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Were the Superheavy Elements made in Space?

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Abstract. A question for decades has been the potential production of heavy or superheavy elements in nature. Once the nuclear weapons tests showed that elements heavier than the Uranium were found in the debris, it was clear that a rapid neutron capture process followed by beta decay was creating heavier elements. The next question was the location of the r-process end? What other heavy elements are made? Did nature make the superheavy elements via the r-process too? The answer is yet to be found. There are many indications that it probably did but the definitive evidence is yet to surface. The laboratory experiments with neutron rich beams and neutron rich targets via cold and hot fusion reactions have created a number of new isotopes in addition to the elements that have completed the periodic table. Furthermore, the new superheavy element factory at the JINR in Dubna has now allowed the identification of over one hundred decay chains of the various isotopes of superheavy elements connecting to the main part of the chart of nuclides via decays. This is where we should look for the definitive evidence for the production of the superheavy elements in nature.

1 Introduction

Nuclear Astrophysics is the engine of the universe operating in various exotic stellar scenarios to synthesize the elements that we observe today. The elemental abundances of the universe from the big bang to the present are shown in Fig. 1 in terms of the relative abundances or the mass fractions of the elements as a function of the mass number A. We believe that microseconds after the big bang, neutrons and protons emerged from the quark-gluon soup to form the primordial elements of H, He, and Li. The formation of the first and following generations of stars are fueled by the energy released in the fusion of the lighter elements up to approximately A=56 of Ni and Iron. Beyond that, by necessity, it is the neutron reactions that are responsible for the synthesis of the heavier elements. The neutron processes are coarsely divided into slow (s-) and rapid (r-) neutron capture where each process is responsible for the existence of approximately 50% of all the heavy elements beyond Fe. This labeling and separation of (s-) and rapid (r-) neutron capture reactions was already recognized in the 1950s by E. M. Burbidge *et al.* (B^2FH) [2, 3]. Also, the concept of fast neutron reactions that can create elements beyond the initial constituents of nuclear devices was noticed then and influenced testing in the early times of the US test program. The s-process is thought to occur in the He-burning layers of the low-mass asymptotic giant branch (AGB) stars [4, 5]. Until very recently, the site for the r- (rapid-neutron capture) process was still unknown. Two of the most

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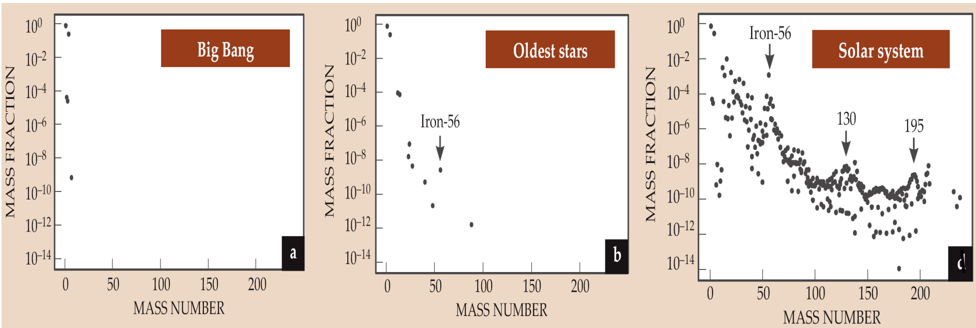

Figure 1. Relative abundances of the elements [1]: a. The relative mass fractions right after the big bang; b. in the oldest stars; and c. in the present solar system.

