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Open Challenges to Nuclear Physics Resulting from the Neutron Star Merger

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Long before Severe Acute Respiratory Syndrome coronavirus-2 (SARS-CoV-2 or COVID-19) disrupted every aspect of our lives and global interactions, we thought perhaps that the observations of the "ringing" of space-time observed on Earth on 17 August 2017 (GW170817) resulting from the merger of two neutron stars would be one of the most significant discoveries of the 21st century. Albert Einstein predicted in 1916 that massive accelerating objects can cause "waves" or disruptions to space-time that would travel at the speed of light. Figure 1 shows a visualization of the impact of a massive object on space-time and the ripples that can result from a collision of massive objects. The detectors from the European (Virgo) and the North American continents (Laser Interferometer Gravitational-Wave Observatory [LIGO]) were awakened to the "chirps" of space-time. The sensitivities of the LIGO detectors had been increased and fortuitously they had just come on-line. The gravitational waves were emanating from a constellation 132 million light years away. While there have been significantly larger "bangs" or disturbances to space-time observed since that time by LIGO and Virgo detectors, none have matched the GW170817 event. The loudest space-time ringing was recently observed in May 2019 and reported in September 2020. This ringing seems to have come from a merger event of two black holes. The energy release of this merger event is estimated to be equivalent to the energies of eight suns, resulting in the most massive black hole merger observed to date. The resulting combined black hole is thought to be 100 to 1,000 times the mass of our sun.

The GW170817 event, however, was not the first or the last detection of gravitational waves resulting from neutron star mergers, but it was the *first detection of gravitation waves simultaneously along with complementary signals by 70 other satellites and space probes!* A significant number of the world's astronomers were engaged in these observations. What made the GW170817 event so important for nuclear physics was the evidence from all the associated observations of gamma-rays, X-rays, visible light, infrared (IR), and ultraviolet spectroscopy, among others, although no neutrinos have been detected.

The role of nuclear physics in understanding the cosmos and the abundances of the elements had its origin in the 1950s, when solar elemental abundances were associated with specific nuclear processes. The B^2FH paper [1] pointed to the observed abundance patterns and their relative intensities and named the various nuclear processes that could have caused the observed abundance distribution. It was clear very early on that the fusion of light nuclei was responsible for energy generation as well as the life and death of stars. It was also clear that the origin of the heavy elements beyond iron required neutron processes. B^2FH identified nuclear reactions and nuclear structure effects, such as shell closures, as paramount to the synthesis of the elements, resulting in the abundances. They confirmed nuclear physics as the "engine" of the Universe—an engine that operates to various degrees as conditions allow in a multitude of cosmic sites and scenarios.

The production of heavy elements beyond iron is traditionally associated with two different types of neutron processes with very different neutron flux values. The *s-process* (slow neutron capture) known to occur in massive red giant branch (RGB) stars (weak s-process) and in asymptotic giant branch (AGB) stars (main s-process) seems reasonably well understood and nuclear physics is used to probe capture neutrons followed by decay close to the path of stability and have been observed in red giant stars and measured in laboratories on Earth. Stellar s-process models can therefore be compared rather reliably to the observed abundances of s-process isotopes in the solar system, in stars, and in meteoritic grains thought to originate from the condensed ejecta of RGB and AGB stars elsewhere in the galaxy. The same models can be used to reliably probe stellar interiors.

The *r-process* (rapid neutron capture) follows a path far from stability where successive neutron captures are much faster than the competing β-decays. The site for an r-process had remained elusive, both from direct observation and the identification of an astrophysical site that had a sufficiently high neutron flux that would enable the r-process to take place and to produce the heavy elements that we see in the solar system all the way to the actinides. The U.S. science academy report on "connecting quarks to the cosmos" identified the 11 greatest unanswered questions for the 21st century and the site of the r-process was one of those 11

