Synthesis of Superheavy Nuclei using Heavy-ion Fusion Reactions.

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The present status related to the synthesis of the superheavy elements is briefly reported. The fusion between deformed nuclei, the gentle fusion or the hugging fusion, has been theoretically proposed as a new type of fusion reaction. In order to investigate this type of reaction, we measured the dependence of the fusion probability on the orientation of deformed nucleus with respect to the beam axis in the fusion reactions of ^{60}Ni with ^{154}Sm and ^{76}Ge with ^{150}Nd. We found that the fusion probability strongly depends on the orientation of the nuclear deformation. When the projectiles collide at the tip of the deformed nuclei, the fusion probability is considerably reduced. On the other hand, when the projectiles collide at the side of the deformed nuclei, the fusion occurs without any hindrance. This phenomenon was understood qualitatively by comparing the distance between the mass centers of two colliding nuclei at the touching configuration with the position of the saddle point of the compound nucleus.

1. Introduction

The study of the superheavy element is the one of new frontier in nuclear physics. The superheavy element (Z=114, N=184) was predicted more than 30 years to be a doubly closed shell nucleus beyond ^{208}Pb. Experimentally, many authors tried to synthesize this element by the bombardment of existing heavy element with energetic ion beams or to search it in materials of the earth and the moon. Up to the present time, there is no definite evidence for the discovery of the superheavy element. The GSI group [1] has synthesized the heavy elements up to Z=112 step by step using the lead based fusion reaction. Recently, the Dubna group [2] reported one α decay chain which is a good candidate for originating from the decay of the parent nucleus ^{289}114. The fusion reaction of ^{48}Ca with ^{244}Pu was used and the production cross section in the 3*n*-evaporation channel was about 1 pb. The Berkeley group [3] also reported three decay chains in the reaction of ^{86}Kr with ^{208}Pb, each consisting of an implanted heavy atom and six subsequent α decay. These decay chains are consistent with the formation of ^{293}118 and its decay by sequential α-particle emission. The reported α–decay sequences are shown in Fig.1 together with the experimental result of the Dubna group and the known isotopes up to now. The production cross section of the reaction of ^{86}Kr with ^{208}Pb, 2.2 pb, is considerably larger compared with the production systematics [1] of the lead based fusion reaction. This experiment was performed following a prediction by Smolanczuk [4]. He calculated the evaporation residue cross section in the 1*n*-evaporation channel for the lead based reaction and gave a large production cross section, 670 pb, for the reaction of ^{86}Kr with ^{208}Pb. This large production cross section mainly comes from a large negative *Q*-value of this fusion reaction and a large fission barrier height of the compound nucleus. These factors result in a small excitation energy at fusion barrier and a large survival probability of a compound nucleus in the de-excitation process.

In order to make a fully equilibrated compound nucleus in the heavy-ion fusion reaction, a projectile must have an enough kinetic energy to surmount one-dimensional barrier (fusion barrier) between projectile and target nuclei. Furthermore, when the product of the atomic numbers of projectile and target, Z_1Z_2, is larger than about 1800, an extra kinetic energy is needed to surmount a saddle point of the compound nucleus. This energy is called as an *extra-extra push energy*. This is because the saddle point locates inside compared with a contact point of two colliding nuclei in the case of heavy reaction system. The compact configuration at touching is more favorable for fusion. The most compact configuration may be realized in the collision between deformed nuclei as pointed out by [5,6], where the gentle fusion [5] and the hugging fusion [6] between well-deformed nuclei have been theoretically proposed. When the symmetry axes of the deformed nuclei are orthogonal to each other at the contact configuration, the two deformed nuclei can take the most compact configuration and then proceeds to the formation of the compound nucleus. Furthermore, it is expected that this touching configuration makes the fusion path far from the competing axial-symmetric fission path. In order to investigate this theoretical prediction experimentally, we have measured the fusion cross sections of the reaction of ^{60}Ni + ^{154}Sm, ^{32}S + ^{182}W, ^{76}Ge + ^{150}Nd and ^{28}Si + ^{198}Pt, where the former two reactions and the latter two reactions make the same compound nucleus ^{214}Th and ^{226}U, respectively. The nuclear deformations β_2 of ^{150}Nd, ^{154}Sm, ^{182}W and ^{198}Pt are 0.36, 0.32, 0.28 and –0.11, respectively.

