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SYNTHESIS OF NEW ELEMENTS WITHIN THE FRAGMENTATION THEORY: APPLICATION TO Z=104 AND 106 ELEMENTS

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SYNTHESIS OF NEW ELEMENTS WITHIN THE FRAGMENTATION THEORY: APPLICATION TO Z=104 AND 106 ELEMENTS

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An important question in the production of superheavy elements through heavy ion collisions has been the choice of the proper target and projectile combination[1]. The Berkeley group[2,3] has bombarded spherical, light projectiles on deformed, heavy targets, whereas the Dubna group[4-6] has used spherical or nearly spherical, but relatively heavier projectiles on spherical, heavy targets. The production cross sections, however, are shown[5] to be very sensitive to the choice of the reaction partners. In this paper, we propose an answer to this question of the optimum choice of the reaction partners on the basis of the theory of fragmentation[7-12].

The fragmentation theory is already successfully applied to the prediction of fission mass- and charge yields[8,11] and to the fragmentation process in heavy ion collisions[9-12]. In the following we discuss its application from a new point of view, giving a theoretical method to select out the projectile and target nuclei for the possible production of superheavy elements. The idea of the method is to choose the reaction partners such that the compound system is formed with a minimum excitation

energy. For a cooler compound nucleus, the number of neutrons emitted would be smaller and consequently the cross section for the formation of the nucleus in the ground state would be large[13].

Since the compound system can be reached by various combinations of the projectile and target, the excitation energy of the compound system has to be calculated for all possible combinations. In this paper, we have made calculations for the compound systems $A=258$, $Z=104$ and $A=260$, $Z=106$ which decay, say, to the isotopes $A=256$, $Z=104$, and $A=258$, $Z=106$ after the evaporation of two neutrons. Various isotopes of element $Z=104$ are synthesized with light projectiles by bombarding ^{242}Pu with ^{22}Ne (Dubna [4]), ^{249}Cf with $^{12,13}C$ and ^{248}Cm with ^{18}O (Berkeley [2,3]) and with heavy projectiles by bombarding $^{206,207,208}Pb$ with $^{48,50}Ti$ (Dubna [4,5]). Some isotopes of element $Z=106$ are synthesized at Dubna[6] by bombarding $^{206,207,208}Pb$ with $^{52,54}Cr$ ions. Our calculations are made for the compound nucleus formed with ions of $Z\geq 20$ and hence do not include experiments with light projectiles.

The theory of fragmentation describes all two-body channels from which the compound system can be formed or into which it can decay. The coordinates of the nuclear system are: the relative distance R, the collective surface coordinates $\alpha^{(1)}$ and $\alpha^{(2)}$ of the individual nuclei, and the mass- and charge fragmentation[7,11] $\eta=\frac{A_1-A_2}{A_1+A_2}$ and $\eta_Z=\frac{Z_1-Z_2}{Z_1+Z_2}$. In the asymptotic region, defined by $R\geq R_c$, where R_c is some critical

distance at which the two nuclei come in close contact with each other, both η and η_Z are discrete variables. In the interaction region ($R<R_c$), the nucleon numbers do not remain good quantum numbers, and both η and η_Z are defined properly by the mass and charge distribution. For homogeneous density ρ, the mass fragmentation coordinate reduces to the volume asymmetry coordinate

$$\eta\equiv\frac{1}{A}\left(\int_{v_1}\rho\,d\tau_1-\int_{v_2}\rho\,d\tau_2\right)\approx\xi\equiv\frac{v_1-v_2}{v_1+v_2}\qquad(1)$$

and correspondingly, $\eta_Z\approx\xi_Z$. v_1 and v_2 are the volumes occupied by the nucleons in two parts of the compound nucleus, divided by passing a plane perpendicularly through the neck.

