Systematics of production cross sections in ^{54}Cr-induced fusion evaporation reactions

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A series of fusion evaporation reactions induced by the ^{54}Cr^{17+} beam have been performed using the gas-filled recoil separator SHANS2. The excitation functions of ^{54}Cr + ^{159}Tb and ^{54}Cr + ^{165}Ho reactions were measured. The systematics of cross sections for reactions with ^{40}Ar, ^{48}Ca, ^{50}Ti, and ^{54}Cr projectiles are compiled and discussed. It is suggested that employing the ^{54}Cr beam holds the potential for synthesizing neutron-deficient actinide nuclei. In addition, we attempted to synthesize undiscovered americium isotopes with ^{175}Lu(^{54}Cr, $3n$–$4n$)^{225,226}Am reactions. No events were observed originating from ^{225}Am and ^{226}Am, and the upper limits were estimated to be 2.1 and 1.7 pb, respectively. The significantly low fission barrier of the compound nucleus ^{229}Am, which leads to the small survival probability, might be a possible reason for the low cross sections.

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I. INTRODUCTION

The fusion evaporation reaction represents the exclusive means of synthesizing superheavy nuclei. The heaviest element Og ($Z = 118$) was synthesized through the ^{48}Ca + ^{249}Cf reaction at an extremely low cross section [1]. For synthesizing heavier elements, experiments can only rely on heavier projectiles ($Z > 20$) rather than heavier targets due to the lack of target materials with $Z > 98$ utilized in experiments. A few reactions have been conducted to synthesize the new elements ($Z = 119$ and 120), including ^{50}Ti + ^{249}Bk [2], ^{50}Ti + ^{249}Cf [2], ^{51}V + ^{248}Cm [3], ^{54}Cr + ^{248}Cm [4], ^{58}Fe + ^{244}Pu [5], and ^{64}Ni + ^{238}U [6] reactions. However, the synthesis of these elements has not yet been confirmed.

In fusion evaporation reactions, the evaporation residue cross section ($\sigma_{\rm ER}$) is expressed as a combination of independent components, including capture cross section ($\sigma_{\rm cap}$) and fusion and survival probabilities ($P_{\rm CN}$ and $W_{\rm sur}$):

$$\sigma_{\rm ER}(E^*) = \sigma_{\rm cap}(E)P_{\rm CN}(E)W_{\rm sur}(E^*), \qquad (1)$$

where E is the beam energy, E^* is the excitation energy of the compound nucleus. Generally, asymmetric systems are preferred for the synthesis of superheavy elements due to an increase in fusion probability with a decrease in charges of the projectile-target combination. In some special asymmetric systems, such as ^{54}Cr + ^{248}Cm, the survival probability compensates for the loss in $P_{\rm CN}$ [7,8]. Therefore, ^{54}Cr may be a potential projectile aimed at synthesizing new elements. In the context of fusion evaporation reactions on producing superheavy elements, the major studies focused on ^{48}Ca-induced reactions rather than those induced by ^{54}Cr. To facilitate the synthesis of the next new element, it is imperative to acquire the $\sigma_{\rm ER}$ data for fusion reactions induced by ^{54}Cr.

With rising Z of compound nuclei ($Z_{\rm CN}$), the cross sections of “cold” and “hot” fusion reactions exhibit an exponential decrease, while the ones of ^{48}Ca-induced reactions for productions with $Z_{\rm CN} \geqslant 112$ are not decreasing continuously (see Ref. [9] and references therein). To research the systematics of $\sigma_{\rm ER}$ in ^{54}Cr-induced fusion evaporation reactions, we opted to investigate the reactions in actinide nuclear region preferentially due to the expected large $\sigma_{\rm ER}$. In this work, we conducted experiments in which ^{54}Cr as a projectile was used to bombard odd-Z ^{159}Tb, ^{165}Ho, and ^{175}Lu targets. The excitation functions of ^{54}Cr + ^{159}Tb, ^{165}Ho reactions and the upper limits of cross sections for ^{225}Am and ^{226}Am produced by the ^{54}Cr + ^{175}Lu reaction were measured. The results of this study provide potential insights for synthesizing nuclei with $Z_{\rm CN} > 91$ using ^{54}Cr as a projectile.

