Isomer yield ratios in ^{184}Re from the $^9\text{Be} + ^{181}\text{Ta}$ reaction

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The isomer yield ratios of ^{184}Re in the incomplete fusion of the $^9\text{Be} + ^{181}\text{Ta}$ system were measured at energies around the Coulomb barrier, using online activation followed by offline γ -ray spectroscopy method. The PLATYPUS code that is based on a classical dynamical model is employed to analyze the measurements. By applying a phenomenological approach, model calculation managed to fairly reproduce the order of magnitude of the yield ratios at above barrier energies. Through the study, it is shown that the PLATYPUS code in conjunction with a phenomenological analysis can provide a reasonable explanation of isomer yield ratios resulted from incomplete fusion of weakly bound projectiles.

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I. INTRODUCTION

Fusion cross sections with weakly bound nuclei have been a subject of great interest in recent decades [1–5]. Investigation on the fusion dynamics is important for understanding the element creation in stars and for studying nuclei near the drip lines. Since the nuclei are weakly bound, they can be easily dissociated in the interaction with other nuclei. Broadly, there are three possibilities of reaction processes regarding weakly bound projectiles: (i) the entire projectile is captured by the target, called complete fusion (CF); (ii) not all breakup fragments are captured, termed incomplete fusion (ICF); and (iii) none of the fragments are captured, called no-capture breakup (NCBU). The experimental disentanglement of all these reaction processes is difficult, and their modeling within a unified framework is also an outstanding challenge.

Different types of model have been developed or are under development to explore the fusion mechanisms, ranging from classical to quantum-mechanical methods. For instance, the continuum-discretized coupled-channels (CDCC) model [6–8] can make reliable predictions of NCBU and total fusion (TF) processes but could not calculate ICF and CF cross sections unambiguously. A quantum-mechanical framework, named the time-dependent wave-packet (TDWP) method [9,10], could calculate the ICF and CF cross section but is yet to be implemented using a three-dimensional reaction model. Some of the challenges of the quantum-mechanical models could be overcome by using the three-dimensional classical

dynamical model, which is based on classical trajectories in conjunction with stochastic breakup [11–13]. The model is implemented in the PLATYPUS code [14].

One of the effective ways to test and develop future realistic models of breakup and fusion is through the investigation of the isomer yield ratios, defined as the cross section of the isomeric states divided by the cross section of the ground states, as they are very sensitive to the angular-momentum distribution brought into the fused system. Therefore, if the fusion products have high-spin isomers that also decay to the daughter nuclei as the ground states do, then both the isomeric state and ground state cross sections could be measured. This will allow the determination of isomer yield ratios to compare the theoretical models to further explore the reaction dynamics. Although much theoretical and experimental effort has been devoted to study the reaction mechanisms induced by weakly bound nuclei as well as the isomeric states in nuclei [15–17], the data on the isomer yield ratios of fusion reactions are limited.

In this work, we are interested specifically in ^{184}Re formed through the $^9\text{Be} + ^{181}\text{Ta}$ reactions, having an isomeric state of 8^+ and a ground state of 3^- . The purpose is as follows: (i) to determine the isomeric yield ratios in ^{184}Re at energies around the Coulomb barrier, (ii) to calculate the isomeric yield ratios using the PLATYPUS code in conjunction with a phenomenological analysis [18], (iii) to compare the theoretical results with the experimental values, and (iv) to explore the mechanisms of the nuclear reactions.

II. EXPERIMENTAL PROCEDURE

The isomer yield ratio measurement was carried out through a stacked-foil activation followed by offline

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identification of the γ ray of the reaction residues. Detailed descriptions of the experiment technique and setup have been presented in Refs. [19,20], and only a brief description is given here. The collimated ^9Be beam was delivered by the Heavy Ion Research Facility in Lanzhou (HIRFL). Two stacks of ^{181}Ta targets having thickness in the range of 0.43–0.59 mg/cm^2 were irradiated in two individual runs. The targets were prepared with Al backings, which were thick enough to stop all the reaction residues and allow us to reduce the energy of the beam on the subsequent target. The beam flux was determined from the charge collected in the Faraday cup installed after the targets by using a precise current-integrator device. The Faraday cup was biased with -400-V electrodes. In addition, two Si (Au) surface-barrier detectors, at angles of $\pm 30^\circ$ with respect to the beam direction, were used to detect the elastically scattered ^9Be particles from an Au foil placed upstream from the target stack. The two sets of beam flux values agree with each other.

