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Were the Superheavies Made in the *r*-Process?

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This question has been asked many times through the decades, resurfacing time and again with unwavering persistence as new discoveries are made by the "Children of the Atom," a term coined by Kit Chapman in his book *Superheavy: Making and Breaking the Periodic Table* [1] for scientists engaged in the search for and the making of the heavy elements. The newest incarnation of the question is with the astounding observation of GW170817 by Laser Interferometer Gravitational-Wave Observatory (LIGO), Virgo gravitational wave observatory (VIRGO), and 70 electromagnetic satellites. The gravitational waves associated with the merger of two neutron stars 132 million years ago and 70 electromagnetic satellites that could simultaneously observe the light emitted by the kilonova event. The light changed from the blues to the orange and red, indicating the synthesis of the elements from the lightest to the region near the rare earths before it shifted into the infrared region. The observation established two-neutron star mergers as a site for the *r*-process and hence a site for the synthesis of the heavy elements in nature. The question remains about the extent of the synthesis of the heaviest elements in the *r*-process [2, 3]. The prevailing opinion among astronomers, astrophysicists, and nuclear physicists is that if the synthesis goes to the rare-earth region, surely it gets to the actinides. Two of the popular sites for the *r*-process were two-neutron star mergers and core-collapse supernovae. Simulations of both scenarios are shown in Figure 1 as a function of the mass numbers reached by the process in that scenario. It was well known that in core-collapse supernovae, there are not sufficient densities of neutrons to produce the elements beyond the A = 130 peak. The merger scenario is shown to make the elements to the actinide region and possibly beyond. Figure 2 shows the potential population well above A = 280. We note that such simulations are limited by the input data. In the figure shown, the input is limited to Z = 110.

The identification of the *r*-process or a rapid neutron capture process where the heavy elements are made dates to the initial weapons tests that revealed the existence of heavier elements in the debris of the tests. This was first pointed out by B2FH [5]. Seaborg of Berkeley was a member of the President's Science Advisory Committee during the Eisenhower presidency, and he became the head of the Atomic Energy Commission, motivating the various device tests in search of heavy and superheavy element production in the tests. Figure 3 demonstrates the production of three tests as a function of mass number A. These analyses and results were published in conference proceedings on heavy elements [6] 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 2.4 x 10^{25} n/cm^2 and

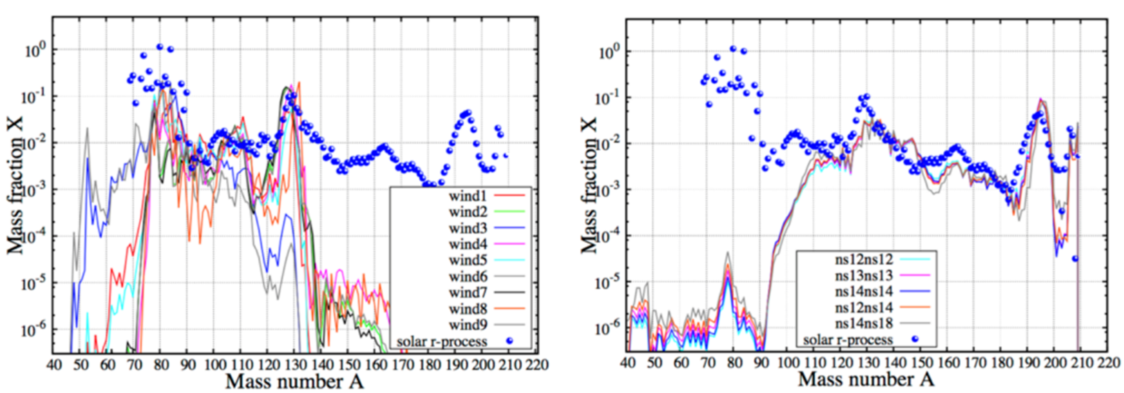

Figure 1. *Simulations of elemental mass fractions (proportional to abundances) produced in two r-process nucleosynthesis simulation scenarios of core collapse supernovae and two-neutron star merger. Supernovae were thought to be the site for the main r-process because neutron star mergers were thought to be too infrequent to explain the abundances of the heavy elements.*

9 x 10^{24} n/cm^2, respectively. The expected neutron star densities are much higher at $10^{43 \text{ or } 41}$ n/cm^2.

