Superheavy Elements: Beyond the 7th Period in the Periodic Table

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ABSTRACT

What is the heaviest element? In order to address this question, the elements up to $Z = 118$ have been synthesized to date by heavy-ion fusion reactions. This has completed the 7th period in the periodic table of elements, and new attempts have been commenced aimed at syntheses of the elements in the 8th period. In this article, we review the current status and future challenges in the research field of superheavy elements, putting some emphasis on perspectives from nuclear reaction theory.

INTRODUCTION

The elements heavier than Plutonium (the atomic number $Z = 94$) are all unstable and do not exist on the Earth. Yet, one can artificially synthesize them using nuclear reactions. There have been continuous efforts since the 1950s (see e.g., Fig. 1 in Ref. [1]), and the elements up to $Z = 118$ have been synthesized to date. Out of these 118 elements, four new elements, $Z = 113$ (Nihonium, Nh), $Z = 115$ (Moscovium, Mc), $Z = 117$ (Tennessine, Ts), and $Z = 118$ (Oganesson, Og) are the most recent ones. They were added to the periodic table of elements in 2016 [2], completing the 7th period in the periodic table (see Ref. [3] for an interesting article on the Chinese characters for these elements). It is worth mentioning that Nihonium is the first element to be named after an Asian country.

The transactinide elements, that is, the elements with $Z \geq 104$, are referred to as superheavy elements. Those superheavy elements are interesting many-body systems, as they can also be viewed as quantum laboratories under the influence of a strong Coulomb field generated by the many protons in their atomic nuclei. In fact, for the following reasons, they offer an ideal opportunity to address a fundamental question of many-body physics: how does a quantum many-body system behave under the influence of a strong Coulomb field? Firstly, in the nuclei of superheavy elements, i.e., in superheavy nuclei, there is a strong interplay between the strong and the electromagnetic interactions, making superheavy nuclei unique many-body systems. That is, while the strong interaction plays a dominant role in normal nuclei, both the strong and the Coulomb interactions contribute in a similar way in superheavy nuclei. Because of this, quantum effects appear more prominent in superheavy nuclei than in normal nuclei. The effect of shell correction on the fission barrier is a typical example [4]. Furthermore, the electric dipole moment (EDM), which is intimately related to fundamental symmetries such as CP symmetry, is enhanced in heavy elements (for alkali atoms, for instance, the enhancement factor scales as Z^3 [5]), providing a good motivation for the study of heavy and superheavy elements. Secondly, it is known in chemistry that the periodic table can be perturbed due to the strong Coulomb interaction among electrons, as can be seen in lantanides and actinides. In superheavy elements, the relativistic effect becomes prominent, and the periodic table may further be disturbed significantly.

Heavy-ion fusion reactions at energies around the Coulomb barrier have been used as a standard tool to synthesize superheavy elements [6, 7]. Apparently, it is essential to understand the reaction dynamics in order to synthesize efficiently new elements beyond the 7th

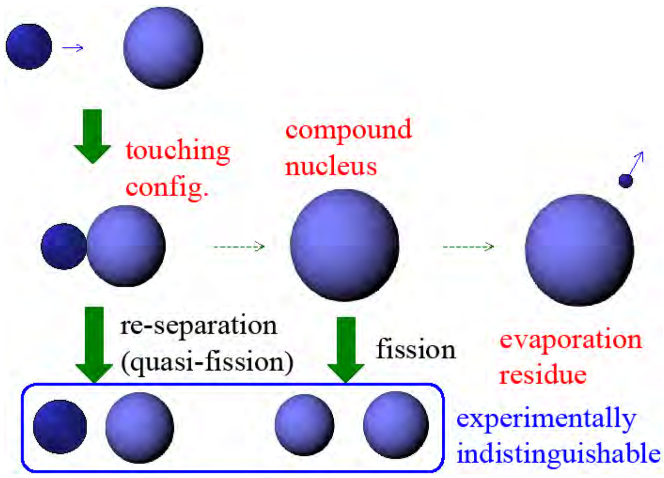

Fig. 1: A schematic illustration of a heavy- ion fusion reaction to form a superheavy element. The re-separation process without forming a compound nucleus (quasi-fission) and a fission decay of a compound nucleus cannot be separated experimentally. The formation of a compound nucleus is identified by detecting evaporation residues.

period in the periodic table (see Ref. [8] for new criteria for a discovery of a new element). However, the fusion reaction in the superheavy region is nothing more than the dynamics of many-body systems under a strong Coulomb field, and there still remain many challenges. In this article, we shall review the current status and future perspectives of nuclear reaction studies for superheavy elements. We refer to two recent articles, Refs. [9, 10], for complementary reviews of superheavy elements from the perspectives of nuclear structure theory.

