the next heaviest noble gas discovered. This would predict a significant increase in the van der Waals interactions associated with atoms of oganesson especially when compared to the values calculated for lighter Noble Gases. Additionally, using this high value for static dipole polarisability and extrapolating from the established linear relationship between static dipole polarisability and the boiling points of noble gases He - Xe, oganesson has a theorised boiling point at between 320 – 380 K. This would mean that oganesson would take on a liquid form at room temperature solely as a result of the heightened non-covalent interactions within the atom. This ,once again, puts Oganesson at odds with its periodic position within the so-called noble 'gases'. [88].

Oganesson also differs greatly in electrical conduction behaviour from the other group 18 elements. Other elements in this group have been experimentally confirmed to adopt the form of insulators in their solid phase, with electronic band gaps varying from 21.51 eV for Neon to 9.32 eV for Xenon. Oganesson, based on band-structure analysis, is found to have a much lower band gap of 1.5 eV (as shown in figure 14), which is a value low enough to put oganesson in the commonly accepted domain of semi-conductors. [90].

This unexpected behaviour of oganesson as a semi-conductor can be explained by its wider chemical structure. Under the large spin-orbit coupling, oganesson has been shown to display the behaviour expected of a Fermi electron gas due to delocalisation effects leading to a process known as electron 'smearing'. This smearing process causes the electrons in oganesson to abandon the established band structure of an atomic nucleus.

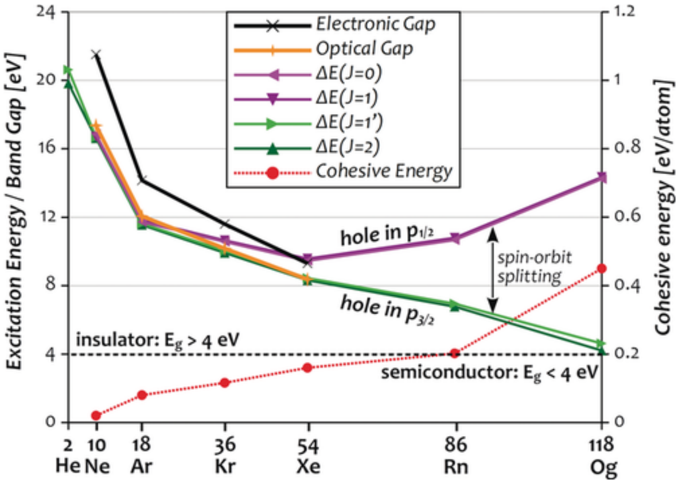


Figure 14: Transition energies of the four lowest excited states of the noble-gas atoms (green: hole in $p_{3/2}$, purple: hole in $p_{1/2}$) compared to optical Og (orange)17 and electronic band gaps (black) along with cohesive energies (red, secondary axis). The spin-orbit splitting is clearly displayed.

Figure 15 displays the Electron Locality Functions of three elements in group 18, xenon, radon and oganesson. The diagrams on the left correspond to ELFs made using non-relativistic calculations and the diagrams on the right correspond to ELFs made using relativistic Hartree-Fock calculations. As shown for oganesson in the bottom right, incorporating relativistic effects within the oganesson atom leads to a more uniform distribution of electrons within the atom. The atom directly cannot be said to be modelled by a clear band structure. This smearing out of the locality functions means that oganesson much more closely resembles a Fermi electron gas rather than a superposition of electron orbitals following a band structure. [89].

Under the Nuclear shell model, oganesson is predicted to be a highly deformed atom, lying eight neutrons away from the magic number $N = 184$. It is predicted to have a very strong repulsive Coulomb interaction associated with its atomic system, causing a very large static dipole polarisability value. As such, the Coulomb interaction cannot be considered a perturbation to a known atomic potential, as is familiar in the case of hydrogen and helium atoms, because its numerical value is too significant. This causes major effects to the theorised shell structure of the protons and neutrons inside oganesson, which can be seen in figure 15 [66].