II. EXPERIMENTAL DETAILS

The experiments were performed at SHANS2 (Spectrometer for Heavy Atoms and Nuclear Structure-2) located behind CAFE2 (China Accelerator Facility for Superheavy Elements) at the Institute of Modern Physics in Lanzhou, China [10]. The ^{54}Cr^{17+} beam was produced by a superconducting linac with continuous wave mode and then collided with ^{159}Tb, ^{165}Ho, and ^{175}Lu targets. The target thicknesses were 400, 350, and

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450 μg/cm^2 respectively. These materials were evaporated onto a carbon foil with a thickness of 60 μg/cm^2. A rotating wheel with a diameter of 50 cm accommodated twenty targets in the form of arcs and rotated at a constant speed during the irradiation.

In the ^{54}Cr + ^{159}Tb and ^{54}Cr + ^{165}Ho reactions, several beam energies were selected in the range between 235 and 271 MeV. In the ^{54}Cr + ^{175}Lu reaction, two distinct beam energies were chosen, resulting in center-of-target energies of 246 MeV (beam dose of 7.4 × 10^{17}) and 259 MeV (beam dose of 5.8 × 10^{17}). According to the calculation using the HIVAP code [11], the $3n$ and $4n$ evaporation channels leading to ^{226}Am and ^{225}Am give rise to the largest cross sections at the selected beam energies respectively.

The evaporation residues (ERs) were effectively separated from the primary beam particles and transmitted to the focal plane detector of the separator. Helium gas at a pressure of 1 mbar was filled in the separator during the irradiation. The transmission efficiency of the separator was measured to be 52(9)% in the test reaction ^{48}Ca + ^{208}Pb. The filtered ERs were implanted into a double-sided silicon strip detector (DSSD) with a thickness of 300 μm and a sensitive area of 48 × 128 mm^2. Due to the shadow implantation depth, there is a possibility for the emitted α particles to escape from the DSSD. To capture the escaped particles, a boxlike configuration consisting of six single-sided strip detectors (SSDs) was installed in front of the DSSD. The sensitive area of each SSD features a dimension of 120 × 63 mm^2. The overall detection efficiency for α-emitting events was determined to be 88(9)%, with approximately 55% attributed to the full-energy α particles by the DSSD. The energy resolution (FWHM) of the DSSD was 30 keV for α particles within the energy range of 6–8 MeV. Two multiwire proportional chambers (MWPCs) were positioned in front of the DSSD to discriminate the α-decay events originating from implanted recoils. Behind the DSSD, we mounted three silicon detectors side-by-side, each has a thickness of 300 μm and featuring a sensitive area of 50 × 50 mm^2, arranged in parallel to proceed effectively anti-coincidence caused by the injection of light particles. All amplified and shaped signals were recorded using a digital data acquisition system with a 100 MHz sampling rate.

III. EXPERIMENTAL RESULT

To investigate the cross section systematics of the reactions involving ^{54}Cr as a beam, the excitation functions of the ^{54}Cr + ^{159}Tb and ^{54}Cr + ^{165}Ho reactions were measured. The identification of α-decay events was based on the unique α-decay energies and half-lives of both parent nuclei and their descendants. Due to difficulties in distinguishing adjacent products with similar decay energies and half-lives, the sum of the cross sections of both channels was given. Taking into account the beam dose, the transmission efficiency, and detection efficiency of SHANS2, the maximum cross sections for $2n + 3n$ and $4n$ evaporation channels in the ^{54}Cr + ^{159}Tb reaction were deduced to be 3.5(9) and 1.2(3) μb at the excitation energies of 44.4 and 48.9 MeV, respectively. The excitation functions, as shown in Fig. 1(a), exhibit an agreement with the calculation performed by the HIVAP code [11]. The same experimental procedure was also carried out for the ^{54}Cr + ^{165}Ho reaction, and the results are presented in Fig. 1(b). The maximum cross sections for the $3n$ and $4n + 5n$ evaporation channels were determined to be 45(12) and 33(9) nb at the excitation energies of 38.5 and 47.6 MeV, respectively.