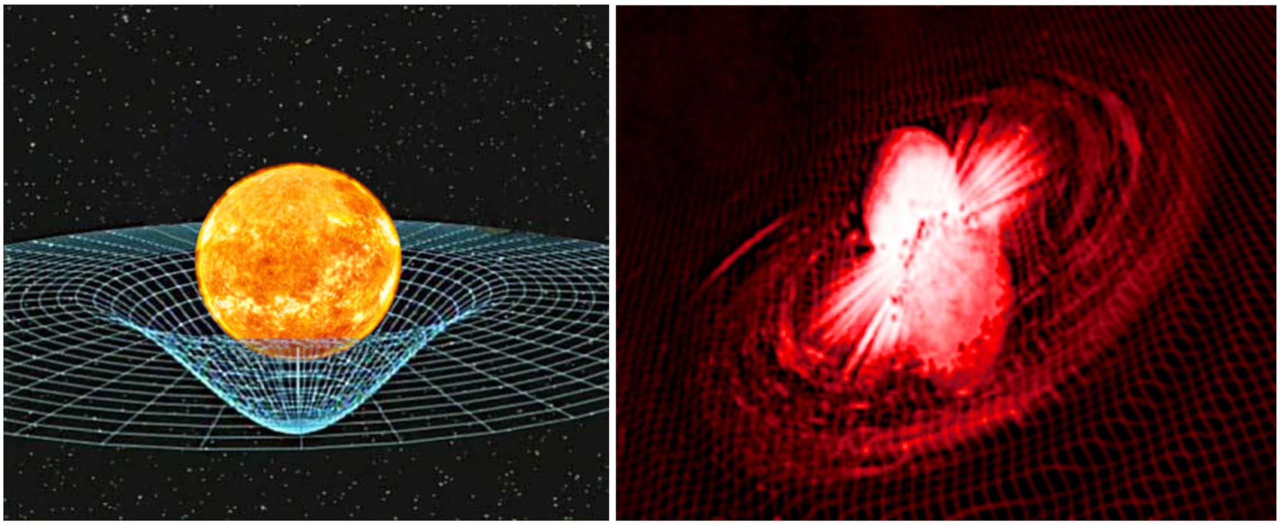

Figure 1. *Visualization of the impact of a single mass distorting space-time and the ripples resulting from the collision of two massive objects.*

questions [2]. Many possible sites had been proposed for the r-process, including core-collapse supernovae, merging neutron stars, and many other exotic models [2].

Modeling of core collapse supernovae with a large density of neutrons, considered a favorite possible site for the r-process, was shown to be depleted of neutrons before making the very heavy nuclei by subsequent rapid neutron captures. Neutron star or black hole–neutron star mergers, were suggested in the 1970s as possible r-process sites. Indeed, they would provide a high enough neutron flux resulting from the fraction of the total mass of the collision to create the heavy elements [3]. The concern was that neutron star mergers are unusual and rare events and this lack of frequency would prohibit sufficient production of the observed abundances of the heavy elements. Astronomers have detected the elemental abundances of many old stars in the galaxy. In many cases, the pattern is robust and identical in the heavier regions of the chart of nuclides. This robustness was evidence of a common origin for the synthesis of 50% of the heavy elements. The r-process path with successive rapid neutron captures is thought to produce very neutron-rich elements that may get unbound with large numbers of neutrons or, if the actinide region is reached in the process ($Z=92$), fission would break apart the heavy nucleus, repopulating lighter mass regions.

The predicted abundance distributions for primordial elements in the Big Bang, for nucleosynthesis in the first stars, and in early star generations is shown on the left side of Figure 2, while the present solar abundance distribution is shown on the right-hand side. It includes all the heavy elements expanding toward the actinides. These solar elemental abundances contain in an entangled way all the history of the Universe; nuclear physics operating in various astrophysical scenarios to give us the observations. A challenge for nuclear physics in studying the origin of heavy elements was the distance of the r-process path from stability, where nuclear structure, decay, and reaction mechanisms lie in these mostly unexplored regions of the nuclear chart. While most of the nuclei of interest have not yet been produced in the laboratory, the quest to build facilities worldwide to reach the r-process path has been undertaken in Europe, the United States, and Asia. Until the possibilities to measure the most neutron-rich elements were in hand, theoretical nuclear properties have been used alongside measurements near stability to unravel the characteristics of the astrophysical site that may have produced over 50% of all the heavy elements.