Superheavy elements tend to have significantly more neutrons than protons. As such, there is a significantly higher smearing effect displayed among the neutrons than the protons as there are more neutrons contained within the same volume. This leads to greater potential for neutron delocalisation effects, as can be seen in figure 16. Nucleonic orbits scale much more slowly radially than electronic orbits and as such they are much less spatially separated. The smearing effect is lessened across all nucleons compared to that experienced for electrons as a result of this. Therefore, as shown in figure 15, the nucleons contained within an atom of oganesson still display a clear band structure even if it is not as clearly defined as for lighter elements like Tin [88]. In particular, the protons of oganesson cannot be said to be delocalised under these calculations.

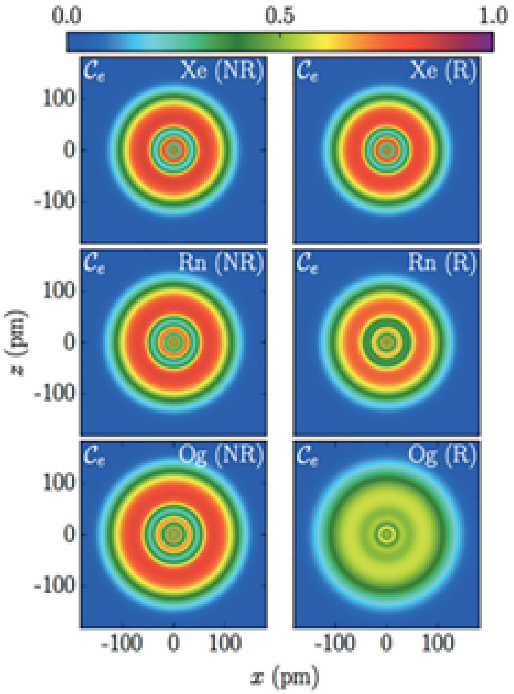


Figure 15: Electron Locality Functions from non-relativistic (NR, left) and Dirac–Hartree–Fock calculations (R, right) for the atoms Xe (top), Rn (middle), and Og (bottom).

Due to the very short atomic half-life of oganesson, all of the chemical properties explored thus far in this report habe been devised from approximative methods and therefore by nature partly theoretical. To preclude this section being of an entirely academic nature, there has been research conducted into theorised stability of heavier oganesson isotopes with a larger neutron excess ; and of the synthetic elements $Z = 112-118$ produced within the last few decades more generally. Oganesson isotopes of mass number $A = 299 - 306$ were predicted to be spherical or almost spherical nuclei, in contrast to the highly deformed nature of the only known oganesson isotope to exist, $A = 294$. The highest binding energies were associated with the mass numbers $290 - 296$ with the longest half-life predicted to be that of mass number 295 which was calculated to be 47 ± 15 ms [91]. This figure still remains too small for any significant application or direct experimentation of the element, which would require a half-life at least within the order of seconds.

Oganesson would fall within the range of the island of stability theorised by the nuclear shell model, wherein isotopes with atomic numbers $Z = 114 - 126$ and neutron numbers $N = 172 - 184$ would have half-lives much longer than other isotopes with atomic and neutron numbers locally outside of this range. It has been shown that it is directly possible using cold fusion methods with a calcium target to synthesise the heavy isotopes of oganesson with mass number $295 - 298$. These would lie close to the island of stability and provide an opportunity to further experimentally test this prediction of the nuclear shell theory. However, both the island of stability and heavier oganesson isotopes remain without experimental basis [92].

