Fusion and one-neutron stripping reactions in the ^{9}Be + ^{186}W system above the Coulomb barrier

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We have measured the complete fusion, incomplete fusion, and the one-neutron stripping reaction for the ^{9}Be + ^{186}W system, at energies not too much above the Coulomb barrier. The online and offline gamma ray spectroscopy methods were used for the derivation of the cross sections. A large value of one-neutron stripping cross section has been observed. The comparison of the data with coupled channel calculations without taking into account the breakup and transfer channels show the usual complete fusion suppression. The possible suppression of the total fusion is discussed.

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I. INTRODUCTION

Fusion reactions between heavy ions have been a subject of great interest in recent decades. More recently, great theoretical and experimental efforts have been devoted to the investigation of the behavior of fusion of weakly bound nuclei, both stable and radioactive [1,2]. Such nuclei have low breakup energy threshold and the breakup process feeds states in the continuum. Stable nuclei of this type, ^{6}Li, ^{7}Li and ^{9}Be, are usually described as clusters of alpha-deuteron, alpha-tritium, and alpha-alpha-neutron, respectively. Radioactive nuclei of great interest are, among others, neutron and proton halo nuclei such as ^{6}He [3], ^{8}He [4], ^{11}Li [5], ^{11}Be [6], ^{8}B [7], ^{17}F [8], and ^{15}C [9]. Following breakup, different processes may occur: noncapture breakup (NCBU), when neither fragment fuses, incomplete fusion (ICF), when part of the fragments fuses, and sequential complete fusion (SCF), when all the breakup fragments are absorbed sequentially by the target. Recently it has been observed [10–13] that breakup following transfer of nucleons is also an important process and, especially for ^{6,7}Li + ^{208}Pb systems [10], is more likely than prompt direct breakup at sub-barrier energies. Experimentally it is not possible to distinguish between SCF and the fusion between the whole projectile before any breakup and the target. The sum of these two processes is called complete fusion (CF). Total fusion (TF) is defined as the sum of CF and ICF.

It is a difficult experimental task to measure separately CF and ICF, since the compound nuclei and residual nuclei are usually very similar, owing to the small charge and mass differences between the whole projectile and its fragments, which may fuse. However, there are some reported works [14–20] on fusion of weakly bound projectiles with heavy and medium mass targets where this separation was achieved. The best methods for reaching this goal are gamma-ray spectroscopy and, for some particular systems, the detection of alpha particles and x rays produced in the decay of the residual nuclei after the evaporation of the compound nucleus. With these methods one may identify each evaporation residue individually, what usually is not the case when the residues are measured directly. By the same reasons it is also very difficult to separate CF and ICF from transfer reactions. Several works which report the measurement of TF [16,21–26], actually measure the sum of TF and transfer cross sections.

Particularly important in this field is the investigation of the effect of the breakup of the weakly bound nuclei on the fusion cross sections. Some comprehensive reviews of this fascinating subject were published some years ago [1,2,27]. However, this subject is not yet fully understood. Maybe the most common question in this field is, "Does the breakup enhance or hinder the fusion cross section?"Before trying to answer this question, one has to be clear about which kind of fusion one is talking about: CF or TF. Then, one must clearly state that the enhancement or suppression of fusion cross section is in relation to which reference. If one compares data with theoretical predictions, one may have different conclusions depending on the interaction potential used and on the reaction channels included in the coupled-channel calculations. If a reliable interaction potential is used and if all reaction channels are included in a full CDCC (continuum discretized coupled channel) calculation, no difference between data and calculations should be present. However, such calculations are not available at the present. So, the enhancement or suppression of fusion cross section should be the effect of ingredients which were not considered in the calculations.

Concerning fusion of weakly bound systems, there are two kinds of effects, when compared with the fusion of tightly bound systems: (i) the static effects associated with the longer tail of the nuclear density, which leads to a lower barrier, when compared with those for similar tightly bound systems; (ii) the dynamical effects associated with the strong coupling between the elastic and the breakup channels. These two kinds of effects may lead to opposite consequences on the fusion cross section.