HEAVY-ION FUSION REACTIONS FOR SUPERHEAVY ELEMENTS

Overview of the reaction process

Nuclear fusion is a reaction in which two nuclei combine together to form a larger nucleus, which is referred to as a compound nucleus. Fig. 1 illustrates schematically the formation of a superheavy element by nuclear fusion. In the first phase of the reaction, two nuclei approach the touching configuration. There is a potential barrier between the two nuclei, due to a cancellation between the long range Coulomb interaction and a short range attractive nuclear interaction, which has to be overcome in order to reach the touching configuration. For medium-heavy systems, a compound nucleus is formed almost automatically once the touching configuration is achieved [11]. In contrast, in the superheavy region, there is a huge probability for the touching configuration to reseparate due to a strong Coulomb repulsion between the two nuclei. Furthermore, even when a compound nucleus is formed with a small probability, it decays most likely by fission, again due to the strong Coulomb interaction. A complication is that quasi-fission characteristics significantly overlap with fission of the compound nucleus, and a detection of fission events itself does not guarantee a formation of the compound nucleus. Therefore, one really needs to detect evaporation residues, that is, those extremely rare events in which a compound nucleus survives without fission.

As an example, Fig. 2 shows the measured cross sections for the ^{48}Ca+^{238}U reaction forming the Cn (Z = 112) element. The filled circles show the capture cross sections [12] for the formation of the touching configuration shown in Fig. 1. On the other hand, the filled triangles and diamonds show the evaporation residue cross sections [13], for which the former and the latter correspond to the processes of emission of 3 and 4 neutrons, respectively. One can see that the evaporation residue cross sections are smaller than the capture cross sections by about 11 orders of magnitude.

Theoretical modelings

Based on the time-scale of each process, the formation process of evaporation residues can be conceptually divided into a sequence of the following three processes (see Fig. 1). The first phase is a process in which two separate nuclei form the touching configuration after overcoming the Coulomb barrier. Here, the couplings of the relative motion to several nuclear collective excitations in the colliding nuclei as well as several transfer processes play an important role [11]. After two nuclei touch with each other, a huge number of nuclear intrinsic motions are activated and the energy of the relative motion of the colliding nuclei is quickly dissipated to internal energies. Because of the strong Coulomb interaction, the touching configuration appears outside the saddle configuration of a fission barrier, and thus a compound nucleus is formed only after the fission barrier is thermally activated whereas most events go to quasi-fission. In order to describe this process, a Langevin dynamics has been developed [17, 18, 19, 20], although the dinuclear system model [21] has also been used. The third process is a statistical decay of the compound nucleus [22], with strong competition between fission and particle emission (i.e., evaporations). Here, the fission barrier height is one of the most important parameters that significantly affect evaporation residue cross sections [23].

