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Investigating the Break-Up of Excited Hassium-270 Through Hot Alpha Emission: A Dynamical Cluster-Decay Model Approach

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Abstract

Identifying and characterizing the decay chains forms a crucial part of nuclide identification in the synthesis of super-heavy elements (SHEs), which is achieved via cold or hot fusion reactions. A systematic theoretical calculation of alpha-decay half-lives in this region of the periodic system may be useful in the identification of new nuclei in both types of reactions. Here, we obtain the alpha-decay half-lives in the framework of the dynamical cluster-decay model (DCM) based on quantum mechanical fragmentation theory (QMFT), built using pre-formation probability and penetration probability. We calculate the α-decay half-life using the DCM ($\ell = 0$ case), which considers the compound nucleus hot due to its recoil energy after neutron emission, providing a more accurate description than other models. Decay half-lives are compared with experimental results.

Keywords: Alpha decay, Superheavy Elements, Fission, Fusion, Half-Life

1. Introduction

A key challenge in nuclear physics is mapping the periodic table beyond known elements and into a predicted region of stability for super-heavy elements (SHEs), the elements with $Z \geq 101$. The identification of SHEs is challenging due to their short half-lives (for example, the most stable known isotope of seaborgium has a half-

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life of 14 minutes, and half-lives decrease with increasing atomic number) and the low yield of the nuclear reactions that produce them. There are mainly two types of reaction mechanisms that produce super-heavy elements, namely, the cold fusion reactions [1] (isotopes of elements with Z up to 113 have been produced using Pb or Bi targets) performed at GSI (Darmstadt, Germany) and the hot fusion reactions [2] (isotopes of elements with Z = 112–116 and 118 have been produced using ^{48}Ca projectile on actinide targets such as ^{233,238}U, ^{237}Np, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, and ^{249}Cf) performed at JINR, FLNR (Dubna). Creating long-lived super-heavy nuclei (SHN) in the lab hinges on accurately predicting their dominant decay mode, particularly spontaneous fission and alpha decay. These processes ultimately dictate the SHN's stability.

Even though both heavy nuclei ($Z \geq 90$) and superheavy nuclei can decay via alpha decay and spontaneous fission, spontaneous fission becomes the dominant factor limiting the stability of superheavy nuclei. This dominance of spontaneous fission was predicted by the liquid drop model developed by Bohr and Wheeler in 1939. Bohr and Wheeler [3] described the mechanism of nuclear fission based on the liquid drop model. They established a limit of $Z^2/A \approx 48$ for spontaneous fission, beyond which nuclei are unstable against spontaneous fission. Alpha decay is indeed the major way SHN sheds excess energy. Out of the 106 observed SHN isotopes, a significant majority, 86, decay by emitting alpha particles, while only 36 undergo fission. Interestingly, 16 of these SHN can decay through both fission and alpha emission. According to the one-body model of Gurney and Condon [4], a-particles are supposed to be preformed within the nucleus and leak through the Coulomb barrier generated by the electrostatic interaction of the a-particle with the constituent protons of the daughter nucleus. The alpha decay of SHN is possible if the shell effect supplies the extra binding energy and increases the barrier height of fission [5-9]. While beta decay is also a possibility for SHN, its slow pace due to the weak interaction makes it less prevalent compared to alpha decay and spontaneous fission. This is particularly important because nuclei stable against beta decay (and thus have a longer fission half-life) are more likely to decay via alpha emission before undergoing fission. As a result, SHN with shorter alpha decay

half-lives compared to fission half-lives become detectable in labs through alpha decay signatures.

