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No chance for synthesis of super-heavy nuclei in fusion of symmetric systems

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ABSTRACT

Predictions of relatively large cross sections (of about 1 picobarn) for synthesis of super heavy nuclei of $Z = 122$ and $Z = 124$ in cold fusion (1n) reactions of symmetric ^{154}Sm + ^{150}Nd and ^{154}Sm + ^{154}Sm systems by R.K. Choudhury and Y.K. Gupta (2014) [1] are examined. The authors state that this result had been obtained by using the fusion-by-diffusion (FBD) model. As predictions of the original FBD model of Swiatecki, Cap, Siwek-Wilczyńska and Wilczyński had been definitely pessimistic regarding fusion of more symmetric systems (in comparison with equivalent asymmetric systems), we feel compelled to present excitation functions of the ^{154}Sm(^{150}Nd, 1n)^{303}122 and ^{154}Sm(^{154}Sm, 1n)^{307}124 reactions, calculated within the original fusion-by-diffusion model. In accordance with our earlier predictions of a general trend of fusion hindrance for near-symmetric systems, the cross sections for synthesis of ^{303}122 and ^{307}124 nuclides in fusion of these two symmetric systems are found to be extremely small and probably never reachable: about 10^{-11} pb and 10^{-13} pb, respectively. It is shown that Choudhury and Gupta obtained their results (overestimating the cross sections by 11 and 13 orders of magnitude) as an effect of an arbitrary and physically unjustified interference in the FBD model.

1. Introduction

R.K. Choudhury and Y.K. Gupta have published in Phys. Lett. B an article [1] predicting large enough to be measured cross sections (about 1 pb) for synthesis of super-heavy nuclei of $Z = 122$ and $Z = 124$ in cold fusion reactions of symmetric systems: ^{154}Sm(^{150}Nd, 1n)^{303}122 and ^{154}Sm(^{154}Sm, 1n)^{307}124, respectively. Surprisingly, the authors of [1] state that they reached this conclusion within the fusion-by-diffusion (FBD) model [2,3] which was known of predicting the smallest cross sections for fusion of the most symmetric combinations of the target and projectile (for a given Z of the compound nucleus) [2]. We dispute such a controversial implementation of the FBD model. The publication of this unrealistic but maybe attractive prediction in Physics Letters B may mislead some experimenters prompting them to perform long and hopeless experiments. Besides, publication of these incorrect results as FBD model predictions may undermine the reputation of the fusion-by-diffusion model. Therefore we feel compelled to present predictions for the cross sections in question correctly calculated according to the original FBD model, and give account of main errors in the improper use of the FBD model by Choudhury and Gupta.

2. Fusion of symmetric and asymmetric systems in FBD model

Due to very large negative Q-values (exceeding the height of the Coulomb barrier) for fusion of symmetric systems, even the one-neutron-out (cold fusion) reactions, ^{154}Sm(^{150}Nd, 1n)^{303}122 and ^{154}Sm(^{154}Sm, 1n)^{307}124, can occur only at kinetic energies well above the Coulomb barrier. Consequently, quite large values of angular momentum are then involved in the capture/fusion process. Therefore the standard l-dependent version of the FBD model [3] should necessarily be used to calculate synthesis excitation functions for these two reactions.

In the angular-momentum-dependent version [3] of the FBD model, the partial evaporation-residue cross section $\sigma_{ER}(E_{c.m.}, l)$ is factorized as the product of the partial capture cross section $\sigma_{cap}(E_{c.m.}, l) = \pi ƛ^2(2l+1)T(E_{c.m.}, l)$, the fusion probability $P_{fus}(E_{c.m.}, l)$ and the survival probability $P_{surv}(E_{c.m.}, l)$. Thus

$$\sigma_{ER}(E_{c.m.}) = \pi ƛ^2 \sum_{l=0}^{\infty} (2l+1) T(E_{c.m.}, l) \cdot P_{fus}(E_{c.m.}, l) \cdot P_{surv}(E_{c.m.}, l), \quad (1)$$

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where $T(E_{c.m.}, l)$ are capture transmission coefficients, $\lambdabar$ is the wave length, $\lambdabar^2 = \hbar^2/2\mu E_{c.m.}$, and μ is the reduced mass of the colliding system.

The capture transmission coefficients $T(E_{c.m.}, l)$ are taken in simple sharp cut-off approximation: $T(l) = 1$ for $l \leq l_{\max}$, and $T(l) = 0$ for $l > l_{\max}$, where $l_{\max}$ is calculated from a value of the capture cross section $\sigma_{cap}(E_{c.m.})$, i.e. the cross section of overcoming the entrance-channel Coulomb barrier at a given bombarding energy $E_{c.m.}$,

$$\sigma_{cap}(E_{c.m.}) = \pi \lambdabar^2 \sum_{l=0}^{l_{\max}} (2l+1) = \pi \lambdabar^2 (l_{\max}+1)^2. \tag{2}$$

The capture cross sections $\sigma_{cap}(E_{c.m.})$ are calculated by using the so-called "diffused-barrier formula" that was derived [2,4] assuming a Gaussian distribution of barriers around a mean value B_0, within the formalism of effective barrier distributions. Parameters of the diffused-barrier formula are empirical, obtained from analysis of fusion excitation functions for about 50 nuclear systems [4]. The parametrization of the diffused-barrier formula accounts for ground-state deformations of the fusing nuclei. Thus the effect of sub-barrier enhancement of the capture cross section for deformed target and/or projectile nuclei is automatically included in the calculated σ_{cap} values.