The quest to produce the heavy and superheavy elements included the excitement focused on the discovery of elements and isotopes within the predicted "island of stability" as longer lifetimes were discovered in the peninsula connected to the chart of nuclides. The thinking was that the island of stability would keep "the memory" of the heavy elements created in an r-process due to the long spontaneous fission half-lives of the elements within that island of stability.

The observation of the two-neutron star merger reinvigorates the question. There is now compelling evidence of fission recycling in metal-poor stars [7]. Further, the tremendous advances made in the production of superheavy elements at the Joint Institute for Nuclear Research (JINR) in Dubna following the implementation and operation of the super heavy element (SHE) factory make it even more compelling to search for direct evidence of fission products from the superheavy elements made in the r-process.

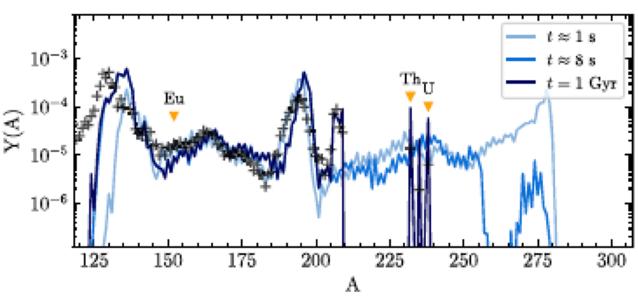

Figure 2. *Abundance patterns for an r-process simulation for various time scales. For freezeout at approximately 1 s, at 8 s when the β-delayed fission is thought to dominate, and at 1 Gyr timescales are shown [4].*

The superheavy element factory at JINR was made operational in 2020, and has in two years achieved a luminosity that is nearly 30 times the beam luminosity achieved anywhere else in the world. Figure 4 shows the luminosity of the beam as a function of year.

The gas-filled separator Dubna Gas Filled Recoil Separator (DGFRS-2) and the new DC280 cyclotron at the SHE factory [9] at JINR coupled with background suppression enabled experiments using ^{48}Ca beam on various targets, including ^{232}Th,^{238}U, ^{242}Pu, and ^{243}Am that have not only

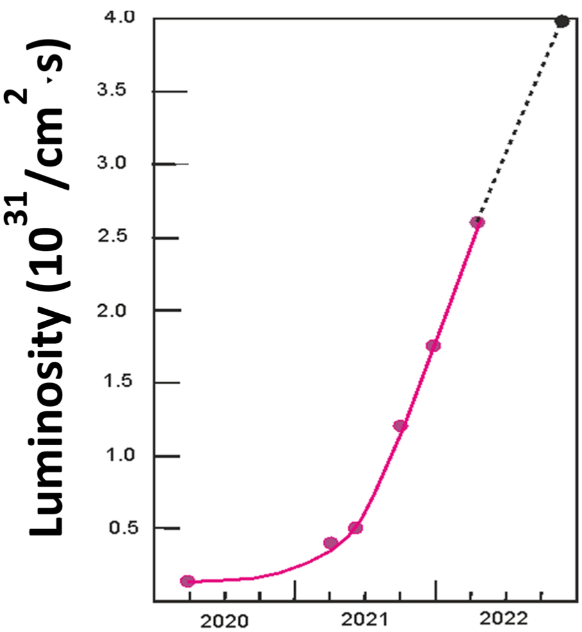

Figure 4. *The luminosity of the beam in units of 10^{31}/cm^2.s as a function of year. The red dots indicate achieved luminosities, and the dotted line is the design limit [8–10].*

