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Synthesis of $^{250-253}$No in ^{206}Pb+^{48}Ca reaction

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Abstract. The dynamical cluster-decay model (DCM) is used to calculate the fusion evaporation residue cross-sections σ_{xn} for x=1-4 neutron emissions in the fusion reaction ^{206}Pb+^{48}Ca→ ^{254}No* at various incident energies. Considering the multipole deformations up to hexadecapole deformations β_{4i} and configurations with "compact" orientation angles θ_{ci} (θ_c=2^0 for ^{206}Pb), the model is shown to give a good description of the measured individual light-particle decay channels, within one parameter fitting, the neck-length ΔR. Considering ^{204,206,207,208}Pb-based reactions, the dependence of 2n-emission yields on the isotopic composition of compound nucleus (CN) is also studied within the DCM. Of the four Pb-isotopes considered, at a fixed excitation energy E*~20 MeV, ΔR is largest for CN with mass number 256, followed by 255, 254 and smallest for 252, which means to suggest that neutrons emission occurs earliest for 256, then for 255, 254 and finally for 252, in complete agreement with experimental data where ^{256}No* has the highest cross-section and ^{252}No* the lowest with ^{255,254}No* lying in between. This result arises due to the penetrability factor, and is related to double magicity of both target and projectile nuclei.

1 Introduction

The search for superheavy elements (SHEs, Z > 100) explores the borderline of the nuclear chart towards its upper end where the strong Coulomb force acting between the many protons dominates the nuclear stability and finally terminates the number of elements by instability against fission. The method that has been successfully used to produce SHEs is that of complete fusion reactions. The formation of SHEs in fusion reactions can conceptually be divided into two steps: In the first step, two colliding nuclei come in close contact and an excited compound nucleus (CN) is formed. Such a compound nucleus involves both spherical and deformed nuclei/ fragments in its formation/ decay process. In the second step, competing with fission and quasi-fission, the CN cools down by the subsequent evaporation of neutrons, yielding an evaporation residue (ER) of a heavy element.

The complete fusion reactions 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 E* of the compound nucleus formed lying between 10-20 MeV. On the other hand, for hot fusion reactions, the CN 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 1-2 neutrons for cold, 3-4 neutrons for hot and ≥4 for very hot fusion reactions. The ^{204,206,207,208}Pb+^{48}Ca reactions encompass both the above noted two classes of cold

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and hot for Z=102, Nobelium element, and thus is of additional interest to study this reaction.

In this paper, we investigate the reaction $^{206}Pb+^{48}Ca \rightarrow ^{254}No^*$ where maximum evaporation residue (ER) cross-sections σ_{ER} are measured for 1-4n emissions. Data is taken from Dubna experiment [1] where individual light particles (LPs) decay channels σ_{xn}, x=1,2,3,4 neutrons are measured. In this experiment, $^{204}Pb+^{48}Ca$ is studied for the first time. Also, the isotopic dependence of σ_{ER} due to the use of various Pb isotopes is of interest since, in a "cold fusion" synthesis of Z=110 element using Pb target, an enhancement of cross section from 3.5 pb to 15 pb was observed by changing the projectile from ^{62}Ni to ^{64}Ni [2, 3]. The model used here for calculating $\sigma_{ER}=\Sigma\sigma_{xn}$ is the Dynamical Cluster-decay Model (DCM) of Gupta and collaborators (see, e.g., [4-8] and earlier references therein), which includes the deformations and orientation degrees of freedom of the colliding or outgoing nuclei. We use "hot" compact configurations, where the compact orientations θ_{ci} are calculated as per the method given in [9]. The deformations are allowed up to hexadecapole, i.e., β_2-β_4. We attempt to analyze the reaction dynamics by reproducing the measured excitation functions (σ_{ER} as a function of E^*) in terms of a single parameter of the model, the neck-length parameter ΔR.

2 The model

In DCM, for a compact configuration, the CN is assumed to be formed with a CN-fusion probability of unity, such that, in terms of ℓ partial waves, the CN decay or the fragment production cross-section

$$\sigma = \sum_{\ell=0}^{\ell_{max}} \sigma_\ell = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_0 P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

with reduced mass $\mu= mA_1A_2/(A_1+A_2)$, and center-of-mass (c.m.) energy $E_{c.m.}$.

