COLD FUSION SYNTHESIS OF A Z=116 SUPERHEAVY ELEMENT

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The synthesis of superheavy elements is analyzed in the frame of the macroscopic-microscopic approach based on the Woods-Saxon superasymmetric two-center shell model. The fusion is considered as a cold rearrangement process. A simple estimate for the fusion cross section was made.

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1. INTRODUCTION

The synthesis of superheavy elements in cold fusion reactions was predicted in Ref. [1] by indicating appropriate methods for the optimum choice of the reaction partners. In the framework of the fragmentation theory it was evidenced that some valleys exist due to the complicated shell effects structure of the potential energy surface. In order that the system formed by the interacting fragments possesses all along the valley a minimal excitation energy, an thus a larger survival probability of the compound nucleus, some precise combinations projectile/target must be selected. Using the microscopic-macroscopic method and the superasymmetric two center shell model based on harmonic oscillators, an extended analysis of all possible combinations highlighted [2–4] that the most favorable channels able to produce isotopes with \( Z \geq 104 \) are connected with the so-called \( ^{208}\text{Pb} \) potential valley, i.e. the same valley as that of the heavy cluster emission [5]. By assuming that a \( ^{208}\text{Pb} \) similar valley exists for \( ^{48}\text{Ca} \), in Ref. [3], the \( ^{48}\text{Ca} \) was proposed as a projectile on various transuranium targets. This prediction was proved of crucial importance during the last three decades, having in mind that the production of many superheavy elements with \( Z \leq 118 \) was mainly based on this idea [6–12]. Other options for superheavy element synthesis were tested experimentally by using \( ^{45}\text{Cr} \), \( ^{64}\text{Ni} \) or \( ^{58}\text{Fe} \) beams [13, 14]. It was found that for these last isotopes, the fast fission channel becomes the most important one and the survival probability for the superheavy element drops several orders of magnitude. In the following, we continue the previous work by using the two center shell model, in order to understand better the behavior of the cold fusion as a many-body process. Consequently, the \( ^{296}_{116}\text{Lv} \) superheavy...
Cold fusion synthesis of a Z=116 superheavy element synthesis is investigated in the macroscopic-microscopic approach with the Woods-Saxon two center shell model. Based on our previous arguments, a special emphasis is dedicated to the reaction $^{248}_{114}$Cm+$^{48}_{20}$Ca. Recently, we have shown that a valley exists for the $\alpha$-decay [15]. In this way, with the same model we can describe $\alpha$-decay, cluster emission, fission and the synthesis of superheavy elements.

2. MODEL

In the macroscopic-microscopic method, the nuclear system is characterized by some collective coordinates. These variables give approximately the behavior of the intrinsic variables [16]. The basic ingredient in the model is the shape parametrization ruled by the macroscopic degrees of freedom. The deformation energy is a sum of two terms: the liquid drop part and a microscopic correction. Usually the microscopic correction is evaluated with the Strutinsky procedure [17].

We use an axial symmetric nuclear shape parametrization obtained by smoothly joining two spheroids of semi-axis $a_i$ and $b_i$ ($i=1,2$) with a neck surface generated by the rotation of a circle around the axis of symmetry. By imposing the condition of volume conservation we are left by five independent generalized coordinates $\{q_i\} (i=1,5)$ that can be associated to five degrees of freedom: the elongation $R$ given by the distance between the centers of the spheroids; the necking parameter $C_3 = S/R_3$ related to the curvature of the neck, the eccentricities $\epsilon_i$ associated with the deformations of the nascent fragments and the mass asymmetry parameter $\eta = a_1/a_2$. Alternatively, the mass asymmetry can be characterized also by the ratio $(A_1 - A_2)/(A_1 + A_2)$. This number is obtained by considering that the sum of the volumes of two virtual ellipsoids characterized by the mass asymmetry parameter $\eta$ and the eccentricities $\epsilon_i (i=1,2)$ gives the volume of the parent. This parametrization was widely used by the Bucharest group in the calculations addressing the cluster and alpha decay [18–26], the dissipation during the fission [27–29], the pair breaking [30], the generalization of time dependent pairing equations [31], the heavy element synthesis [32,33], the fission [34–37] or the cranking inertia [38,39]. In contrast to the cluster approximations [40–43], the two-center shell model offers the opportunity to treat the alpha decay as a supersymmetric fission process.