popular sites for the r-process had included core collapse supernovae and two-neutron star mergers. While it was known that simulations of core collapse supernovae ran out of neutrons before the synthesis of the elements beyond the A=130 peak of observed solar abundances, they were favored since they are more frequently observed in the cosmos. Two-neutron star merger simulations on the other hand proceed to the synthesis of the elements well beyond the A=130 peak, all the way to the actinides [6, 7]. The observation of gravitational waves GW170817, associated with a two-neutron star merger event arriving on earth after an event that took place 132 million years ago, by both European (VIRGO) and American (LIGO) gravitational wave detectors allowed the opportunity for humanity to simultaneously observe the elemental synthesis associated with the kilonova. The 70 electromagnetic satellites that could focus on the same location in space, allowed the measurements and hence the observations of the blue light associated with light element synthesis and eventually the shift into the red-orange region expected from atomic excitations of rare-earth elements, before disappearing into the IR. At the time, there was no IR detector on the various satelites but that has now been remedied since the launch of the James Webb telescope on Christmas Day in 2021. Also, the LIGO, VIRGO, and GAGRA gravitational detectors all began new observation cycles on May 24, 2023. The commonly accepted belief among astrophysicists is that if the synthesis of the elements reached the rare-earth region, then almost certainly the process continued to the synthesis of the actinides. Simulation of a two-neutron star merger r-process is shown in Fig. 2. The prevailing opinion amongst astronomers, astrophysicists, and nuclear physicists is that if the element synthesis reaches the rare-earth region, it will surely proceed to the actinides. Simulations are limited by the input nuclear data and in this case, only elements up to Z=110 are included. The result is the synthesis of elements with a limit of a mass number of 290. The question remains, *how far did the r-process go?*, and even further, *Did the r-process make the superheavy elements in space? What is the evidence for the creation of the superheavy elements in nature?*

2 Heavy and Superheavy Elements

The heavy and the superheavy elements are now made in powerful accelerators with neutron rich targets and neutron rich beams via cold and hot fusion reactions around the world.

Figure 3 shows the years of their initial year for the elements with Z=104 to 118. The last row of the periodic table of elements Z=113, 114, 115, 116, 117, and 118 were made by ^{48}Ca beams. Some decades ago however, Professor Glenn T. Seaborg of the University

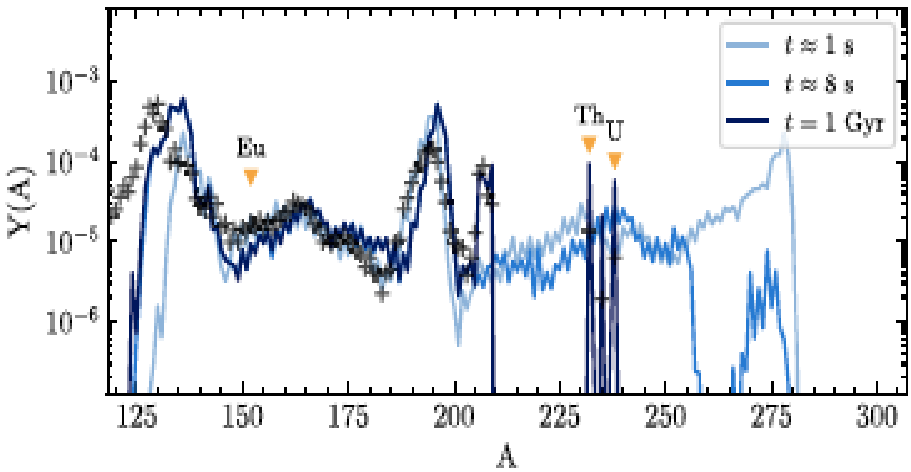

Figure 2. The black crosses are the observed relative solar abundances. The light blue line shows the result of the nucleosynthesis simulation at 1s, the darker blue line is a reflection of the abundances at approximately a time of 8s when the β-delayed fission dominates over neutron induced fission, and the final time in black at 1 Gyr. The Th/U mass numbers are indicated as well as the A=150 region of the Eu elements [7]

