LE JOURNAL DE PHYSIQUE-LETTRES

Classification
Physics Abstracts
25.90 — 27.90

ON THE PRODUCTION OF SUPER-HEAVY ELEMENTS BY FUSION REACTIONS AT BARRIER ENERGIES

Y. AVISHAI

Institut de Physique Nucléaire de Lyon, Université Claude-Bernard, Lyon I and IN2P3
43, bd du 11-Novembre-1918, 69621 Villeurbanne, France

(Reçu le 25 septembre 1978, accepté le 28 septembre 1978)

Résumé. — On considère la réaction de fusion $^{48}\text{Ca}(^{248}\text{Cm}, 2n)^{294}\text{X}_{116}$ avec pour condition que l'énergie et le moment cinétique soient aussi faibles que possible. Il est suggéré que, pour une énergie aux environs de la barrière coulombienne, la partie à bas moment cinétique de la section efficace de réaction correspond à une formation de noyau composé. Une telle énergie serait donc optimale.

Abstract. — We discuss the fusion reaction $^{48}\text{Ca}(^{248}\text{Cm}, 2n)^{294}\text{X}_{116}$ under the condition that energy and angular momentum should be minimized. It is suggested that at barrier energies, the low angular momentum part of the reaction cross-section leads to compound nucleus formation, and therefore, those energies are optimal.

Two recent experiments [1, 2] to synthesize super-heavy elements (SHE) by the reaction

have reported negative results. While it is clear that similar experiments at various bombarding energies and different projectile target combinations will continue, it is useful, at this point, to reassess the chance for complete fusion into SHE.

The basic question to be asked can be divided into three parts, i.e. : 1) If two nuclei approach each other, do they have a non-zero probability to stick ? 2) Is the configuration of two sticking nuclei coupled strongly with the compound nucleus (CN) of the combined system ? 3) Will the CN thereby formed decay by neutron and gamma emission or by fission ?

Along these criteria, the arguments which disfavor fusion into SHE could be summarized as follows : a) The target projectile combinations lead, in general, to effective interactions which do not allow fusion by any known mechanism, since, in general, they lack a molecular valley. b) In the few cases when one expects to have a measurable fusion cross-section, it cannot always be achieved by low bombarding energy. At high bombarding energy the remaining CN will be in a highly excited state, so that the ratio $\Gamma_n/(\Gamma_n + \Gamma_f)$ of neutron to neutron plus fission widths is vanishingly small. According to Moretto's calculations [3], the effects of closed shells on the stability of the SHE diminish above 25 MeV of excitation energy. c) Further, at higher bombarding energies, the reaction

cross-section will go mainly to deep inelastic collisions (D.I.C.). d) It has been pointed out recently that in the energy domain of D.I.C., there is also a lower critical angular momentum below which there will be no fusion [4].

Yet the idea of fusion into SHE should not be discarded, due to the following reasons. a) The system $^{48}\text{Ca} + ^{248}\text{Cm}$ suggests a rare opportunity since its effective interaction possesses a molecular valley, while its fusion fissility parameter

$$X = Z_1 Z_2 / (A_1 + A_2) = 6.48 \quad (2)$$

is not very large. b) At energies close to the interaction barrier, the competition from D.I.C. will be minimized since the friction forces (proportional to the relative velocity) will vanish. Furthermore, in the absence of tangential friction, the argument on lower critical angular momentum no longer holds. c) As discussed below, the beam energy in future experiments can be reduced and be put exactly equal to the effective s wave barrier. In fact, we will consider also the possibility of sub-Coulomb fusion.

I shall now examine the experiment reported in reference [1] from the point of view that energy and angular momentum should be minimized. The reaction energy at the middle of the target in the centre of mass system was 214 MeV. While the exact value of the interaction barrier is somewhat model dependent, it is expected to be somewhere between 199 and 203 MeV. Indeed, the reason for performing the experiment at about 10 MeV above the barrier is based on calcula-

tions of Tsang [5], which show that the potential energy *versus* the quadrupol mass distribution of the two ions has a minimum which is closed to the fission barrier of $^{296}\text{X}_{116}$. At higher bombarding energy, it is expected that the distance between the potential minimum and the fission barrier will be overcome. Yet, since the Q value is estimated at -167 MeV, this leaves the CN at 47 MeV excitation, which is much too high. It therefore seems reasonable to start with a lower bombarding energy so that the interaction barrier is crossed with small but still not negligible probability, and then to ask what next. This involves answering the second question raised previously, namely, the coupling between the quasi-molecular states and excited states of the CN. It is exactly this important coupling upon which our knowledge is very little if not zero. What can be done is first to assume that the coupling is maximal, and thereby to obtain an upper limit on the CN formation cross-section. Secondly, one might explore other reaction channels that compete with CN formation. Starting with the second point, it is argued that in order to form a CN the shape of the combined system should be less deformed than the fission saddle point shape, since otherwise the system will undergo quasi-fission. Classical calculations of Nix and Sierk [6] for