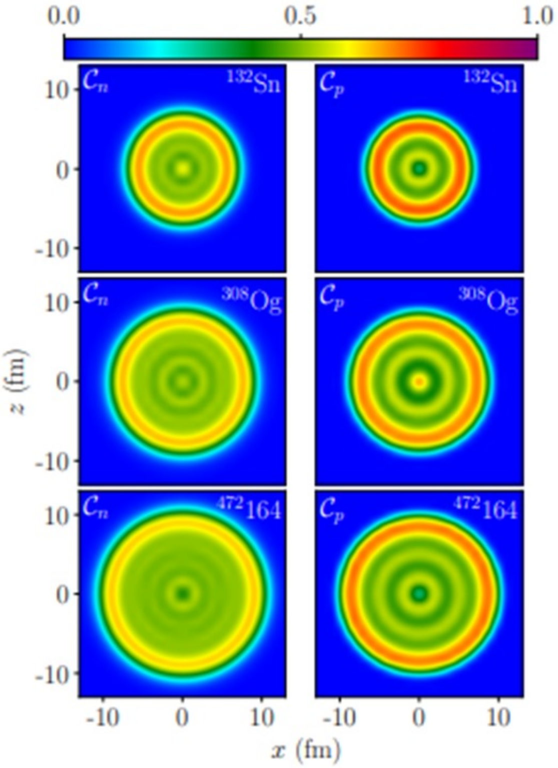


Figure 16: Nucleon Localisation Functions from non-relativistic (NR, left) and Dirac–Hartree–Fock calculations (R, right) for the atoms Sn (top), Og (middle), and theoretical Z=164 element (bottom).

In this section, a case-study of the element oganesson has been presented. Oganesson had been chosen because of its unusual theorised chemical properties for its position in the periodic table. Oganesson experiences highly relativistic effects due to its high electron and nucleon number, causing a range of interesting effects. These include its liquidity at room temperature, its semiconducting behaviour and induced electron delocatisation effects. The stability of proposed isotopes that are yet to be experimentally discovered has been explored with an inconclusive set of results to provide evidence for the 'island of stability' hypothesis.

The analysis of Oganesson has pushed our research to the very limit of the known limit of the periodic table. However, every elemental discovery, regardless of its fascinating structure, prompts further questions. Will there be more elements found? And if so, how many?

8 Beyond the periodic table

8.1 Properties above $Z \geq 120$

Now that elements up to $Z = 118$ have been confirmed to be experimentally observed, a majority of the scientific community has shifted in attempts to synthesise elements 119, 120 and beyond. Hence, studies on the properties and structure of these elements are also of great interest. Beyond element 120, the major relativistic effects experienced by superheavy elements become even greater. As such, studies of these hyper heavy elements return drastic deviations from the expected trends.

An example of this is that beyond $Z = 120$, the 7d, 8p 6f and 5g shells start to fill almost simultaneously, which is a filling pattern unseen in lighter elements. Current theoretical predictions have the 5g shell starting to be filled at $Z = 122$ and being fully complete at $Z = 144$ [93]. This is not agreement with the current periodic table model, which would dictate the 5g orbital starting to fill at $Z = 121$ and being completed at $Z = 138$.

Due to these phenomena, among multiple others that affect the electronic configurations of elements beyond $Z \geq 120$, the current layout of the periodic table has come into question, as it would have to be redesigned in order to still accurately display the trends in superheavy elements. Using Dirac-Fock calculations, the order in which electronic shells become occupied could be calculated up to $Z = 172$, allowing for an accurate periodic table that places hyper heavy elements correctly to be constructed. An interesting result from this study is the significant deviation from the Madelung rule due to shell stabilization between the $8p_{1/2}$ and $9p_{1/2}$ shells. The results of these anomalies can be seen in figure 17 [94, 95].

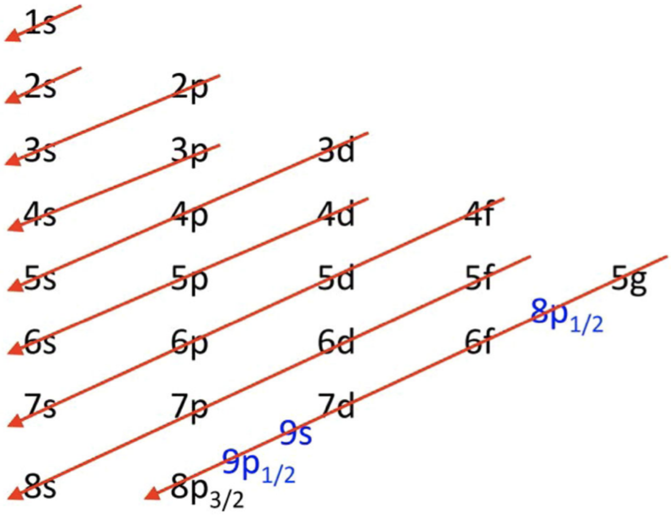


Figure 17: The ordering of successive shells for elements ranging up to $Z = 172$ according to Madelung rules. Anomalies of Madelung rule due to relativistic effects of the p shell at high Z are highlighted in blue. Adapted from [54, 95]