If one wants to study the systematic behavior of fusion cross sections for weakly bound systems, it is necessary to start with a standard behavior of the fusion cross section to which

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the data should be compared. A reliable bare potential to be used in the calculations is another fundamental requirement. Also, if one wants to plot the fusion excitation functions for different systems in the same graphic, a proper normalization method should be used. Canto *et al.* [28,29] have recently developed a method which accounts for all the above features. As the bare interaction potential they use the double-folding parameter-free São Paulo potential (SPP) [30,31]. They were able to disentangle static and dynamical effects by analyzing a new quantity derived from the fusion cross section, called the universal fusion function (UFF), as will be explained in Sec. III. This method was applied for several weakly bound systems, with stable and radioactive projectiles, for CF and TF. Only inelastic channels were coupled in the calculations, so the deviations of the experimental fusion functions from UFF should be caused by breakup plus transfer dynamical effects, as far as all static effects were considered in the SPP by considering realistic matter densities (even in the case of halo nuclei). The qualitative systematic results show [28,29,32,33] that CF is suppressed in relation to a benchmark curve at energies above the Coulomb barrier and enhanced at sub-barrier energies. On the other hand, TF (or TF + transfer, since in several situations it is not possible to separate these two processes) coincides with UFF, showing no effect caused by breakup + transfer couplings, for stable weakly bound systems. For neutron-halo nuclei, TF is also suppressed [29]. An investigation of a quantitative systematic behavior for the suppression of CF induced by ^{9}Be, at energies above the barrier, as a function of the target charge (or mass) [14] was not conclusive.

In the present work we report the measurement of CF, ICF, and one-neutron stripping reactions for the ^{9}Be + ^{186}W system at energies not too much above the Coulomb barrier.

II. EXPERIMENT AND RESULTS

The experiment was performed with a ^{9}Be beam at the HI-13 Tandem Accelerator of the China Institute of Atomic Energy (CIAE), Beijing. The target was a 97.3%-enriched ^{186}W metallic foil of 1.1 mg/cm^2 thickness with a 1.3 mg/cm^2 carbon backing. The fusion excitation function was measured at beam energies of 41, 45, 49, and 53 MeV using the online single γ-ray method. After that, the γ-γ coincidence measurements were performed at a beam energy of 44 MeV. The same target was used for all beam exposures. The irradiation times were of 0.5 h duration at all energies for single γ-ray measurements and 78 h at 44 MeV energy for γ-γ coincidence measurements. The beam current was ~6 nA, and the beam flux was calculated by the total charge collected in the Faraday cup placed behind the target using a precision current integrator device. Both online and offline γ rays emitted by the reaction products were detected with an array consisting of 12 Compton-suppressed high purity germanium (HPGe) detectors and two low-energy photon spectrometer detectors. The absolute efficiency and energy calibration of the array were made using ^{60}Co, ^{133}Ba, and ^{152} Eu standard calibrated sources.

The compound nucleus ^{195}Pt formed following the CF of ^{9}Be with ^{186}W decay predominantly by neutron evaporation, leading to different residual Pt nuclei. The possible fusion of ^{8}Be with the target, following the one-neutron transfer or breakup of ^{9}Be into ^{8}Be + n, cannot be separated from the fusion of ^{9}Be with the target, and therefore it is considered also as CF, as was done in other works [15,16,18,19], where CF was defined as the fusion of the total charge of the projectile with the target. The ^{188}Os isotope could also be identified. This isotope results when the target nucleus (^{186}W) captures an α fragment, produced in the breakup of ^{9}Be (in the case of ICF). The one-neutron stripping channel (^{187}W) was identified in offline measurement. In the present ^{9}Be + ^{186}W system the observed yields of ^{187}W could arise both from the transfer of one neutron to the target or the breakup of ^{9}Be into ^{8}Be + n ($Q = -1.67$ MeV) followed by the fusion of one neutron with the target (in the case of ICF). Since it is difficult to distinguish these two components, in this paper our experimental definition of one-neutron stripping reaction includes 1n transfer and incomplete fusion of one neutron with the target. The identification of the different residual nuclei produced in the reaction was done according to their characteristic γ-ray energies and also, when possible, was checked by analyzing the γ-γ coincidence measurements at 44 MeV. Figures 1(a) and 1(b) show, respectively, the online γ-ray spectrum obtained at the bombarding energy of 49 MeV and offline γ-ray spectrum after the end of the irradiation, where the nuclei produced in the reaction are labeled in the figure.