Each stack was irradiated for about 13 h by the ^9Be ions with a beam current of about 20 enA. In the first run, the energy of ^9Be projectile bombarding the first target of the stack was, on average, 50.3 MeV with a full width at half maximum (FWHM) of 0.3%. In the second run, the same initial energy was used, and a thick Al foil ($11.1 \text{ mg}/\text{cm}^2$) was placed in front of targets to reduce the beam energy. This enabled the energy of the ^9Be ion, falling on the first target of the stack, to be around 39.3 MeV. It should be noted that for the experiment using a stacked target technique, Fisichella *et al.* [21] has pointed out the potential ambiguities of associating effective beam energies to product yields for the targets within the stack and suggested a method for the energy calculations. Following that approach, we extracted the target thickness distributions by comparing the experimental residual energy spectra of α particles from ^{241}Am crossing the targets with the SRIM [22] simulations. The beam profiles inside each Ta part of the targets were then calculated by the SRIM code using the extracted thickness distributions. In associating the effective beam energies, the used cross-section function was deduced by fitting the experimental ICF data from Ref. [19]. Finally, the effective bombarding energy range of 35.9–50.0 MeV was exploited.

After irradiation, the activated targets were transferred to a separate laboratory for offline measurements. The first activity measurement was done by the eight CANBERRA High Purity Germanium (HPGe) detector groups. Each group consisted of two detectors in a face-to-face geometry, where single γ -ray and γ - γ coincidence measurements could be performed simultaneously. The Ge crystal part of the detector was surrounded by a Pb annular cylinder of 3-cm thickness to reduce background from natural radioactivity. The absolute efficiency of the detector was determined by using a set of activity calibrated radioactive sources (^{60}Co , ^{133}Ba , and ^{152}Eu) placed in front of the HPGe detector. The radioactive sources and the targets were counted in the same geometry.

Because the residue of a ^{184}Re isomer has a long lifetime, the second activity measurement was carried out about 2 months after the activation, using a commercial ORTEC Compton Suppression Counting System. The system could

FIG. 2. (a) Offline γ -ray spectrum for the $^9\text{Be} + ^{181}\text{Ta}$ system at beam energy of 46.8 MeV measured 8 d after the activation with measuring time of 38 h; (b) background spectrum.

The experimental cross sections of the ^{184}Re nucleus in the $^9\text{Be} + ^{181}\text{Ta}$ reactions were extracted using the half-lives, characteristic γ rays of decay, and intensities listed in Table I, as well the formula described in the Ref. [19]. Specifically, the cross sections of the ground state in ^{184}Re were deduced from the data of the CANBERRA HPGe groups, and those of the isomeric state were deduced from the data of the ORTEC Counting system. It should be pointed out that the decay of the ^{184}Re isomeric state by isomeric transition (IT) led to population of the ground state and by electron capture (EC) emitted γ rays with same energies as the decay of the ground state (see Fig. 1 and Table I). That led to overestimation of the yield of the ground state. However, when the cross sections of the isomeric state were determined accurately, the contribution to the ground state could also be deduced. Actually, the ground state cross sections were extracted using the data measured 8 d after the activation, and at that moment less than 3% of isomeric states (169 d half-life and 74.5% IT branch ratio) have decayed to the ground state. As for the contamination of γ rays from isomer decay to the γ rays from ground-state decay, it was also estimated to be very small. For example, the contamination in the count of the 903.3-keV γ ray was estimated to be less than 2.5%, if considering $\sim 10\%$ of the intensity ratio (3.7% and 38.1% for isomeric- and ground-state decay, respectively) and $\sim 20\%$ of the radioactivity ratio