8.2 Limits of the periodic table

As atoms become larger, we start to see limits put in place where the models we currently use to understand atomic and nuclear physics begin to break down. This occurs both with the electronic and nuclear components.

According to the most modern electronic shell structure predictions, there is an end to the periodic table at $Z \sim 172$ due to electrons in the 1S entering into the negative energy continuum, or the super critical region, when using a mean field approximation of the Dirac equation [54, 96] (this can be seen in figure 18). When extending to a system with multiple electrons, the nuclear charge becomes screened by the inner electrons, which shifts the critical nuclear charge Z_{crit} at which the inner electron exist in the supercritical regions. This shift, however, is only slight and does not have a significant impact on Z_{crit}.

Near Z_{crit}, the single particle approximations typically used to model and calculate superheavy nuclei's properties (such as Hartree-Fock) break down such that the complete QED Lagrangian must be used for proper treatment of these hyper heavy atoms. Additionally, Zα expansions which are utilised to calculate QED shifts for particles energy levels also break down [97].

Attempts to explain the physics beyond the supercritical region have been made by multiple physicists and hence there are multiple current theories with different explanations and approaches. The most common interpretation of what happens beyond the supercritical region is that the 1s state becomes a resonance that is inside the negative energy continuum of the Dirac equation. This makes spontaneous electron pair production possible as a result of vacuum fluctuations [98]. This can be thought of as the 1s state being occupied by an electron from the Dirac sea, which therefore leaves a hole that escapes in the form of a positron while the electron remains inside the inner 1s orbital. This interaction can be thought of as an inverse pair annihilation. As the 1s orbital allows for two electrons, it is theorised that this process occurs twice, at which point the 1s orbital becomes stabilised due to Pauli's principal [99].

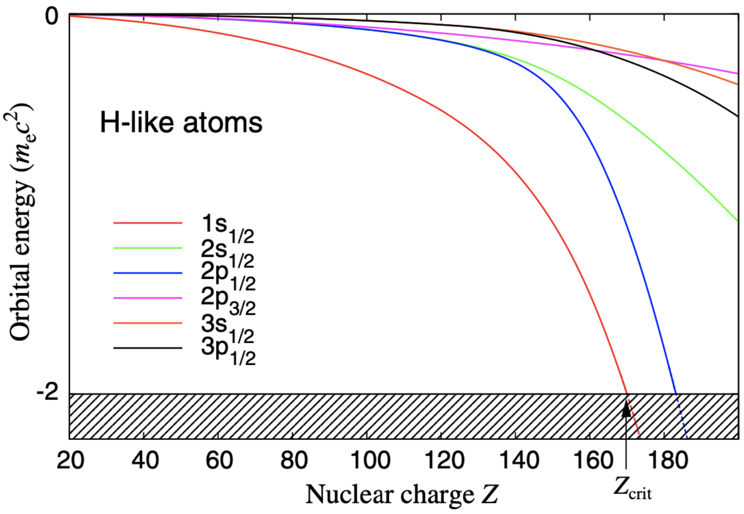


Figure 18: Figure represents the energy of hydrogen like orbitals. The $1s_{1/2}$ orbital can be seen falling into the negative energy continuum at $Z_{crit} \sim 172$. Adapted from [96]

Although there is as of yet no clear consensus on how to treat systems beyond the supercritical region, there is also no direct evidence to suggest that the periodic table explicitly ends at $Z \sim 172$, even though modern studies have not as of yet probed further into the periodic systems of elements [95].