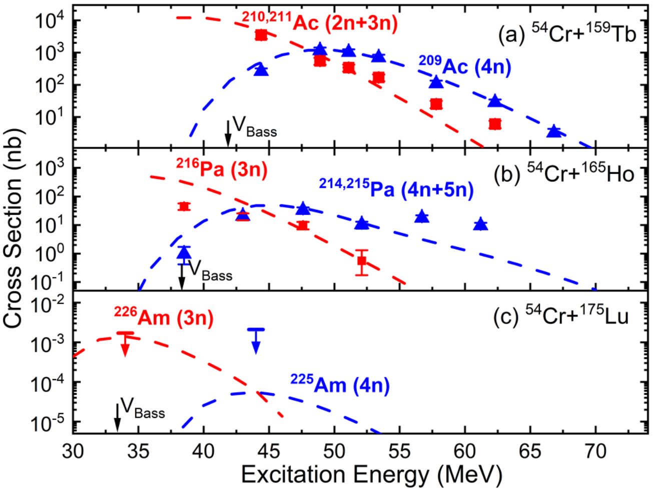

FIG. 1. The production cross sections of ^{54}Cr + ^{159}Tb (a), ^{54}Cr + ^{165}Ho (b), and ^{54}Cr + ^{175}Lu (c) reactions measured in this work. Excitation functions calculated with HIVAP code [11] are shown by dashed lines in the corresponding color. The arrows denote the Coulomb barriers given by Bass potential [12].

Another objective of this study is to synthesize ^{225}Am and ^{226}Am isotopes. Recently, the identification of the most neutron-deficient americium isotopes ^{223}Am and ^{229}Am has been reported in the multinucleon transfer reactions of ^{48}Ca + ^{248}Cm [13]. The attempts to investigate the $^{226–228}$Am isotopes were all unsuccessful [14]. In the present work, the ^{54}Cr + ^{175}Lu reaction was carried out to search for the unknown isotopes ^{225}Am and ^{226}Am. Theoretically, ^{225}Am and ^{226}Am isotopes were predicted to decay by emitting α particles with Q_α of 10.039 and 9.597 MeV respectively [15]. Based on a new Geiger-Nuttall law [16,17], the α-decay half-lives of ^{225}Am and ^{226}Am were calculated to be 1.20 and 13.7 μs. Considering that, it is possible to measure the decay events as pile-up signals by our digital data acquisition system.

In order to detect the pile-up signals, each signal from DSSD was recorded in a 20-μs-long trace in the first 15 hours and a 30-μs-long trace in subsequent periods. If the nuclei were transmitted through the separator to the detection system, we would be able to observe both the ERs and their correlated α-decay chains within the designated time window in the same pixel. However, it is unfortunate that, despite our extensive search efforts, no α-decay events could be attributed to ^{225}Am or ^{226}Am. Finally, the upper limits of the “one event” cross section for ^{225}Am and ^{226}Am were estimated to be 2.1 and 1.7 pb at the excitation energies of 44 and 34 MeV, respectively. These findings, which are summarized in Table I, will help to address the existing research gap regarding experiments involving ^{54}Cr as a beam.

TABLE I. Information for the ^{54}Cr + ^{159}Tb, ^{54}Cr + ^{165}Ho and ^{54}Cr + ^{175}Lu reactions in the present work. E_{lab} is the beam energy at the center of the target. E^*_{CN} is the excitation energy of the compound nuclei. $\sigma_{\max}$ is the maximum value measured experimentally in this study.

Reaction (channel)	Isotope	E_{lab} (MeV)	E^*_{CN} (MeV)	$\sigma_{\max}$
^{54}Cr + ^{159}Tb (2n+3n)	^{210,211}Ac	237.1	44.4	3.5(9) μb
^{54}Cr + ^{159}Tb (4n)	^{209}Ac	243.1	48.9	1.2(3) μb
^{54}Cr + ^{165}Ho (3n)	^{216}Pa	237.4	38.5	45(12) nb
^{54}Cr + ^{165}Ho (4n+5n)	^{214,215}Pa	249.5	47.6	33(9) nb
^{54}Cr + ^{175}Lu (3n)	^{226}Am	246.4	34	<1.7 pb[a]
^{54}Cr + ^{175}Lu (4n)	^{225}Am	259.4	44	<2.1 pb[a]

[a] Given as the upper limits of the "one-event" cross section.

