Exploring the synthesis of key superheavy nuclei using 40Ar as the projectile? postprint

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Abstract

This paper provides a comprehensive analysis of all stages of the heavy-ion fusion evaporation reaction, aiming to enhance the understanding of the entire process and identify the influencing factors in calculating the evaporation residue cross-section. By focusing on the synthesis of superheavy nuclei with $Z = 114$, we discuss the capture cross-section, fusion probability, and survival probability of the 48Ca + 244 Pu reaction and compare them with those of the 40Ar+ 248 Cm reaction. Moreover, a systematic study examined the evaporation residue cross-sections for the synthesis of superheavy nuclei with $Z = 112 - 116$ using 40Ar as the projectile nucleus. The results indicate that utilizing 40Ar as the projectile nucleus for synthesizing isotopes with $Z = 114$ offers advantages such as lower incident energy and reduced experimental costs. Furthermore, using 40Ar as the projectile nucleus enables the synthesis of a new key isotope, 285115, thereby facilitating its identification.

Full Text

Preamble

Exploring the Synthesis of Key Superheavy Nuclei Using 40Ar as the Projectile

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This paper provides a comprehensive analysis of all stages of the heavy-ion fusion-evaporation reaction, aiming to enhance understanding of the entire process and identify the factors influencing evaporation residue cross-section calculations. Focusing on the synthesis of superheavy nuclei with $Z = 114$, we discuss the capture cross-section, fusion probability, and survival probability for the 48Ca + 244Pu reaction and compare them with those for the 40Ar + 248Cm

reaction. Moreover, a systematic study examines the evaporation residue cross-sections for synthesizing superheavy nuclei with Z = 112-116 using 40Ar as the projectile nucleus. The results indicate that using 40Ar as the projectile nucleus for synthesizing isotopes with Z = 114 offers advantages such as lower incident energy and reduced experimental costs. Furthermore, employing 40Ar as the projectile enables synthesis of a new key isotope, 285115, thereby facilitating its identification.

Keywords: Superheavy nuclei, Dinuclear system model, Heavy-ion fusion

Introduction

The synthesis of superheavy nuclei (SHN) represents a crucial research frontier in modern nuclear physics. Utilizing 48Ca beams and actinide targets, hot fusion reactions via neutron evaporation channels have successfully produced SHN with charge numbers Z = 112-118 [1-7]. Most microscopic-macroscopic models propose that element Fl (Z = 114) possesses a closed proton shell [8-11], with recent data from Ref. [12] underscoring the significance of proton shell closures in Fl nuclei. The Dubna group first synthesized Fl isotopes in 1999 through the 48Ca + 244Pu reaction at the Dubna Gas-Filled Recoil Separator (DGFRS), observing two decay chains corresponding to 288Fl and 289Fl [13]. Subsequently, the isotope 287Fl was observed at an excitation energy of E* = 53 MeV with a maximum production cross-section of 1.1+2.6−0.9 pb [14], and additional isotopes were obtained via reactions with 242Pu, 240Pu, and 239Pu targets [15-17]. Notably, recent investigations of the 48Ca + 242Pu reaction have provided valuable data that help constrain theoretical predictions [12, 18]. However, current experimental data remain insufficient for fully understanding the structural properties of the Fl isotope chain, necessitating additional experimental efforts. This work demonstrates that new methods for synthesizing Fl isotopes warrant investigation.

The synthesis of element 119 (Z = 119) and exploration of the limits of nuclear existence pose significant challenges [19-29]. Recently, the 54Cr + 243Am reaction has been proposed as the most promising pathway for synthesizing this new element [30-32]. Alpha decay constitutes an important decay mode for SHN [33-35], and experimentally, new elements and isotopes can be identified by observing position-time correlated α-decay chains from unknown parent nuclei to known descendants [36-38]. Studying isotopes along the α-decay chain is therefore crucial for identifying new elements. However, as shown in Fig. 1 [Figure 1: see original paper], some nuclides along the predicted α-decay chains of 293,294119 remain undiscovered. This paper proposes using 40Ar as the projectile nucleus, which holds promise for synthesizing new nuclides along the α-decay chain of element 119, thereby facilitating its identification.

