Fusion between heavy nuclei and nuclear fission process

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- **We studied fusion between heavy nuclei involving ^{238}U target nucleus for the synthesis of superheavy element. Fusion probability was determined from the in-beam fission measurement, and the effect of deformation of ^{238}U on fusion was found. Our understanding on fusion was applied to produce new isotopes in superheavy nucleus.**

Abstract

Fusion reaction for the synthesis of superheavy nuclei (SHN) was investigated by measuring the fission fragments produced in the collision between heavy nucleus and actinide target nucleus. We also produced superheavy nuclei, and their cross sections were measured. The obtained fusion probability was consistent with those determined by the in-beam fission measurement.

The study was carried out under the international collaboration including Tohoku University, GSI in Germany and Flerov Laboratory of Nuclear Reactions (FLNR) in Russia. The results are published in Physical Review C [1] and other journals.

1. Background of the study

The liquid-drop model predicts that the heaviest nucleus which can be formed is the rutherfordium (atomic number is 104). However, due to the extra binding energy of nucleus originating from shell structure, heavier elements than 104 are expected to exist. Search for the existing limit of element is an important issue in nuclear physics and chemistry. Until now, the element 113 was produced at RIKEN, and elements up to 118 were produced at FLNR. To understand the nuclear properties more deeply, we need to produce new nuclei in the SHN region.

Superheavy nuclei can be produced by fusion reaction between heavy nuclei. The production cross sections are extremely low, a pico-barn (pb, 1 pb=10^{-36}cm^2) order, meaning that it takes several days to produce one atom even at a modern accelerator facility. The precise estimation of the cross section is essential to plan experiment. The reaction proceeds in three steps as shown in Fig.1: (1) Cross section that two colliding nuclei reach contact after passing over the Coulomb barrier, (2) Fusion probability of a system to make an equilibrated compound nucleus, and (3) Deexcitation of excited compound nucleus by evaporating neutrons in competition with fission. The process of (1) is well understood, and the survival probability (3) can be calculated by statistical model. Our issue is to understand the process (2), where quasifission competes with fusion. When fusion-fission and quasifission have different properties, we can obtain information on fusion probability by measuring these yields.

Actinide nucleus such as ^{238}U has a nuclear shape like rugby ball as shown in Fig. 1. We

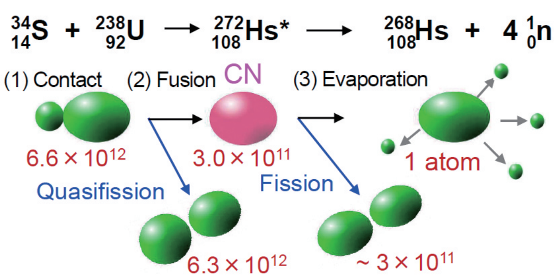

Fig. 1. Synthesis of superheavy nucleus in fusion reaction between ^{34}S and ^{238}U. Compound nucleus (CN) decays mostly by fission (fusion-fission). Event numbers at each stage of reaction to produce one atom are indicated [1].

thus need to understand the effects of nuclear orientation on fusion.

2. Circumstances of the study

Due to deformation of ^{238}U, the Coulomb barrier felt by the colliding nuclei changes with the incident angle relative to the symmetric axis of ^{238}U. It was known that nuclear contact on the polar sides of ^{238}U occurs even at low incident energy (Fig. 1) [2]. Occurrence of fusion from this configuration was, however, not understood until around 2000. We have measured the cross sections of ^{248,249,250}Fm as evaporation residues produced in fusion of ^{16}O + ^{238}U and concluded that the polar collisions result in fusion [3].

Then we started a campaign to study reactions using heavier projectiles. At bombardment of projectiles, such as ^{30}Si and ^{34}S ions, on the polar sides of ^{238}U, the corresponding Coulomb barrier is about 15 MeV lower than the collision on equatorial side. Fusion reaction at low incident energies populates compound nucleus with low excitation energy. This constrains number of evaporated neutrons, so that the neutron-rich SHN isotopes can be produced than the typical incident energies used so far.