(169 d and 35.4 d for half-lives of isomeric and ground states, respectively), assuming similar amounts of isomeric state and ground state produced after the target activation. The cross sections of the ground state were corrected by subtracting the contribution from the isomeric state, according to the determined cross sections for each energy point. The results are presented in Table II. Note that the ^{184}Re can not only be from ICF but also the sum of ICF plus a possible contribution from the CF with $\alpha 2n$ evaporation. It is not possible to distinguish them experimentally, and therefore we consider this as higher limit of the ICF cross section. Errors in the measured cross sections include systematic uncertainties that could arise from different sources such as (i) target thickness ($\sim 3\%$), (ii) detector efficiency ($\sim 5\%$), and statistical error on γ -yield extraction. The systematic uncertainties are added in quadrature to the statistical errors to get the total errors in the cross sections.

IV. COMPARISON WITH PLATYPUS CALCULATIONS

The PLAYPUS code [14] that is based on a classical dynamical model is employed to understand the isomer yield ratios observed. The model uses classical trajectories in conjunction with stochastic breakup. This is done through including a breakup function that undergoes Monte Carlo sampling. The breakup function encodes the effect of Coulomb and nuclear interactions that cause the breakup, making this approach a quantitative dynamical model for relating the sub-barrier NCBU to the above-barrier ICF and CF of weakly bound nuclei, rather than a breakup model. A detailed description of the model has been presented in Refs. [11–13].

To give a reliable explanation of the isomer yield ratios, it is a prerequisite to reproduce the experimental fusion excitation functions of the corresponding reaction system. In the calculation, the nuclear interactions between the projectile/fragments and targets were considered to be a Woods-Saxon potential and determined from the global Broglia-Winther parametrization [24]. The breakup function parameters were extracted from the function in Ref. [25], which was determined by systematically fitting the measured prompt-breakup probabilities. Figure 4 shows the calculated fusion excitation functions for the CF, ICF, and TF processes, as a function of $E_{c.m.}/V_B$, comparing with the corresponding experimental data at above-barrier energies. Here $E_{c.m.}$ and V_B refer to beam energy and Coulomb barrier energy ($V_B = 35.2$ MeV) in the center-of-mass frame, respectively. The experimental cross-section data were presented in Ref. [19]. One can see from Fig. 4 that good agreement has been achieved only at energies above $1.1 E_{c.m.}/V_B$, as the present classical dynamical model does not treat quantum tunneling. Therefore, the description of the experimental isomer yield ratios below 41.8 MeV is beyond the scope of this study.

In the heavy-ion-induced fusion reactions around the Coulomb barrier, the residues decay more favorably along the yrast lines, and the isomer yield ratios strongly depend on the transferred orbital angular momentum. In the ICF process, after the breakup of the projectile, one fragment reaches the target radius, forming the ICF product, while the other fragment flies away from the interaction region. The three-

FIG. 3. Offline γ -ray spectrum for the ${}^9\text{Be} + {}^{181}\text{Ta}$ system at beam energy of 46.8 MeV measured 63 d after the activation with measuring time of 48 h. See text for details.

body propagation then turns into a two-body propagation, for which the definite interaction potential and initial conditions can be determined by the positions and velocities of the three particles at the moment the ICF product is formed. The spin distribution of the ICF product is then calculated according to the trajectories and initial conditions using the PLATYPUS code. In the code, the differential cross section is obtained with $d\sigma_J/dJ = \pi \hbar^2 / (2\mu E_{\text{c.m.}}) \sum_J (2J+1) P_J$, where μ is the

reduced mass for the projectile-target relative motion and P_J is the probability for a certain value of J brought by an α particle into the compound nucleus through the ICF mechanism.