Experimental Opportunities

Identifying the most important or impactful nuclei to measure was determined by sensitivity studies gauging the effects of various astrophysical scenarios in separation from the effects of small changes in nuclear physics properties, such as masses, β-decays, and β-delayed neutron capture reaction rates that shape the final abundances observed in nature [4]. *This work was enormously important*

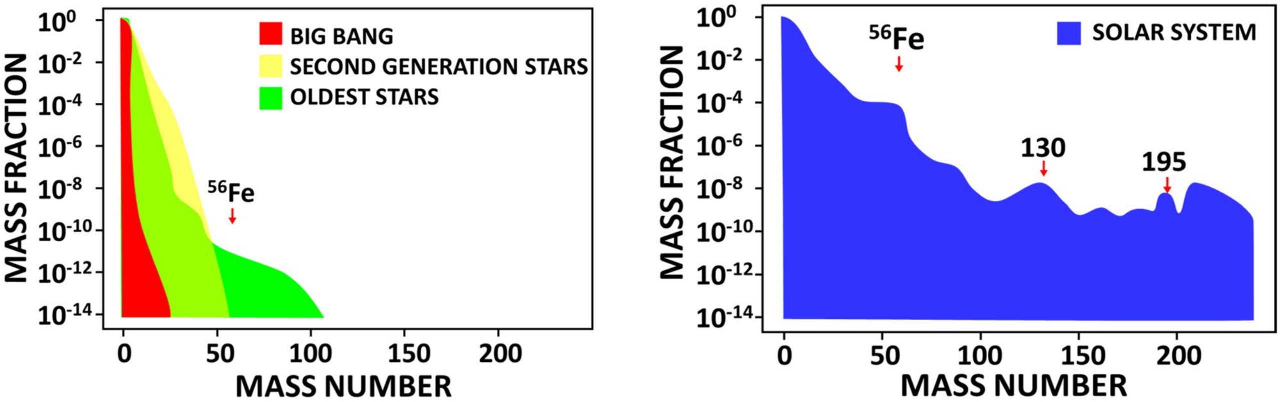

Figure 2. *A schematic description of the elemental abundances. The mass fraction (related to elemental abundances) in the Big Bang in the first generation, the very oldest stars, is shown in the multicolored left side of the figure, while the right side shows the observed solar elemental abundances.*

for determining the experimental agenda at nuclear physics facilities worldwide. Another approach was to advance precision measurements of nuclear masses for nuclei produced in fission, coupled with a reverse-engineering approach. The measurements at the Argonne National Laboratory and Jyvaskyla led to the preference of a cold r-process or the merger scenarios as favored potential sites for the r-process.

The *transformation* in our understanding of heavy element nucleosynthesis and the identification of at least one astrophysical site for the origin of the heavy elements along with new questions and challenges to nuclear physics came with the GW170817 observation of the gravitational waves and the associated electromagnetic transients. The identification of this site is the answer to one of the "11 greatest unanswered questions in physics." The remarkable happenstance that enabled the simultaneous measurements of the gravitational waves (GW170817) and associated electromagnetic spectra was the key. The source of the merger was pinpointed early, and numerous satellites and spectrometers tuned in. The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and Large Area Telescope were two of those electromagnetic transients. Figure 3 shows the evolution of the visible light spectrum. The visible light is the result of atomic excitations of all the elements being created in the event. The wavelength is in the blue for the lighter atoms, with wider spacing of atomic levels turning to orange in the visible and eventually going into the IR when the rare-earth elements are approached. The GW170817 observation led to global excitement from all aspects of society, with claims in the world press about having found the origin of gold (Au) in the Universe. Some financial presses were busy calculating the value of all that gold at today's market value. Alas, the optical spectra did not reach Au or rather the electromagnetic spectrum went into the IR region by the synthesis of the lanthanides before gold was made. The remarkable observation was the existence of the lanthanides in the ejecta. As remarkable as this observation was in providing proof of a site that made the r-process heavy elements, significant questions remain for astrophysics, as well as open new frontiers and questions for nuclear physics. The main astrophysics question is about the frequency of neutron star merger events, the details of the associated gamma-ray burst, its orientation, and so on.