The collective Hamiltonian, depending on the coordinates $R,\eta,\eta_Z,\alpha^{(1)}$, and $\alpha^{(2)}$ and their canonically conjugate momenta, is given by:

$$H=T_{kin}\left(R,\eta,\eta_Z,\alpha^{(1)},\alpha^{(2)},P_R,P_\eta,P_{\eta_Z},P_{\alpha^{(1)}},P_{\alpha^{(2)}}\right)+V(R,\eta,\eta_Z,\alpha^{(1)},\alpha^{(2)}).\qquad(2)$$

As we shall see, already the real part of the potential V is sufficient to give qualitative conclusions about the probability of forming a cool compound nucleus.

The potential V is calculated by using the macro-microscopic formalism of Strutinsky[14]. For the interaction region ($R<R_c$), we have used the liquid drop model of Myers and Swiatecki[15] with its modified[16] surface asymmetry constant, and the single-

particle states $E_i(R,\eta,\eta_Z,\epsilon,\beta_1,\beta_2)$ of the asymmetric two-centre shell model (ATCSM)[17] with protons and neutrons moving in two separate single particle potentials[11]. The nuclear shape associated with each set of the parameters of ATCSM is defined in terms of five coordinates, shown in Fig. 3 (b). For simplicity shapes are assumed rotational symmetric around the line connecting the centres and are thus described by the quadrupole deformation coordinates β_1 and β_2 only. For the asymptotic region ($R>R_c$), the potential is given by the Coulomb interaction plus the sum of the ground state binding energies of the two fragments[9-11]

$$V(R,\eta,\eta_Z,\beta_1,\beta_2)=\frac{Z_1Z_2e^2}{R}-B(A_1,Z_1,\beta_1)-B(A_2,Z_2,\beta_2)+$$
$$+2B(A/2,Z/2,\beta_1=\beta_2). \qquad (3)$$

The binding energies are taken from the atomic mass tables, given be Seeger[18] for $Z\geq 20$, where the liquid drop energy is smoothed out with the shell corrections determined with the Nilsson model. Since for separated fragments the two-centre shell model approaches the Nilsson model for each fragment, we obtain smooth continuation of V from the asymptotic to the interaction region.

Figs. 1 (a) give the result of our calculation for the potential $V(R,\eta)$ for the compound nuclei $^{258}104$ and $^{260}106$. These plots, therefore, represent the potential $V(R,\eta)$ for various combinations of the target