In Eq. (1), P is the WKB penetrability, with first turning point

$$R_a = R_1(\alpha_1,T)+R_2(\alpha_2,T)+\Delta R(\eta,T) = R_t(\alpha,\eta,T)+\Delta R(T) \tag{2}$$

and P_o is the solution of stationary Schrödinger equation in η [$=(A_1-A_2)/(A_1+A_2)$], the mass asymmetry coordinate,

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V(R,\eta,T)\right\}\psi^\nu(\eta)=E^\nu\psi^\nu(\eta) \tag{3}$$

with

$$P_0(A_i) \propto \left|\psi(\eta(A_i))\right|^2 \tag{4}$$

and, mass fragmentation potential

$$V_R(\eta,T)=\sum_{i=1}^{2}[V_{LDM}(A_i,Z_i,T)]+\sum_{i=1}^{2}[\delta U_i]\exp\left(-\frac{T^2}{T_0^2}\right)+V_P(R,A_i,\beta_{\lambda i},\theta_i,T)$$
$$+V_C(R,Z_i,\beta_{\lambda i},\theta_i,T)+V_\ell(R,A_i,\beta_{\lambda i},\theta_i,T) \tag{5}$$

where V_{LDM} is T-dependent liquid drop energy, δU the shell correction, also made T-dependent, and V_c, V_P and V_ℓ are T-dependent Coulomb, nuclear proximity and angular momentum dependent potentials for deformed, oriented co-planar nuclei. The mass parameters, of the kinetic energy term in Hamiltonian, are the smooth classical hydrodynamical masses, used for simplicity. For details, refer to, say, [4].

Apparently, in DCM, both the light particles ($A_2 \le 4$), referring to ER cross-section, and the complex, heavy mass fragments, referring to fusion-fission (ff) process, are treated as the dynamical collective mass motion of *preformed clusters or fragments* through the barrier. The same formula [Eq. (1)] is also applicable to the non-compound, competing quasi-fission (qf) decay channel σ_{qf} or, equivalently, the capture cross-section $\sigma_{capture}$ where $P_0=1$ for the *incoming channel*, since both the target and projectile nuclei can be considered to have not yet lost their identity.

3 Calculations and Results

First of all, we have calculated the channel cross sections σ_{xn}, x=1-4, as a function of the angular momentum ℓ. We notice that σ_{xn} first increase with ℓ up to about ℓ=110 ħ, but then decrease with the increase of ℓ, i.e., $\sigma_{xn}(\ell)\rightarrow 0$ ($\sigma_{xn}(\ell)<10^{-15}$ nb) for 140≤ ℓ≤45 ħ. Also, the cross-section for 1n emission is minimum at the considered E^*, as is observed to be the case here experimentally (see Table I). Using this limiting ℓ window, the excitation functions for the evaporation channels 1n, 2n, 3n and 4n of $^{254}No^*$, formed in $^{206}Pb+^{48}Ca$ reaction, are calculated for the hot fusion process at $R=R_a=R_t+\Delta R$, with $\Delta R(E^*)$ for the best fit to each xn emission channel cross-section data. The calculated cross-sections in Table I are also confronted with experimental data for each decay channel, taken from [1]. Apparently, the model reproduces the data nicely with in one parameter fitting. The interesting result of Table I is that the 4n emission occurs earliest (largest ΔR), then the 3n, a little later 2n, and finally the 1n emission at the latest (smallest ΔR).

Table I : Experimental and DCM calculated evaporation residue cross-sections σ_{xn}, x= 1,2,3 and 4 with the best fitted ΔR used in the decay of $^{254}No^*$ formed in $^{206}Pb+^{48}Ca$ reaction at different CN excitation energies E^*.

E* (MeV)	1n			2n			3n			4n		
	ΔR (fm)	σ_{DCM} (pb)	σ_{Expt} (pb)	ΔR (fm)	σ_{DCM} (pb)	σ_{Expt} (pb)	ΔR (fm)	σ_{DCM} (pb)	σ_{Expt} (pb)	ΔR (fm)	σ_{DCM} (pb)	σ_{Expt} (pb)
19.8	1.435	29.2	29	1.816	100	106						
23.0	1.358	57.1	58	1.833	500	495						
23.6	1.35	54	54	1.807	489	489						
24.1				1.745	475	479						
25.7				1.78	325	356						
28.9				1.658	166	159	2.04	7.2	7.9			
30.7				1.581	56	56	2.192	30	30			
36.6				1.405	3.8	3.63	2.0	18	18			
40.0				1.345	1.52	1.51	1.723	1.74	1.74	1.976	0.103	0.103
43.9				1.332	1.37	1.39	1.695	1.53	1.53	2.02	0.265	0.26