The macroscopic part of the deformation energy is computed within the finite range liquid drop model [44] as presented in Ref. [45]. The shell effects are obtained as a sum between the shell and the pairing microscopic corrections. In this context, the Strutinsky procedure [17] was used. These corrections represent the varying parts of the total binding energy caused by the internal quantum structure. A microscopic potential must be constructed to be consistent within our nuclear shape parametrization. In this context, a two-center shell model with a Woods-Saxon potential was developed recently [46]. The Hamiltonian is obtained by adding the spin-orbit and
Fig. 1 – (a) Fragmentation potential from the symmetric partition up to the superasymmetric one (the $\alpha$-decay) for the synthesis of the element $Z=116$ as a function of the mass asymmetry and the distance between the centers of the fragments. (b) The potential energy for the entrance channel $^{248}\text{Cm}+^{48}\text{Ca}$ for the superheavy element synthesis. The fusion trajectory is plotted with a thick line.

the Coulomb terms to the Woods-Saxon potential. The eigenvalues are obtained by
3. RESULTS AND DISCUSSION

The two center shell model is able to describe two tangent nuclei with an orthogonal system of wave functions in a single Hermite space. Therefore, a precise description of scission configurations can be provided. In order to find the best combination of projectile/target, we computed the potential energy for two tangent nuclei, in their ground states, for different channels \((A_1, Z_1)\) and \((A_2, Z_2)\). We selected for each mass asymmetry \((A_1, A_2)\) the charge partition that corresponds to the minimal value of the total energy. The fragmentation potential was calculated within the macroscopic-microscopic approach in a wide range of mass asymmetries from sym-

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**Fig. 2** – Family of nuclear shapes along the cold fusion trajectory for \(^{48}\text{Ca}^{2+}^{248}\text{Cm}\). The distance between the centers of the two fragments in fm are marked on the plot.
Fig. 3 – (a) Upper panel: Barrier for the $^{248}$Cm+$^{48}$Ca system. (b) Lower panel: Effective mass in the cranking approximation (full line) and GOA model (dotted line).

Symmetric fission up to the most asymmetric channel, namely the alpha decay. In order to realize these calculations, several approximations should be used. First of all, the deformations of the two fragments were varied linearly in the overlapping region from their ground-state values at scission up to the spherical ones when the elongation is zero. Secondly, we estimated the variation of the neck parameter as function of the distance between the centers such that the potential energy has minimal values for the $^{248}$Cm+$^{48}$Ca reaction. This neck dependence was renormalized by taking into account the elongation of the touching configuration for all partitions. The last approximation is related to the modality in which the identities of the two fragments are
preserved during the fusion at the microscopic level. Each fragment at the touching configuration has a proper Fermi energy and hence, proper BCS occupation probabilities of the single particle levels. For a cold rearrangement process, these probabilities must be varied from those pertaining to both fragments to those that characterize the compound system. These probabilities were modified linearly in the region where the identities of the two fragments is lost. Such a procedure was also considered in Refs. [18, 19] were the half-lives of cluster decay were reproduced. The results concerning the fragmentation potential are plotted in fig. 1 as a function of the distance between the centers of the fragments and the mass asymmetry. The behavior of the energy was briefly discussed in Ref. [15] where it was mentioned that it is possible to discern several minimums; the ground-state minimum of the nearly spherical compound nucleus \((A_1 - A_2)/(A_1 + A_2) \approx 0\) and \(R \approx 0\) fm), an isomeric minimum for fission \((A_1 - A_2)/(A_1 + A_2) \approx 0.3\) and \(R \approx 7\) fm) and a molecular minimum for the alpha-decay \((A_1 - A_2)/(A_1 + A_2) \approx 1\) and \(R \approx 6\) fm). The \(^{48}\)Ca proceeds through a path that follows the minimal values of the external potential energies up to the touching configuration. When the two nuclei start to overlap, the trajectory shifts to smaller mass asymmetries and arrives in a pronounced valley. This valley starts from the ground state and reaches the molecular minimum for alpha-decay. This valley was called \(\alpha\)-valley in Ref. [15], and shifts
suddenly the mass asymmetry from the ground state, that is, has a similar behavior to the magic valley evidenced in the cluster decay [18, 19]. In fig. 1 (b), a detailed plot of the fragmentation potential in the region of the entrance channel $^{248}\text{Cm}^{+}48\text{Ca}$ is displayed. It can be observed that, due to shell effects, the maximal values of the fragmentation potential exhibit a structure that resemble to a series of crenels. To form a superheavy element, the trajectory must proceed through a minimal value in this region, and the mass asymmetry changes towards lower values. The shapes concerning the $^{248}\text{Cm}^{+}48\text{Ca}$ fusion reaction are plotted in Fig. 2 and the corresponding potential and effective mass [38, 39, 51] in Fig. 3.