Are There Frequent Neutron Star Mergers to Make the Observed Heavy Elements All the Way to Uranium and Higher, or Do Other Processes Also Contribute?

Nuclear physics questions that arise from the observation of gravitational waves and the electromagnetic transients lead us back to some questions posed 50 years ago and to other new and unresolved challenges in the present. The observations of lanthanides in the two-neutron star merger event ejecta almost guarantees that the r-process continued on to the actinides. This poses the question about the endpoint of the r-process, which most likely occurs through fission of very neutron-rich super-heavy elements. This has revitalized studies of n-induced fission and spontaneous fission. Is fission of extremely neutron-rich nuclei similar to what we have studied? If the actinides are made, then by necessity fission will have a significant role. Do the large numbers of neutrons and protons result in unusual fission modes?

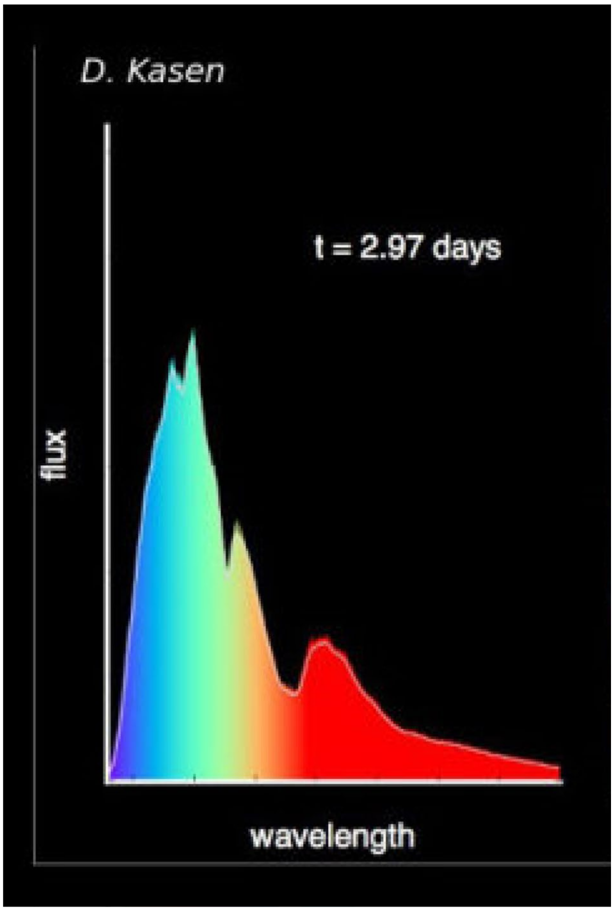

Figure 3. *The wavelength of light seen from the source of the gravitational waves as a function of time [5]. The reddish or orange region is thought to be created by the synthesis of the lanthanides.*

We can separate the nuclear physics questions into three; however, they are fundamentally related and interdependent in many ways:

- What is the role of fission?
- Were the super-heavy nuclei made in nature?
- What is the role of clusterization in the very neutron-rich nuclei?