As mentioned previously, nuclear phenomena may also play in a part in determining the limits of the periodic table. An example of such a phenomena is that as the electron density of the 1s shell starts to contracted towards the nucleus due to the increased fields of larger nuclei (which can be seen in figure 19), the probability for inner 1s electrons to undergo electron capture with a proton in the nucleus also increases. Hence with increasing Z, the stabilization of the 1s shell decreases and may ultimately place a limit for the superheavy elements due to K capture at a critical value of Z [96].

Another factor that may influence the limit of the periodic table may be due to the large disparity between the nuclear and electronic timescales. In order to classify a superheavy species with an atomic number Z as an element, we require it to exist for a minimum amount of time in the order of $\mathcal{O}(10^{-14})$ s. This is the minimum amount of time required for a nucleotide to acquire its valence electrons, which determines an atoms chemical properties. This therefore would point to the conclusion that, if any isotope for super or hyper heavy nucleotide do not have a nuclear lifetime of 10^{-14} s, a corresponding element does not exist [54, 100].

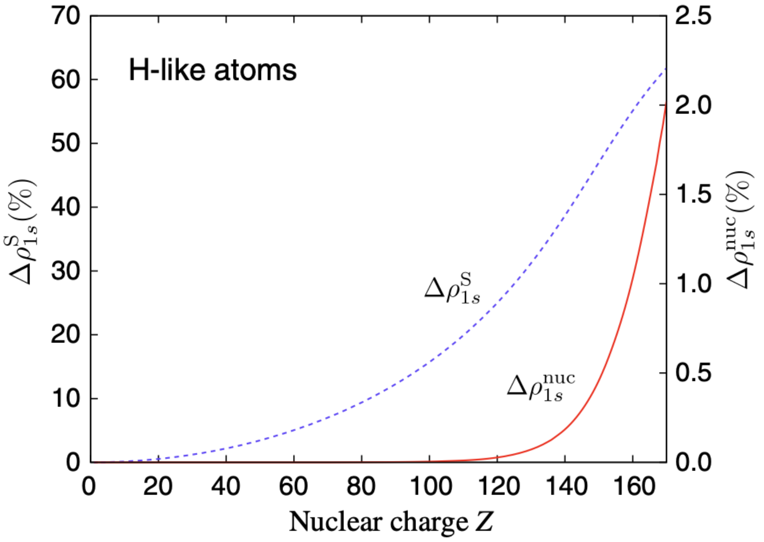


Figure 19: Fraction of the electron density for 1s shell due to the small component $\Delta\rho^{S}_{1s}$ (represented by the dashed line) and the fraction and of the 1s electron density that is located in the nuclear radius $\Delta\rho^{nucleus}_{1s}$ (represented by the solid line) as a function of nuclear charge for hydrogen like atoms. Adapted from [96]

This is contrasted with the fact that in order to define a nucleotide, its lifetime must be longer than the timescale of a single particle to create the nuclear mean field, which is approximately $T_{s.p} \approx 1.3 \cdot 10^{-22}$s [101]. Hence, it is expected that there exist no elements for superheavy nuclei that have a lifetime approximately within the bounds of $\mathcal{O}(12^{-22})$ and $\mathcal{O}(12^{-14})$. Ideally, by a prediction of the lifetimes of nuclei beyond $Z \geq 120$, it could be predicted not only which isotopes of hyper heavy nuclei have corresponding elements, but also whether it is the electronic or nuclear constraints that determine the end of the periodic table, Unfortunately, there are no reliable methods to predict lifetimes of nuclei beyond $Z \geq 120$. This is mainly due to the difficulties of predicting the effects of Coulomb frustration at the hyper heavy regime. Because of this, it is a real possibility that the periodic table ends significantly before Z_{crit} due to the nuclear lifetimes of hyper heavy nuclei [102].

9 Conclusion

This project has consisted of a scientific review, supplemented with historical context, on the topic on unnatural, or artificially synthesised, elements.