Peering into the fringes of the periodic table: Identifying super-heavy elements (SHEs) stands as a captivating challenge in the realm of nuclear physics. Their fleeting existence and extreme properties demand innovative techniques and a deep understanding of nuclear forces. In cold fusion experiments, scientists leverage a clever strategy: they track alpha decay chains backward, relying on the characteristic alpha particles emitted by known radioactive elements at the end of the chain. This approach allows them to pinpoint the presence of a SHE that might have initiated the decay sequence. However, hot fusion reactions throw a different curveball. Unlike cold fusion, hot fusion produces nuclei rich in neutrons – isotopes that haven't been observed in any other experiment. Here, the traditional method of tracing alpha decay chains becomes inapplicable. This is where the concept of alpha decay systematics, built upon robust theoretical calculations, comes into play. By establishing a systematic understanding of alpha decay behavior in SHEs, scientists can develop a powerful tool for identifying the products of hot fusion reactions. This approach goes beyond mere identification; studying the alpha decay properties of these exotic nuclei offers a treasure trove of information. By analyzing the characteristics of alpha decay, researchers can glean valuable insights into the very core of these nuclei – their binding energies, the intricate interplay of forces within their structure, and the underlying mechanisms that govern their radioactive decay.

During the past few years, several experimental [1–2,10–14] and theoretical works [15–28] have been devoted to understanding the formation of SHN and their *a*-decay half-lives. In a recent work [27], half-lives of α-decay chains of ^{289}115* were calculated by one us and collaborators using the Preformed Cluster Model (PCM).

Table 1. The PCM (T = 0) and the DCM (ℓ = 0) calculated Alpha-decay half-lives and other characteristic properties for ^{270}Hs^{266}Sg+α. The measured $T_{\alpha}^{1/2}$ (Expt.) = 7.6^{+49}_{-22} s [2].

		Our Calculations (PCM and DCM)					Other Calculations $T_{\alpha}^{1/2}$(s) Q_{α} = 9.068 MeV				Expt. $T_{\alpha}^{1/2}$(s)
		Q_{α}(T) (MeV)	ΔR (fm)	P_0	P	$T_{\alpha}^{1/2}$ (s)	[29]	[30]	[31]	[32]	
T = 0, l = 0 with P = P*10^4	PCM	8.69	1.241	7.92*10^{-10}	4.23*10^{-13}	7.69	15.919	7.257	33.778	12.161	7.6^{+49}_{-22}
T = 0.84 (l = 0)	DCM	5.967	0.784	2.66*10^{-10}	1.04*10^{-13}	8.02					
T = 0.90 (l = 0)	DCM	5.329	0.779	5.07*10^{-10}	6.08*10^{-14}	7.23					
T = 0.96 (l = 0)	DCM	4.649	0.770	1.12*10^{-9}	2.79*10^{-14}	7.15					

In studying spontaneous alpha decay of super-heavy nuclei (SHN), theorists often assume the fragments (like the emitted alpha particle and the remaining nucleus) are in their ground state (zero temperature). While this approach yields calculated half-lives that are somewhat close to experimental values, there's a persistent discrepancy by a factor of 10^4. This limitation arises because the model doesn't account for the recoil energy (ER) gained by the SHN remnant (residue) after emitting a neutron-rich cluster (xn) – in this case, likely an alpha particle (α). To address this shortcoming and incorporate the influence of this recoil energy, researchers propose using the more sophisticated Dynamical Cluster-Decay Model (DCM) for cases where the angular momentum (ℓ) of the emitted cluster is zero.

This work investigates the alpha decay of a particularly unstable isotope, Hassium-270 (^{270}Hs), formed through a high-energy fusion reaction. The experiment involved combining Radium-226 (^{226}Ra) and Calcium-48 (^{48}Ca), with the resulting ^{270}Hs *ejecting four neutrons (4n) in the process. Interestingly, after this hot fusion birth, ^{270}Hs* carries a significant recoil energy (E_R) between 9 and 15 MeV, similar to the $E_{cm.}$* The choice of Radium-226 as a target is intriguing. An analysis of binding energy suggests it naturally favors fission (splitting) over fusion (combining) with Calcium-48. This forced fusion process pushes the newly formed ^{270}Hs into a region with even weaker binding energy per nucleon, making it exceptionally unstable. This instability is

further reflected in the decay pattern. Unlike natural radioactive elements that follow established decay series, ^{270}Hs exhibits a unique decay chain. This distinctiveness points towards a different decay process, possibly one characterized by high energy (hot) and no net angular momentum ($\ell = 0$) alongside a non-zero temperature ($T \neq 0$). To understand the alpha decay chain(s) of ^{270}Hs, the researchers plan to employ two models. The first, PCM, assumes a ground state ($T = 0$) for calculations, which might not fully capture the energetic nature of this scenario. The second model, DCM, offers a more nuanced approach. It incorporates the deformations of the nucleus (up to β_2) and considers the "hot" characteristics of the decay process (focusing on the $\ell = 0$ case) to provide a more accurate description.