Fission

Fission has been studied experimentally and theoretically for more than 80 years. The merger event raised new questions and re-energized old ones about the fission mechanism. Neutron-induced fission and the resulting fragment distributions are well known, with small variations dependent on the nucleus that fissions [6–8]. Figure 4 shows the asymmetric fission fragment distributions as a function of mass number A for low-energy neutrons. Increasing the energies of the neutrons causes the disappearance of the valley between the two distribution peaks and eventually with high enough energies, the distribution curve becomes one with a maximum peak at symmetric fission. The fission fragments will contribute to the flow of r-process recycling, the spontaneous fission of the actinides, and therefore the signatures in the visible or IR through the rate of heating. The ^{254}Cf nucleus was first observed in weapons tests and known to have an anomalously long half-life. The long half-life allows this nucleus to potentially make a significant contribution to the observed brightness some tens of days after the event. Dynamic nucleosynthesis calculations identified solely the spontaneous fission of ^{254}Cf contributing to the heating rate [9].

Experimental Opportunities

Fission studies in the laboratory or weapons test/debris samples were typically measured immediately after device set off, days later, weeks later, and rarely one or two months later. Those samples remain and can be measured for long-lived products that have lasted all the years since the end of the device tests. The fission fragments would be in the lighter mass regions and result in clear signatures in the visible part of the electromagnetic spectrum. We must, however, have a good idea of the fission fragment distribution

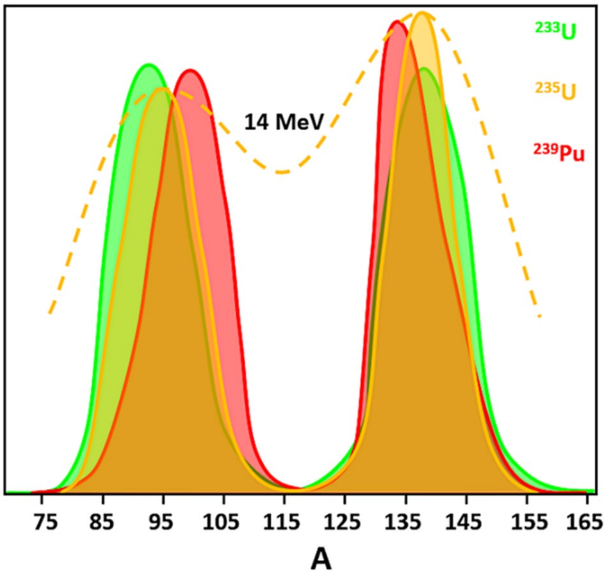

Figure 4. *Low-energy (thermal) neutron-induced fission fragment distributions with ^{233,235}U and ^{238}Pu. The dotted line indicates the fission of ^{235}U with 14 MeV neutrons.*

in a very high neutron density environment. Fission has become the focus of studies using the most modern theoretical tools to include all the interactions of the neutrons and protons from the Hartree–Fock–Bogoliubov equations.

Are there long-lived fission products that can definitely resolve the fission of the actinides question in the r-process? This can be answered by measurements of remaining samples. If yes, the half-lives can be converted to signatures observed in the electromagnetic transients. The signatures for these long-lived fission products will be in the visible part of the electromagnetic spectrum and easily discernible. What does the fission fragment distribution look like in high neutron density and high-energy neutron environments? What about spontaneous fission? These questions are being investigated by theorists and need further exploration.

The modeling of light curve luminosities and their evolution from the neutron star merger event required contributions from various aspects of the merger ejecta. The masses of the material ejected, the densities, and the velocities of the neutrons in the ejecta impact nucleosynthesis and the light curve. The availability of different energies of neutrons will impact the heavy elements made by neutron capture and the n-induced fission fragment distributions. There is of course the spontaneous fission process that terminates nucleosynthesis and has to also be included.

Were the Superheavy Nuclei Made in Nature?

Were they made in nature via the r-process?