In heavy-ion fusion reactions, the entire process of compound nucleus formation and decay is typically divided into three stages: the capture process, where the colliding system overcomes the Coulomb barrier; the formation of the compound nucleus by surpassing the inner fusion barrier; and the de-excitation of the excited compound nucleus to counteract fission. The evaporation residue cross-section is expressed as a sum over partial waves with angular momentum J at the center-of-mass energy Ec.m. [39–41]:

σER(Ec.m.) = 2 Ec.m. ΣJmax (2J + 1) T(Ec.m., J) × PCN(Ec.m., J) × Wsur(Ec.m., J).

Here, the transmission probability T(Ec.m., J) is affected by the Coulomb barrier and strong channel coupling with internal degrees of freedom, which significantly enhances the capture cross-section by several orders of magnitude at sub-barrier energies [42]. When capture cross-sections are measured experimentally within a near-barrier energy range, the barrier height and barrier distribution function can be derived from the data, allowing T(Ec.m., J) to be readily calculated or approximated. However, direct measurement of capture cross-sections in SHN synthesis is challenging, and they are typically inferred from the total yield of fission fragments, requiring T(Ec.m., J) to be estimated using theoretical models that describe the initial reaction stages.

PCN represents the fusion probability, though this stage has not been extensively studied. For light and medium nucleus fusion, the fissility of the compound nucleus is low, and the probability of forming a compound nucleus after overcoming the Coulomb barrier approaches unity (PCN 1). However, during heavy nucleus fusion, the system may reseparate into two fragments without forming a compound nucleus (quasifission), causing PCN to be significantly less than 1 and making accurate calculation challenging. The formation dynamics of SHN in massive fusion and multinucleon transfer reactions are complex, involving numerous degrees of freedom including radial elongation, mass or charge asymmetry, shape configuration, and relative motion energy [43–46]. Several models have been developed to describe fusion hindrance in massive systems, including macroscopic dynamical models [47], fusion-by-diffusion models [48], dynamical models based on Langevin-type equations [49], and dinuclear system (DNS) models [50–52]. Currently, no consensus exists regarding the mechanism of compound nucleus formation, and quite different, occasionally contradictory, physical models are employed for its description.

Wsur represents the survival probability, typically calculated using statistical models. In these calculations, the fission barrier of the excited compound nucleus is the most important yet ambiguous parameter, as theoretical estimates of fission barriers in the SHN region remain unreliable and exhibit significant variations among different models [53].

Our aim is to theoretically analyze the three stages of fusion reactions to understand the factors influencing evaporation residue cross-sections at each stage and explore the possibility of synthesizing key new isotopes using 40Ar as the projectile nucleus. Section II introduces the theoretical framework, Section III presents analysis and discussion of results, and Section IV summarizes our work.

II. Theoretical Framework

The most widely used method for calculating capture cross-section is the coupled-channel approach. The computer code CCFULL, based on coupled-channel formalism, performs these calculations (for detailed description, see Ref. [54]) by numerically solving the following set of coupled-channel equations:

[dr^2 + J(J + 1) ^{2} + VN$^{(0)}$(r) + ZPZTe^2/r + n - E] n(r) + Σ Vnm(r) m(r) = 0,

where r represents the radial part of the relative motion coordinate, denotes the reduced mass, E is the bombarding energy in the center-of-mass frame, n is the excitation energy of the n-th channel, and Vnm are the matrix components of the coupling Hamiltonian including both Coulomb and nuclear terms in the collective model. VN$^{(0)}$ is the nuclear potential in the entrance channel.

However, for SHN, an empirical coupled-channel (ECC) method is typically used to calculate capture cross-sections [55]. In this approach, the transmission probability T(Ec.m., J) can be calculated using the Hill-Wheeler formula [56], which approximates the radial variation of the Coulomb barrier between colliding nuclei with a parabolic form. Considering the multidimensional character of realistic barriers, we introduce the barrier distribution function f(B) to determine the total transmission probability [57]:

T(Ec.m., J) = f(B) [1 + exp(2π/ ω(l) [B + ^{2}B(l)l(l+1) - E])]$^{-1}$ dB.

Here, ωB indicates the width of the parabolic barrier, RB defines its position, and f(B) represents the empirical dynamical barrier distribution function. Under Gaussian approximation, this can be expressed as:

f(B) = N exp[-(B-Bm)^2/(2$\Delta_1{}^2$)] for B < Bm, f(B) = N exp[-(B-Bm)^2/(2$\Delta_2{}^2$)] for B > Bm,

where Bm = (Bs + B_0)/2, B_0 is the height of the Coulomb barrier in the waist-to-waist orientation, Bs is the minimum height of the Coulomb barrier with variance of dynamical deformation, and N is the normalization constant. Δ_2 = (B_0 - Bs)/2, while Δ_1 is typically 2-4 MeV smaller than Δ_2.