In the course of this project, this history has been examined from a number of different perspectives. The initial steps of synthesising elements have been explored, from the development of the first cyclotron to the eventual advancement in genetic relation techniques onto cold and hot fusion methods. The process of verifying an element that has been artificially created has been explained, most notably in relation to prior putative discoveries that have led some claimants to Nobel Prizes and additions to the periodic table, and others to early retirements.

The current frontiers of the established group of elements have been considered. The team led by Yuri Oganessian at the Dubna research laboratory have heralded a slew of new element discoveries. These elements are much heavier than those that have been analysed experimentally before, with a number of exciting and hitherto unknown chemical properties due to relativistic and quantum mechanical effects. These effects have been explored with a particular focus on the case-study of oganesson, which appears to be a very unusual incorporation to the established picture of chemical elements indeed.

The limits of the periodic table have been considered, with the door left open to more inclusions to the currently known menagerie. This project has taken in the experimental feasibility of synthesising even heavier elements than those already analysed, along with the theorised chemical structures they may form. The proposed "island of stability" has been visited, in the domain of hyperheavy elements with atomic numbers larger than 120. It it not clear if these hyperheavy elements will ever be fully documented by scientific research or explored by chemical laboratories. What is clear however, is that the research into unnatural elements is unlikely to cease, and that the search to synthesis ever heavier and more bizarre elements will continue in the many years to come.

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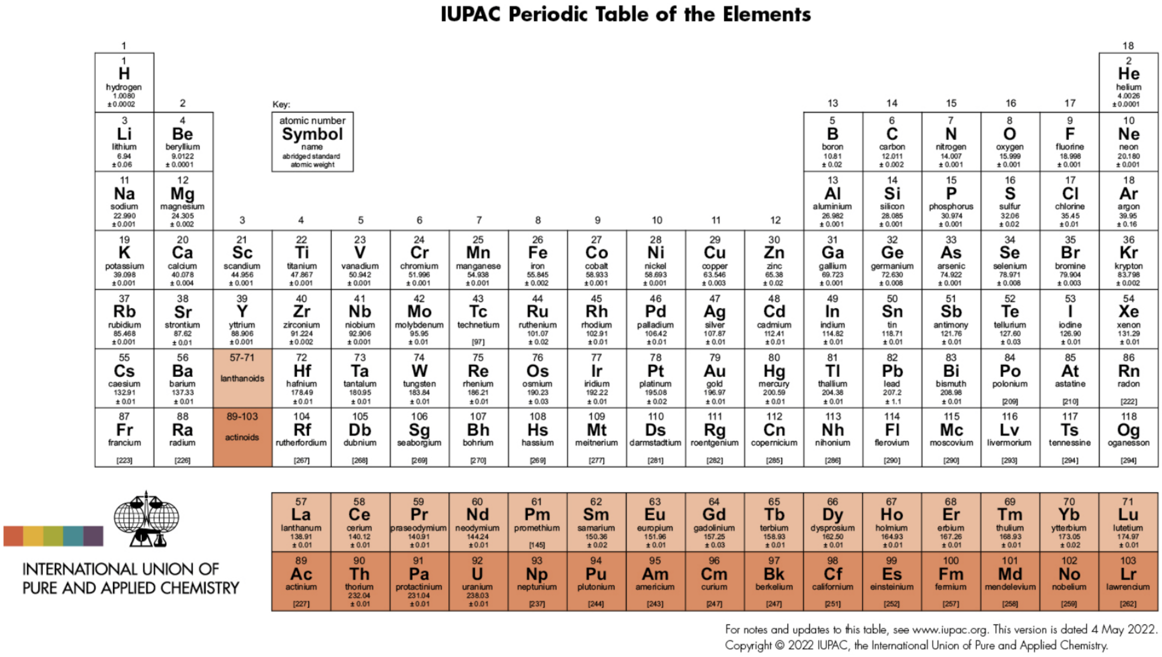
A Periodic table of elements



IUPAC Periodic Table of the Elements

Key:
atomic number
Symbol
name
abridged standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002											13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]	110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]
			57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02	63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
			89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.04 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

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Figure 20: A depiction of the current periodic table as of May 2022. Figure was adapted from [103]