IV. EXPERIMENTAL DISCUSSION

A. The systematics of production cross sections

In our previous experiment [55], we measured the maximum cross section of the 1n evaporation channel (σ_{1n}) in the ^{54}Cr + ^{209}Bi reaction, which is consistent with the values reported in Refs. [9,29]. The maximum σ_{1n} in cold fusion reactions with ^{208}Pb and ^{209}Bi as targets are shown in Fig. 2(a). It is well known that the maximum σ_{1n} exponentially decreases in correlation with the increase of Z_{CN}. For comparison, the maximum σ_{3n} and σ_{4n} in hot fusion reactions induced by ^{40}Ar, ^{48}Ca, ^{50}Ti, and ^{54}Cr beams are shown in Fig. 2(b). An exponential decrease in cross sections with increasing Z_{CN} was observed with Z_{CN} lower than 95. The values of the cross section exhibit a rapid and substantial decline resembling a "valley." The survival process of the compound nuclei is likely to have a significant impact on this phenomenon. The survival probabilities depend strongly on the fission barriers. Therefore, the occurrence of this "valley" may be associated with the decline in the fission barriers of compound nuclei [18,56]. In the subsequent subsection, further evidence supporting the earlier assertion is provided by the conclusion of the ^{54}Cr + ^{175}Lu reaction.

The fission barriers of the compound nuclei in partial hot fusion reactions sourced from Ref. [53] are depicted in Fig. 3(a). For comparison, other values obtained from macroscopic-microscopic calculations [54] but with the coefficients of the liquid-drop formula and shell corrections given by the Weizsäcker–Skyrme (WS4) mass model [15] are also shown in Fig. 3(a). Considering the hot fusion