We also investigated the possible presence of other transfer channels in our data. The first one is the one-neutron pickup channel ^{186}W(^{9}Be, ^{10}Be)^{185}W, which is expected to have small cross section, due to the small probability that ^{9}Be picks up one additional neutron from ^{186}W, and has a Q value of -0.39 MeV. Although, owing to the experimental limitations, the ^{185}W nucleus cannot be identified in the offline γ spectrum, we tried to extract its cross section using both the online singles and coincidence γ-ray spectra. However, γ rays from the ^{185}W nucleus have not been found in both situations. Then, we investigated the possible production of ^{187}Re from the one-proton stripping transfer reaction, which has a large negative Q value of -10.9 MeV. The strong transitions for ^{187}Re are most likely the 134.2-keV $7/2^+ \to 5/2^+$, 206.2-keV $9/2^- \to 5/2^+$, and 182.3-keV $11/2^- \to 9/2^-$ lines [34–36]. All of these transitions could not be identified in the online γ spectrum (see Fig. 1). Finally, the yield of the lines from ^{188}Os might also come from the two-proton stripping transfer reaction. We attributed this yield to ICF owing to the large negative Q value of this channel: -16.1 MeV.

To obtain the fusion cross sections, the online singles γ-ray spectra were used. The γ-ray cross sections $\sigma_\gamma(J)$ were calculated from the relation

$$\sigma_\gamma(J) = \frac{N_\gamma(J)}{\epsilon_\gamma\ N_b\ N_t}, \quad (1)$$

where $N_\gamma(J)$ is the number of counts under the γ-ray peak after correcting for the internal conversion, ϵ_γ is the absolute efficiency of the γ lines, N_b is the total number of beam particles incident on the target, and N_t is the number of target nuclei per cm^2. The quantity N_b was determined by dividing

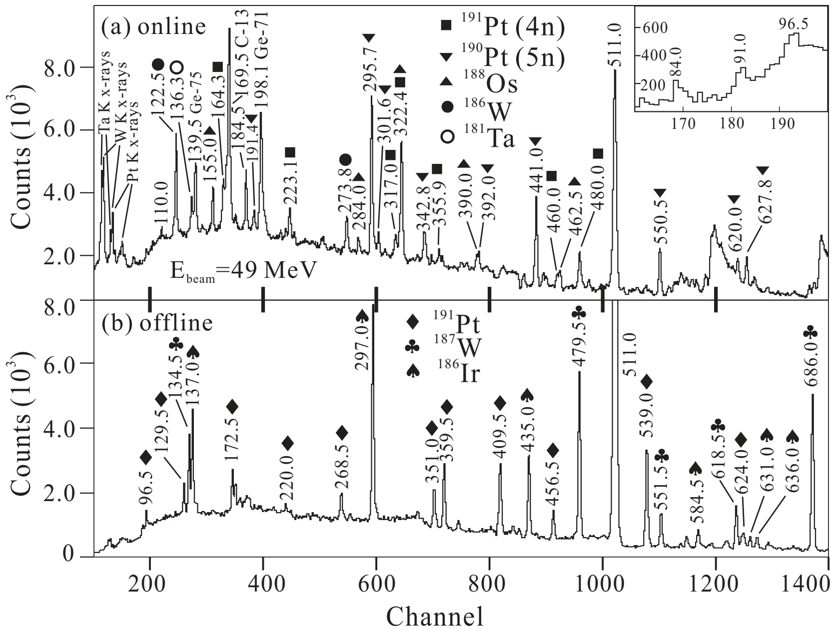

FIG. 1. Typical γ-ray spectra obtained from (a) online measurement at the bombarding energy of 49 MeV, and (b) offline measurement after the end of the irradiation. The inset of (a) shows the low-energy spectrum from one of the low-energy photon spectrometer detectors, where the $13/2^+ \rightarrow 9/2^-$ 91.0-keV transition in ^{191}Pt can be clearly seen. The black spades in panel (b) indicate the decay lines of ^{186}Ir formed following the ^{181}Ta(^{9}Be, $4n$) reaction, in which ^{181}Ta is the target holder.

the charge Q collected in the Faraday cup by the equilibrium charge value $\bar{Z}e$.