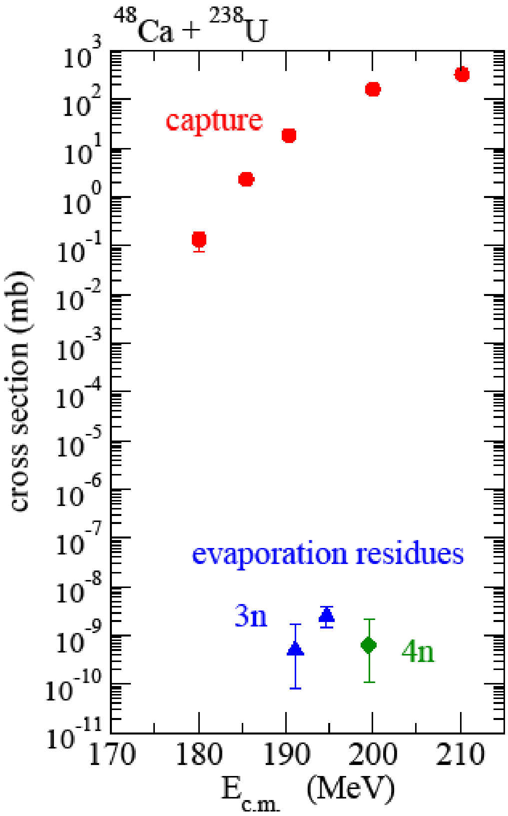

Fig. 2: The measured evaporation residue cross section as a function of the bombarding energy in the center of mass frame for the $^{48}Ca+^{238}U$ reaction leading to the formation of Cn ($Z = 112$) element. The filled circles show the capture cross section [12] to form the touching configuration shown in Fig. 1. The filled triangles and diamonds show the evaporation residue cross section [13], for which the former and the latter correspond to the 3*n* (emission of 3 neutrons) and the 4*n* (emission of 4 neutrons) channels, respectively.

For a given partial wave ℓ, the probability for formation of an evaporation residue is given as the product of the probability for each of the three processes, that is,

$$P_{\rm ER}(E,\ell) = T_\ell(E) P_{\rm CN}(E,\ell) W_{\rm sur}(E^*,\ell), \qquad (1)$$

where E and E^* are the bombarding energy in the center of mass frame and the excitation energy of the compound nucleus, respectively. As has been mentioned, there is no way to access experimentally the formation of the compound nucleus and no experimental data are available for $P_{\rm CN}$. This causes large uncertainties in theoretical calculations. An important theoretical challenge is then to reduce theoretical uncertainties in model calculations, especially for $P_{\rm CN}$, and to make reliable predictions for evaporation residue cross sections.

Hot fusion and cold fusion reactions

Since the formation of evaporation residues is a very rare process, it is important to choose appropriate combinations of the projectile and the target nuclei in order to efficiently synthesize superheavy elements. For this purpose, two different experimental strategies have been employed. One is the so called "cold fusion" reactions, for which the compound nucleus is formed with relatively low excitation energies so that the competition between neutron emissions and fission can be minimized, thus maximizing $W_{\rm sur}$ in Eq. (1) [6, 7]. To this end, ^{208}Pb and ^{209}Bi are used as the target nuclei. An advantage of this strategy is that alpha decays of the evaporation residues end up in a known region of the nuclear chart, and thus superheavy elements can be identified unambiguously. Nihonium was synthesized at RIKEN using this strategy [16]. The other strategy is the so called "hot fusion" reactions, for which more asymmetric combinations of the projectile and the target nuclei are used as compared to the cold fusion reactions, so that the formation probability of the compound nucleus, $P_{\rm CN}$ in Eq. (1), can be optimized. For this purpose, the neutron-rich double magic nucleus ^{48}Ca has been used as a projectile [7, 24]. This strategy has been successfully employed by the experimental group at Dubna, led by Oganessian, to synthesize superheavy elements up to $Z = 118$ (see e.g., Fig. 2). See also Ref. [25] for the very first direct measurement of the mass numbers of superheavy elements synthesized by the hot fusion reactions.

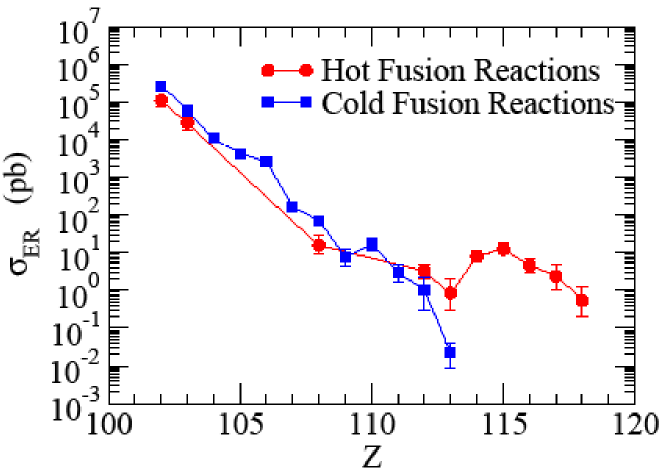

Fig. 3: The measured evaporation residue cross section as a function of the atomic number Z of a compound nucleus. The filled circles denote the results of the hot fusion reactions, in which ^{48}Ca nucleus is used as a projectile. The maximum of a sum of the 3*n* and 4*n* cross sections are shown for each Z. The filled squares show the results of the cold fusion reactions, in which the ^{208}Pb or ^{209}Bi nuclei are used as a target. Here, the maximum of the 1*n* cross section is shown for each Z. The experimental data are taken from Refs. [14,15,16].