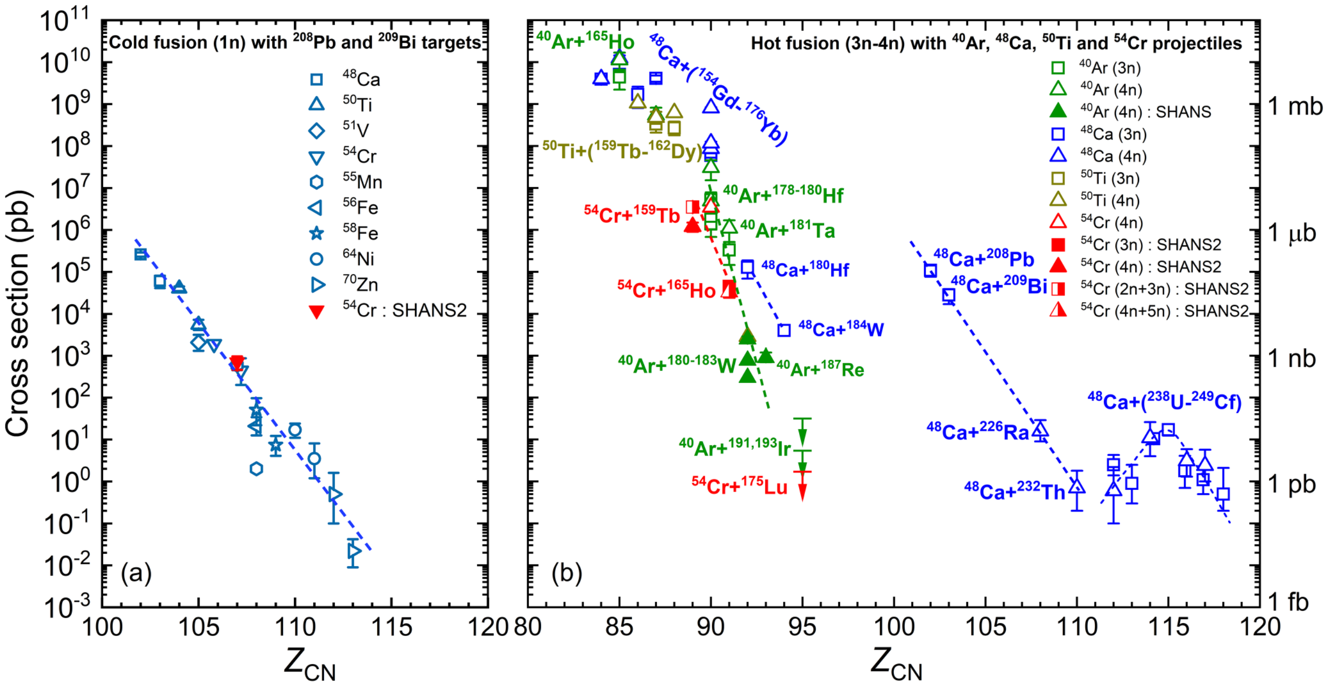

FIG. 2. Systematics of maximum cross sections compiled from previous experiments and this work for cold (a) and hot (b) fusion reactions. Open symbols in (a) mark the maximum cross sections of 1n channel in cold fusion reactions with ^{208}Pb and ^{209}Bi as targets [18–29]. In (b) the highest cross sections of 3n and 4n channels are plotted for the reactions of ^{40}Ar, ^{48}Ca, ^{50}Ti, and ^{54}Cr as beams [1,18,30–52]. The data provided by SHANS [52] and SHANS2 experiments were depicted using solid or half-solid symbols. The horizontal axis represents the charge numbers of the compound nuclei for each reaction. The symbols are denoted by the projectiles employed in reactions. The dotted lines are drawn to guide the eye.

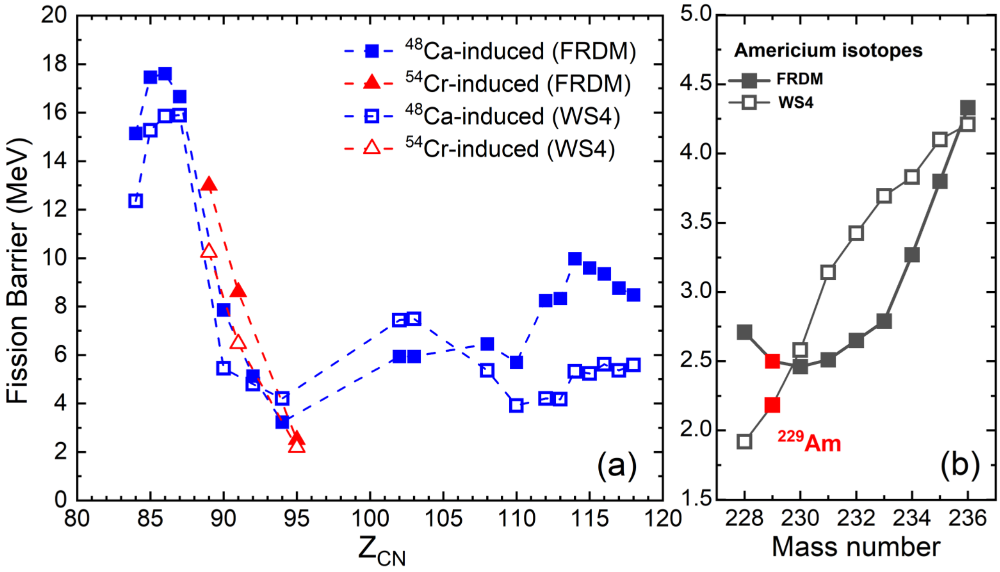

FIG. 3. (a) The variation in fission barriers of hot fusion reactions with ^{48}Ca and ^{54}Cr as beams. (b) Fission barriers of americium isotopes $^{228-236}$Am. The fission barriers from FRDM and WS4 mass models are represented by solid and hollow patterns, respectively. The value for the compound nucleus ^{229}Am is highlighted with a red solid square. The data are sourced from Refs. [15,53,54].

reactions induced by ^{48}Ca and ^{54}Cr, the fission barriers decrease rapidly with the increase of Z_{CN} within the range of $85 < Z_{CN} < 95$. Therefore, the fission barriers dominate in σ_{ER} during the synthesis of nuclei in the actinide nuclear region.