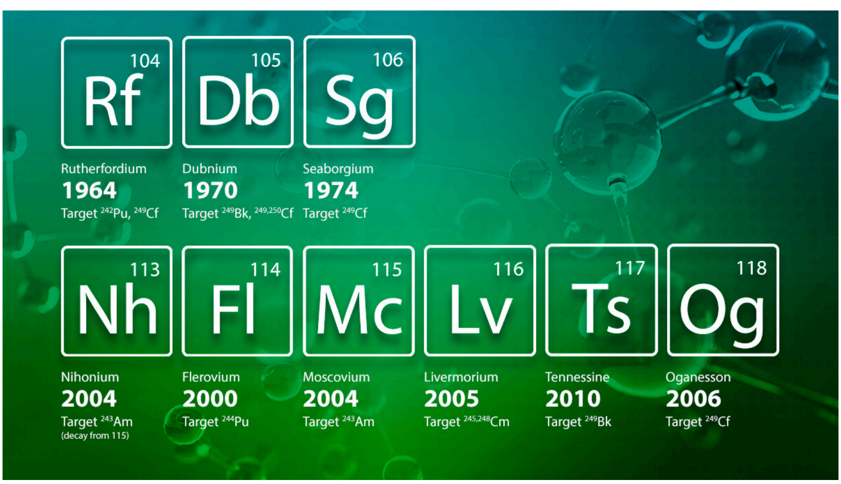

Figure 3. The nine superheavy elements and their year of discovery by various physics experiments.

of California and Lawrence Berkeley Laboratory was the one directing the research and the planning/development of weapons tests as a way of producing the heavy and superheavy elements in device tests. Seaborg was the head of the Atomic Energy Commission and numerous nuclear weapons tests were being designed with that final goal in mind. The suggestions for the r-process had already been made by B^2FH and studies of debris from various tests had indeed shown that significant amounts of Es (Einsteinium, Z=99) and Fm (Fermium, Z=100) were present in various analyses of test debris. Figure 4 shows the production results from three such tests as a function of mass number A. These analyses and results were published in

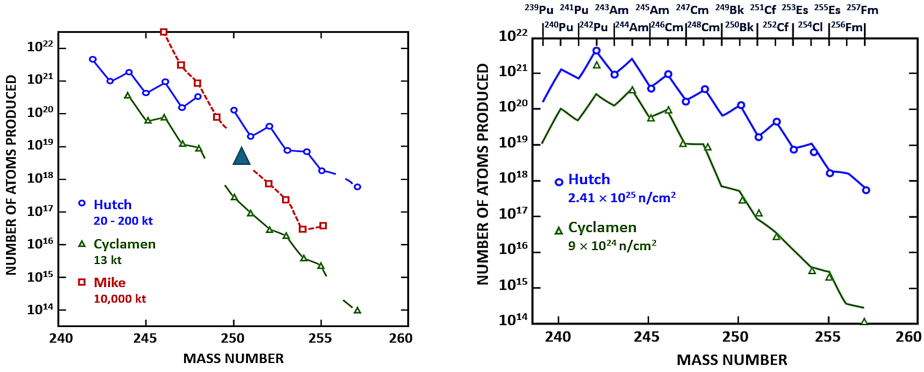

Figure 4. Number of atoms detected as a function of mass number A for three device tests [8].

a conference proceedings on heavy elements [8] for three tests, Hutch, Cyclamen, and Mike. The strongest of these was the Mike device at 10,000 kt. It was an underwater test and made the collection of debris more challenging. Nonetheless all three devices showed production of heavy elements including Es and Fm. The number of atoms detected were above 10^{19} or 10^{18} atoms in these tests. Neutron star densities of the Hutch and Cyclamen devices were determined to be 2.4x10^{25} n/cm^2 and 9 x10^{24} n/cm^2 respectively. The estimated neutron-star densities are of course much higher at 10^{43} or 10^{41} n/cm^2. These weapons device tests offered a hint.

The search for evidence from heavy and superheavy elements in nature has been ongoing for many decades. Observations from old r-processed stars, careful analyses of meteorites, and other long lived evidence etched in nature somehow were objects of those searches. There was also some excitement revolving around the isotopes made in the laboratory near the predicted ***island of stability***. The hope was to reach the ***island of stability*** or approach it with very long lived nuclei that could then be detected either by their unique spontaneous fission fragments or by the longevity of the fission fragments produced. To date, these searches have not revealed the sought after proof of the creation of the superheavy elements in nature by the r-process.

More recently [9], astronomers who have observed elemental abundances in numerous old and hence, r-process enhanced stars, and interpret the relationships and correlations between the abundances of elements Z=44 to 47 (A=99-110) with heavier elements of Z=63-78 (A>150) as evidence of fission recycling resulting from the fission fragments of nuclei and elements made in the r-process of mass numbers >260. Figure 5 shows the correlations of ruthenium, rhodium, palladium, and silver (atomic numbers Z = 44 to 47) with those of Eu, Gd, Dy, Ho, Er, Tm, Yb, Hf, Os, and Pt elements (Z = 63-78) whereas there are no correlations with other nearby elements such as Cd, Sn, or Te with Z= 34-42 and Z= 48-62.

