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Fusion reactions around the barrier for Be+^{238}U*

Bo Mei(梅波)[1,2,3†] Dimiter L. Balabanski[3] Wei Hua(滑伟)[1‡] Yu-Hu Zhang(张玉虎)[2] Xiao-Hong Zhou(周小红)[2]
Cen-Xi Yuan(袁岑溪)[1] Jun Su(苏军)[1]

[1]Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China
[2]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[3]Extreme Light Infrastructure Nuclear Physics, "Horia Hulubei" National R&D Institute for Physics and Nuclear Engineering, Strada Reactorului 30, 077125 Bucharest Magurele, Romania

Abstract: Fusion-evaporation cross sections of ^{238}U(^{9}Be, 5n)^{242}Cm are measured over a wide energy range around the Coulomb barrier. These measured cross sections are compared with model calculations using two codes, namely HIVAP2 and KEWPIE2. HIVAP2 calculations overestimate the measured fusion-evaporation cross sections by a factor of approximately 3. In KEWPIE2 calculations, two approaches, namely the Wentzel-Kramers-Brillouin (WKB) approximation and the empirical barrier-distribution (EBD) method, are used for the capture probability; both of them properly describe the measured cross sections. Additionally, fusion cross sections of ^{7,9}Be+^{238}U measured in two experiments are applied to constrain model calculations further through three codes, i.e., HIVAP2, KEWPIE2, and CCFULL. Parameters in these codes are also examined by comparison with measured fusion cross sections. All the comparisons indicate that the KEWPIE2 calculations using the WKB approximation agree well with the measured cross sections of both fusion reactions ^{7,9}Be+^{238}U and the fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm. Calculations using the fusion code CCFULL are also in good agreement with the measured fusion cross sections of ^{7,9}Be+^{238}U.

Keywords: fusion-evaporation reaction, ^{238}U fusion, cross sections near barrier energies

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I. INTRODUCTION

Fusion-evaporation reactions of heavy-ions around the Coulomb barrier are widely used to produce heavy as well as super-heavy exotic nuclei [1-3]. Accurate cross sections are required for evaluating production rates of these heavy exotic nuclei and for the optimization of projectile-target combinations as well as the projectile energy in planned fusion-evaporation experiments. A growing interest in the investigations of fusion reactions with light weakly bound nuclei recently emerged [4-9]. In particular, comparisons of fusion reactions for light nuclei along an isotopic chain can be used to probe a possible impact of nuclear structure, e.g., clustering and halos [10-12]. For instance, fusion reactions around the barrier were measured for ^{7,9}Be+^{238}U [7] as well as ^{9,11}Be+^{238}U [13, 14] to explore the effect of weakly bound systems. It seems that the impact of weakly bound nucleons is not clear, and consequently, more experimental studies are needed. The effect of the deformation of ^{238}U was also investigated by measuring the fusion reactions of different projectiles, namely ^{16}O [15], ^{36}S [16], ^{30}Si [17], and ^{40,48}Ca [18], with the ^{238}U target. According to these studies reported in Refs. [15-18], the deformation of ^{238}U should be considered in model calculations to explain the measured cross sections for fusion reactions between ^{238}U targets and various projectiles at sub-barrier energies.

Theoretically, the fusion-evaporation reaction can be divided into two steps: the fusion of two nuclei into a compound nucleus and its subsequent decay by the evaporation of light-particles, γ-ray emission, and fission. Different codes, e.g., HIVAP [19] and KEWPIE [20], were developed to describe these two steps and calculate cross sections of fusion-evaporation reactions, while another code, CCFULL [21], was proposed for fusion calculations. However, model calculations through these codes often present very large uncertainties from their in-

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† E-mail: meibo5@mail.sysu.edu.cn

‡ E-mail: huaw@mail.sysu.edu.cn

put parameters, such as the fusion and fission barriers as well as the nuclear level-density parameter, which are usually determined by fitting some fusion experimental data. Owing to the large uncertainties from the input parameters in these codes, severe deviations from new experimental data may occur for calculated cross sections. For example, a significant discrepancy (by a factor of approximately 10) was observed between predictions from the HIVAP code [19] and the cross sections of the ^{238}U(^{9}Be, 5n)^{242}Cm reaction measured at the Institute of Modern Physics (IMP) in Lanzhou, China [22]. The above-mentioned codes and their parameters were recently improved in Refs. [23, 24]; in these studies, more accurate experimental data were available. Compared to HIVAP [19], HIVAP2 [23] included a modified Woods-Saxon potential for a unified description of the fusion barrier as well as the fission barrier. In addition, its parameters were optimized according to a large amount of recent experimental data. In comparison with KEWPIE [20], KEWPIE2 [24] was improved by incorporating various theoretical models, and some parameters were corrected. As a result, KEWPIE2 shows a better agreement with experimental data. Although they were greatly improved, sensitive parameters used in the enhanced codes, namely HIVAP2 [23] and KEWPIE2 [24], are not well constrained yet, and they should be further validated by using more recent experimental cross sections.

