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FISSION CROSS SECTION IN THE SYNTHESIS OF THE ^{264}Rf NUCLEUS VIA ^{26}Mg + ^{238}U COMBINATION

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Abstract. Our understanding of the fission mechanism has been still limited up to date, especially, for mass distribution of heavy nuclei or actinide ones. Since the heavy isotopes on the neutron-rich side of the nuclear chart cannot be accessed via capture reactions, it is thought that the mechanism can be studied via compound nuclei produced by multi-nucleon transfer reactions, in which the fission process should be understood. In this paper, we mention the role of the transfer reaction ^{26}Mg + ^{238}U and an estimation of the cross section of the fission led by the compound nucleus, ^{264}Rf.

Keywords: multi-nucleon transfer, fission, cross section, heavy nuclei, synthesis

1 Introduction

Most of the recent nuclear data have been obtained in the regions of the isotopes lighter than ^{208}Pb by using fission, a deep-inelastic and transfer reaction. The data for heavier nuclei are still very limited because there are challenges in studies such as the small probability of synthesis and unclear interaction mechanism. Multi-nucleon transfer reactions performed with the help of neutron-rich unstable beams are considered as a candidate to reach the region heavier than ^{208}Pb. Since many nuclei in a wide range of mass are produced in one reaction, it is advantageous to use the transfer reactions to search the excitation energy of the fission system and its dependence of the fission properties. It is necessary to note that the excitation energy dependence of the fission yield can provide information on the shell damping. There are large uncertainties of model calculations for the fission fragment charge distribution based on unexpectedly large shell damping energy (E_D) [1]. The experimental data of transfer reactions are very useful to confirm the value of E_D. In addition, it is believed that if the projectiles lacking in neutron bombard heavy targets, proton-stripping and neutron pick-up channels for the projectiles are available while in the case of neutron-rich projectiles, proton pick-up and neutron-stripping channels for the projectiles also open up. This is the route reaching to the neutron-rich heavy region. Another interest of this transfer reaction is the probability fission fragment mass distribution. There are several peaks of fragments corresponding to their mass in the fission reaction of ^{18}O + ^{238}U [2]. The probability of emission of fragments strongly depends on the energy and the number of evaporated proton or neutron. The mechanism for the mass distribution has been unclear so far. The phenomena of mass asymmetric, sharp transition from asymmetric to symmetric distribution

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found in Ref. [3] and the reduction of the peak to the valley (P/V) ratio of the fission yield at higher excitation energies have not been explained until now [2]. With the mention motivation, we investigated the roles of the transfer reaction ^{26}Mg + ^{238}U and its fission cross sections, which is important to uncover the fission mechanism of heavy nuclei.

2 Roles of transfer reaction ^{26}Mg + ^{238}U

As mentioned above, nuclear physicists propose to directly measure the transfer reaction ^{26}Mg + ^{238}U to study the compound nucleus, ^{264}Rf* (Z = 104, N = 160). It should be noted that the data of the ^{264}Rf* isotope have been very limited up to date. There are fourteen isotopes and three isomeric states found for this element. However, there is an anomaly of mass distribution of the Rf isotopes. We have not observed even-mass numbers of Rf distributing continuously in the range of A = 253–268. In addition, the isomeric state of ^{263m}Rf has not been confirmed yet. These problems are expected to be revealed via the transfer reaction ^{26}Mg + ^{238}U. The data of these isotopes, such as half-life, isomeric states, quantum transition, and excitation energy have been extremely limited up to date. It is also expected that the mass yield for the fission of ^{264}Rf*, which is unavailable at present, can be obtained with the transfer reaction ^{26}Mg + ^{238}U.

Since reaction ^{26}Mg + ^{238}U can produce a series of fragments (Fig. 1), we can investigate the probability of emission of fragments. It is believed that the probability is different for each energy and proton or neutron number. Furthermore, the variation of the width of the fragment mass distribution with excitation energies is a promising probe for studying quasi-fission, while it is believed that quasi-fission proceeds through a mass asymmetric fission barrier. Therefore, the mass distribution of ^{26}Mg + ^{238}U is very helpful to understand the reaction mechanism.

