Special topic paper

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Science brings nations together: Mary Good and the heaviest atoms and nuclei

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Abstract: The 20th century started with the realization that working together and collaborating expedites new discoveries. The Solvay Conference in 1911 brought together scientists to try to understand the real nature of matter, the new elements, and their properties. Through global conflicts, the scientists stayed in communication and organized IUPAC and IUPAP to stay current in advances internationally in chemistry and physics, respectively. The outcomes include the discovery and naming of the elements that complete the periodic table of elements and the chart of nuclides with the heavy atoms and all of their isotopes. Mary Lowe Good forged new directions in developing tools in the field of radiochemistry. She exemplified cooperation and collaboration nationally and internationally. Now the advances in the heavy elements by Yuri Ts. Oganessian and colleagues staying close to the principles of international cooperation and sharing the new information about the connection of the production of super heavy elements to the main part of the chart of nuclides. The future lies in determining whether there are more elements to be discovered and what are their chemical properties.

Keywords: actinides; chemical physics; heavy atoms and nuclei; heavy elements; inorganic chemistry; Mary L. Good; new elements; superheavy elements; superheavy nuclei.

Introduction

The first Solvay Conference held in Brussels (1911) is often considered one of the most important meetings of the era bridging the fields of Chemistry and Physics. Advances in Chemistry included the organization of the chemical elements into the first periodic table by Mendeleev, while physicists were reporting discoveries of new elements. Marie and Pierre Curie and Ernest Rutherford were detecting and trying to explain the new elements observed in their laboratories from radioactive decay. Work continued into the enrichment of the Mendeleev table of elements towards and beyond element 100 by Seaborg [1] and many others. In 2016, four new elements were named [2–4], nihonium (Nh, element 113), moscovium (Mc, element 115), tennessine (Ts, element 117), and oganesson (Og, element 118). These new elements completed the last row of the periodic table, but the challenging questions remain – is possible to have elements beyond 118 and what is the ultimate limit for elements? There are already preliminary results indicating that element 120 has been made [5]. The road to confirmation of new elements, element 120 or unbinilium as it is temporary placeholder name in the periodic table, is however long and will eventually be decided by a joint IUPAC–IUPAP Joint committee [6].

Other challenges for chemists and physicists working together exist including understanding and implementing the new quantum world of chemistry and physics. Element 118 is in the column of noble gases but the chemical nature of this element is yet to be quantified and understood [7].

The International Union of Pure and Applied Chemistry (IUPAC) was founded in 1919 amidst the fervor of new element identification with the goal of uniting the international community of scientists in the dual function of

Article note: A special issue of PAC in honor of Dr. Mary L. Good (1931–2019), a leader and pioneer in the field of inorganic chemistry. In addition to a distinguished career in academia, industry, and government.

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advancing chemistry as well as assisting and collaborating with scientists in other fields: engineers, technologists, and policy makers to solve critical world problems through its in-depth knowledge of the chemical sciences. A similar organization, the International Union of Pure and Applied Physics (IUPAP), was founded in 1922 with the goals of fostering international cooperation, promotion of international agreements on uses of symbols, units, nomenclature and standards, the free circulation of scientists, and the encouragement of research and education. Both unions of chemists and physicists were affected by WWII but vowed to stay strong and united against future struggles. Chemistry was an essential and crucially significant ingredient in the discovery and use of uranium (U element 92) and plutonium (Pu element 94) in the development of the first nuclear weapons, and eventually for nuclear energy and other applications of nuclear science.

Mary Lowe Good

Mary L. Good was born in 1931, began her studies in physics but graduated with a degree in chemistry. She worked in between the fields of chemistry and physics for her whole career [8–10]. Figure 1 shows an early photograph of Mary Good alongside her video from the Science History Museum on the three parts of her chemistry career. She was a chemist, and industrial scientist, and a policy maker. Throughout her career, she rose to leadership positions in academia, in the broader chemistry community in the USA and the international community of chemists, and in government. She was steadfast in promoting international collaboration through her leadership in the American Chemical Society (ACS) and IUPAC. Early in her career, she was the director of the radiochemistry laboratory at Louisiana State University in Baton Rouge and then expanded her research to the Louisiana State University New Orleans (LSUNO), where she spent a major portion of her academic career as a researcher and professor. She was a trend setter in adopting new methods to understand the newly developed cross-disciplinary area of chemistry and physics. She was a pioneer in the use of Mössbauer spectroscopy to identify various states of elements. She advanced the use of Mössbauer spectroscopy with Doppler shift methods to study nuclear structure, a technique which allows the measurements of hyperfine transitions between the excited and ground states of a nucleus. The technique was critical to the identification of the various states of the elements. She also played a significant role in understanding the role of catalysts in expediting chemical reactions.