In the DNS model framework, PCN is obtained by numerically solving a set of master equations, where the neutron and proton numbers of the projectile-like fragment are considered as variables along with the corresponding potential energy surface variables [58]. The time evolution of the distribution probability function P(Z_1, N_1, E_1, t), which describes the probability at time t of finding Z_1 protons and N_1 neutrons in fragment 1 with excitation energy E_1, is governed by:

dP(Z_1, N_1, E_1, t)/dt = Σ WZ_1,N_1;Z_1' ,N_1(t) × [dZ_1,N_1P(Z_1 ', N_1, E_1, t) - dZ_1' ,N_1P(Z_1, N_1, E_1, t)] - [Λqf[Θ(t)] + Λfs[Θ(t)]] P(Z_1, N_1, E_1, t).

Here, WZ_1,N_1;Z_1' is the mean transition probability from channel (Z_1, N_1) to (Z_1 ', N_1), and dZ_1,N_1 denotes the microscopic dimension corresponding to the macroscopic state (Z_1, N_1). All possible proton and neutron numbers of fragment 1 are considered in the sum, but only one-nucleon transfer is considered in the model ($Z_1' = Z_1 \pm 1$, $N_1' = N_1 \pm 1$). The quasifission rate Λqf and fission rate Λfs are estimated using the one-dimensional Kramers formula, and the potential energy surface of the DNS in the fusion process is defined as:

$U(Z_1, N_1, Z_2, N_2, R) = EB(Z_1, N_1) + EB(Z_2, N_2) - EB(ZCN, NCN) + VC(R) + VN(R)$,

where $Z_{1,2}$ and $N_{1,2}$ denote the proton and neutron numbers of the two fragments, respectively. EB(Zi, Ni) and EB(ZCN, NCN) are the binding energies of the fragment (Zi, Ni) and the compound nucleus. We utilize the Coulomb potential VC(R) and nuclear potential VN(R) from Ref. [59].

Wsur is calculated using a statistical model:

Wsur(Ec.m., x, J) = P(E*CN, x, J)   [Γn/(Γn + Γf)],

where E*CN represents the excitation energy of the compound nucleus, P(E*CN, x, J) denotes the probability of emitting x neutrons, and Γn and Γf represent the partial decay widths for neutron evaporation and fission, respectively.

III. Results and Discussion

Figure 2 [Figure 2: see original paper] illustrates the dependence of barrier height on collision orientation with static deformation for the 48Ca + 244Pu reaction. The quadrupole deformation parameter is taken from Ref. [8]. Since 48Ca is spherical, we vary only the orientation   of 244Pu. The Coulomb barrier height differs by 18.23 MeV between pole-to-pole (= 0°) and waist-to-waist (= 90°) collisions, demonstrating that collision orientation significantly impacts the capture cross-section. In SHN synthesis, both static deformation and substantial dynamic deformations caused by nucleus-nucleus interactions must be considered.

Figure 3 [Figure 3: see original paper] presents the capture and evaporation residue cross-sections for three reactions involved in SHN synthesis. V_0 represents the Coulomb barrier height in the waist-to-waist direction, while Vs represents the minimum barrier height that changes with dynamic deformation (the Coulomb barrier height at the saddle point). The difference V_0 - Vs increases with the masses of the interacting nuclei. The ECC model describes the capture cross-sections for SHN synthesis reactions very well, including the sub-barrier energy region, whereas CCFULL calculations cannot reproduce experimental capture cross-sections at sub-barrier energies. This is because, for SHN (which exhibit low-energy vibrational excitations), realistic nucleus-nucleus interactions can produce very large dynamic deformations, requiring consideration of numerous coupling channels that complicate microscopic calculations of T(Ec.m., J) and render them unreliable.

Additionally, we provide fusion cross-sections σfus (σfus = σcap × PCN) for these three reactions and calculate the evaporation residue cross-sections. The results show that the calculated evaporation residue cross-sections reproduce experimental data very well.