Fig. 3 compares the measured evaporation residue cross sections due to the hot fusion reactions (the filled circles)

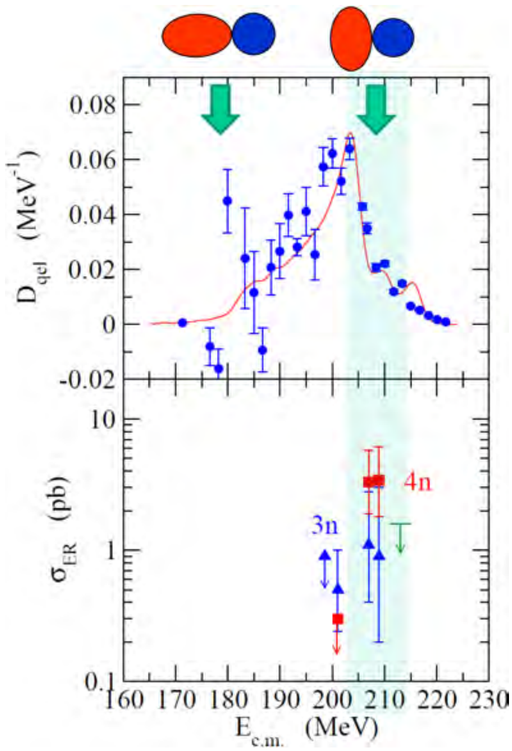

Fig. 4: (Upper panel) The experimental quasi-elastic barrier distribution, D_{qel}, for the ^{48}Ca+^{248}Cm system [31]. The solid line shows the result of a coupled-channels calculation that includes the deformation of ^{248}Cm as well as a transfer coupling. The shaded region corresponds to the so called side collision. (Lower panel) Experimental evaporation residue cross sections for this system taken from Refs. [13, 32].

with those due to the cold fusion reactions (the filled squares). For the cold fusion reactions, the cross section drop rapidly as a function of Z of the compound nucleus. It would therefore be difficult to go beyond Nihonium using this strategy. In contrast, for the hot fusion reactions, the cross section remain relatively large between Z = 113 and 118. This is due to the fact that the compound nuclei formed are in the proximity of a predicted island of stability [26, 27] and/or an increase of dissipation at high temperatures [28], both of which increase the survival probability, W_{sur}.

ROLE OF DEFORMATION IN HOT FUSION REACTIONS

Quasi-elastic barrier distribution

In the hot fusion reactions, by fixing the projectile nucleus to be ^{48}Ca, the target nuclei are found in the actinide region, in which the nuclei are well deformed in the ground state. An interesting and important question to ask is how deformation of the target nuclei affects the evaporation residue cross section. When a target nucleus is deformed, a single Coulomb barrier in the entrance channel is replaced by a multitude of Coulomb barriers, since the height of the Coulomb barrier depends on the orientation angle of the target nucleus. The way in which the barrier heights are distributed can be studied by measuring the so called quasi-elastic barrier distribution, D_{qel}, which is defined as the first energy derivative of the ratio of the quasi-elastic cross section to the Rutherford cross section at backward angles [29, 30]. Very recently, such measurements were carried out for the ^{48}Ca+^{248}Cm system by Tanaka et al. [31]. Fig. 4 shows the experimental data together with the result of a coupled-channels calculation, which takes into account the deformation of the target nucleus, ^{248}Cm. The figure clearly indicates that the maximum of the evaporation residue cross section is obtained with the so called side collision, that is, the configuration in which the projectile approaches from the shorter axis of the target nucleus (with an orientation angle of $\theta = \pi/2$ with respect to the beam direction). We mention that this is a nice confirmation of the notion of compactness proposed by Hinde et al. [33], who argued that the side collision leads to a compact touching configuration for which the effective barrier height for the diffusion process is low, enhancing the formation probability, P_{CN}. This notion has further been confirmed theoretically [34] using an extended version of the fusion-by-diffusion model, which takes into account the deformation effect of the target nucleus on the injection point for the diffusion process (See Fig. 5).