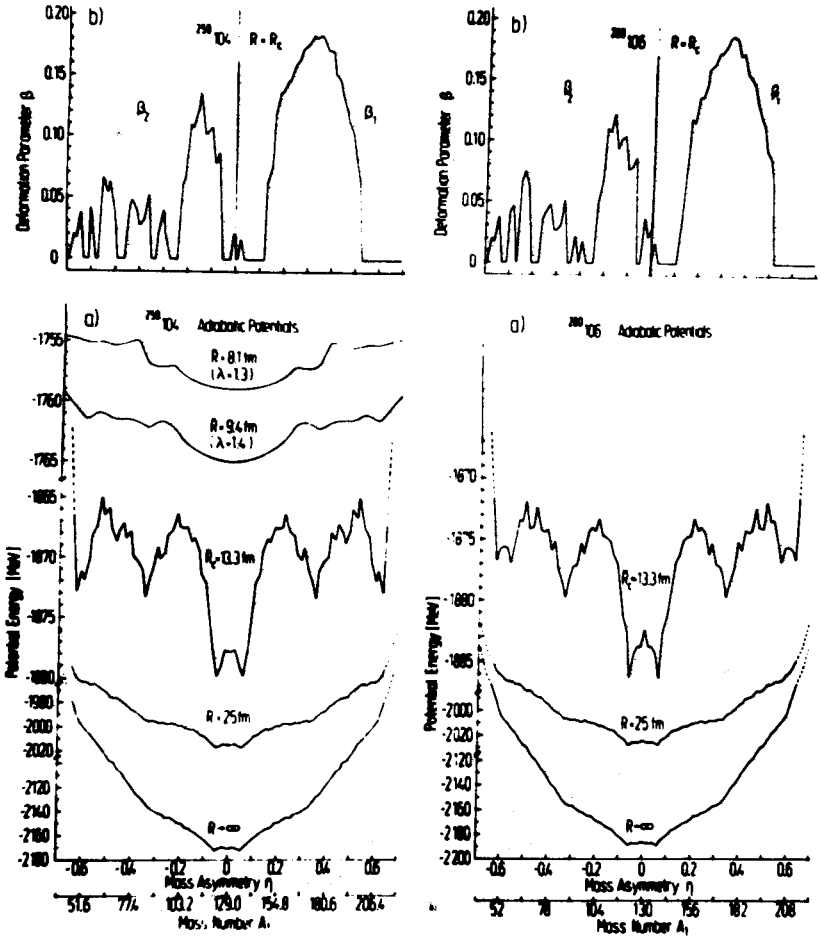

Fig. 1. a) Potential energy as a function of mass-asymmetry η and the relative separation R for the compound system $^{258}104$ and $^{260}106$. Curves for $R\geq R_c$ include the minimization in charge-asymmetry coordinate η_Z, except for the dashed part. Scales used for $R<R_c$ and $R\geq R_c$ are different. b) Deformation parameters (Ref.[18]) for $R=R_c$, as function of the mass number of the two fragments.

and projectile nuclei leading to the same compound nucleus. In the overlapping region ($R<R_c$), a full three dimensional minimization in ϵ, β_1 and β_2 is carried out, thereby assuming adiabatically in the coordinates ϵ, β_1 and β_2. The minimization procedure, however, is very time consuming and we have therefore made our calculations for only two R (or λ) - values in the case of the compound nucleus $^{258}104$. Since for the fixed length λ of the nucleus the distance R changes with η, we have labelled these curves by an average value of $R=z_1+z_2$ (see Fig.3(b)) The coordinate η_Z is not included in these calculations. In the asymptotic region ($R \gtrsim R_c$) we have applied our earlier method [10] of minimizing $V(R,\eta,\eta_Z)$ for each possible fragmentation in masses and charges. The minimization in the β-coordinates is then automatically carried out. This method thus involves the calculation of the charge dispersion potential $V(\eta_Z)$ for each R-and η-value, illustrated in Fig. 2 for two η- and different R-values. The distance R_c of closest approach is calculated by using the empirical relation of Gutbrod et al. [19] and the calculations shown in Figs. 1(a) are carried out for an average value.

We notice from Figs. 1 (a) that for each compound nucleus deep minima in the potential energy occur at only a few η-values. As the two nuclei come close to each other ($R \lesssim 7$-8 fm), the potential $V(R,\eta)$ becomes more or less flat. This happens because for $R \approx 8$ fm the neck has already started to disappear (see Fig. 3(b)), so that the placing of a dividing plane which determine η, is no more significant. The