Beyond academia, Mary Good became engaged in industry as director of research and eventually as vice president of technology at Signal Research Center which later became Allied Signal, Inc. She also became the acting secretary of commerce during the Clinton administration.

Fig. 1: A photo of Mary Good at the beginning of her career. Image reproduced with permission from the Science History Institute Museum & Library. The video is available on YouTube.

She was a constant proponent of women in STEM education, technology, and applications, and was generous with her time and experience, sharing with potential students and scientists worldwide. Mary Good became the first woman member of the board for the American Chemical Society, later elected as president of the society. She was spearheading the international collaborations introduced by IUPAC and became the first woman to serve on the Executive Committee and the first female president of an IUPAC Division (Division II). Her spirit for international cooperation continued to the naming of the new elements that were added to the chart of nuclides in 2016 as shown in the Fig. 2.

Mary Good received many awards during her lifetime for service to science, education, and government. Among the most notable awards are the Glenn T. Seaborg medal, The Priestley Medal, the Othmer gold medal, and the Vannever Bush Award. She was the first woman recipient of the Glenn T. Seaborg medal (1996) and the Priestly medal (1997). The Seaborg medal was established to recognize and encourage research in nuclear and radiochemistry or its applications. The Priestley Medal is the highest honor conferred by the American Chemical Society and is awarded for distinguished service in the field of chemistry. The Othmer gold medal was established by a philanthropist and professor of chemical engineering, to recognize "outstanding individuals who contributed to progress in chemistry and science through their activities in areas including innovation, entrepreneurship, research, education, public understanding, legislation, and philanthropy." Mary Good received the Othmer medal in 1998 and went on to receive the Vannevar Bush Award of the United States National Science Foundation's highest honor in 2004. Her citation for this award highlights her broad interdisciplinary contributions and states: *"For her achievements as an educator and industrial research manager. An extraordinary statesperson, a distinguished public servant, and a remarkable scientist, she has contributed broadly to the understanding and promotion of the value of science and technology."* The Science History Institute and Museum highlights her story. Mary Good was not afraid to take risks, or try new things, and that is also the legacy of Mary Good to IUPAC. This paper tries, in her spirit, to coalesce chemistry and physics in search of new elements and their properties with a nod to international scientific collaborations in search of knowledge for all of mankind.