2. Methodology

The DCM provides a theoretical framework for the decay of hot, rotating compound nuclei (CN) formed in light-heavy-ion reactions. It postulates the emission of preformed clusters through a dynamical tunneling process. This model is a two-step model, where the first step is the quantum mechanical preformation probability of the decay products or clusters formed in the mother nucleus, and the second step is the penetration of the so-formed clusters through the interaction barrier. In this model, the preformation probability (P_o) of all possible clusters within the mother nucleus and their penetration probability (P) will be calculated. The experimental data is reproduced within one parameter description, i.e., the neck length parameter $\Delta R(T)$.

Within the DCM, specifically when considering zero angular momentum ($\ell = 0$) for the emitted cluster, or alternatively, within the PCM when accounting for a non-zero temperature ($T \neq 0$), a key concept emerges: the decay constant. This quantity, along with the half-life time, is expressed as :

$$\lambda = P_0 \nu_0 P, \qquad T^{1/2} = \ln 2 / \lambda \tag{1}$$

Where P_0 and P represent the probabilities of two crucial steps in the decay process: pre-formation (P_0) and penetration (P). These probabilities are calculated at :

$$R = R_a = R_1 + R_2 + \Delta R$$

considering temperature-dependent potentials, denoted as $V_R(\eta, T)$ and $V\eta$ (R, T). These potentials account for the influence of temperature on the decay process. Within this framework, the mass asymmetry, a key factor in the decay, is defined as:

$$\eta = (A_1 - A_2)/(A_1 + A_2)$$

and

$$V(\mathrm{R},\eta,\mathrm{T}) = \sum_{i=1}^{2}[V_{LDM}(A_i,Z_i,T)] + \sum_{i=1}^{2}[\delta U_i]\exp\left(-\frac{T^2}{T_0^2}\right) + \mathrm{V_P}(\mathrm{R},\mathrm{A_i},\beta_{\lambda i},\theta_i,\mathrm{T}) + \mathrm{V_C}(\mathrm{R},\mathrm{Z_i},\beta_{\lambda i},\theta_i,\mathrm{T}) + \mathrm{V_\ell}(\mathrm{R},\mathrm{A_i},\beta_{\lambda i},\theta_i,\mathrm{T}), \quad (2)$$

where V_C, $V_{P,}$ and V_ℓ represent potential energy terms specific to deformed and oriented nuclei. These terms account for the non-spherical shapes and specific orientations of the decaying nucleus and the emitted cluster during the decay process.

The assault frequency for the radius of nucleus R_0,

$$\nu_0 = v/R_0 = (2E_2/\mu)^{1/2}/R_0 \quad (3)$$

with $E_2 = (A_1/A)Q$.

P_0, the preformation probability, is determined by solving the stationary Schrödinger equation. This equation describes the behavior of the system at a fixed distance ($R = R_a$), which corresponds to the first turning point in the potential energy barrier for an emitted cluster with zero angular momentum ($\ell = 0$).