The last factor in Eq. (1), the survival probability $P_{surv}(E_{c.m.}, l)$, is the probability for the compound nucleus to decay to the ground state of the final residual nucleus via evaporation of light particles and γ rays, thus avoiding fission. P_{surv} is calculated with standard statistical-model expressions using the Weisskopf formula for the particle (neutron) emission width Γ_n, and the conventional transition-state-theory formula for the fission width Γ_f. In version [3] of the FBD model, the fission barrier B_f is taken as minus the ground-state shell effect, $E_{shell(g.s.)}$, corrected by the macroscopic deformation energy $E_{def(sd)}$ at saddle configuration: $B_f = -E_{shell(g.s.)} + E_{def(sd)}$. Ground-state shell corrections of Möller et al. [5] are used. The level density parameters a_n and a_f for neutron evaporation and fission channels are calculated as proposed by Reisdorf [6], with shell effects accounted for by the Ignatyuk formula [7].

The fusion probability $P_{fus}(E_{c.m.}, l)$ in Eq. (1) is the probability that the colliding system, after reaching the capture configuration (sticking), will eventually overcome the saddle point and fuse, thus avoiding reseparation. Cross sections for synthesis of superheavy nuclei are dramatically small because the fusion probability P_{fus} is hindered, often by many orders of magnitude, due to the fact that the saddle configuration of very heavy compound nuclei is more compact than the configuration of two colliding nuclei at sticking. In the scenario of the FBD model, the radial motion of the approaching nuclei stops at a distance equal approximately to the sum of radii of these nuclei (or at a somewhat larger distance in case of a sub-barrier collision). At that stage of the reaction, a neck connecting the two nuclei starts growing very rapidly due to large savings in surface energy in this process of filling the crevice between the touching nuclei. This "neck zip" occurs at approximately a fixed mass asymmetry of the initial configuration and at practically constant length of the system. (A small amount of nuclear matter is sufficient to fill the crevice between the touching nuclei. This is why the total length of the combined system remains approximately constant.) The neck zip leads the system towards the bottom of the fission valley for asymmetry of the initial configuration. This is the "injection point" from where, in most events, the system just continues to move down the asymmetric fission valley towards scission (reseparation). The only chance for fusion and formation of a compound nucleus is to climb from the injection point *uphill* over the saddle configuration in the process of thermal fluctuations in shape degrees of freedom.

By solving the Smoluchowski diffusion equation, it was shown in Ref. [8] that the probability of overcoming a parabolic barrier for the system injected on the outside of the saddle point at an energy H below the saddle is:

$$P_{fus} = \frac{1}{2}\left(1 - \mathrm{erf}\sqrt{H/T}\right), \tag{3}$$

where T is the temperature of the fusing system. The energy threshold H opposing fusion is thus the difference between the potential energy of the saddle point, E_{saddle}, and the potential energy of the combined system at the injection point, E_{inj}, both including rotational energy terms. E_{inj} is calculated using algebraic expressions given in Ref. [3] which approximate the potential energy surface along the fission valley.

All details regarding the calculations of the capture cross sections σ_{cap}, survival probabilities P_{surv} and stochastic fusion barriers H determining the fusion probabilities P_{fus}, can be found in [3].

It is difficult to precisely determine on purely theoretical grounds the location of the injection point along the fission valley. According to the scenario presented above, the total length of the system at the configuration of the injection point should be approximately the sum of diameters of the colliding nuclei (or somewhat larger in case of sub-barrier collisions). Geometry of the injection-point configuration could be determined more precisely in the empirical way by collecting the systematics of the injection point distances, s_{inj}, obtained [3] from analysis of the available 27 excitation functions for production of super-heavy nuclei in cold fusion (1n), mostly sub-barrier reactions, for systems ranging from ^{48,50}Ti + ^{208}Pb to ^{70}Zn + ^{209}Pb. The variable s is defined as the excess of length of the system at a given configuration over the sum of the projectile and target diameters, so for the touching configuration $s = 0$. It was found in [3] that the empirically determined injection point distances for this set of reactions vary in the range $s_{inj} = 1.8$–3.8 fm, that means that the injection takes place for shapes slightly longer than those for the touching configuration, in agreement with the theoretical scenario discussed above. In the l-independent FBD model [2], a constant mean value of the empirically determined s_{inj}-distances was used to predict excitation functions for not yet studied systems. For the l-dependent model [3], a "fine tuning" correction to the $s_{inj} = \mathrm{const}$ option was proposed in form of a linear parametrization,

$$s_{inj} \approx 2.30 \text{ fm} - 0.062(E_{c.m.} - B_0) \text{ fm/MeV}, \tag{4}$$

accounting for a trend of slightly decreasing s_{inj} with increasing the excess of energy above the Coulomb barrier, $E_{c.m.} - B_0$, observed at sub-barrier energies (see Fig. 1). Obviously, this parametrization was expected to be used for interpolation rather than extrapolation far beyond the explored range of $E_{c.m.} - B_0$ values, especially if the extrapolation would lead below the physically acceptable limit [2] of the touching configuration $s = 0$.

Coming to the question of prospects for synthesis of superheavy nuclei in fusion of nearly symmetric systems, one has to note that a key role in that question is played by the factor of hindrance of the fusion process, and specifically, the height of the barrier H that the fusing system must overcome in the *stochastic* process of shape rearrangement from the injection-point configuration to the saddle-point configuration. As was pointed out in [2,3], the barriers H for experimentally explored cold fusion reactions range from about 2 MeV for relatively light and asymmetric systems such as Ti + Pb ($Z = 104$) up to about 7 MeV for a heavier and more symmetric system Bi + Zn ($Z = 113$). These barriers result in a considerable hindrance of the fusion probability P_{fus}