Today, superheavy element are made with neutron-rich targets and beams via fusion evaporation reactions and followed by the decay of the compound nucleus of neutrons, chains of alpha decays, and spontaneous fission channels. The synthesis of element 118 (Oganesson) was via the reaction of ^{48}C on ^{249}Cf. Confirmation for the existence of element Oganesson and other super-heavy elements was made by the direct measurements of the decay channels. The search for the theoretically predicted “island of stability” and the super-heavy elements was ongoing from the early 1970s [10]. Tests were carried out in the explosion of various devices with ^{232}Th and ^{238}U targets creating very high neutron exposures. The analyses of the debris for heavy elements from various device explosions showed elements up to and including ^{257}Fm. Figure 5 shows the number of atoms of a given mass number that were detected in the debris of three devices (Hutch, Cyclamen, and Mike). The Hutch event debris analysis showed a larger number of atoms of heavier masses than either Cyclamen or Mike. The conclusion was that even higher neutron flux rates were needed to make the super-heavy elements. While it is possible that the limitation was the sensitivities and detection thresholds of the detection systems of the times, the question persists regarding the synthesis of super heavy elements in nature [11].

Experimental Opportunities

The spontaneous fission of the heavy elements in the debris samples could potentially result in long-lived fission products that may still persist. Are super heavy elements made in nature by the sequential fast neutron captures of the r-process? The r-process path is far from stability and in a very neutron-rich region of the chart of nuclides. What would be the mechanism of reaching the region of super heavy element creation? What would be the signatures for the synthesis of the super heavy elements?

A mechanism was proposed by Ref. [11] assuming a very large neutron-to-seed ratio in a fully dynamical r-process simulation that could in fact produce super heavy nuclei all the way to A~300 that would then decay on a time scale of days. The mechanism they presented is one where even heavier mass and charge numbered parent nuclei are created by the r-process. The parent nuclei then decay by beta decay and alpha decay to reach the relevant region of the super heavy elements. Neutron-induced fission as well as spontaneous fission return as critical challenges for both the very neutron-rich nuclei created by the r-process and the super heavy elements. The schematics of the process are shown in Figure 6.

The answer to the question about the creation of the heavy elements in nature has become essential for both the search for signatures from astrophysical phenomena (in this case, one of the r-process sites in the two-neutron star merger), as well as the results from the super heavy element factory coming on-line this year at the Joint Institute for Nuclear Research. There is a flurry of theoretical and experimental activity in understanding fission and fission fragment distributions. Predictions indicate that decay of super-heavy nuclei proceeds beyond alpha decay by larger cluster decays such as $^{12,\,14}$C and eventually leads to very highly asymmetric fission. The prediction specifically for the fission of ^{294}Og is two fragments centered on ^{208}Pb (doubly magic) and ^{86}Kr (singly magic). This prediction and others for the fission modes of superheavy nuclei point to sharp distributions of clusters as the dominant decay mode [12, 13]. This mode of decay is distinctly different than other asymmetric fission modes with a distribution of fission fragments shown in Figure 4 for Pu or U. This mode results in *sharp peaks* of light fragments at or near magic numbers. An important aspect of such a super asymmetric fission mode for the superheavies is dependent on the

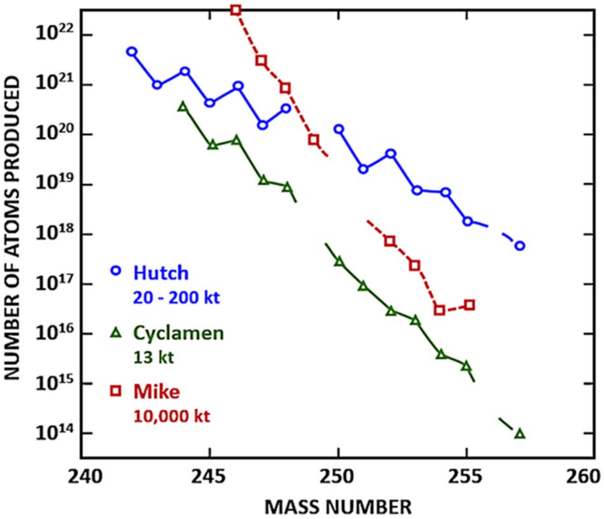

Figure 5. *The number of atoms of a given mass number produced by the three exploded devices. The Hutch event produced the most atoms of heavy elements, with a neutron flux of 2.4 x* 10^{25} *n/cm*^{2}.