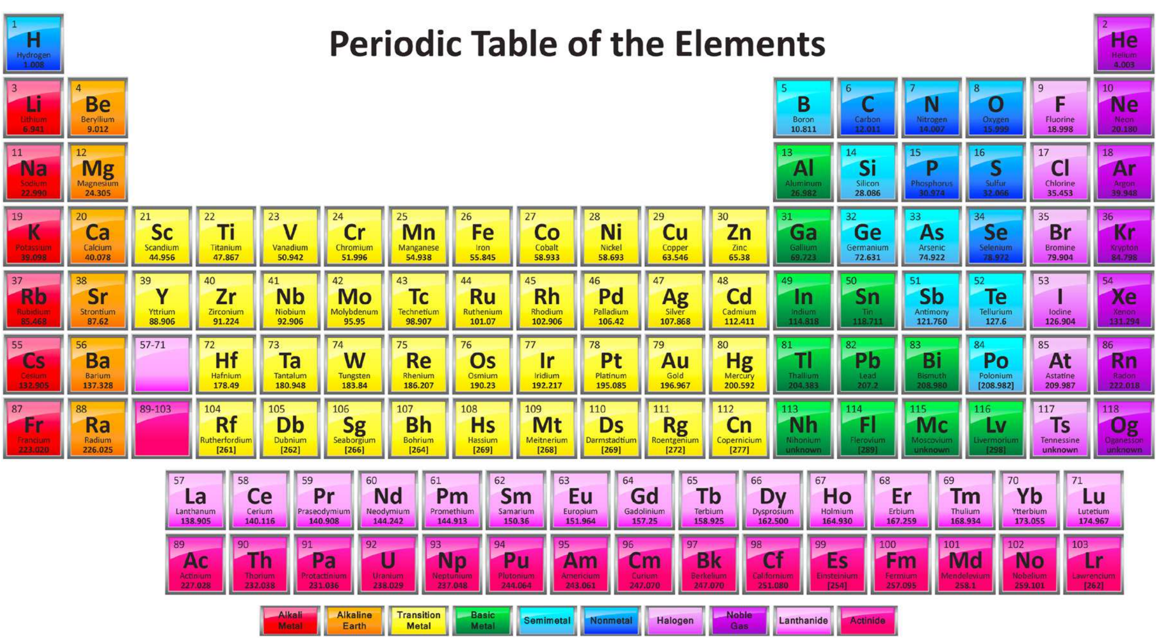

Fig. 2: The periodic table of elements including the elements officially named in 2016, elements nihonium (Nh, element 113), moscovium (Mc, element 115), tennessine (Ts, element 117), and oganesson (Og, element 118). Are there more elements?

Heaviest atoms and nuclei

An a pioneer of the 20th century, Mary Good worked in the interface of Chemistry and Physics as new elements were discovered and studied with state of the art tools to determine their chemical properties. Today, new elements can only be created with large physics experiments at powerful accelerators, efficient separators, and state of the art modern detectors and electronics. These accelerators can produce high intensity beams, and, combined with neutron rich targets, attempts have been made to extend the periodic table of elements as well as the chart of nuclides representing the elements along with their isotopes. Achievements to date have made use of broad international collaborations, since one country alone cannot provide all the resources required of creative new ideas coupled to technological advancements. Figure 3 shows which elements were made in significant amounts with ^{48}Ca beams and neutron rich targets at the super heavy element factory at the Joint Institute of Nuclear Reactions (JINR) in Dubna, Russia.

Prodigious amounts of the heavy elements will help answer outstanding questions about the cosmos. The physics depiction of the elements and their isotopes are presented as the chart of nuclides in Fig. 4. A schematic diagram of the chart of nuclides. Over 50 % of the heavy elements are thought to be made in space by a process called the rapid neutron capture process (r-process) in a neutron rich environment to allow successive captures of neutrons. A recent observation of gravitational waves from two merging neutron stars pointed to a potential site for this process. While a two-neutron star merger was identified as a possible source for the synthesis of the heavy elements with rapid neutron capture, the question regarding the potential production of superheavy elements in nature remains [11–14]. The island marked as superheavy elements was predicted to exist and some elements have been discovered in that region. The remaining question was how to connect this region to the main body of the chart of nuclides. Figure 4 connects the r-process path with the island of superheavy elements schematically, and recent work from JINR connects nuclei produced in this remote part of the chart of nuclides to the main body of the chart of nuclides for the first time.

The physics experiments face the challenge of producing enough of the heaviest elements to study their chemical properties. This process has to return to Chemistry but production has been limited to a few atoms at a time, hardly enough material to characterize the properties of the elements or place them in the periodic table of elements. The newly discovered elements added to the periodic table of elements required the cooperation of various laboratories across the world, including the United States (Oak Ridge National Laboratory, Lawrence

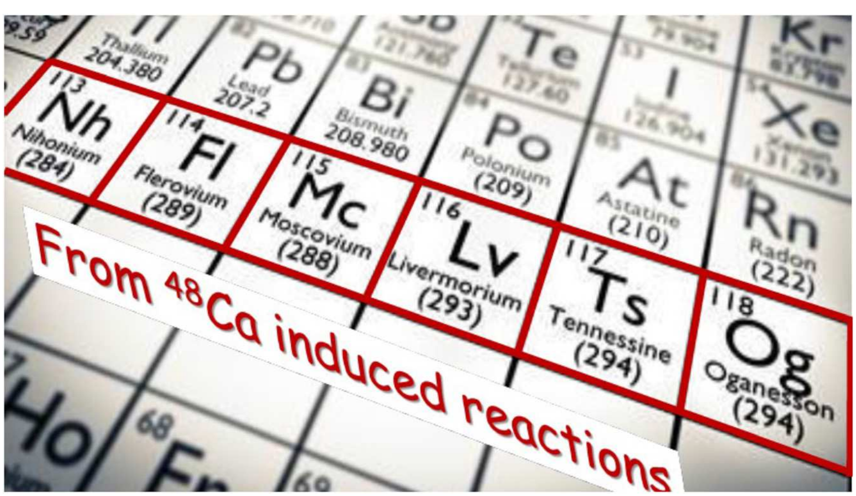

Fig. 3: The last elements completing the periodic table of elements including nihonium (Z = 113), flerovium (Z = 114), moscovium (Z = 115), livermorium (Z = 116), tennessine (Z = 117), and oganesson (Z = 118) produced in hot fusion reactions using ^{48}Ca. FLNR at JINR pioneered reactions between ^{48}Ca beams and enriched actinide targets that led to the new element discoveries.