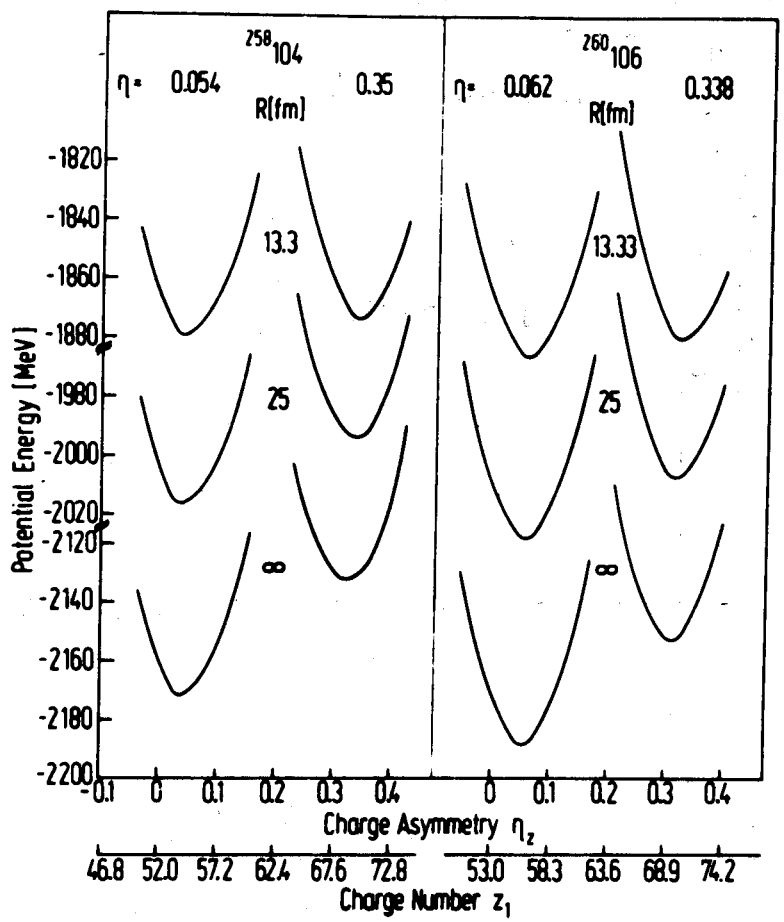

Fig. 2. Charge dispersion potential for different η- and R -values of the compound systems $^{258}104$ and $^{260}106$.

interesting point is that these deep minima in $V(R,\eta)$ are not only stable in η but also no new minima appear after the two nuclei overlap to form the compound system. The

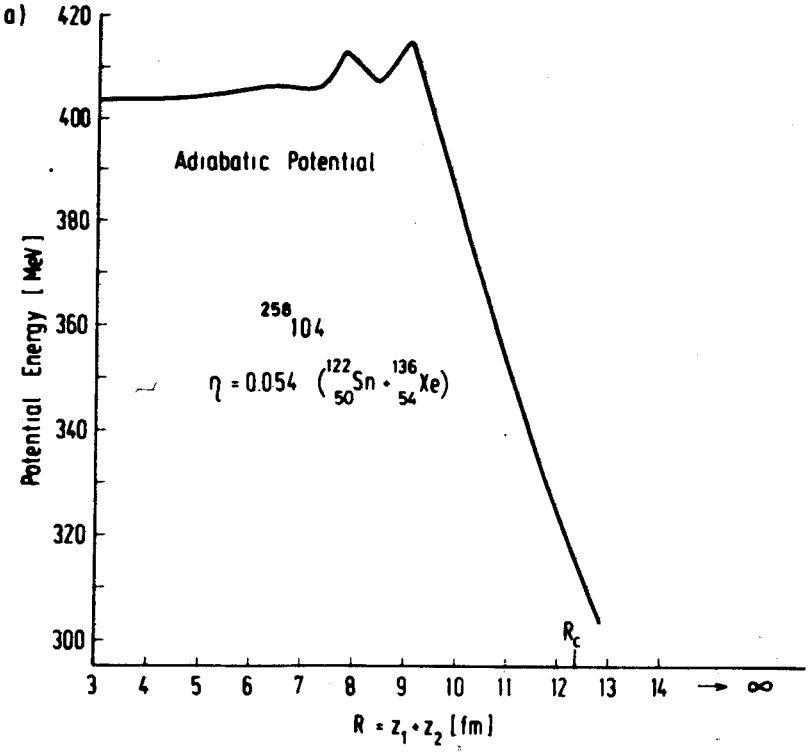

Fig. 3. a) Potential energy as a function of relative distance R for the collision of $^{122}_{50}Sn + ^{136}_{54}Xe \rightarrow ^{258}104$. b) The corresponding nuclear shapes. The length λ of the nucleus is in units of $2R_0$, where R_0 is the radius of the spherical compound system.

slight shifting or the wipping of a certain minimum at a certain R-value can be associated with the charge dispersion effects. Fig. 2 shows that for $\eta = 0.35$ in $^{258}104$, the minima in V shift with R. Therefore, the potential $V(\eta, R=R_c)$ which is easily computable through Eq. (3) gives already the positions of the minima with respect to η and η_Z. Evidently, the potential minima in Figs.1(a) are related to shell effects, with at least one of the two nuclei being a spherical nucleus. This fact is demonstrated in Figs. 1(b) where the static deformations [18] β_1 and β_2 are plotted for $R = R_c$.