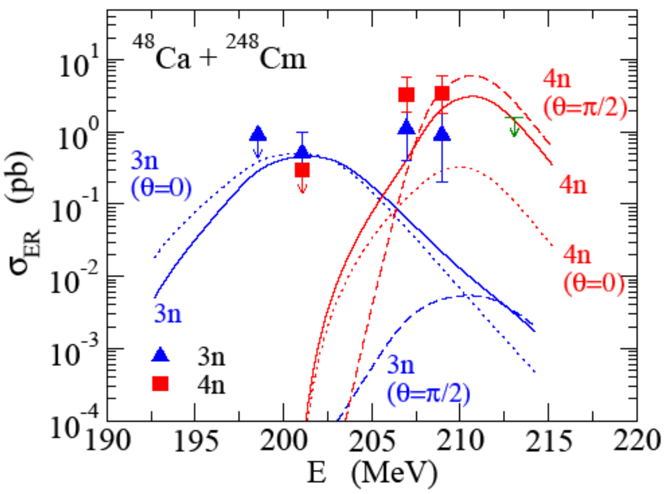

Fig. 5: The evaporation residue cross section for the ^{48}Ca+^{248}Cm system using the extended fusion-by-diffusion model [34].

Another important aspect of the measurement of Tanaka et al. is that it provides good information on capture cross sections. Capture cross sections can in principle be measured experimentally, but often the presence of deep-inelastic collisions complicates their experimental determination. The quasi-elastic cross sections measured by Tanaka et al. are almost free from the deep-inelastic component [31], and thus the capture cross section, or the capture probability T_ℓ in Eq. (1), constructed from the measured quasi-elastic cross section, is cleaner than that from direct measurement. This will be helpful in reducing theoretical uncertainties in modeling the formation process of evaporation residues.

A remaining theoretical challenge

Even though the quasi-elastic barrier distribution has nicely demonstrated the role of deformation in synthesizing superheavy elements, there still remains a theoretical challenge concerning hot fusion reactions with a deformed target. That is, it has yet to be clarified how the shape of the di-nucleus system evolves towards a compound nucleus. As we have mentioned, the di-nucleus system is rapidly heated up after touching, which will reduce several quantal effects such as nuclear deformation. However, nuclear deformation would persist for a while given that the notion of compactness is correct, as has been indicated by the quasi-elastic barrier distribution. In order to clarify this, one would need to develop a microscopic dynamical theory, in which the heat-up process can be described in a consistent manner from the approaching phase to the formation of a compound nucleus. The shape of the whole system would then be determined self-consistently at each time during evolution. A candidate for such theory is the one developed by Mukamel et al. in the 80s in the context of deep-inelastic collisions [35], even though no practical calculation has been carried out based on this theory.

TOWARDS Z = 119 AND 120

The heaviest element synthesized so far is Z = 118 (Oganesson). To go beyond this and synthesize the elements Z = 119 and Z = 120 by hot fusion reactions with a ^{48}Ca projectile, one would need Es (Z = 99) and Fm (Z = 100) targets. However, these elements are both short lived and are not available in sufficient amounts to perform fusion measurements [36]. Heavier projectile nuclei, such as ^{50}Ti, ^{51}V, and ^{54}Cr, would then have to be used instead of ^{48}Ca. For instance, a new measurement campaign has already been started at RIKEN to synthesize the element 119 using the ^{51}V + ^{248}Cm reaction [37].

An important issue here is to assess how much evaporation residue cross sections are affected if a projectile nucleus other than ^{48}Ca is used. One can consider the following two effects. Firstly, while ^{48}Ca is a double magic nucleus, ^{50}Ti, ^{51}V, and ^{54}Cr are open shell nuclei with valence nucleons outside the ^{48}Ca core. In the approach phase, ^{48}Ca could come closer to a target nucleus with less friction as compared to the other heavier projectile nuclei [38]. At the same time, the resultant compound nuclei would be at a larger excitation energy with the ^{48}Ca projectile as compared to the heavier projectiles. The former reduces the evaporation residue cross section while the latter enhances the cross sectionwhen the heavier projectiles are used. Secondly, reactions with the heavier projectiles are less asymmetric than those with ^{48}Ca. This leads to a higher effective barrier for the diffusion process (that is, the second phase in the reaction process shown in Fig. 1), reducing the evaporation residue cross section.