3 Superheavy Element Factory

The creation of new elements is still the focus of global competition with the best separators, accelerators, and beam/target combinations to get enough atoms to test the characteristics of the elements created. The best way for us to understand what we have created artificially in the laboratory is to connect them to the elements and their properties that we do understand! In this regard, there has been tremendous progress at the JINR in Dubna with the operation

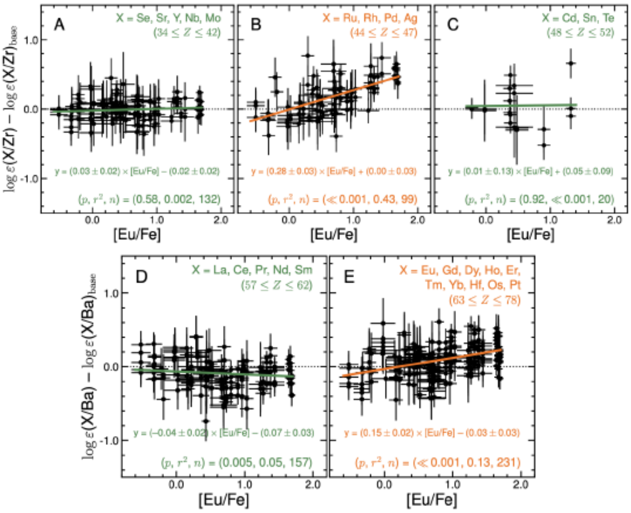

Figure 5. Observational signatures of transuranic fission fragments in stars [9] and their correlations.

of the *Superheavy Element Factory*. The construction and operation of the gas filled recoil separator, DGFRS-2, has yielded unsurpassed luminosities enabling the creation of new isotopes of the elements and perhaps most significantly, the decay chains connecting the new to the existing and somewhat better understood regions of the chart of nuclides [10–14] .

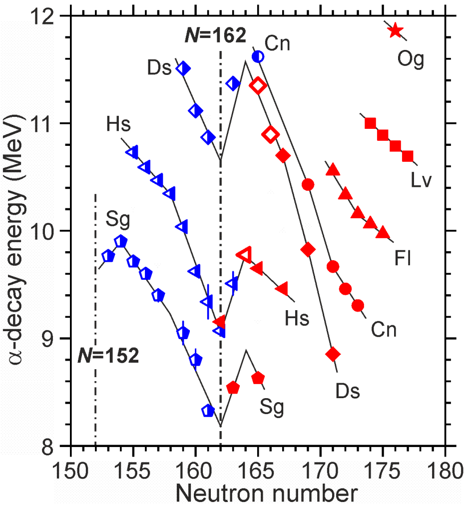

Figure 6. The alpha decay energies as a function of neutron number for element Sg, Hs, Ds, Cn, Fl, Lv, and Og from Reference [12].