Study for reactions using actinide nucleus grew to be also important from 2000, because FLNR produced SHN heavier than element 112 using ^{48}Ca plus actinide nuclei, and the cross sections are far larger than those obtained by the so-called 'cold fusion' reactions using lead and/or bismuth targets.

3. Content of the study

Figure 2 shows the potential energy of ^{274}Hs produced in the ^{36}S + ^{238}U reaction. The shell properties of nucleus largely changes the energy surface, which would also influence fusion reaction itself. Two reaction paths are shown. One is the equatorial collision leading to the compound nucleus shape (CN), which is then followed by fission with mass symmetry (fusion-fission). The other path comes from the polar collision. It would prefer quasifission by descending through the mass-asymmetric energy valley. We can obtain information on the yields for fusion and/or quasifission by measuring the fission fragment mass distribution.

The experiments were carried out at the tandem facility at Tokai, JAEA. The experimental setup is shown in Fig. 3. Both fission fragments produced by irradiating the ^{238}U target foil by the beams were detected in coincidence by position sensitive multi-wire proportional counters (MWPCs), and the fragment masses were determined by kinematical consideration.

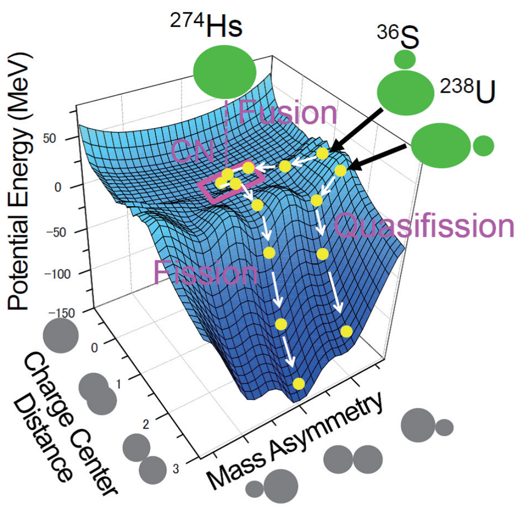

Fig. 2. Potential energy surface for ^{274}Hs plotted as functions of mass asymmetry and charge center distance. Two different fission modes, fusion-fission and quasifission, are indicated.