The net effect will be a combination of these effects. Among them, the effect of friction in the approach phase could be best studied with a microscopic theory such as the Time- Dependent Hartree-Fock (TDHF) method. By combining results of a TDHF calculation and Langevin dynamics, one would be able to discuss how much evaporation residue cross sections are reduced (or enhanced) when the heavier projectiles are used instead of the ^{48}Ca nucleus [39].

TOWARDS THE ISLAND OF STABILITY

One of the main motivations for the study of superheavy elements, in addition to synthesizing new elements, is to look for the island of stability, which was theoretically predicted some 50 years ago [26, 27]. Heavy nuclei in the transactinide region are unstable against alpha decay and spontaneous fission, but the shell effect due to magic numbers can stabilize a certain number of nuclei in that region. The predicted proton and neutron magic numbers are Z = 114 and N = 184 [26, 27], respectively, and the region around these magic numbers is referred to as the island of stability. A more modern Hartree-Fock calculation has also predicted (Z, N) = (114, 184), (120, 172), and (126,184) as candidates for the next double magic nucleus beyond ^{208}Pb [40].

The heaviest Flerovium element (Z = 114) synthesized so far is ^{289}Fl, which was synthesized using the ^{48}Ca+^{244}Pu hot fusion reaction [41]. Notice that 9 more neutrons are needed in order to reach the predicted magic number, $N = 184$. This implies that neutron-rich beams are indispensable in order to reach the island of stability. An experimental challenge towards this goal is how to deal with the low intensity of such beams. On the other hand, from a theoretical point of view, the reaction mechanism of fusion of neutron-rich nuclei is quite complex and has not yet been clarified completely [42]. In particular, a simultaneous treatment of fusion, breakup, and transfer processes has yet to be developed [43]. Another possibility, besides fusion, to reach the island of stability is to use a multi-neutron transfer reaction with neutron-rich beams [44]. Clearly more studies are needed, both experimentally and theoretically, in order to find optimum reactions and experimental conditions, including reaction systems, to reach the island of stability most efficiently. Of course, studies of the structure of neutron-rich nuclei are also an important ingredient for this purpose.

ASTROPHYSICAL PERSPECTIVES

It is worth mentioning that an investigation of nuclear reactions of neutron-rich nuclei discussed in the previous section may also help in clarifying an important question of modern science: how and where were heavy elements created in the universe? This concerns the r-process nucleosynthesis, whose pathway is through the neutron-rich region of the nuclear chart. A recent simultaneous detection of gravitational and electromagnetic waves from the neutron star merger event GW170817 has confirmed that mergers of neutron stars are important sites of r-process nucleosynthesis [45, 46]. However, there still may be many unknown features of the r-process nucleosynthesis. One of the key issues is the role of fission of neutron-rich nuclei. When heavy nuclei are created during nucleosynthesis, those nuclei decay by fission, producing lighter fragments, which may be recycled for nucleosynthesis [47, 48, 49]. That is, fission will determine the end point of r-process nucleosynthesis. However, fission is a typical example of large amplitude collective motion, in which the shape of a quantum many-body system changes greatly, and its microscopic understanding has not yet been achieved. In order to clarify the role of fission in r-process nucleosynthesis, a study of nuclear reactions for superheavy elements could play an important role, since superheavy elements detected in such reactions are evaporation residues, which have survived without fission. That is, by combining nuclear physics and astrophysics, with fission as an important key process, one would be able to achieve a comprehensive understanding of the synthesis of heavy and superheavy elements both in the universe and in laboratories. This will certainly be an important future direction in the research field of superheavy elements.

OUTLOOK

How does a strong Coulomb field affect behavior of quantum many-body systems? How and where were heavy elements around us created in the universe? These are important questions in the research field of superheavy elements. Such questions involve many research fields, not only nuclear physics and astrophysics but also chemistry. Nucleonic many- body problems in nuclear physics and electronic many-body problems in chemistry share similar problems. Moreover, understanding the electronic structure of heavy and superheavy elements plays an important role in understanding opacity of electromagnetic radiation from r-process nucleosynthesis.

The 7th period in the periodic table of elements has now been completed. Going beyond the 7th period to the 8th period is a real challenge now. Given this situation, it would be extremely useful to develop a multidisciplinary science for superheavy elements, including physics, astronomy, and chemistry. By combining those research fields, it is likely that we will be able to answer fundamental questions relating to superheavy elements and achieve a comprehensive understanding from this wide perspective.

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