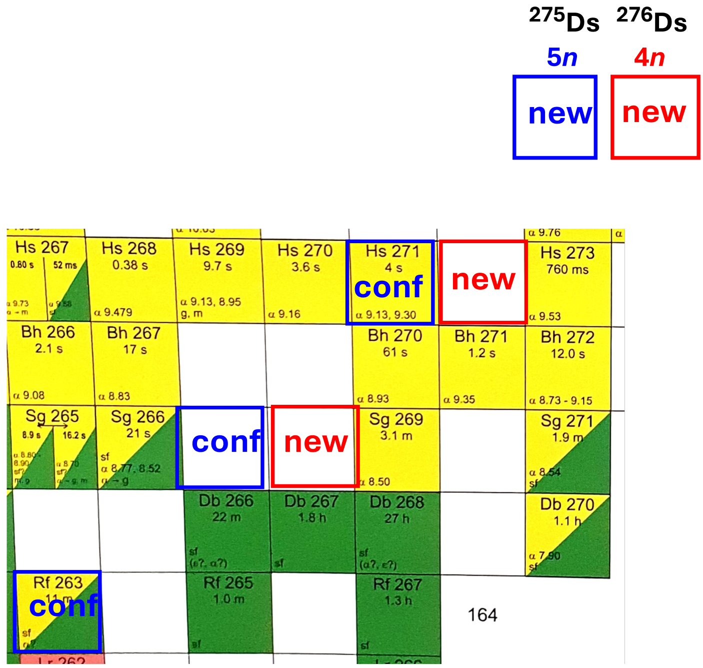

Figure 7. New results from ^{232}Th + ^{48}Ca reaction to produce ^{280}Ds resulted in three new nuclei, a new isotope, and confirmation of several others including ^{275,276}Ds, ^{271,272}Hs, and ^{267,268}Sg [15, 16]. The most significant part is connecting the superheavy elements and isotopes to the main part of the chart of nuclides.

Perhaps the most astounding or remarkable part of these developments are the first observations of decay chains to the main part of the chart of nuclides. A part of that work is shown in Figure 7. The new results are from the ^{232}Th + ^{48}Ca reaction to produce ^{280}Ds. This reaction resulted in three new nuclei, a new isotope, and confirmation of several others including ^{275,276}Dy, ^{271,272}Hs, and ^{267,268}Sg [15, 16]. The remarkable advances reported from the JINR are the hundreds of chains from the superheavy elements and their isotopes that decay to the main part of the chart of nuclides.

4 Conclusions

The results from the Super Heavy Element Factory in Dubna may hold the key to answering the questions regarding the production of the heavy elements in nature. The exquisite, rapid, and immense progress of work reporting on the hundreds of decay chains to the main part of the chart of nuclides finally give us the guidance necessary to search for the most definitive evidence to answer the question about the production of the superheavy elements in nature. Figure 8 pinpoints the endpoints of the decays from elements Flerovium (Z= 114) and Hassium (Z= 108) superimposed on the chart of nuclides. Now, we can search for the unique signatures of the various exotic fission modes of the heavy and superheavy nuclei.

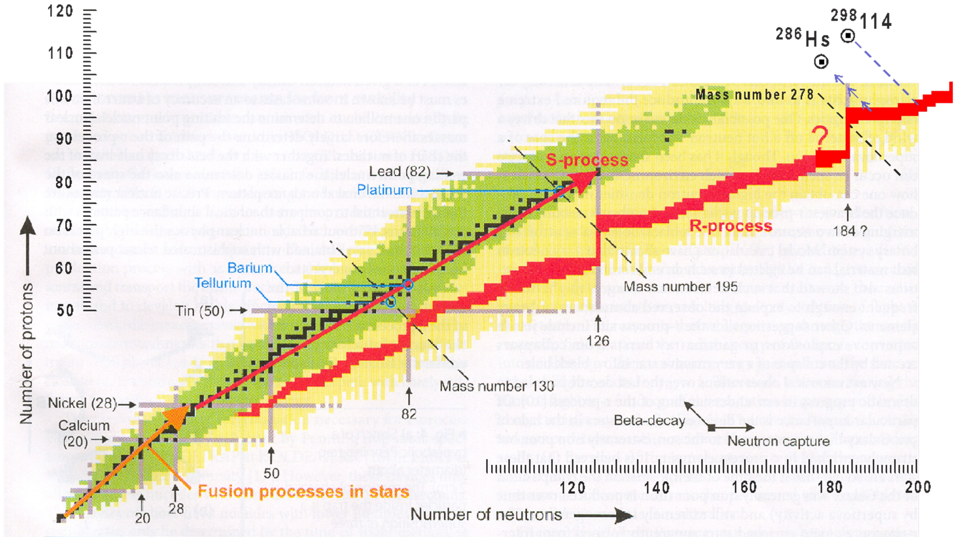

Figure 8. Chart of nuclides with superheavy element locations of Hassium(Z=108) and Flerovium (Z=114). The connection of new decay chains to the main part of the chart of nuclides will be essential to answering the open questions regarding the persistent signature of the superheavy elements having been made in nature [12].

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