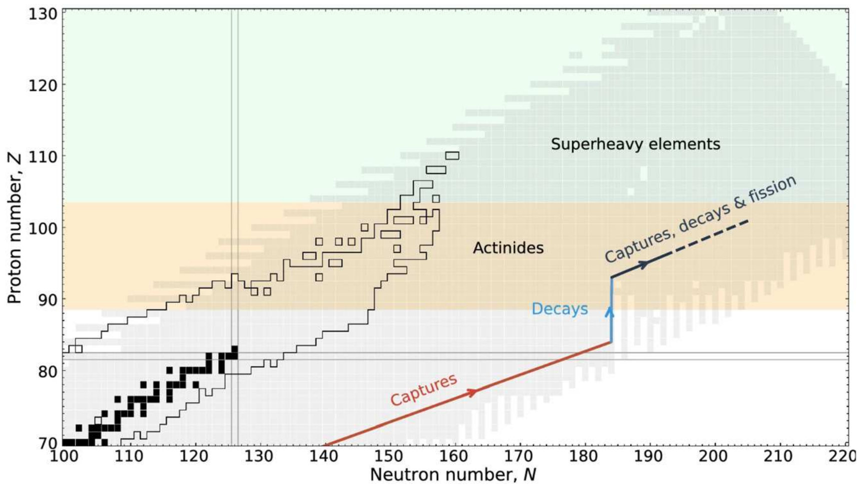

Fig. 4: The chart of nuclides in the actinide region with indication of the r-process path [11]. This path is far from the expected island of stability and the superheavy element region. However, data is limited regarding cluster decay in the region and the possibility to populate the superheavy nuclei in the r-process.

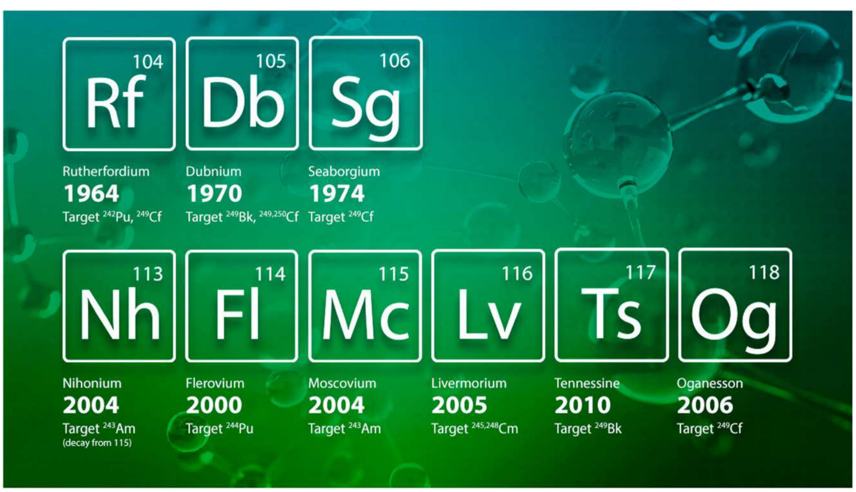

Fig. 5: The nine superheavy elements and their year of discovery by various physics experiments. The target element impinged by the beam during the nuclear reaction is indicated.

Livermore National Laboratory, Lawrence Berkeley Laboratory, Michigan State University), Russia (Flerov Laboratory of Nuclear Reactions at the Joint Institute of Nuclear Research or FLNR), Japan (RIKEN), and Germany (GSI). Figure 5 lists the discoveries of the new elements and the initial year of discovery.

After 2016, there was a continued worldwide effort to manufacture more of the superheavy elements and their isotopes. Unfortunately, the global COVID-19 pandemic and then the invasion of Ukraine by Russia brought an end to sharing the many advances. Instead, each nation continued their individual effort with its own merit and capacity. Russia had made large investments in new instrumentation of a Super Heavy Element (SHE) factory [15], new and high efficiency gas filled recoil separators, which were to be engaged collaboratively to produce the new elements and their isotopes. Alas, the war of 2022 only allowed countries to proceed separately. IUPAP engaged this effort with the united intentions of insuring the free circulation of scientists across national boundaries to sponsor a conference which would allow international exchange of information under the goal of *Science Brings Nations Together*. The conference on the *"Heaviest Nuclei and Atoms"* was in honor of the 90th birthday of **Yuri T. Oganessian** and it was held in Yerevan, Armenia at the end of April of 2023 [5].