In the following, we made a simple estimate for the fusion cross section. We investigate the formation of the superheavy nucleus $^{293}\text{Lv}$ obtained in the reaction $^{248}\text{Cm}^{+}48\text{Ca}$ after the evaporation of three neutrons. The cross section is

$$\sigma = \pi \frac{\hbar^2}{2\mu E_{\text{cm}}} P_{\text{CN}}(E_{\text{cm}}) P_{3n}(E_{\text{cm}})$$

where $\mu$ is the reduced mass, $E_{\text{cm}}$ is the bombarding energy in the center of mass system, $P_{\text{CN}}$ is the transmission probability through the barrier while $P_{3n}$ is the survival probability of the compound nucleus after the evaporation of three neutrons. This last probability is estimated statistically within the formula

$$P_{3n} = \int_0^{E' = Q_n} dE' T_{n}(E', E, A_0 - 1) \rho(E') \frac{1}{2\pi \rho(E') \Gamma(E', A_0 - 1)} \times \int_0^{E'' = Q_n} dE'' T_{n}(E'', E''', A_0 - 3) \rho(E''') \frac{1}{2\pi \rho(E''') \Gamma(E''', A_0 - 2)}$$

where $Q_n \approx 6\text{ MeV}$ is the Q value for evaporation of one neutron, $T_{n}(E^*, E, A_0 - 1)$ is the neutron transmission at the initial excitation energy $E^*$ to a state of energy $E$ of the residual $A_0 - 1$ nucleus, $\rho(E)$ is the Gilbert Cameron density of the residual nucleus, and $\Gamma(E^*, A_0)$ is an energy width that take into account the most important three decay channels:

$$\frac{1}{\Gamma(E, A)} = \frac{1}{\Gamma_n(E, A - 1) + \Gamma_f(E, A) + \Gamma_{\gamma}(E, A)}$$

namely, $\Gamma_f$ for the fission process, $\Gamma_{\gamma}$ for the $\gamma$-deexcitation and $\Gamma_n$ for neutrons. The energy $E^*$ is is a measure of the excitation of the compound system and it is considered as a difference between the total energy of the projectile/target combination and that of the ground state of the compound system. Such calculations use a formalism similar to those intended for the calculation of the fission reaction, for example in Refs. [52] where details about the quantities used previously can be found. The theoretical data [9] as function of the bombarding energy are plotted in Fig. 4.

In conclusion, using the macroscopic-microscopic approach based on the Woods-
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Saxon two-center shell model, it is possible to give additional insights that favor the $^{48}\text{Ca}$ isotope as projectile and to evaluate the cross sections for superheavy elements. On the other hand, the one-center model is not compatible with the scission configurations and the passage from the internal to the external region is subject to interpolations, as in Ref. [53] that concerns superheavy elements.

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