Since we can have a wide range of excitation energy of fragments in a wide range of mass numbers of the reaction, the excitation energy of isotopes from ^{208}Pb to ^{264}Rf can be obtained. The observation of light and heavy isotopes in the region of Mg up to Rf in this measurement is also important to make the role of fission in the nucleosynthesis in the universe clearer. For nuclear power plants, the data of this measurement are very helpful for the spent-fuel management since the fraction of remaining ^{238}U is still high. For nuclear physics, reaction

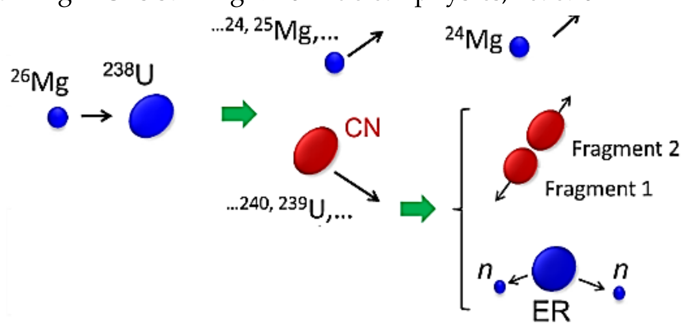

Fig. 1. Multi-nucleon transfer reactions

^{26}Mg + ^{238}U is important to provide much more new data for the nuclear database of elements and to confirm the value of E_D, as well to answer the question why we could not observe isotope ^{264}Rf. Furthermore, the reaction is also useful for the study of the shell evolution of fragments and fission barrier height.

3 Fission in the synthesis of the ^{264}Rf nucleus via the ^{26}Mg + ^{238}U reaction

The fission properties of the compound nucleus, ^{264}Rf, at the excitation energy of 145 MeV are thought to be clearer with the data of the fission cross section. It is worth noting that there is a competition between the compound formation and the quasi-fission in the early stages of the synthesis of heavy nuclei. After formation, the compound nuclei have a high probability to de-excite to stable states by emitting light particles, such as neutron, proton or alpha. The cross section data are useful to develop theoretical models for fission, for example, using the Langevin calculation [4-6]. Subsequently, important key parameters in the model such as shell damping energy will be investigated. This would be also useful for the development of a theory of heavy-element synthesis.

Figure 2 shows the evaporation cross sections of the neutron and proton of the compound nucleus at 145 MeV after the formation via the ^{26}Mg + ^{238}U reaction. The results indicate that the probability for multi-nucleon transfer is very small. The 1n or 1p emission dominates over the one of many-neutron (or proton) evaporation. It is possible for the formation of $^{264\text{-}258}$Rf isotopes since they have the cross section in the order of picobarn. The other isotopes with $A < 257$ ($^{A<257}$Rf) are mostly not synthesized by emitting more neutrons in this reaction. Subsequently, the proton-rich isotopes of this element should be very limited. The cross section for 1p-evaporation is much smaller than the one for 1n-evaporation. As the cross section is in the order of femtobarn, the maximum number of evaporated protons should be about a factor of 4. This means that it is difficult for the elements with $Z < 100$ to be produced in this interaction.

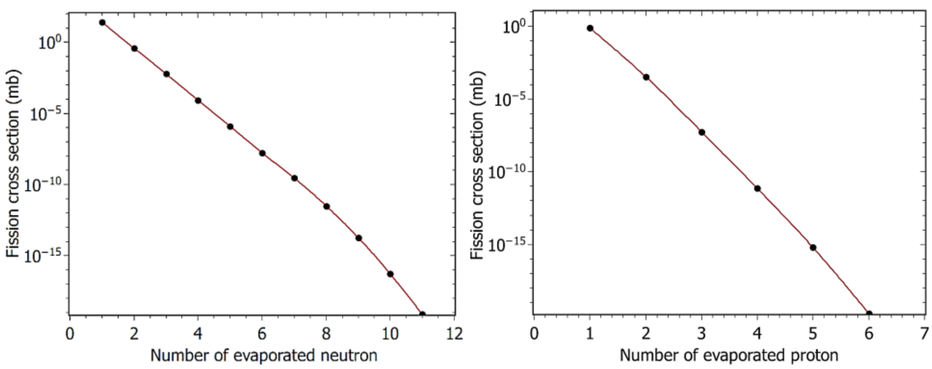

Fig. 2. Evaporation cross section of the neutron (left panel) and proton (right panel) emission of compound nucleus ^{264}Rf at 145 MeV after the formation via ^{26}Mg + ^{238}U reaction.

