A comparative study of hot and cold fusion reactions using ^{206}Pb+^{48}Ca as an example

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Introduction

The synthesis of superheavy nuclei (Z>100) has been of fundamental interest for nuclear physicists since 1940s. The method being successfully used for the synthesis of superheavy elements is that of complete fusion reactions, which are classified as cold fusion and hot fusion reactions. Theoretically, "cold fusion" reactions correspond to lowest interaction barriers and largest interaction radii, i.e., of non-compact, elongated nuclear shapes, with excitation energy of the compound nucleus formed lying between 10-20 MeV. At excitation energies of 10-20 MeV, 1-2 neutrons are emitted from the compound nucleus. Cold synthesis of superheavy elements (SHEs) was first proposed theoretically by Greiner, Gupta and collaborators at Frankfurt [1], as early as in 1974-75, on the basis of Quantum Mechanical Fragmentation Theory. They suggested the use of cold compound systems that were formed for all target-projectiles systems that lie at the bottom of the potential energy minima. Experimentally, however, it became possible to identify the true signatures of cold fusion phenomenon only in late 1990's. On the other hand, for hot fusion reactions, the compound nucleus excitation energy is around 30-35 MeV and for the very hot fusion reactions it is 40-50 MeV. Compound nucleus de-excites with the emission of 3-4 neutrons for hot and ≥4 for very hot fusion reactions.

In the present work, we choose to apply our considerations to ^{206}Pb+^{48}Ca reaction where individual light particle decay channels σ_{xn}, x=1,2,3,4 neutrons are measured in a Dubna experiment [2] at various excitation energies E^*, covering hot and cold fusion reactions. We make a comparative study of the hot and cold fusion reactions, using the above said reaction as a tool and analyze it on the basis of the Dynamical Cluster-decay Model (DCM) of Gupta and collaborators (see, e.g., [3] and earlier references therein), where the effects of deformations upto hexadecupole (β_2-β_4) and compact orientations θ_c are included.

The model

In DCM, the compound nucleus decay cross-section in terms of partial waves is

$$\sigma = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_0P; \quad k=\sqrt{\frac{2\mu E_{cm}}{\hbar^2}} \quad (1)$$

where, $\mu = [A_LA_H/(A_L+A_H)]m$ is the reduced mass and $E_{c.m.}$, the center of mass energy, and ℓ_{max}, the maximum angular momentum for the light particles (LPs) cross-section $\sigma_{LPs} \rightarrow 0$. The preformation probability P_0 is the solution of stationary Schrödinger equation in $\eta = (A_H - A_L/(A_H + A_L)$, such that $P_0(A_i) \propto |\,\psi(\eta(A_i))\,|^2$. It contains the structure information of the compound nucleus via the fragmentation potential,

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

used in stationary Schrödinger equation. Here, V_{LDM} is the T-dependent liquid drop energy [4] and δU, the "empirical"

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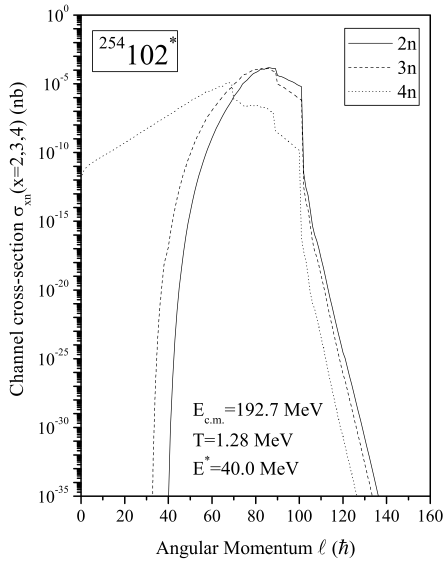

FIG. 1: Channel cross sections σ_{xn}, x=2,3,4, for $^{254}102^*$, plotted as a function of ℓ. The cut-off point is σ_{xn} <10^{-35} pb, limiting the ℓ_{max} =140 $\hbar$.

shell corrections [5], also taken T-dependent. The T-, $\beta_{\lambda i}-$ and θ_i-dependent proximity V_P, Coulomb V_C and angular momentum-dependent potential V_l are given [6] as

$$V_P(s_0(T)) = 4\pi\bar{R}(T)\gamma b(T)\Phi(s_0(T)) \quad (3)$$

$$V_C = \frac{Z_1Z_2e^2}{R} + 3Z_1Z_2e^2 \sum_{\lambda,i=1,2} \frac{R_i^\lambda(\alpha_i,T)}{(2\lambda+1)R^{\lambda+1}} \times Y_\lambda^{(0)}(\theta_i)\left[\beta_{\lambda i} + \frac{4}{7}\beta_{\lambda i}^2 Y_\lambda^{(0)}(\theta_i)\right], \quad (4)$$

$$V_l = \frac{\hbar^2\ell(\ell+1)}{2I_s}. \quad (5)$$

with the shortest distance s_0 giving compact θ_{ci}. P in Eq. (2) is the WKB integral, with first turning point $R_a(\eta,T) = R_1 + R_2 + \Delta R(T)$; R_i are radius vectors of the two nuclei and $\Delta R(T)$, a parameter that assimilates the neck formation effects, constant for all the fragments at a given excitation energy.

Calculations and Results

We consider the hot fusion reaction ^{206}Pb+^{48}Ca at E^*=40 MeV, where data for

Table 1: Comparison of experimental and calculated channel cross-section with fitted ΔR

No. of neutrons emitted	Cross-section (nb) Experimental	Calculated	ΔR (fm)
2n	$1.52^{+0.43}_{-0.34}$	1.59	1.598
3n	$1.70^{+0.25}_{-0.25}$	1.63	1.933
4n	$0.11^{+0.12}_{-0.07}$	0.098	1.334

$2n$, $3n$ and $4n$ emision is obtained [2]. Fig. 1 shows our DCM calculated channel cross sections for $2n$, $3n$ and $4n$ emissions from $^{254}102^*$, plotted as a function of ℓ. Apparently, the cross section is negligible (σ_{xn} <10^{-35}) for ℓ >140 $\hbar$. Table1 shows the comparison between the experimental and theoretical channel cross-sections and the values of fitted parameter ΔR. We observe from Fig. 1 that the behavior of $4n$ emission is different from that of $2n$ and $3n$. The $4n$ emission starts early since even the lowest ℓ=0 contributes to the croos-section. However, Table 1 shows that ΔR for $4n$ emission is the smallest, which means that the reaction time is the largest. The larger ΔR values for $2n$ and $3n$ suggest that these emissions start early, but $4n$ emission lasts longer, though with a smaller cross-section. In fact, only $4n$ emission should be treated as a hot process since $2n$ and $3n$ emissions are cold processes. The DCM calculations treating ^{206}Pb+^{48}Ca as a cold fusion reaction are underway and could result in an interesting comparison.

References

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