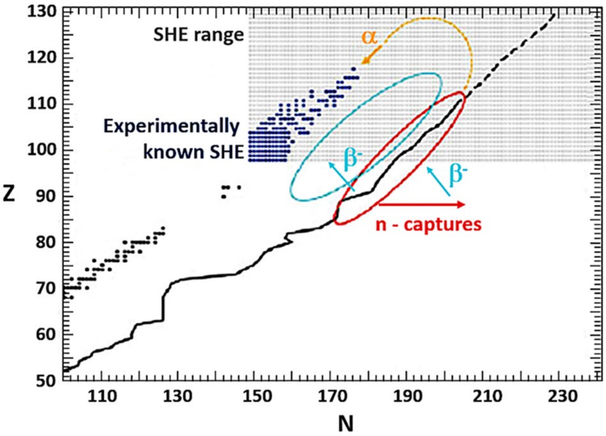

Figure 6. *The r-process path is shown in a solid black line with indications of the direction of neutron captures, β-decays, and alpha cluster emission.*

dynamics of fission and quantum tunneling. The tunneling aspects are also being explored in terms of entrance to the fusion evaporation reactions or the entrance channel dynamics, which show that, at low energies, it is the quantum tunneling effect that contributes to the fusion process [14]. It remains to be seen what the role of this quantum tunneling effect will be on the spontaneous fission channel.

Experimental Opportunities

As the super heavy element factory comes on-line in Dubna, as well as other facilities around the world, the search is on for the observation of the cluster fission predicted by these calculated, highly asymmetric fission modes. The predictions for the highly asymmetric fission fragments is nuclei near closed shells. Hence, the lighter components may still exist in the debris of device tests.

The history and the exciting developments around a better understanding of the r-process have raised new questions. Nuclear clusters were only seen as the building blocks of chemical evolution and life with burning of alpha particles to make ^{12}C and eventually ^{16}O. Now it becomes clear that the clusterization in nuclei is not limited to the alpha particles and plays a significant role as neutron and proton numbers reach extreme values. Will we observe the spontaneous fission clusters? Will clusters be revealed as a signature source for astrophysical events? Nuclear physics, as the engine of the Universe, allows us to explore deeper and further, where it is the shell closures that determine rates of synthesis or the cluster decay of super heavy nuclei, to point to our fundamental understanding of quantum tunneling effects in nuclei and signatures of the exotic events in the cosmos.

References

1. E. M. Burbidge et al. (B2FH), *Rev. Mod. Phys.* 29 (1957) 547.
2. J. J. Cowan et al., *Rev. Mod. Phys*. 93 (2021).
3. J. M. Lattimer and D. N. Schramm, *Ap. J. Lett*. 192 (1974) 145.
4. M. Mumpower et al., *Prog. in Part. & Nucl. Phys*. 86 (2016) 86.
5. M. Nicholl et al., *Ap. J. Lett*. 848 (2017) L18.
6. A. Chatillon et al., *Phys. Rev. Lett.* 124 (2020) 202502.
7. S. Goriely et al., *Phys Rev. Lett*. 111 (2013) 242502.
8. M. Bender et al., *J. Phys. G: Nucl. Part. Phys.* 47 (2020) 113002.
9. Y. Zhu et al., *Ap. J. Lett*. 863 (2018) L23.
10. R. W. Hoff and E. K. Hulet, *Proceedings of the Symposium Commemorating the 25th Anniversary of Elements 97 and 98 held on January 20, 1975*, edited by G. T. Seaborg, K. Street, Jr., S, G. Thompson, *and* A. Ghiorso. Chemical Sciences Division of Lawrence Berkeley National Laboratory, Berkeley, CA.
11. I. Petermann et al., *Eur. Phys. J.* A 48 (2012) 122.
12. M. Warda et al., *Phys. Rev.* C 98 (2018) 041602 (R).
13. Z. Matheson et al., *Phys. Rev.* C 99 (2019) 041304.
14. T. Tanaka et al., *Phys. Rev. Lett.* 124 (2020) 052502.