Dynamical Cluster-decay Model (DCM) applied to ^{48}Ca induced reactions on lanthanide targets

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Introduction

The experimental data on evaporation residue (ER) cross sections is available for ^{48}Ca beam with ^{154}Gd, ^{159}Tb, ^{162}Dy and ^{164}Ho targets at various E_{lab}= 185-209.4 MeV [1], in which heavy elements in the vicinity of closed shells at Z=82 and N=126 are produced that decay predominantly by xn, x=3-5, neutron emission. These reactions are expected to contain non-compound nucleus (nCN) decay effects [2] since the targets are strongly deformed. In ^{48}Ca+ ^{154}Gd reaction, ^{202}Po* compound nucleus is formed that decays to both the ground and metastable states by emission of 4n and 3n,5n, respectively.

We have made our calculations for ^{48}Ca+^{154}Gd reaction at E_{CN}*=53.61 MeV using the Dynamical Cluster-decay Model (DCM) [3], based on the Quantum Mechanical Fragmentation Theory (QMFT), which includes the deformation and orientation effects of the outgoing co-planar or non-coplanar decay fragments. We have fitted the measured ER decay channels 3n, 4n and 5n where 3n and 5n ERs are from the metastable states of ^{199m}Po and ^{197m}Po, respectively, and 4n ERs are from the ground state of ^{198}Po at E_{CN}*=53.61 MeV formed in ^{48}Ca+^{154}Gd reaction, for a best fit of the neck-length parameter ΔR, the only parameter of the DCM. The calculations are made for quadrupole deformations (β_{2i}) with optimum orientations θ_i^{opt} of the two nuclei lying in the same plane (co-planar nuclei, $\Phi=0^0$).

Methodology

DCM is based on QMFT in which the decay of excited compound nucleus is worked out in terms of the coordinates namely: Relative separation coordinate R, Mass [and charge] asymmetry coordinate $\eta=(A_1-A_2)/(A_1+A_2)$ [and $\eta_Z=(Z_1-Z_2)/(Z_1+Z_2)$], deformation $\beta_{\lambda i}$ (λ=2,3,4: i=1,2), orientations θ_i, and azimuthal angle Φ between the two nuclei. Then, in terms of these collective coordinates, using the partial wave analysis, CN decay cross-section is defined as

$$\sigma=\frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)P_0P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

where the preformation probability P_0 refers to η- and the penetrability P to R-motion. The same formula is applicable to the nCN decay process where P_0=1. The Performation Probability, P_0 is given by the solution of stationary Schrödinger equation in η, at a fixed $R=R_a$, the first turning point(s) of the penetration path(s) for each ℓ-values

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

with ν=0,1,2,3...., referring to ground-state (ν =0) and excited-states solutions. Then, the g.s. preformation probability is

$$P_0(A_i)=\left|\Psi_R(\eta(A_i))\right|^2\sqrt{B_{\eta\eta}}\,\frac{2}{A} \tag{3}$$

Penetrability, P, is given as the WKB integral

$$P=\exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_b}\left\{2\mu\left[V(R,T)-Q_{eff}\right]\right\}dR\right] \tag{4}$$

where $Q_{eff}=V(R_a)=V(R_b)$=TKE(T) is the effective Q-value of the decay process, and R_a and R_b are the two turning points of WKB integral. For the decay occurring to metastable state of a nucleus, the Q-value gets modified to a Q-value given by the Q-value for the ground-state to ground-state decay minus the excitation energy ε, i.e., the metastable energy difference w.r.t. the ground state. The modified Q-value in Eq. (4) is then $Q_{eff}^*=Q_{eff}-\varepsilon$ [4]. For η-motion, the potential V(η) used in Schrödinger equation is the sum of liquid drop energy, shell corrections, Coulomb, nuclear proximity and angular momentum dependent potential, which for 3n and 5n are modified by energy ε when used for decay to metastable state.

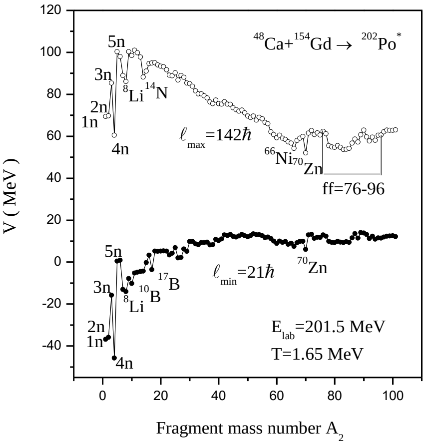

FIG. 1: Fragmentation potentials V as a function of light fragment mass number A_2, for the decay of ^{202}Po* to metastable ^{199m}Po and ^{197m}Po nuclei, plotted at ℓ_{min} and ℓ_{max} values, for best fitted ΔR values given in Table I.

Calculations and Results

FIG. 1 shows the fragmentation potential V(A_2) for the decay of ^{202}Po*, with 3n and 5n channels corrected for metastable ^{199m}Po and ^{197m}Po, respectively. In other words, the fragmentation potential energies for 3n and 5n decays are modified to obtain the metastable state energies of ^{199m}Po and ^{197m}Po by subtracting the respective metastable state energies (ε_i) from their respective ground-state, i.e., for metastable state $V^m(xn)=V(xn)-\varepsilon_i$, where x=3,5. Using this and the corresponding scattering potentials V(R) with Q_{eff}* for 3n and 5n decays, Table I shows the best fitted xn-channel cross sections for ^{48}Ca+^{154}Gd reaction at laboratory energy E_{lab} =201.5 MeV, equivalently, at temperature T=1.65 MeV. We observe that metastable 3n and 5n states are fitted exactly, with no nCN contribution required. In table II, our preliminary calculations for g.s. decay show that for the observed ground-state 4n channel a large nCN contribution is required, where the nCN is treated as the quasi-fission like process.

Table I: The DCM calculated 3n and 5n ERs, corresponding to metastable states ^{199m}Po and ^{197m}Po, compared with experimental data.

Channel	ΔR	σ^{DCM}_{xn}(mb)	σ^{Exp}(mb)
1n	1.5	3.19×10^{-3}	-
2n	0.1	3.72×10^{-12}	-
3n	-0.8	2.8×10^{-19}	-
4n	2.4	0.838	2.9
5n	1.8	9.7×10^{-6}	-

Table II: DCM calculated 4n ER corresponding to the ground state ^{198}Po, compared with experimental data.

Channel	ΔR	σ^{DCM}_{xn}(mb)	σ^{Exp}(mb)
1n	1.3	5.92×10^{-3}	-
2n	0.8	1.3×10^{-7}	-
3n	2.35	1.10	1.10
4n	-1.8	1.96×10^{-23}	-
5n	2.542	1.00	1.00

This result for ground-state decay calls for the inclusion of higher multipole deformations β_{3i},β_{4i} and the corresponding compact orientations θ_{ci}

Summary and Conclusions

Concluding, the DCM-calculations match the experimental data for ER cross-sections for 3n and 5n metastable-decay channels, i.e., to ^{199m}Po and ^{197m}Po nuclei, and are thus best fitted with no nCN contribution required, shown here for the first time. On the other hand, the observed ground-state 4n channel seems to require a considerable nCN contribution as expected[2].

References

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