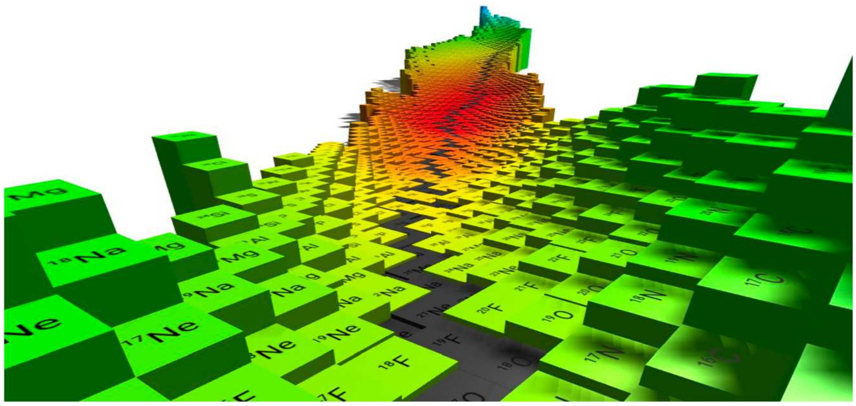

Fig. 6: What are the limits of nuclear existence? We do not know the boundaries where adding protons (left side) or neutrons (right side) take us to the "drip lines" where the nuclear force is no longer able to keep the nucleons inside bound as a nucleus. The extreme boundaries result in "dripping" out neutrons on the right side and protons on the left side of the chart of nuclides.

Fundamental questions to chemistry and physics

The question of limits arising from the additions of neutrons and protons across an isotopic chain is one of the fundamental questions for nuclear science, mapping the limits of the strong force holding the nucleus together. What are the limits or drip-lines where a nucleus will no longer hold an additional proton or an additional neutron?

Figure 6 shows the expanse of the chart of nuclides. The expanding periodic table also leaves several open fundamental challenges for chemistry in the expansion of the periodic table of the elements for the future.

- Are there more elements to be made beyond element 118?
- Is there a limit to how many more elements can be made in the laboratory?
- Are the superheavy elements made in space?
- What are the chemical properties of the new elements and how can we determine them if we make only a handful of atoms at a time?

Advances at the super heavy element factory (SHE)

The production of the heavy elements are only possible in the physics accelerator laboratories. Initial challenges included the availability of neutron rich target material and neutron rich beam development to enable fusion reactions that result in the heaviest elements. In addition, high luminosity accelerators and super-high efficiency gas-filled recoil separators [15] are crucial for the production of these exotic super heavy elements. For the past 20 years, the luminosities have been such that the production has been on the order of an atom a week or less. The JINR laboratory has undertaken the task of building A Super Heavy Element (SHE) factory and improved gas-filled recoil separators to increase the yield. Figure 7 shows that the luminosity, or beam intensity, starting with the constant intensity (2000–2020), the luminosity has now surpassed those values by achieving 15 times what was previously possible. The SHE-factory is in fact designed to obtain 100 times the former values [16]. This effort has been led for several decades by Yuri T. Oganessian. The republic of Armenia issued a stamp to honor the naming of the element 118 as Oganesson as shown in Fig. 8 [17]. The reaction to produce element 118 was by the reaction of ^{48}Ca on ^{249}Cf. The SHE-factory cyclotron is a DC-280, designed and built at the Flerov Laboratory of Nuclear Reactions at the JINR in Dubna. It was coupled to the DGFRS-2, gas-filled spectrometer and yielded the luminosities measured in Fig. 9.