2. Experiments and results

The experiments were carried out at the tandem-booster facility of Japan Atomic Energy Research Institute (JAERI). The fusion residues emitted from targets to the beam direction were separated in-flight from the primary beam and various products of background reactions by the JAERI recoil mass separator. The experimental details are shown in [7]. The evaporation residue cross sections measured in the reaction of ^{32}S with ^{182}W are shown Fig. 2, where the cross section of each residue is shown as a function of the center-of-mass kinetic energy. These cross sections were compared with the calculation, where the fusion cross section was calculated by the coupled channel code CCDEF [8] by taking account of the target deformation and the coupling of the inelastic channel to the fusion process. The evaporation residue cross sections were calculated by the statistical model code HIVAP [9]. As shown in Fig. 2, the evaporation residue cross sections in the reaction of ^{32}S with ^{182}W were well reproduced by the calculation (the solid curves). This indicates that the deformation of ^{182}W, as well as the inelastic couplings of target and projectile to the fusion process, makes an enhancement of the fusion cross section at subbarrier energy region. On the other hand, the measured evaporation residue cross sections in the reaction of ^{60}Ni with ^{154}Sm shown in Fig. 3 were well below the calculated cross section (the dashed curves) at the subbarrier energy (E_{cm}<190 MeV), while the cross sections measured above E_{cm}>200 MeV were consistent with the calculation. It is noted that the Coulomb barrier height depends on the collision angle of ^{60}Ni with respect to the symmetry axis of the deformed nucleus ^{154}Sm. For example, the barrier height for the collision at the tip of the ^{154}Sm is 174 MeV, while it for the collision at the side of the ^{154}Sm is 198 MeV. The present result indicates that the collision at the tip of the deformed ^{154}Sm nucleus does not proceed to the formation of the compound nucleus, even if the barrier at the tip is surmounted. On the other hand, the collision at the side of the ^{154}Sm nucleus forms the compound nucleus without any hindrance. This tendency was also observed in the reaction of ^{76}Ge with ^{150}Nd, where we observed a strong hindrance of the evaporation residue cross section at the subbarrier energy region as compared with the calculation taking account of the nuclear deformation of ^{150}Nd, while the measured evaporation cross section were consistent with the same calculation at the above-barrier energy region.

The present result is qualitatively explained by considering relative positions of the saddle point and the distance between the mass centers of two colliding nuclei at touching point. According to the liquid drop model calculation of [10], the saddle point of ^{214}Th is located at $1.5R_0$, where R_0 is the radius of ^{214}Th. In the reaction of ^{60}Ni with ^{154}Sm, the longest distance between the mass centers at the touching point is $1.7R_0$ and the shortest distance is $1.4R_0$. That is, the touching configuration at the tip is elongated more than the saddle point and thus even if the Coulomb barrier at this point is surmounted, the reaction system does not automatically proceed to form the compound nucleus. On the other hand, in the reaction of ^{32}S with ^{182}W, the longest distance at the touching configuration is $1.5R_0$, approximately the same position as the saddle point. Therefore we expect that the reaction system automatically fuse when the Coulomb barrier is surmounted in this reaction. The same argument can be applied in the reaction of ^{76}Ge with ^{150}Nd, where the saddle point is located at 1.4 times of the radius of the ^{226}U. This location of the saddle point is approximately close to the distance between the mass centers at the side collision. This explains the strong hindrance of the fusion cross section and thus the measured evaporation residue cross sections considerably smaller than the calculation at subbarrier energy.