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta} + V(R,\eta,T)\right\}\psi^{\nu}(\eta) = E^{\nu}\psi^{\nu}(\eta) \quad (4)$$

The solutions to the Schrödinger equation come in various forms, denoted by the symbol v, which can take values like 0, 1, 2, and so on. The solution with $\nu = 0$ corresponds to the ground state, meaning the lowest energy configuration for the system. Other values of v represent excited states, which have higher energy levels. Considering the mass parameter, represented by $B\eta\eta$, the pre-formation probability, 5) is determined by a function that resembles the Boltzmann distribution. This function

$$|\psi|^2 = \sum_{\nu=0}^{\infty} |\psi^{\nu}|^2 \exp(-E^{\nu}/T) \tag{6}$$

Within equation (1), the symbol P represents the probability of an emitted cluster successfully tunneling through the potential energy barrier. This probability is calculated using the WKB integral.

$$P = \exp\left[-\frac{2}{\hbar} \int_{R_a}^{R_b} \{2\mu[V(R,T) - Q_{eff}]\}^{1/2} dR \right] \tag{7}$$

This analytical solution depends on the location of the second turning point, denoted by R_b . This second turning point is defined by a specific condition: the potential energy (V) at the first turning point (Ra) must be equal to the potential energy at the second turning point (Rb). This equality is expressed as :

$$V(R_a)=V(R_b)=Q_{eff}. \tag{8}$$

In essence, the potential energy at the first turning point (V(Ra)) serves as an effective measure of the available decay energy, denoted as Q_{eff} (T). This effective Q-value also depends on the temperature (T) measured in MeV (Mega Electron Volts). The temperature is related to the excitation energy E^*_{CN} of the compound nucleus formed during the fusion reaction.

$$E^*_{CN} = AT^2/10 - T \text{ (MeV)} \tag{9}$$

Within the context of this hot fusion process,

$$E^*_{CN} = E_R + Q_{\alpha} \tag{10}$$

In this calculation, Q_{α} represents the standard Q-value associated with the alpha decay of the specific isotope. However, for the recoil energy E_R of the newly formed nucleus after implantation, we've relied on the value measured in actual experiments.

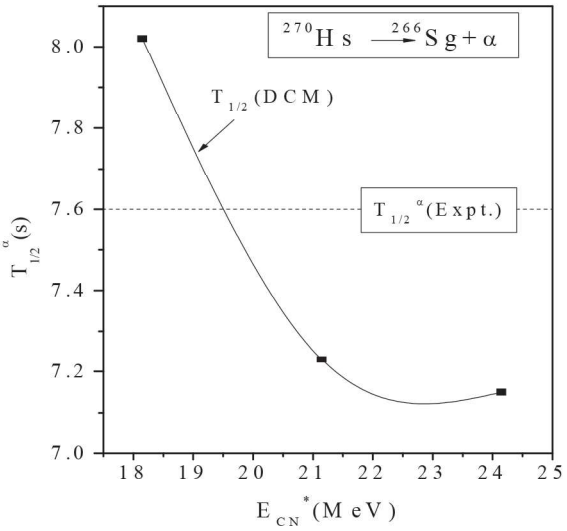

Figure 1. This graph explores how the calculated alpha decay half-life of Hassium-270 (^{270}Hs) changes with varying degrees of excitation energy (ECN*) in the compound nucleus. The experimentally determined half-life [2] is also shown as a dashed line.

3. Discussion of Results

Our calculations show that the DCM accurately predicts the α-decay half-life of Hassium-270 when considering the recoil energy, aligning closely with experimental data. In the ^{226}Ra+^{48}Ca reaction, at E^*_{CN} = 41 MeV, the ^{270}Hs* nucleus is formed with the recoil energy range E_R=9-15 MeV, which is followed by an α-decay populating ^{266}Sg with $T_{\alpha}^{1/2}$ =7.6 s [2].

As a first step, we employ the Pre-Compound Model (PCM) to determine the theoretical half-life for the alpha decay of ^{270}Hs isotope. The results so obtained are shown in the first column of Table 1. Interestingly, the experimental half-life is reproduced only after multiplying penetration probability P by a factor of 10^4, just as for the case of α-decay chains of ^{289}115*[27].

To gain a more comprehensive understanding, we will also calculate the alpha decay half-life of ^{270}Hs using the DCM (ℓ = 0) at different E_R=9, 12, and 15 MeV, meaning thereby different E^*_{CN} or T-values. The results of our calculations for $T_{1/2}^{\alpha}$ are given in Table 1 and presented

in Figure 1 as a function of $E^*_{CN.}$ Apparently, our calculations fit the experimental data exactly at E^*_{CN}=19.5 MeV, equivalently E_R=10.5 MeV.