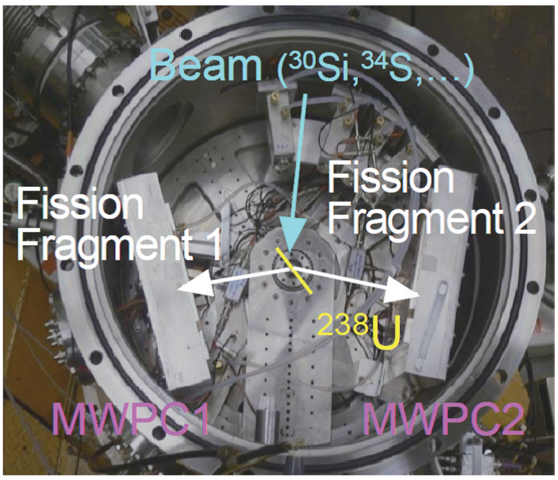

Fig. 3. Experimental setup for in-beam fission study

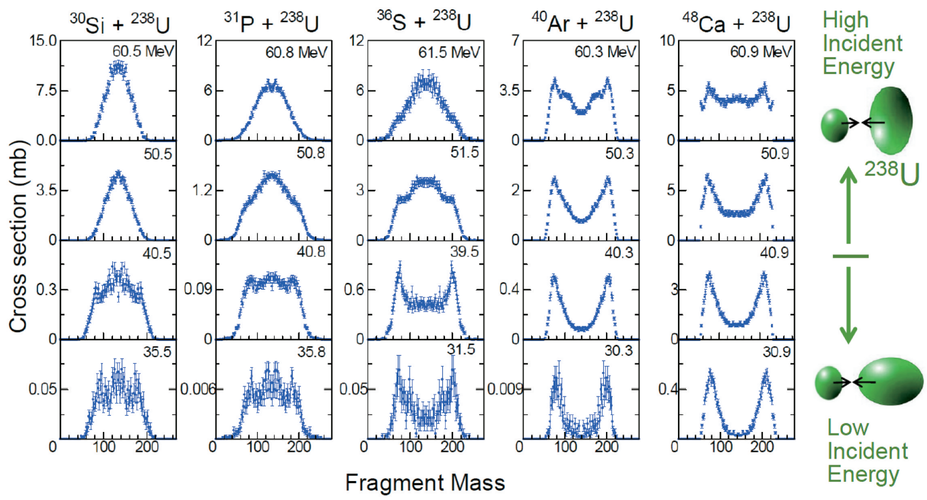

Fig. 4. Fission fragment mass distributions
Numerical values show the excitation energy of compound nucleus in MeV. Locations of the Coulomb barriers from two approaching angles are shown.

Figure 4 shows the fragment mass distributions [4,5]. In the reaction ^{30}Si + ^{238}U, the spectra show a symmetric shape at high incident energies, whereas the asymmetric fission mode appears at low energies. The result fits the idea that the equatorial collision leads to fusion and the polar collisions prefer quasifission (Fig. 2). The orientation effects were evident for every reactions shown in Fig. 4. The yield for quasifission is larger for heavier projectile due to the strong Coulomb repulsive force of the system. Exceptions are the reaction ^{48}Ca + ^{238}U that the ^{48}Ca nucleus gives larger fusion probability than ^{40}Ar at the same excitation energy. It is interpreted that fusion probability is also sensitive to the potential surface around the nuclear contact.

Under the collaboration with FLNR, we developed a model to interpret the data quantitatively [6]. Evolution of nuclear shape is calculated with a fluctuation-dissipation model. With the analogy of Brownian motion of a pollen on water surface, a nucleus receive a random force arising from the motion of nucleons, and the system also feel a friction generated by the change of a nuclear shape. Trajectory of nuclear shape with time was calculated to the end of binary decay point, and the orientation of the initial impact between colliding nuclei was taken into account. In the Monte Carlo procedure, fusion-fission is defined as the fission after reached the compound nucleus shape (Fig. 2). The results are shown in Fig. 5. The calculation demonstrates the measured spectra of ^{30}Si + ^{238}U and ^{34}S + ^{238}U and their energy dependence. In the figure, the calculated fusion-fission spectra are also shown. Fission from the compound nucleus shape has mass symmetry shape both for ^{30}Si + ^{238}U and ^{34}S + ^{238}U reactions. Fusion probability is thus determined from fusion-fission yields to all the fission events. The reaction ^{34}S + ^{238}U has significantly smaller fusion probability than ^{30}Si + ^{238}U.

The production of SHN has been carried out at energies corresponding to (a) and (b). Lower energies of (c) and (d) had not been chosen because of the unknown behavior of fusion cross section.

Experimental data and the analysis in Fig. 5 show the fusion probability possible to produce SHN even at lower incident energies of (c) and (d). For example, the ^{34}S + ^{238}U reaction gives 4.9 % at the energy (c). By inputting this value

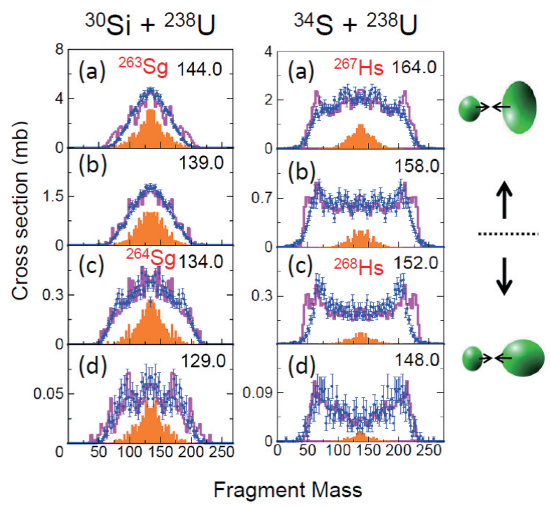

Fig. 5. Calculated spectra (histogram) are compared with the experimental data (circle with error bar). Fusion-fission events are shown by the filled histogram. Numerical values are the center-of-mass energy, $E_{c.m.}$ We also produced isotopes at the indicated energies.