For the even-even evaporation residues (ERs) (^{190,192}Pt), the cross section was extracted from the extrapolated value of the intensity at $J = 0$ obtained from the measured γ-ray intensities for various transitions in the ground-state rotational band. The same equation $\sigma_\gamma(J) = a/\{1 + \exp[-(J - J_0)/b]\}$ has been used as in Ref. [17]. In the case of odd-A ^{191}Pt nuclei, it is not possible to add the cross sections of all the transitions that feed the ground state since the decay scheme of this nuclei involves long-lived isomers as well as low-energy transitions. Given the fact that the heavy-ion-induced fusion-evaporation reactions favor populating high-j orbitals near the Fermi surface, the cross section of ^{191}Pt was obtained using the measured intensities of the $13/2^+$ ($\nu i_{13/2}$) state at 149.0 keV. Five transitions at energies of 91.0, 322.4, 355.9, 380.2, and 450.2 keV have been considered. It needs to be mentioned that the 322.4-keV transition was contaminated by a $4^+ \rightarrow 2^+$ 322.9-keV line in ^{188}Os. However, the contribution of the 322.9-keV line from ^{188}Os could be estimated from the intensity ratio I_γ(322.9 keV)/I_γ(155.0 keV) [37] in which the intensity of the clean 155.0-keV line can be obtained in this experiment. We note that the relative intensities of these five transitions extracted in our experiment for ^{191}Pt, being 294, 1000, 177, 163, and 205, respectively, agreed very well with the data in Ref. [38].

Incomplete fusion cross sections due to the capture of α fragment by the target forming the compound nucleus ^{190}Os were investigated. The dominant channel is found to be $2n$ ER (^{188}Os). The cross section was obtained by adding the cross sections of all lines that directly feed the ground state of ^{188}Os. No γ lines following $1n$ channel (^{189}Os) were observed in the spectra over the energy range of the present measurement. The cross section of ^{189}Os, calculated by the code PACE2 [39] at α energies equal to 4/9 of the beam (^{9}Be) energies, was found to be negligibly small, which is consistent with the experimental finding.

For the residue nuclei ^{187}W and ^{191}Pt with half-lives of 23.72 h and 2.83 d, respectively, the offline γ-ray method could be used in the determination of their relative cross sections. The number of activated nuclei A at the end of irradiation can be obtained from the counts in the respective peak C_γ by

$$A = \frac{C_\gamma\, \lambda \exp(\lambda t_1)}{\theta_\gamma\, \epsilon_\gamma\, [1 - \exp(-\lambda t_2)]}, \tag{2}$$

where θ_γ denotes the intensity branching ratio associated with the particular γ line corresponding to the residual nucleus, and ϵ_γ the efficiency of the HPGe detector at the peak energy. t_1 is the time of the measurement, t_2 the time waited between the end of irradiation and measurement, and λ the decay constant of the isotope. As the beam flux and target are the same for residue nuclei ^{187}W and ^{191}Pt during the irradiation time t_3, the cross section for the ^{187}W residue at 44 MeV energy can be obtained using the expression

$$\sigma_{187\mathrm{W}} = \frac{A_{187\mathrm{W}}}{A_{191\mathrm{Pt}}} \frac{1 - \exp(-\lambda_{191\mathrm{Pt}} t_3)}{1 - \exp(-\lambda_{187\mathrm{W}} t_3)} \times \sigma_{191\mathrm{Pt}}, \tag{3}$$

where the cross section $\sigma_{191\mathrm{Pt}}$ at $E_{\mathrm{beam}} = 44$ MeV was obtained using the measured cross section at $E_{\mathrm{beam}} = 45$ MeV in the online γ-ray method and normalizing it with the result calculated by the code PACE2 [39].