For the maximum cross sections in the actinide nuclear region, as presented in Fig. 2(b), the ones in the ^{54}Cr-induced reactions demonstrate a relatively gradual decline. The decreasing trend from ^{54}Cr + ^{159}Tb to ^{54}Cr + ^{165}Ho reactions is slightly lower than the reactions induced by ^{40}Ar and ^{48}Ca beams. This observation suggests that fusion evaporation reactions induced by ^{54}Cr exhibit potential for synthesizing actinide nuclei. More related experiments and theoretical investigations are needed to ensure its credibility.

B. The probable cause of the low cross sections in the ^{54}Cr + ^{175}Lu reaction

In the ^{54}Cr + ^{175}Lu reaction, two beam energies were applied above V_{Bass}. In this case, the production cross section is primarily influenced by fusion and survival probabilities. Fusion probability strongly depends on the entrance channel effect.

In Refs. [57,58], the mean fissility parameter x_m is defined as a linear combination of the effective entrance channel fissility parameter x_{eff} and compound nucleus fissility parameter x_{CN}, $x_m = 0.75x_{eff} + 0.25x_{CN}$. The x_{eff} is taken as

$$x_{eff} = \frac{4Z_1Z_2\Big/\left[A_1^{1/3}A_2^{1/3}\left(A_1^{1/3}+A_2^{1/3}\right)\right]}{(Z^2/A)_{crit}}, \tag{2}$$

where Z and A are the proton and mass numbers of the compound nucleus. The $(Z^2/A)_{crit}$ is given by

$$(Z^2/A)_{crit} = 50.883(1 - 1.7826I^2), \tag{3}$$

where $I = (A - 2Z)/A$. The compound nucleus fissility parameter x_{CN} is given by

$$x_{CN} = \frac{(Z^2/A)}{(Z^2/A)_{crit}}. \tag{4}$$

The utilization of x_m may serve as a criterion for evaluating the reaction mechanism. The dominance of the quasifission is observed where $x_m > 0.765$ [57,59]. In the ^{54}Cr + ^{175}Lu reaction, the calculated value of $x_m = 0.739$. The value suggests that the quasifission may not be the predominant factor contributing to the observed low cross sections. That means the nonobservation of new americium isotopes cannot be solely attributable to the increase in the charge numbers of the target nuclei from ^{165}Ho to ^{175}Lu.

The fission barriers of $^{228-236}$Am are depicted in Fig. 3(b). One can see that the fission barriers of ^{229}Am according to the FRDM and WS4 mass model are remarkably small, with an estimated value of approximately 2.5 MeV. It is suggested that fission would be the dominant way resulting in a significantly low survival probability for ^{229}Am. It can be concluded that the low cross section of interesting nuclei could be attributed to this low survival probability. In Ref. [14], similar results were also given in previous ^{40}Ar + ^{191}Ir and ^{40}Ar + ^{193}Ir reactions.

V. SUMMARY

In this study, we measured the excitation functions of the ^{54}Cr + ^{159}Tb and ^{54}Cr + ^{165}Ho reactions. We conducted an investigation into the systematics of ^{54}Cr-induced reactions. By comparing with the hot fusion reactions induced by ^{40}Ar and ^{48}Ca, we proposed that ^{54}Cr as the beam holds potential for synthesizing actinide nuclei. Simultaneously, we employed the ER-α method to search for new extremely neutron-deficient Am isotopes in the ^{54}Cr + ^{175}Lu reaction.

Unfortunately, no evidence pertaining to the nuclei of interest was observed. The upper limits of the one-event cross section were estimated to be 2.1 and 1.7 pb for ^{225}Am and ^{226}Am. Based on the fission barriers obtained from different models, the nonobservation of new americium isotopes may be attributed to the low survival probability resulting from the significantly small fission barrier in ^{229}Am, which was formed as the compound nucleus in the reaction.

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