indicate for example that, if the energy is just above the energy of two touching spheres, then the two nuclei will virtually cease to approach each other, and instead, they will undergo strong deformations and then recede. However, it must be noted that the Nd + Nd system is rather different from $^{48}\text{Ca} + ^{248}\text{Cm}$. Its effective interaction does not have a molecular valley and its fusion fissility parameter is equal to 12. Besides, the classical calculations are not justified at low energies, and among others, they miss the effect of quantum fluctuations in transverse directions and they break down below the interaction barrier. It might be argued that sub-barrier fusion is very small but, as long as it is measurable, it might be compensated by the low excitation energy of the CN.

An argument against the competition from quasi-fission for systems with molecular valley is based on fusion calculations for Ar + Th by Deubler and Dietrich [7]. They obtained an agreement with the experimental fusion cross-section by the formula $\sigma_f = \pi b_m^2$ where b_m corresponds to the maximum angular momentum for which the effective interaction in the entrance channel has a molecular valley. In other words, the assumption that once the barrier is crossed (at low partial waves), the system is committed

to complete fusion is reasonable. Thus, for systems which have deep enough quasi-molecular valley, one might adopt the conventional picture according to which the low partial wave part of the reaction cross-section is exhausted by CN formation, while the higher part leads to D.I.C. and quasi-elastic processes. There is no theoretical substantiation of low partial wave quasi-fission events.

It is rather interesting to enquire about the experimental situation with regard to the reaction channels which compete with CN. The yield of trans curium elements from the Ca + Cm reaction in reference [1] is approximately 10^{-27} cm^2 . This is the contribution from all angular momenta. Since we are interested in minimizing the angular momentum of the CN, we must consider only the contribution up to some L_0 , above which the CN will fission anyhow. Therefore, any competition to CN below L_0 is of order $10^{-27}(L_0/L_1)^2$ where L_1 is the peripheral angular momentum. For $L_0 = 10$,

$$L_1 = (R_1 + R_2)(2\mu E)^{1/2}/\hbar \approx 200,$$

the low partial wave competition to CN formation at the indicated energy ($242 < E_L < 267$) is then about $2.5 \times 10^{-30} \text{ cm}^2$. At the same time, a simple barrier penetration calculation at c.m. energy equal to the barrier energy (≈ 200 MeV) yields

$$\sigma_{R,L_0} = \sum_{l=0}^{L_0} (2l+1) P_l \approx 1 \times 10^{-27} \text{ cm}^2$$

(for $L_0 = 10$), where P_l is the penetration probability for the l th partial wave.

I therefore conclude that for this system, at this regime of energies, the reaction cross-section from the low partial waves goes to CN, and the question of the yield of SHE then depends on the decay mode of the CN, i.e., $\Gamma_n/(\Gamma_n + \Gamma_f)$.

In conclusion, the message of the present note is as follows: For the system $^{48}\text{Ca} + ^{248}\text{Cm}$, the optimal beam energy for the reaction (1) is that energy that is equal to the interaction barrier. At this energy, the low partial waves penetrate easily, so that no loss of low spin CN formation cross-section occurs. It is further suggested that competition from D.I.C. and quasi-fission is not very large, so that a substantial part of the reaction cross-section leads to the formation of CN. Due to our lack of knowledge of the exact behaviour of $\Gamma_n/(\Gamma_n + \Gamma_f)$ it is also possible to put the beam energy a few MeV below the barrier, and to obtain the CN by sub-Coulomb fusion.

Approximate yields of $^{294}\text{X}_{116}$ based on these guidelines and Moretto's estimates of $\Gamma_n/(\Gamma_f + \Gamma_n)$ will appear shortly.

References

- [1] HULET, E. K. *et al.*, *Phys. Rev. Lett.* **39** (1977) 385.
- [2] OGANESEAN, Y. T. *et al.*, *Nucl. Phys. A* **294** (1978) 213.
- [3] MORETTO, L. G., *Nucl. Phys. A* **180** (1972) 337.
- [4] LEFORT, M., *J. Physique Colloq.* **37** (1976) C5-57.
- [5] TSANG, C. F., *Lawrence Berkeley Laboratory Report LBL-2366* (1973) 146.
- [6] NIX, J. R. and SIERK, A. J., *Phys. Scr.* **10A** (1974) 94.
- [7] DEUBLER, H. H. and DIETRICH, K., Preprint.