Based on this theoretical description of SHN synthesis, we investigated the production of key superheavy isotopes. Figure 4 [Figure 4: see original paper] shows the capture and evaporation residue cross-sections for Z = 114 isotopes synthesized using 40Ar as the projectile nucleus. The maximum evaporation residue cross-section for the 40Ar + 248Cm reaction occurs in the 3n channel, with a value of 4.6 pb at an incident energy of 181.77 MeV. The maximum cross-section in the 4n channel is similar but slightly lower. Experimental fusion reactions with 48Ca as the projectile yield a maximum cross-section of 5 pb for synthesizing Z = 114 isotopes [14]. Thus, using 40Ar as the projectile to synthesize Z = 114 isotopes not only reduces experimental costs and requires lower incident energy but also produces a maximum evaporation residue cross-section comparable to that induced by 48Ca fusion reactions.

To gain deeper insight into the physical mechanisms underlying SHN synthesis with 40Ar and 48Ca, we analyze PCN using the DNS model, which naturally explains the existence of an inner fusion barrier during compound nucleus formation and includes the competition between fusion and quasifission during dinuclear system evolution. Figure 5(a) [Figure 5: see original paper] shows PCN for Z = 114 isotope synthesis induced by 48Ca and 40Ar. The PCN for 40Ar is an order of magnitude higher than that for 48Ca. Figures 5(b) and 5(c) display the driving potentials and inner fusion barrier heights for the 48Ca + 244Pu and 40Ar + 248Cm reactions, respectively. Their inner fusion barrier heights are 9.15 MeV and 7.56 MeV, respectively. A larger inner fusion barrier makes it more difficult for the dinuclear system to evolve into a compound nucleus, while a smaller barrier facilitates this evolution. The higher PCN for the 40Ar + 248Cm reaction thus arises from the greater mass asymmetry of the reaction system, which results in a lower inner fusion barrier.

We also analyzed Wsur in the 3n channel for both reactions. Figure 6(a) [Figure 6: see original paper] shows a higher Wsur for the 48Ca + 244Pu system. In this reaction, after forming the compound nucleus 292114, three neutrons evaporate to produce 289114. Similarly, the 40Ar + 248Cm reaction forms 288114, which evaporates three neutrons to yield 285114. Thus, the Z = 114 isotope synthesized using 48Ca + 244Pu is relatively neutron-rich. Figure 6(b) [Figure 6: see original paper] depicts fission barrier heights along the Z = 114 isotope chain, marking the positions of 289114 and 285114. The fission barrier height difference between these nuclei is approximately 1 MeV, which translates to roughly an order of magnitude difference in survival probabilities, making the survival probability higher for the 48Ca + 244Pu reaction system.

The Dubna group measured Ds isotopes from the 40Ar + 238U reaction [63], obtaining a cross-section of 0.18+0.44−0.12 pb for the 5n evaporation channel at E^* = 49 MeV. Figure 7 [Figure 7: see original paper] shows our calculations for the 2n, 3n, 4n, and 5n evaporation channels. For the 5n channel, our results agree with experimental data within error bars. In these calculations, we used fission barriers from Ref. [64].

Figure 8 [Figure 8: see original paper] presents the maximum evaporation residue cross-sections for synthesizing SHN with Z = 112–116 using 40Ar as the projectile, along with corresponding neutron evaporation channels and incident energies. The maximum evaporation cross-sections for these reactions occur in the 3n channel and are all in the picobarn range, similar in magnitude to those produced by 48Ca-induced fusion reactions. This suggests the potential of using 40Ar as a projectile for SHN synthesis. Most importantly, the 40Ar + 249Bk reaction in the 3n channel can synthesize the crucial new isotope 286115, which belongs to the α-decay chain of element 119, with a predicted maximum cross-section of 7.9 pb. Therefore, before attempting to synthesize element 119, we recommend experimentally producing 286115 via the 40Ar + 249Bk reaction to facilitate identification of the new element.

IV. Summary

For the capture process, the ECC method effectively describes experimental capture cross-sections in fusion reactions for synthesizing SHN, including the sub-barrier energy region. The dynamics of the fusion process remain unclear, and certain critical parameters of the survival process, such as fission barrier heights, are uncertain, necessitating extensive experimental and theoretical research. This study systematically investigated the synthesis of SHN with Z = 112–116 using 40Ar as the projectile, employing available experimental data and relatively accurate theoretical methods. The results indicate that 40Ar can be used as a projectile to synthesize Z = 114 isotopes, enabling investigation of the stability of nuclei predicted to possess the proton magic number Z = 114. Additionally, 40Ar can synthesize the key nucleus 286115, which lies on the α-decay chain of element 119, aiding in identification of this new element. We hope this work provides valuable insights for future experiments using 40Ar as a projectile to synthesize crucial superheavy nuclei.

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