The cross sections obtained in the present work are presented in Table I. It is worth mentioning that the ICF probability, defined as the ratio between ICF and TF cross sections, is around 0.22 for our data, in good agreement with the predictions of Rafiei *et al.* [13] of the value of 0.24 for the present system.

TABLE I. Measured and derived cross sections.

E_{Lab} (MeV)	^{190}Pt (mb)	^{191}Pt (mb)	^{192}Pt (mb)	^{188}Os (mb)	^{187}W (mb)	σ_{CF} (mb)	σ_{ICF} (mb)
41	29.0 ± 6.0	156.6 ± 13.9	35.0 ± 3.4	61.3 ± 18.0		220.6 ± 23.3	61.3 ± 18.0
44					158.8 ± 19.7		
45	71.8 ± 10.4	257.3 ± 21.1	18.9 ± 2.0	93.7 ± 12.7		348.0 ± 33.5	93.7 ± 12.7
49	239.6 ± 25.4	211.6 ± 17.1	13.0 ± 1.4	128.7 ± 13.1		464.2 ± 43.9	128.7 ± 13.1
53	471.0 ± 44.7	138.2 ± 13.8	10.0 ± 1.2	184.7 ± 25.9		619.1 ± 59.8	184.7 ± 25.9

III. COUPLED-CHANNELS CALCULATIONS AND DISCUSSION

To investigate the influence of dynamic breakup effects on the fusion cross section, we followed the methodology suggested by Canto *et al.* [28,29] to use a reduction procedure that eliminates static effects of the weakly bound nucleons. The collision energy and the cross section are reduced as

$$E \rightarrow x = \frac{E_{c.m.} - V_B}{\hbar\omega}, \quad \sigma_F \rightarrow F(x) = \frac{2E_{c.m.}}{\hbar\omega R_B^2}\sigma_F, \quad (4)$$

where V_B, R_B, and $\hbar\omega$ are the barrier energy, radius, and curvature, respectively, and σ_F is the fusion cross section. These dimensionless fusion cross sections were called fusion functions $F(x)$. This reduction method is used in the approximated Wong formula [40] for the fusion cross section:

$$\sigma_F^W = \frac{\hbar\omega R_B^2}{2E_{c.m.}} \ln\left[1 + \exp\left(\frac{2\pi(E - V_B)}{\hbar\omega}\right)\right]. \quad (5)$$

If this formula is valid, $F(x)$ could be written as

$$F_0(x) = \ln[1 + \exp(2\pi x)] \quad (6)$$

and $F_0(x)$ would be the same for any system. Owing to this characteristic, the function $F_0(x)$ was called [28,29] the universal fusion function (UFF). The UFF could then be used as a benchmark to assess the influence of channel couplings on the fusion of these systems: one should evaluate the experimental fusion function $F_{exp}(x)$ and then compare it to the UFF. However, this reduction method has two shortcomings. The first is that Wong approximation is not valid for light systems at sub-barrier energies. The second is that comparisons of $F_{exp}(x)$ with UFF show the global effect of channel coupling on the fusion cross section, and not the effect of the breakup process on fusion; that is, the effect of couplings to the continuum states. These shortcomings were solved by Canto *et al.* [28,29] by the introduction of a renormalized fusion function, $\bar{F}_{exp}(x)$, which compensates both problems. This function is defined as $\bar{F}_{exp} = F_{exp}\frac{F_0(x)}{F_{CC}(x)}$, where $F_{CC}(x)$ is the fusion function associated with the fusion cross section predicted by proper coupled-channel calculations including all relevant couplings to bound channels. Note that $\bar{F}_{exp}(x)$ is such that in an ideal situation where all coupling channels are correctly taken into account, F_{CC} is identical to the UFF.