In order to get access to the isomer yield ratios, we took the phenomenological approach used in Ref. [18] to analyze the results. Figure 5 presents the calculated angular-momentum distribution for the compound nucleus from ICF of ${}^9\text{Be} + {}^{181}\text{Ta}$ system at a beam energy of 50.0 MeV. The relative population of the isomeric to ground state is calculated by splitting the compound nucleus angular-momentum distribution into two regions with a cutoff angular momentum, J_{eff} . The lower angular-momentum region feeds the ground state, and the higher region feeds the isomeric state. To account for the spread in the angular momentum due to the neutron evaporation and cascade decay of γ rays, a spreading param-

TABLE I. List of states in ${}^{184}\text{Re}$ identified in the present measurement along with their half-lives $T_{1/2}$, J^π , E_γ , and absolute intensities I_γ [23]. The intense γ rays (in bold) were chosen to evaluate the cross sections. For the decay of the ${}^{184}\text{Re}$ isomeric state, the 215.3- and 216.5-keV γ rays could not be resolved in the experiment, and the sum of their intensities was used. The other γ rays corresponding to the same state were also used to cross-check the deduced cross-section values.

Residue	$T_{1/2}$	J^π	E_γ (keV)	I_γ (%)
${}^{184}\text{Re}^g(\alpha 2n)$	35.4 d	3^-	252.8	3.0
			792.1	37.7
			894.8	15.7
			903.3	38.1
			215.3	2.8
${}^{184}\text{Re}^m(\alpha 2n)$	169.0 d	8^+	216.5	9.5
			252.8	10.8
			792.1	3.7
			894.8	2.8
			903.3	3.7
			920.9	8.2

TABLE II. Measured cross sections of isomeric state σ_m and ground state σ_g and the isomer ratios σ_m/σ_g for ${}^{184}\text{Re}$ formed through the ${}^9\text{Be} + {}^{181}\text{Ta}$ system.

E_{lab} (MeV)	$E_{\text{c.m.}}/V_B$	${}^{184}\text{Re}^m$ (mb)	${}^{184}\text{Re}^g$ (mb)	σ_m/σ_g (${}^{184}\text{Re}$)
50.0	1.35	33.2 ± 4.5	50.0 ± 3.2	0.66 ± 0.07
49.1	1.33	32.7 ± 3.7	55.7 ± 3.7	0.59 ± 0.06
46.8	1.27	36.7 ± 1.9	71.3 ± 4.3	0.51 ± 0.03
43.2	1.17	34.1 ± 2.8	77.3 ± 5.8	0.44 ± 0.04
41.8	1.13	30.7 ± 2.8	84.1 ± 4.7	0.36 ± 0.02
39.3	1.06	23.6 ± 3.3	72.0 ± 4.9	0.33 ± 0.03
37.9	1.03	14.7 ± 2.2	61.3 ± 3.9	0.24 ± 0.02
36.7	0.99	12.6 ± 1.6	43.5 ± 3.2	0.29 ± 0.02
35.9	0.97	7.5 ± 0.9	28.4 ± 3.1	0.26 ± 0.03

FIG. 4. Measured and calculated excitation functions for the CF, ICF, and TF of the $^9\text{Be} + ^{181}\text{Ta}$ system at above barrier energies. The experimental data has been presented in Ref. [19]. See text for details.

eter, δ , was introduced [18]. The isomer ratio was calculated by:

$$R = \frac{\sum_J \sigma_J^{(2)}}{\sum_J \sigma_J^{(1)}}, \quad (1)$$

$$\sigma_J^{(1)} = \frac{\sigma_J}{1 + \exp\left(\frac{J_{\text{eff}} - J}{\delta}\right)}, \quad (2)$$

$$\sigma_J^{(2)} = \frac{\sigma_J}{1 + \exp\left(\frac{J - J_{\text{eff}}}{\delta}\right)}. \quad (3)$$

The σ_J is the cross section as function of the total angular-momentum distribution, and $\sigma_J^{(1)}$ and $\sigma_J^{(2)}$ refer to the cross sections associated with the ground state and isomeric state,

FIG. 5. Calculated angular-momentum distribution for compound nucleus from ICF of $^9\text{Be} + ^{181}\text{Ta}$ system at beam energy of 50.0 MeV. The division of population between the ground and isomeric state is indicated by the dashed blue and dotted green lines, with $J_{\text{eff}} = 8 \hbar$ and $\delta = 0.5$. See text for details.