An activation technique was successfully applied to study fusion reactions at the Heavy Ion Research Facility in Lanzhou (HIRFL). In previous experiments, cross sections of several fusion reactions, e.g., ^{9}Be+^{181}Ta [25] and ^{9}Be+^{169}Tm/^{187}Re [26] were measured by using the offline gamma ray spectroscopy method. Stacks of heavy targets combined with energy degraders (Al foils) were used to determine the excitation function of fusion reactions without tuning the beam energy. A similar experimental setup was applied to measure cross sections of the fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm. The off-line measurement of the α radioactivity of ^{242}Cm was performed by using silicon detectors. Preliminary results and comparisons with model calculations through the old HIVAP code [19] were reported in Ref. [22], where significant discrepancies were observed. To examine this significant discrepancy between measured cross sections and model calculations, further calculations with the most recent codes (HIVAP2 [23], KEWPIE2 [24], and CCFULL [21]) using the improved input parameters were performed in this study. Furthermore, fusion cross sections of ^{7,9}Be+^{238}U measured in other experiments [7, 13, 14] were used to benchmark model calculations with the most recent codes. All these experimental data allowed us to constrain the important parameters used in model calculations for fusion-evaporation reactions.

II. EXPERIMENTAL DATA MEASURED AT IMP AND MODEL CALCULATIONS

In the conducted experiment, a ^{9}Be beam with an intensity of approximately 3.5 particle-nA was supplied by the sector-focusing cyclotron of HIRFL at IMP. This ^{9}Be beam at 63 MeV was focused onto a stack of 20 ^{238}U targets. In particular, ^{238}U targets with a thickness of approximately 100 μg/cm^{2} were prepared by molecular plating technique onto Al backing foils (~800 μg/cm^{2}). One self-support Al foil with a thickness of approximately 300 μg/cm^{2}, used as a beam energy degrader and a catcher for the evaporation residues, was placed immediately behind each ^{238}U target. For the determination of beam intensities, four silicon detectors were used to monitor the elastic scattering events of ^{9}Be from a Au foil (270 μg/cm^{2}) placed upstream from ^{238}U targets. Approximately 80 days after the irradiation, when events from short-lived fission products were substantially reduced, the α radioactivity of the long-lived ^{242}Cm ($T_{1/2} = 163$ days, 100% α decay) on Al catcher foils was measured by using silicon detectors placed in an off-line chamber. The background events from the α decay of ^{238}U targets as well as other fusion-evaporation residues were carefully subtracted. Further details about this experiment and the data analysis were reported in Ref. [22].

In Fig. 1, cross sections of the fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm above 40 MeV measured in this experiment at IMP in Lanzhou are compared with model calculations using different codes. The shape of the cross section distribution and its peak position around 52 MeV (in the center-of-mass system) can be roughly reproduced by almost all model calculations. However, HIVAP2 [23] calculations in which default parameters (e.g., $E_d = 18.5$ MeV and $r_a = 1.120$ fm for the level-density and the fission barrier based on a modified Woods-Saxon potential) extracted from Ref. [23] were used overestimated the cross sections of ^{238}U(^{9}Be, 5n)^{242}Cm by a factor of approximately 3. HIVAP2 [23] describes the measured data in a much accurate manner than HIVAP [19], considering that the HIVAP [19] calculations overestimated these experimental data by a factor of ~10, as reported in Ref. [22].

KEWPIE2 [24] calculations based on two approaches for the capture process and optimized parameters are also presented in Fig. 1. In these calculations, the Wentzel-Kramers-Brillouin (WKB) approximation and the empirical barrier-distribution (EBD) method were applied to estimate the fusion probability and the capture cross section. In KEWPIE2, there are two free parameters, namely the reduced friction parameter β for the fission decay channel and the shell-damping energy E_d for nuclear level density [24]. In the above KEWPIE2 calculations, $\beta =$ 5 and 5.8 zs^{-1} were used for the WKB and EBD methods, respectively, while $E_d = 23$ MeV was adopted