In order for the iso-spin (N/Z ratio) effect, i.e., a comparative role of different $^{204,206,207,208}Pb$ isotopes used with ^{48}Ca on nuclear reaction dynamics, we study the variation of the above noted best fitted ΔR with mass number A of compound systems $^{252,254,255,256}No^*$ formed in $^{204,206,207,208}Pb+^{48}Ca$ reactions for, say, 2n decay cross-section σ_{2n} at a fixed excitation energy $E^*\sim 20$ MeV (actually used CN excitation energies are E^*=19.8, 23.0 and 23.6 MeV). We observe that at all the three incident c.m. energies, the compound system with A=256 has the highest value of ΔR followed by 255, 254 and finally for 252, which means to suggest that neutrons emission occur earliest for 256, then for 255, 254 and finally for 252. This is in complete agreement with experimental data [1] according to which the compound system $^{256}No^*$ has the highest cross-section and the $^{252}No^*$ lowest, with cross-sections for $^{255,254}No^*$ lying in between.

Next, we carry out a linear (straight line polynomial) fitting of ΔR_{2n}, thus obtained above for the best fitting of experimental data on σ_{2n}, with mass number of the Pb-isotope ($\Delta R_{2n}= c+mA_{Pb}$, with constants c and m determined for each E^*). Using the actual fitted values of ΔR_{2n} for the case of $^{254}No^*$ isotope and the straight line polynomials (with fixed slope m) for other three isotopes, we have calculated the σ_{2n} cross-sections for the above noted three chosen excitation energies. Our calculations for all the four isotopes $^{252,254,255,256}No^*$ are depicted in Fig. 1, compared with experimental data [1]. As is apparent from Fig. 1, the σ_{2n} cross-sections so obtained are nearly the same as the experimental cross-sections. Thus, our straight line polynomial results reproduce the experimental data well with in a simple parameterization of ΔR for each E^*. It is found that here the penetrability P plays a more significant role than the preformation factor P_0, being the highest for $^{256}No^*$ due to the double magic character of both the target and projectile (^{208}Pb and ^{48}Ca) nuclei, and the lowest for $^{252}No^*$, exactly similar to what is observed experimentally for cross-sections.

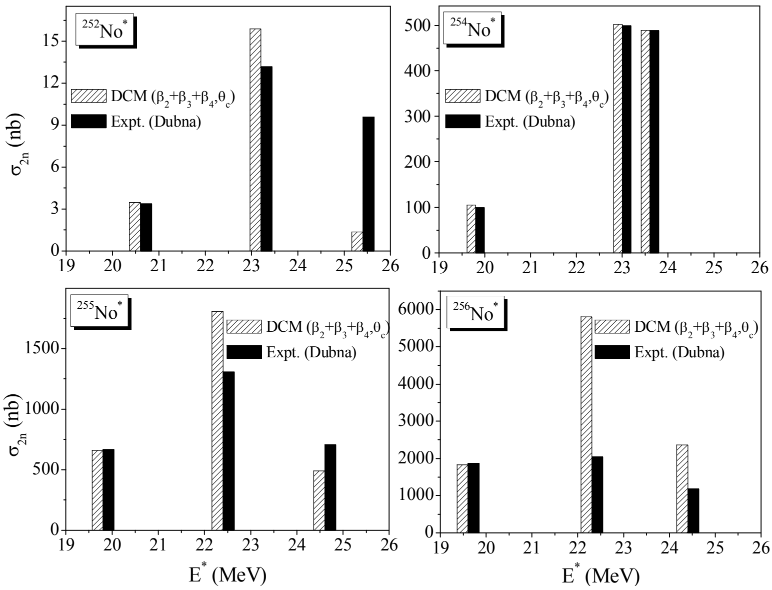

Figure 1. Calculated and measured evaporation residue cross-section σ_{2n} as a function of the compound nucleus excitation energy E^* for $^{204,206,207,208}Pb+^{48}Ca$ reactions forming the CN $^{252,254,255,256}No^*$ (see text for details).

4. Summary

The excitation functions for hot evaporation channels 1n, 2n, 3n and 4n of $^{254}No^*$ formed in $^{206}Pb+^{48}Ca$ reaction are studied. It is shown that 4n emission occurs earliest (largest ΔR), then the 3n, a little later 2n , and finally the 1n emission at the latest (smallest ΔR). For a comparative study of the compound systems $^{252,254,255,256}No^*$, interestingly, like in experiments, the neck length parameter ΔR come out to be highest for $^{256}No^*$ and lowest for $^{252}No^*$. This result in DCM arises due the penetrabilty factor P, and agrees quite well with the shell model since $^{256}No^*$, resulting from $^{208}Pb+^{48}Ca$ reaction, has both ^{208}Pb and ^{48}Ca as doubly magic nuclei. Also, as expected, projectiles with a larger number of neutrons increase the production cross section of superheavy nuclei.

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