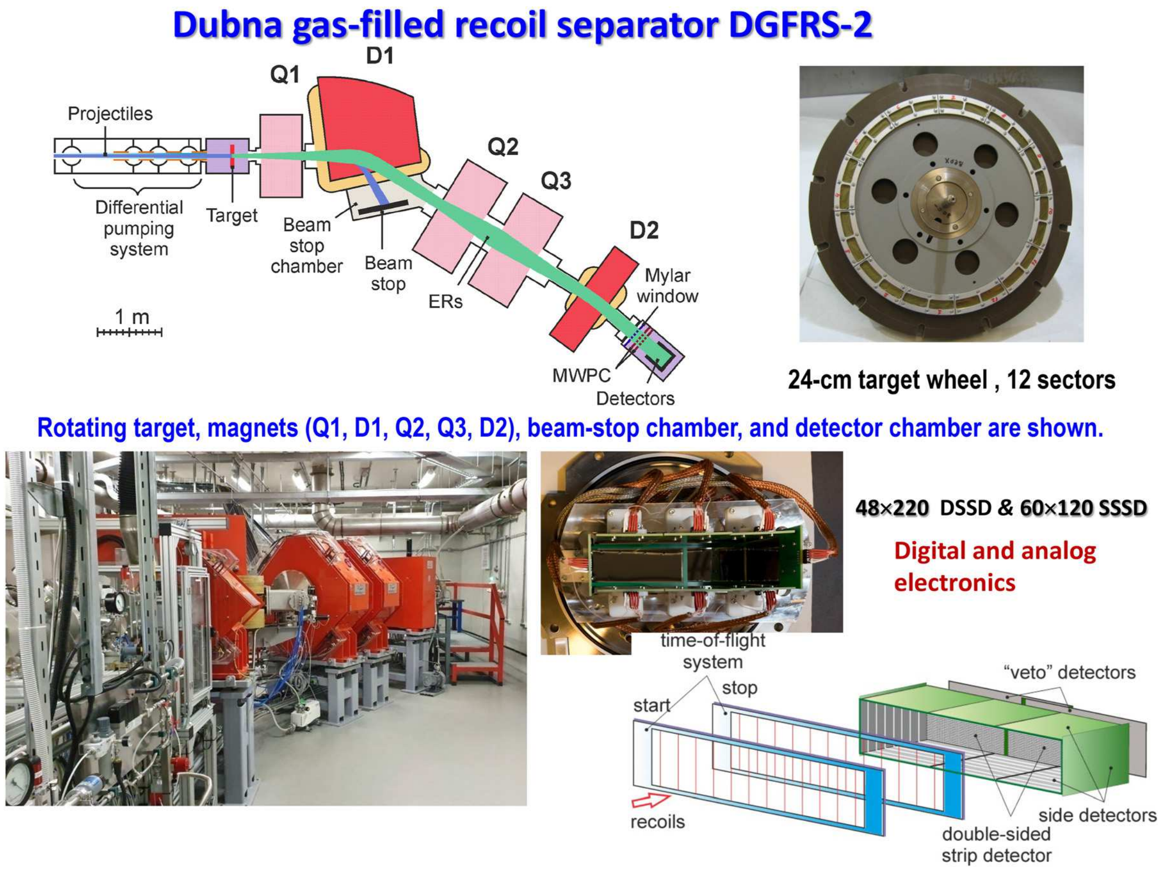

Fig. 7: Layout and photo of the Dubna Gas-Filled Recoil Separator (DGFRS-2) developed to significantly improve the efficiency of studies of heavy and superheavy nuclei made at the SHE-factory [15].

Fig. 8: The republic of Armenia stamp issued in honor of the naming of element 118 and the reaction used to produce it including the alpha decays that were used to verify the new element [17].