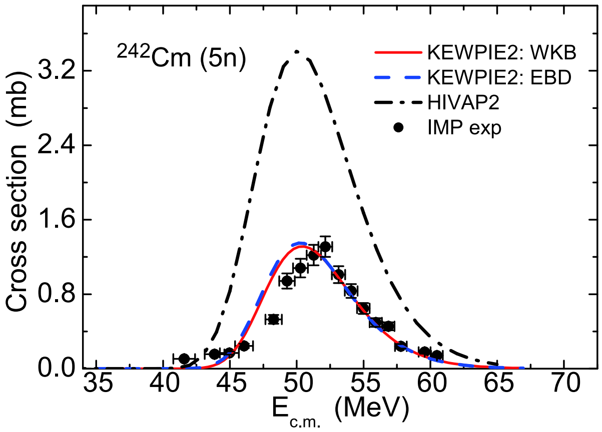

Fig. 1. (color online) Measured fusion-evaporation cross sections of ^{238}U(^{9}Be, 5n)^{242}Cm compared with model calculations by using HIVAP2 [23] (dash-dotted line) and KEWPIE2. In KEWPIE2 calculations, two approaches, i.e., the Wentzel-Kramers-Brillouin (WKB) approximation (solid line) and the empirical barrier-distribution (EBD) method (dashed line), were utilized. Note that all the cross sections are in the center-of-mass (CM) system.

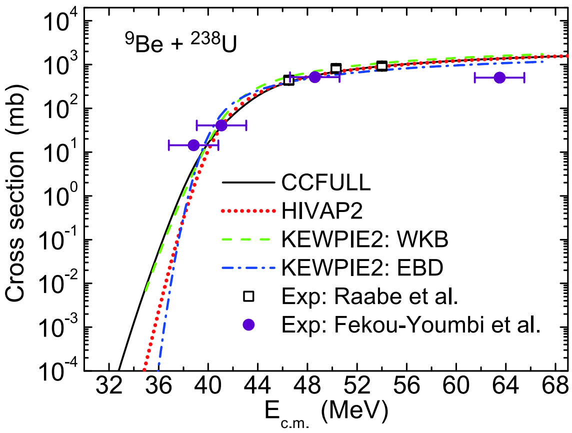

Fig. 2. (color online) Fusion cross sections for ^{9}Be+^{238}U measured by Raabe *et al.* [7] and Fekou-Youmbi *et al.* [13, 14] are compared with model calculations by using the HIVAP2 [23] (dotted line), KEWPIE2, and CCFULL [21] (solid line). Two approaches, i.e., the Wentzel-Kramers-Brillouin (WKB) approximation (dashed line) and empirical barrier-distribution (EBD) method (dash-dotted line), were applied in KEWPIE2 calculations.

for both methods. These values are consistent with those recommended in Ref. [24]. KEWPIE2 calculations using both WKB and EBD methods are in good agreement with measured cross sections of ^{238}U(^{9}Be, 5n)^{242}Cm. Discrepancies between KEWPIE2 calculations and measured cross sections at low energies, as shown in Fig. 1, may be caused by calculations of the fusion probability or the evaporation probability (i.e., calculations for the first or second step of the reaction). In what follows, we describe how other experimental data are applied to check the fusion cross sections of ^{9}Be+^{238}U calculated by various models.

III. OTHER EXPERIMENTAL DATA AND MODEL CALCULATIONS FOR Be+^{238}U

To validate different model calculations further, fusion cross sections for ^{9}Be+^{238}U around the Coulomb barrier measured in two experiments [7, 13, 14] are also compared with model calculations by using three codes, namely HIVAP2 [23], KEWPIE2 [24], and CCFULL [21], in Fig. 2. The parameters in our coupled-channel calculations by CCFULL [21] are similar to those used in Refs. [15-18], where the deformation of ^{238}U was found to be important for reproducing the measured fusion cross sections. Default parameters from Ref. [23] were used in our HIVAP2 calculations. In KEWPIE2 [24] calculations, two approaches, namely the WKB approximation and the EBD method, were applied for the determination of capture cross sections. The parameters used in these KEWPIE2 calculations are the same as those in the above calculations for the fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm. Figure 2 indicates that all the model calculations with various codes are consistent with two experimental data sets above 38 MeV measured in Refs. [7, 13, 14]. This agreement indicates that the discrepancies between KEWPIE2 calculations and experimental cross sections of the above fusion-evaporation reaction measured at low energies (see Fig. 1) may stem from calculations of the evaporation probabilities of different channels as opposed to calculations of the fusion probability.

For the fusion reaction ^{9}Be+^{238}U at lower energies (below 38 MeV), there is no experimental cross section. According to the comparison of model calculations below 38 MeV, fusion cross sections calculated by CCFULL agree excellently with KEWPIE2 calculations using the WKB approximation. However, those from HIVAP2 as well as KEWPIE2 calculations using the EBD method drop much faster and thus are much smaller, as shown in Fig. 2. This comparison indicates that more fusion experimental data at energies lower than 38 MeV, where the predictions by various models large differ, are required to benchmark the above model calculations.