As the bare interaction potential we used the double-folding São Paulo potential (SPP) [30,31], based on a double-folding potential with realistic densities and on the Pauli nonlocality involving the exchange of nucleons between projectile and target. There are no free parameters in this potential. We performed coupled-channel (CC) calculations using the code FRESCO [41]. The first three excited states of ^{186}W ground state rotational band were included in the calculations (β_2 = 0.226 [42], r_o = 1.2 fm, and λ = 2). The barrier parameters predicted by the SPP are V_B = 34.42 MeV, R_B = 11.28 fm, and $\hbar\omega$ = 4.26 MeV. As the proper ^{9}Be density is taken into account in the SPP double folding potential, the resulting effects can be assumed to be the whole dynamic effect of the ^{9}Be breakup (prompt or nonresonant plus sequential or resonant) on the CF cross section, disentangled from possible static effects of the low breakup threshold energy, since no coupling associated to ^{9}Be was included in the calculations. As transfer channels were also not included in the calculations, actually the effects that will be mentioned here are due to dynamical breakup plus transfer couplings.

Figure 2 shows the renormalized experimental complete fusion function $\bar{F}_{CF\text{-}exp}(x)$ for the ^{9}Be + ^{186}W system in comparison with the UFF. The linear scale is used instead of the usual logarithmic one, since it is more suitable for the analysis at energies above the barrier, as is the situation for our data ($x = 0$ corresponds to the fusion barrier). A suppression of CF cross section of the order of 40% is observed, when compared with theoretical predictions which do not take into account breakup and transfer couplings. This result is in reasonable agreement with those obtained for

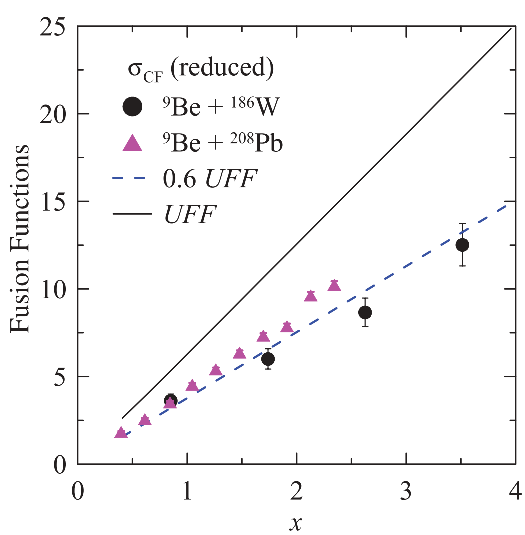

FIG. 2. (Color online) Renormalized experimental fusion function (see text) for complete fusion plotted against $x = (E_{c.m.} - V_B)/\hbar\omega$. The full curve is the universal fusion function (UFF) obtained by using the prescription of Refs. [28,29]. The experimental data for the ^{9}Be + ^{208}Pb system were taken from Ref. [16].

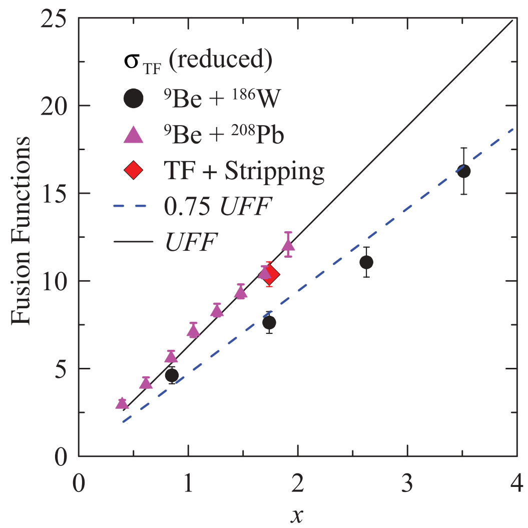

FIG. 3. (Color online) Renormalized experimental fusion and transfer functions (see text) for total fusion and one-neutron and two-proton stripping plotted against $x = (E_{c.m.} - V_B)/\hbar\omega$. The full curve is the universal fusion function (UFF) obtained by using the prescription of Refs. [28,29].The experimental data for the ^{9}Be + ^{208}Pb system were taken from Ref. [16]

^{9}Be + ^{208}Pb [15,16] and ^{9}Be + ^{124}Sn [17], for which a CF suppression of the order of 30% was found, and shows a considerably higher CF suppression than for ^{9}Be + ^{144}Sm, for which the CF suppression was found to be between 10% and 16% [14,18,19], and for ^{9}Be + ^{89}Y [20], which shows a 20% CF suppression. However, qualitatively, all CF induced by ^{9}Be shows suppression at energies above the barrier when compared with calculations that do not take into account breakup and transfer couplings. For illustration purposes, the reduced CF cross sections for the ^{9}Be + ^{208}Pb system are show in Fig. 2.