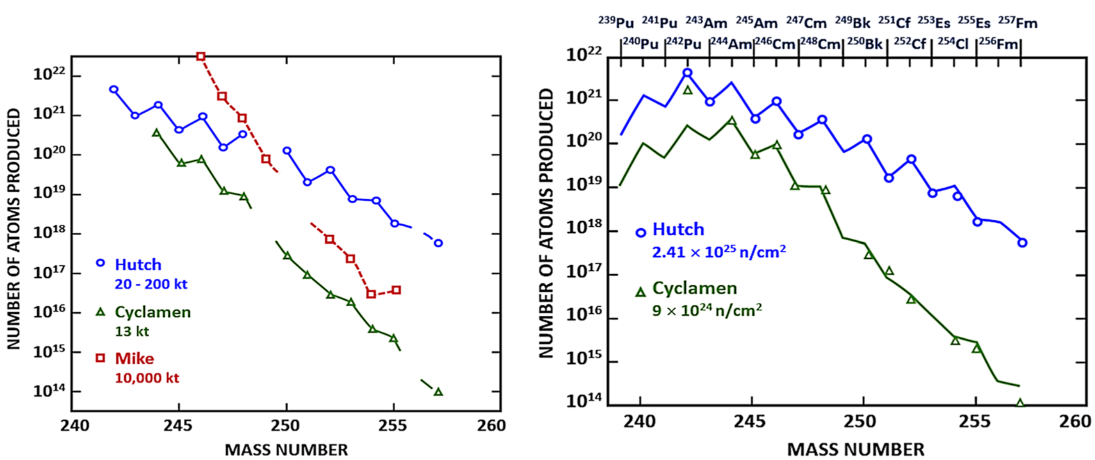

Figure 3. *Number of atoms detected as a function of mass number A for three device tests [6].*

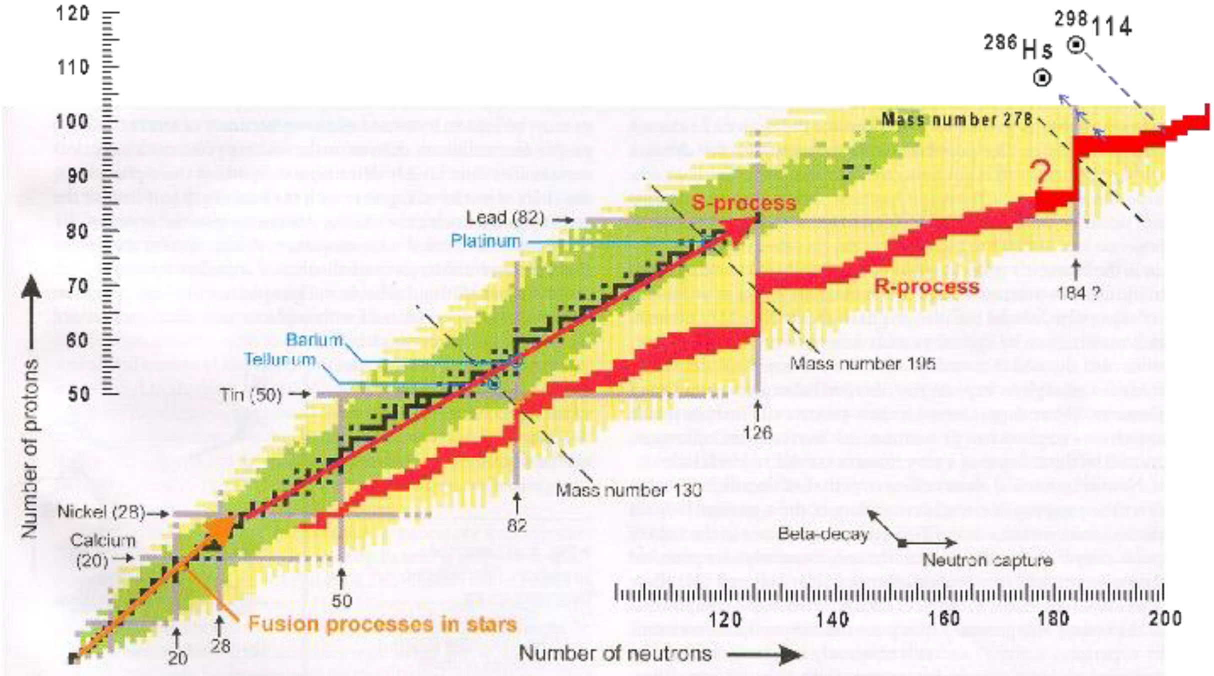

Figure 5. *The chart of nuclides with the r-process path in red. The dashed black lines indicate the decay chains observed for various superheavy isotopes [10].*

resulted in the production of new superheavy isotopes such as ^{286}Mc, ^{288}Mc, and ^{276} Ds [8–10] but the identification of hundreds of decay chains from the superheavies to the mainland of the chart of nuclides. The new decays include ^{286}Fl, ^{287}Fl, ^{183}Cn, ^{275}Ds, ^{276}Ds, ^{272}Hs, ^{268}Sg, and others. Figure 5 shows the decays of element 114 (Flerovium) and element 108 (Hassium) to the *r*-process path. The answer to this outstanding question of decades is waiting to be solved imminently.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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