Complete fusion cross sections for ^{7}Be+^{238}U around the barrier measured in one experiment [7] are presented in Fig. 3, where they are also compared with model calculations utilizing HIVAP2 [23], KEWPIE2 [24], and CCFULL [21]. Parameters used in these model calculations are the same as the above calculations for the fusion reaction ^{9}Be+^{238}U and fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm. These comparisons demonstrate that the model calculations by both KEWPIE2 using the

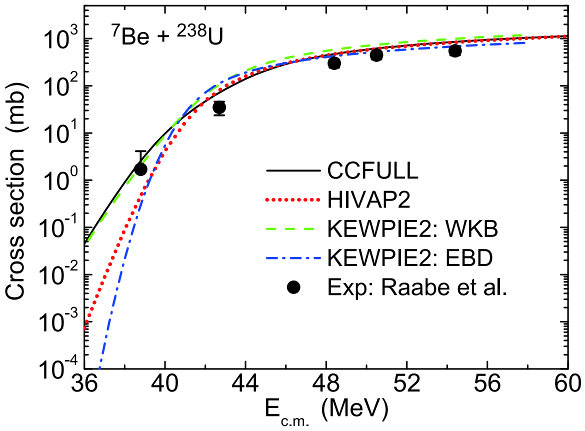

Fig. 3. (color online) A comparison of fusion cross sections for ^{7}Be+^{238}U measured by Raabe *et al.* [7] with model calculations by using the HIVAP2 [23] (dotted line), KEWPIE2, and CCFULL [21]) (solid line). In KEWPIE2 calculations, two approaches, namely the WKB approximation (dashed line) and the EBD method (dash-dotted line), were used.

WKB approximation [24] and CCFULL [21] are generally in line with measured fusion cross sections of ^{7}Be+^{238}U. Above 42 MeV, the measured complete fusion cross sections are slightly smaller than model calculations, which might be due to the neglect of the contribution of the incomplete fusion in the experimental data reported in Ref. [7]. At low energies (below ~40 MeV), it seems that the calculations by both KEWPIE2 using the EBD method and HIVAP2 drop too fast and thus underestimate the measured fusion cross sections of ^{7}Be+^{238}U. A similar fast drop tendency was observed in KEWPIE2 with the EBD method and HIVAP2 calculations for ^{9}Be+^{238}U at low energies (below 38 MeV), as shown in Fig. 2.

According to all the comparisons shown in Figs. 1, 2 and 3, it seems that both KEWPIE2 using the WKB approximation [24] and CCFULL [21] can well describe the measured fusion cross sections for ^{7,9}Be+^{238}U. Furthermore, KEWPIE2 calculations using the WKB approximation [24] are also consistent with the fusion-evaporation cross sections of ^{238}U(^{9}Be, 5n)^{242}Cm measured around the Coulomb barrier. More experimental data at very low energies, especially for fusion cross sections of ^{9}Be+^{238}U below 40 MeV, are needed to check the model calculations constrained by the above experimental data. Constrained model calculations will be very helpful for the optimization of experiments aimed at producing heavy exotic nuclei by fusion-evaporation reactions.

IV. SUMMARY

In summary, cross sections of the fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm around the Coulomb barrier were measured at IMP employing an activation method. These experimental cross sections were compared with model calculations through two different codes, namely HIVAP2 and KEWPIE2, using two methods (i.e., WKB and EBD) for the capture probability. Significant deviations were observed for the HIVAP2 calculations, although they were improved with respect to those resulting from an older version of the HIVAP model. By contrast, the KEWPIE2 calculations utilizing both WKB and EBD methods agreed well with measured fusion-evaporation cross sections.

To constrain model calculations further, fusion cross sections of ^{7,9}Be+^{238}U measured in other experiments were also compared with model calculations by using three codes, i.e., HIVAP2, KEWPIE2, and CCFULL. Important parameters applied in these codes were also checked by comparison with measured fusion cross sections. Comparisons with all the experimental data indicate that the KEWPIE2 calculations using the WKB approximation are in good agreement with measured cross sections of fusion reactions ^{7,9}Be+^{238}U as well as the fusion-evaporation reaction ^{238}U(^{9}Be, 5n)^{242}Cm. In addition, fusion calculations by CCFULL are also consistent with measured fusion cross sections of ^{7,9}Be+^{238}U around the Coulomb barrier. More experimental data at lower energies may help to validate these model calculations further. Benchmarked model calculations will be useful for future fusion-evaporation experiments.

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