The present experimental result is consistent with the idea of the proposed hugging fusion or the gentle fusion between deformed nuclei. In order to convince the present consideration, further experimental studies of fusion between deformed nuclei is needed.

References

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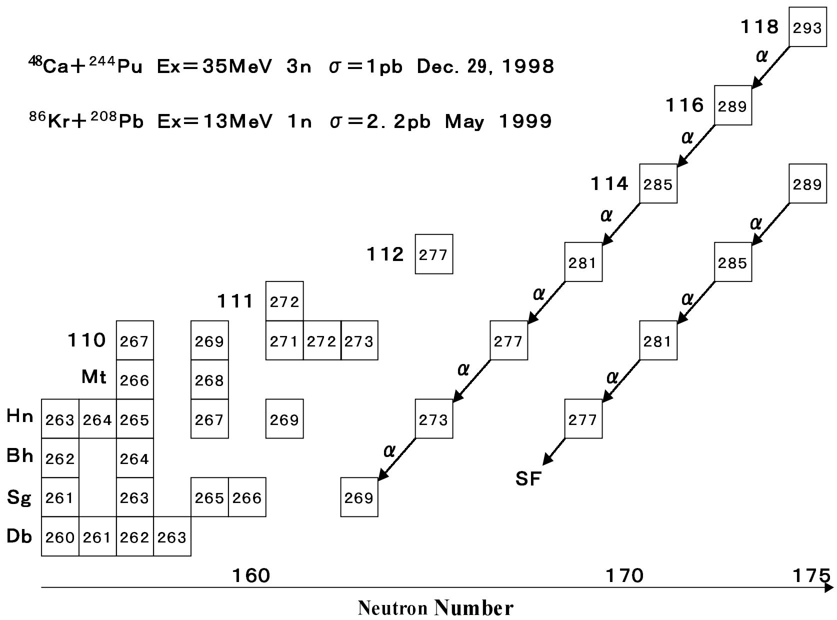

Fig. 1 α decay chains observed in the reactions of ^{48}Ca with ^{244}Pu [2] and ^{86}Kr with ^{208}Pb [3] together with the known heavy isotopes above Z=105.