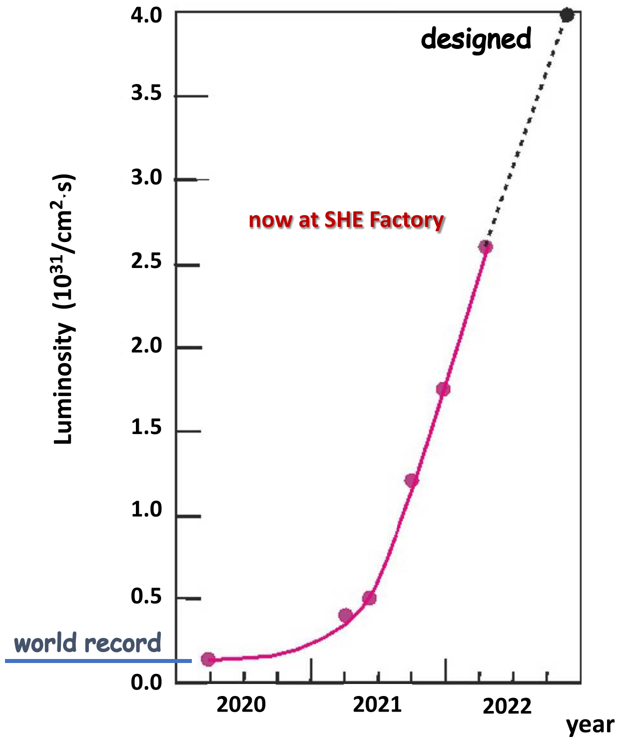

Fig. 9: This figure shows the luminosity achieved over the last 20 years focusing on the increase in luminosity since 2020. After a constant luminosity from 2000 to 2020, SHE is now producing at 15 times the previous record and it is designed to go up to 100 times that luminosity.

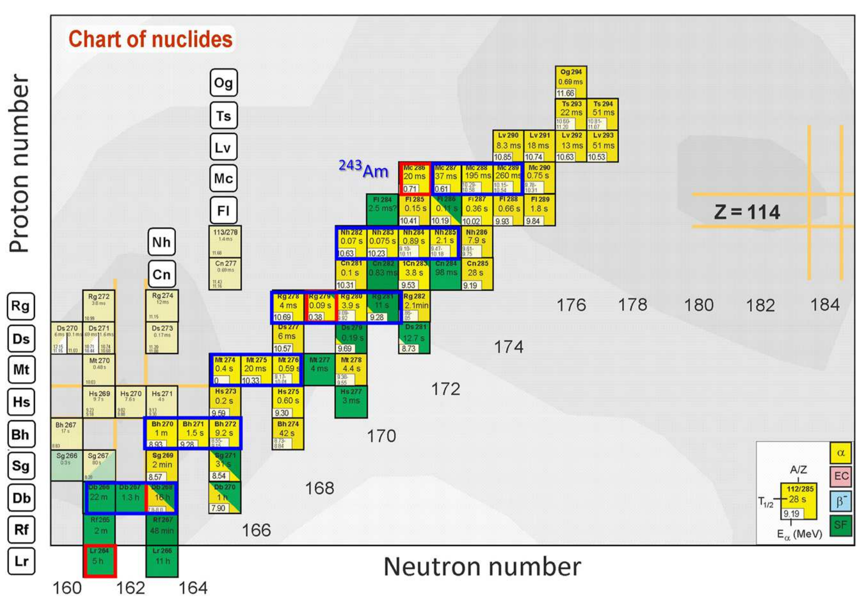

Fig. 10: Results of the first experiments [16, 18] at the DGFRS-2 for the reaction of ^{48}Ca on ^{243}Am. The new results included 125 new decay chains of $^{286-289}Mc$ in comparison to 37 decay chains measured until 2012. In addition, the decay properties of 22 isotopes shown in blue. The most remarkable part is the connection to the main part of the chart of nuclides.

Results

The new instrumentation developed and implemented allowed identification of new isotopes including ^{286}Mc, ^{264}Lr, and ^{276}Ds for the first time. Results also included the decay properties of 22 previously produced isotopes, and 125 new decay chains of $^{286-289}$Mc [16, 18–20] shown in Fig. 10. The most profound results are that the decay chains connect to the main part of the chart of nuclides. This is perhaps the most important result of the decades long pursuits and studies of the superheavy elements. The region of superheavy nuclei that were predicted to be longer lived or stable was in fact approached with longer half-lives. It was labelled as the **island of stability**. An open challenge was whether these nuclei exist and whether they connect with stability in the chart of nuclides.

Conclusions

The new path forged Chemistry by the Solvay conference and distinguished scientists like Mary Lowe Good, who believed in the creation of a world of camaraderie and collaboration amongst the chemists, physicists, and other scientists of the world. It was in this spirit that we remember Mary Good and celebrate the open and sharing spirit of Yuri Oganessian in the production of new elements and new isotopes of heavy atoms and the push forward for the development of new tools to determine the chemical properties of the new elements. The example of Mary Good is for every scientist to be outstanding in science, to think about economic impacts of the new discoveries, and always to be a diplomat.

Acknowledgments: This work was supported by the US National Science Foundation and the US Office of Naval Research. The IUPAP sponsored conference to follow the example of global cooperation of scientists, “Science Brings National Together: An international conference on Heavy Atoms and Nuclei” was held in Yerevan, Armenia at the end of April, 2023. The results were shared and openly available to all https://indico.jinr.ru/event/3622/.

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