Both Table 1 and Figure 2 showcase a comparison of our findings with previous calculations based on various empirical relationships. Additionally, we have included experimental data for a more comprehensive evaluation. The only parameter of our model is the neck length parameter ΔR. Interestingly, our DCM and or PCM (with an empirical factor of 10^4) calculated half-life fits the data within experimental error. The only other calculation (empirical formula) that is close to experiments is that of Royer and Zhang [30] reaction. It is clear from Table 1 and Figure 2, as well as from Table II that the calculations agree nicely with experiments within a constant empirical factor for the PCM (T = 0) but without any multiplying factor for the PCM (T = 0). This successful inclusion of temperature in the calculations of α-decay half-lives has been achieved in PCM (T = 0). The temperature arises from the measured recoil energy of SHNSHN. No other calculation is so complete and close to experiments as PCM (T = 0) presented here.

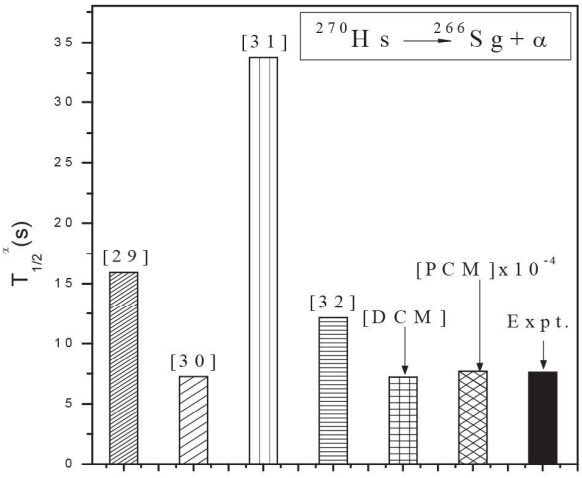

Figure 2. This histogram presents a comparison of various methods for calculating the alpha decay half-life of the isotope Hassium-270 (^{270}Hs). The bars represent the distribution of half-life values obtained using two theoretical models (DCM and PCM) and contrasted with experimental measurements and results from established formulas.

4. Summary and Conclusions

This study demonstrates the advantage of DCM for predicting α-decay half-lives in super-heavy elements formed through hot fusion reactions. The incorporation of recoil energy and non-zero temperature effects allows for more accurate predictions. We have investigated the alpha decay of a highly unstable isotope, Hassium-270 (^{270}Hs), formed through a unique hot fusion reaction. Unlike typical alpha decay, this isotope wasn't produced by spontaneous emission but rather by the ejection of four neutrons from a heavier nucleus (^{274}Hs*). This hot fusion process leaves ^{270}Hs in an excited state with significant energy. We have employed two models to analyze the alpha decay of ^{270}Hs: PCM and DCM. The PCM, commonly used for spontaneous decay, produced a theoretical half-life within a reasonable range (factor of 10,000) of the measured value. However, for a more accurate description, the scientists turned to the DCM. This model considers the "hot" nature of ^{270}Hs due to the recoil energy it gained during the hot fusion reaction. Taking this temperature effect into account, the DCM achieved an exact fit to the experimental data, but only when a specific recoil energy value within the measured range was used. This approach aligns with our previous work on another hot fusion-produced isotope, ^{289}115*. In both cases, the PCM provided a good starting point, but the DCM's ability to capture the unique hot fusion characteristics led to a more precise description of the alpha decay process. DCM can be a key player in the hunt for new SHEs. By analyzing the types of particles a newly synthesized nucleus emits, DCM can help decipher its decay patterns and confirm its identity as a SHE. Additionally, the model can predict how a SHE might decay based on its properties, further solidifying the case for a new discovery. Furthermore, DCM can guide researchers in developing better methods to create SHE with more easily detectable decay signatures. Finally, the model can be used to search for the theorized island of stability, a region where SHE might exhibit enhanced resistance to decay.

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