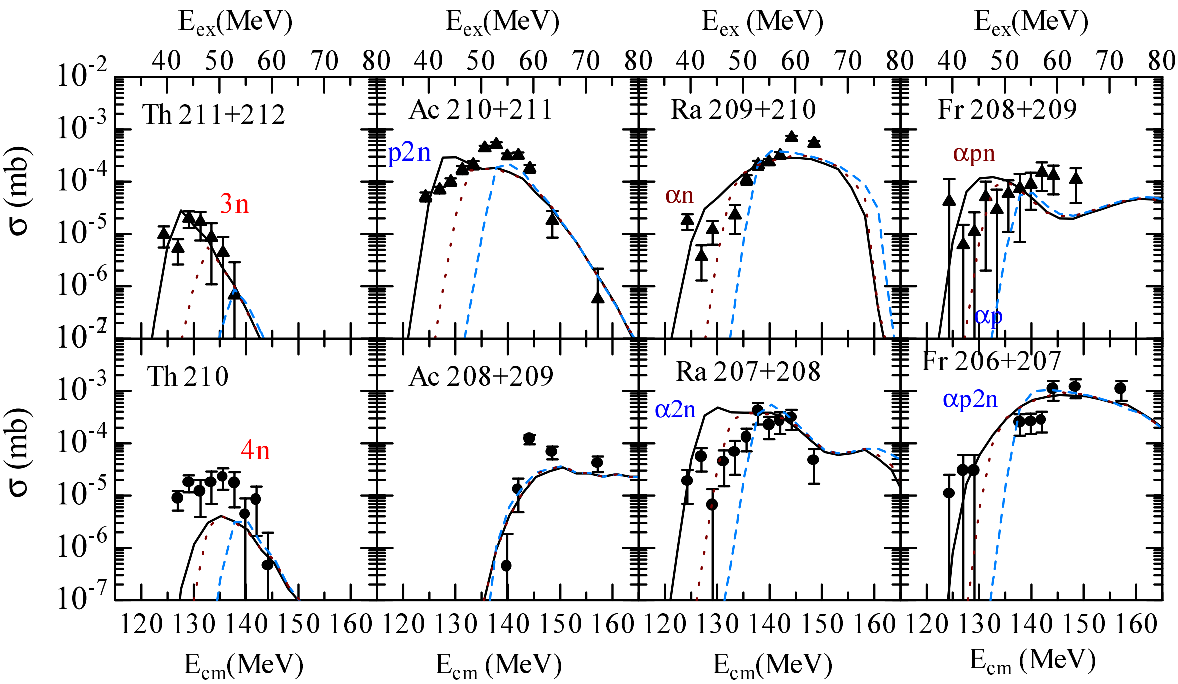

Fig. 2 Evaporation residue cross sections measured in the reaction of ^{32}S with ^{182}W as a function of the center-of-mass energy. The excitation energy E_{ex} of the compound nucleus is also shown. The Solid curves show the calculation including the deformation of ^{154}Sm and the inelastic couplings of ^{182}W and ^{32}S. The long dashed curves show the calculation without the deformation and the inelastic couplings. The short dashed curves show the calculation including the deformation only.

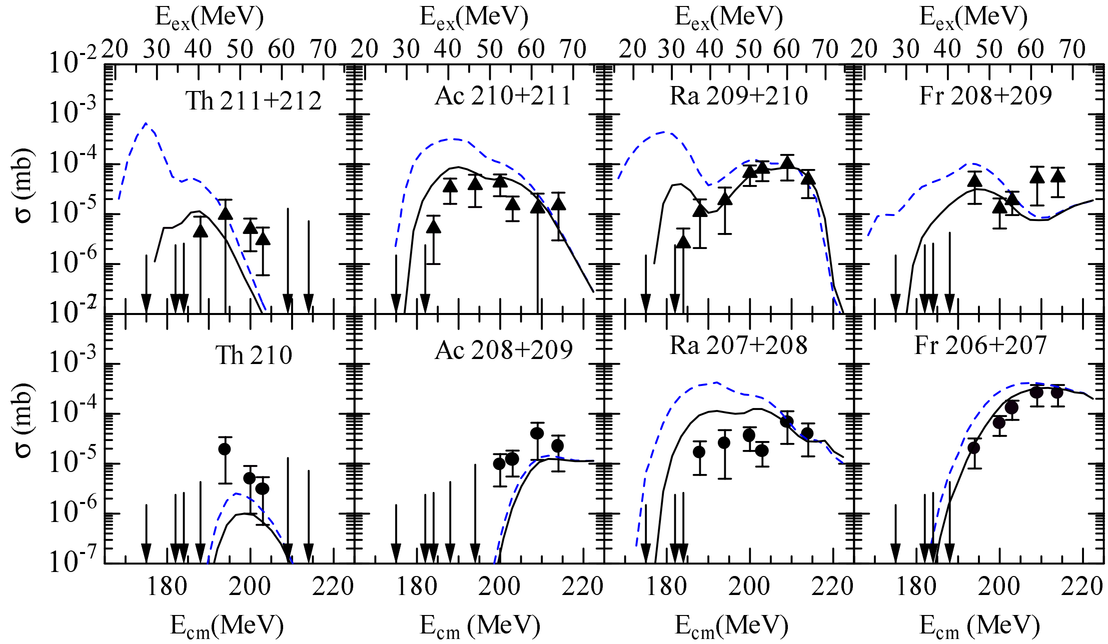

Fig. 3 Evaporation residue cross sections measured in the reaction of ^{60}Ni with ^{154}Sm. The dashed curves show the calculation taking account of the deformation of ^{154}Sm. The solid curves show the calculation including an extra-extra push energy in addition to the deformation.