FIG. 6. The calculated and measured isomer ratios for ^{184}Re formed through $^9\text{Be} + ^{181}\text{Ta}$ system, assuming different J_{eff} and δ values. See text for details.

respectively [18]. As an example, Fig. 5 shows the division of population between the ground and isomeric states of ICF products at a beam energy of 50.0 MeV, with $J_{\text{eff}} = 8 \hbar$ and $\delta = 0.5$.

As a starting point, we assumed that the spreading parameter δ had a fixed value of 0.5 and investigated the dependence of extracted isomer ratio on the cutoff angular momentum J_{eff} . The calculated results for ^{184}Re of ICF products with $J_{\text{eff}} = 8, 9$, and $10 \hbar$ are shown by thick lines in Fig. 6, comparing with the corresponding experimental data. One can see that in the low-beam-energy region, the experimental data are close to the result obtained with $J_{\text{eff}} = 8 \hbar$. With increasing beam energy, it gradually deviates and approaches the result obtained with $J_{\text{eff}} = 10 \hbar$. This implies that in the higher energy range the predicted angular momentum for ^{184}Re is more than sufficient to reproduce the experimental data if δ is fixed to 0.5 and J_{eff} to 8 or 9 $\hbar$. To find a global description of the experimental isomer ratios, we set $J_{\text{eff}} = 10 \hbar$ and varied the spreading parameter δ from 0.01 to 3. The results are shown by the thin lines in Fig. 6. It appears that adopting a larger δ value gives a big difference to the extracted isomer ratio in the low-energy region but a minor difference in the high-energy region. Clearly, neither the fixed cutoff angular momentum nor the fixed spreading parameter is appropriate to describe the data, and only a condition between the two extreme approximations is sufficient. After the compound nucleus was formed in the reaction, the angular momentum of reaction residue would be affected by the emitted particles. In the case of ^{184}Re , it is formed mainly through the evaporation of one neutron in the ICF process. With increasing the beam energy, the evaporated neutron may take away an average larger value of the angular momentum. This may cause the measured isomer yield ratios to be lower than the PLATYPUS prediction.

It should be noted that other factors could also affect the isomer yield ratios in the experiment. For example, emitted γ

quantum at the process of deexcitation may shift the angular-momentum distribution of the compound nucleus, and, unlike the previous phenomenological approach, only the spreading of the angular momentum at a cutoff spin is not enough. To get an accurate description of the isomer ratio data, complete knowledge of the decay path of the compound nuclei is required.

V. SUMMARY

This article presents the results of an isomer-yield-ratio study on ^{184}Re formed in $^9\text{Be} + ^{181}\text{Ta}$ collisions around Coulomb barrier energies. The experiment was carried out though a standard stacked-foil irradiation by the ^9Be beam followed by offline measurement of the γ ray from activation product. The theoretical analysis was performed with the PLATYPUS code that is based on a classical dynamical model. The predicted CF, ICF, and TF cross sections at above-barrier energies are in good agreement with the experiment data. Using a phenomenological approach to split the calculated angular-momentum distribution by a cutoff spin, J_{eff} , and a spreading parameter, δ , the extracted values can match

the measured isomer ratios. To describe isomer yield ratios accurately, the decay process of the compound nucleus is still needed, as that process may lead to the angular momentum at the yrast line being different from that of the compound nucleus. In addition, the measured isomer yield ratios below 41.8 MeV beam energy is yet to be studied using a model that could treat quantum tunneling properly. This study extends the information on the isomer yield ratios of reactions induced by weakly bound nuclei, giving evidence that the PLATYPUS code is capable of providing an insightful explanation of the reaction mechanisms at above-barrier energies.

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