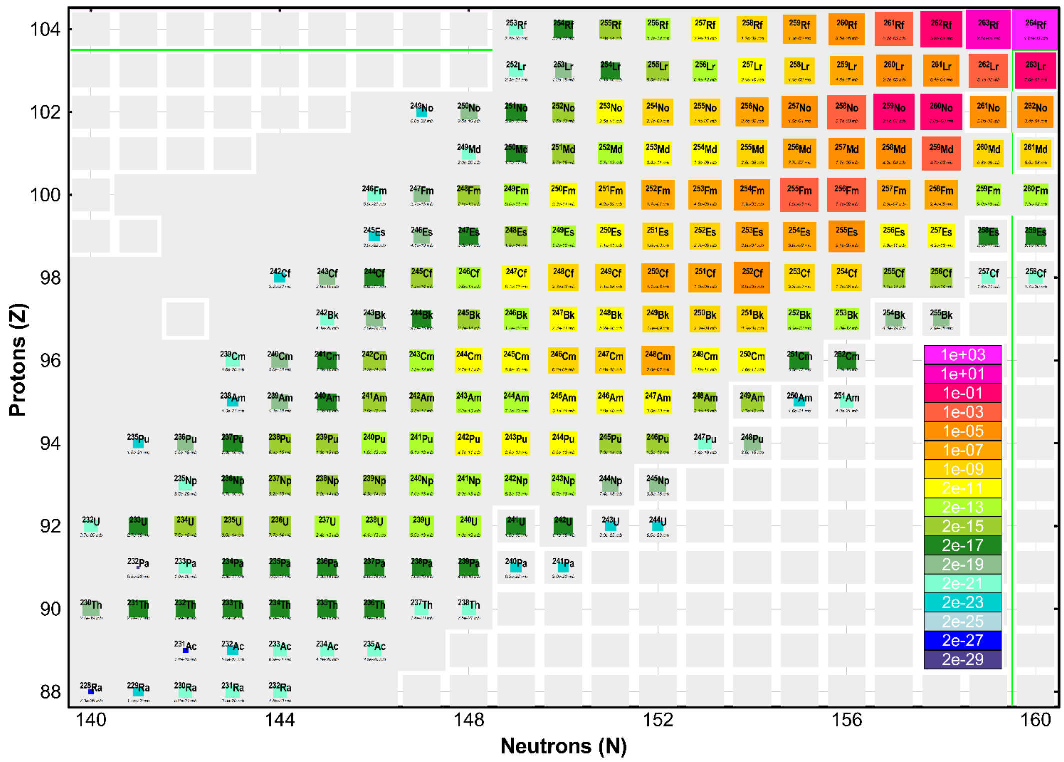

Fig. 3. Isotopes produced in the interaction with small fission cross sections. The number column shows the fission cross section of the isotope production.

Although the cross section is very small, there is a chance for lighter nuclei to be formed in the interaction ^{26}Mg + ^{238}U. All the possible isotopes produced in this reaction are shown in Fig. 3. The obtained results show that the fissions producing $^{259,\,260}$No, $^{255,\,256}$Fm, $^{251,\,252}$Cf, $^{247,\,248}$Cm, and ^{244}Pu have larger cross sections compared with the other isotopes of the same element. The differences of Z-number and A-number of these isotopes are $\Delta Z = 2$ and $\Delta A = 4$. This result shows an evidence of the α-decay chains from $^{263,\,264}$Rf nuclei. This phenomenon also indicates that the fissions emitting α particles dominate over the nucleon evaporation, or the α-decay strongly occurs after the compound nuclei formation or after 1n-evaporation. Two α-decay chains should be

$$^{264}Rf(\alpha)^{260}No(\alpha)^{256}Fm(\alpha)^{252}Cf(\alpha)^{248}Cm(\alpha)^{244}Pu \text{ and } ^{264}Rf(n)\,^{263}Rf(n)^{259}No(\alpha)^{255}Fm(\alpha)^{251}Cf(\alpha)^{247}Cm.$$

4 Conclusion

The combination for the production of ^{264}Rf isotopes has been considered. The fission cross sections indicate that the neutron evaporation dominates over the proton one. The nucleon evaporation has a cross section smaller than the α-emission. In other words, α-decay plays a main role in the fission process. Two α-decay chains should be observed in the fission. The results also predict about 170 isotopes heavier than Ra can be produced. It means that two groups of nuclei exist in the fission with the light nuclide group having the mass range of A = 4–32 and the heavy group having the mass range of A = 232–264.

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