to a statistical model, the cross section for ^{268}Hs produced by four neutron evaporation is calculated to be 0.3 pb. Similarly, the ^{30}Si + ^{238}U reaction at energy in (c) gives 11 pb for ^{264}Sg (4n). These values are achievable by using a modern experimental facility.

We produced isotopes shown in Fig. 5 at GSI. The campaign was started from the time that the author (K.N.) stayed as a visiting researcher from 2004. GSI is known for the success to produce new elements from 107 to 112 by 'cold fusion' reaction. At that time GSI started to use the actinide-based reactions, and the synthesis of element 112 in the reaction ^{48}Ca + ^{238}U was the first plan. We had common experimental interest in using the ^{238}U target, making a smooth collaboration between GSI and JAEA. After the approval of our experiments on ^{30}Si + ^{238}U and ^{34}S + ^{238}U, intense ^{30}Si and ^{34}S beams (1–2 pμA) were developed and successive two experiments were carried out. In the experiment, in-flight recoil separator called SHIP was used to separate evaporation residue from the primary beams. In the reaction ^{30}Si + ^{238}U, three α-decay chains starting from known isotope ^{263}Sg were registered at the center-of-mass energy ($E_{c.m}$) of 144.0 MeV, then three spontaneous fission events from the new isotope ^{264}Sg were detected at the sub-barrier energy of 133.0 MeV [7]. The obtained cross sections were 67 pb and 10 pb, respectively. The values give fusion probability consistent with those obtained from the in-beam fission experiment shown in Fig. 5. In the ^{34}S + ^{238}U reaction, one α-decay chain starting from the known isotope ^{267}Hs was obtained at $E_{c.m}$ =163.0 MeV. At the low energy 152.0 MeV, one α-decay from a new isotope ^{268}Hs was identified [1]. The corresponding cross sections 1.8 pb and 0.54 pb, respectively, also give consistent values in the fusion probability.

4. Importance of the result and its impact

Nowadays, fusion reaction using actinide target nucleus is the major approach for the synthesis of SHN. In this sense, our understanding on fusion is important in this field. To beyond the element 118, a larger cross section is expected than the cold fusion. Also, relatively neutron rich SHN can be produced than by the cold fusion. Among the isotopes produced by actinide-based reaction, nuclei with longer life-time, which is useful for the single-atom chemistry are found. To find out the location of the closed shell structure in SHN region, we need to explore more new isotopes. The proposed method to estimate the fusion probability is efficient because the in-beam fission experiment can be done in several hours.

In this work we clearly showed the asymmetric fission valley (Fig. 2) by measuring quasifission mode, whereas typical fission study from the compound nucleus cannot populate such an asymmetric channel. Heavy-ion induced fission is a unique tool to study the global potential energy surface.

These results are published in several journals, and we received several invited talks including the International Nuclear Physics Conference (INPC2010) [5].

5. Perspectives

Using the incident energy corresponding to Fig. 5(d), we estimate to produce SHN by 3n evaporation with the similar cross section to 4n channel. The sub-barrier fusion reaction would allow us to produce many new isotopes in SHN region. An example is seen in the reaction ^{26}Mg + ^{248}Cm that ^{271}Hs (3n) was produced [8], in which our result is refereed. It is also our scope to measure neutron multiplicity in fission to obtain information on fission time scale to cleary isolate fusion-fission and quasifission.

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