Figure 3 is similar to Fig. 2, but it shows the total fusion function $\bar{F}_{\text{TF-exp}}(x)$, that is, the sum of CF and ICF. It is interesting to mention that if the ^{188}Os yield is not only ICF but the sum of ICF plus a possible contribution from the two-proton stripping transfer cross section, what has been called TF is, in fact, the sum of TF with a possible two-proton stripping transfer cross section, since it is not possible experimentally to distinguish the ICF from this transfer channel. The same situation has occurred in previous works on fusion of ^{9}Be with other targets [15,16,18,19], when what was attributed to ICF was also ICF plus possible transfer leading to the same nucleus. From Fig. 3 one can observe a TF suppression of the order of 25%. This is a striking result, since for several systems involving stable weakly bound nuclei (^{6}Li, ^{7}Li, and ^{9}Be) no TF suppression is found at energies above the barrier [28,29,32,33] (for better comparison, the reduced TF cross sections for the ^{9}Be + ^{208}Pb system are show in Fig. 3). Only for neutron-halo nuclei such as ^{6}He, ^{8}He, and ^{11}Be [4,28,29,33], for which transfer reactions have very high cross sections, was TF suppression observed at this energy regime. However, due to the large positive Q value ($Q_{gg} = +3.8$ MeV) of the 1n-transfer (direct one-step) process, a large cross section may be expected for this channel in the ^{9}Be + ^{186}W system. Our result seems to indicate that for systems with large transfer cross sections, like the one investigated in this work and those with halo nuclei, total fusion is suppressed, at energies above the barrier, when compared with standard coupled-channel calculations not including breakup and transfer channels. It is very interesting to observe in Fig. 3 that, when the measured one-neutron stripping cross section is added to TF, no suppression is found in comparison with UFF. (Note that, as the $E_{\text{beam}} = 44$ MeV for the one-neutron stripping reaction is close to the energy at 45 MeV for TF, we add it to TF at 45 MeV in Fig. 3.) It should be pointed out that the large yields of ^{187}W could arise from either the direct one-step process, 1n transfer, or the two-step process, breakup of ^{9}Be into ^{8}Be + n and then fusion of the neutron with the target (incomplete fusion). If we assume that the two-step process (ICF) is important, then the sum of complete fusion and ICF, referred to as TF, shows no suppression, which agrees with the systematics of ^{9}Be-induced reactions. However, the relative importance and/or experimental difficulty in distinguishing between these two processes cannot be resolved. In the previous works on fusion of ^{9}Be with other targets [14–20], ICF was considered as the fusion of one alpha particle with the target. So, exclusive experimental investigation of ^{9}Be-induced reactions and a more detailed understanding of those reactions are still required.

IV. SUMMARY

In this work we report the measurement of complete fusion, incomplete fusion, and the one-neutron stripping cross sections for the ^{9}Be + ^{186}W system by the online and offline gamma ray spectroscopy methods, at energies above the Coulomb barrier. We compared the data with coupled-channel calculations which do not take into account the breakup and transfer channels, using a double-folding interaction potential as the bare potential. The results for complete fusion show the usual suppression found in other similar systems at this energy regime. However we obtained the unexpected result of suppression of the total fusion, not reported before for stable weakly bound nuclei. This suppression vanishes when the measured one-neutron stripping cross section is added to the total fusion cross section. As several systems induced by ^{9}Be reactions in the literature did not measure the one-neutron stripping cross sections, it would be interesting to extend such studies with new data.

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