Next, in the dynamical fragmentation theory applied to nucleus-nucleus collision [10], one has to solve the stationary Schrödinger equation

$$H(R, \eta, \eta_Z, a^{(1)}, a^{(2)})\psi = E\psi \qquad (4)$$

with the following initial state $(R \rightarrow \infty)$

$$\psi_i \sim e^{ikz}\, \delta^{1/2}(\eta - \eta_0)\delta^{1/2}(\eta_Z - \eta_{Z_0})\chi_{n_1}(a^{(1)}, \eta_0, \eta_{Z_0}) \otimes \chi_{n_2}(a^{(2)}, \eta_0, \eta_{Z_0}). \qquad (5)$$

The δ-type wave functions describe the mass and charge motion. The wave functions χ_{n_1} and χ_{n_2} represent the intrinsic states of the incoming nuclei, specified by η_0 and η_{Z_0} and are also assumed to be the surface vibrational states described by $a^{(1)}$ and $a^{(2)}$, respectively. Since the static deformations β_1 and β_2 depend strongly on the fragmentation coordinates η and η_Z (see Figs. 1(b)), the Hamiltonian couples the surface vibrations and the mass- and charge fragmentations strongly. Then, if the transfer of mass and charge occurs, the shapes of the

two incoming nuclei would change which would apparently cause a strong transfer of energy into the surface degrees of freedom. Thus, two different cases of initial fragmentation can be distinguished which would lead to different excitations of the com pound system: i) the initial fragments lie outside the potential energy minima in Figs. 1 (a), which according to Figs. 1 (b) correspond to both β_1 and $\beta_2 \neq 0$, and ii) the initial fragments lie on the energy minima, which refer then to either one or both nuclei to be spherical. We might remind here that for reasons of large fusion probability, we are interested in the case of minimum excitation energy of the compound system.

In case i), a large mass and charge transfer would occur in the direction to the minima of potential $V(\eta)$ as the two nuclei start to overlap. The forces which drive the system are given by $-\partial V/\partial \eta$ and $-\partial V/\partial \eta_Z$ according to classical mechanics. Since the nuclei would change shapes during the running of the system in the direction to the potential minima, a large amount of energy is transferred into the excitation of the surface vibrations. On the other hand in case ii) no mass and charge transfer would occur since then the driving forces $\partial V/\partial \eta$ and $\partial V/\partial \eta_Z$ are zero. In that case, quantum mechanically the η -dependence of the wave functions is approximately given by the zero-point motion around the potential minima.

Hence, we find that if the target and projectile are chosen with respect to the minima in the potential $V(R, \eta, \eta_Z)$ and further if the bombarding energy is so chosen that

the compound system is reached straight in a central collision, the excitation would be minimum. For non-central collisions, the compound system carries a large amount of angular momentum which is then highly excited.

As a first test of our suggested selection rule, we have given in Table 1 the possible combinations of the projectile and target, corresponding to the minima of V in η of Figs. 1(a), which we consider could synthesize to produce the elements $Z=104$ and 106. Since, in general a transfer of 2 protons could produce a gain or loss of 7-10 MeV (see Fig. 2), we have also listed the neighbouring combinations with ± 2 protons/neutrons.

It is interesting to find that the combinations $^{50}_{22}Ti + ^{208}_{82}Pb$ and $^{54}_{24}Cr + ^{206}_{82}Pb$ are used in Dubna experiments [5,6] for the synthesis of $Z=104$ and 106 elements, respectively. Secondly, on the basis of the estimates for fission half-life, Bengtsson et al.[20] have suggested the combination $^{112}_{50}Sn + ^{136}_{54}Xe$ for the production of $Z=104$ element. It is encouraging that both the studies stress on Sn and Xe beams for their use as target and projectile for the production of $Z=104$ in the laboratory.
Fig. 3(a) gives an illustrative plot of $V(R, \eta=0.054)$ for $^{122}_{50}Sn + ^{136}_{54}Xe$ leading to the compound nucleus $A=258, Z=104$.

In Table 1, we have also given the quadrupole deformation parameters [18]. As already pointed out, all these combinations have at least one of the two nuclei with a spherical shape. This result is in agreement with all the successful experiments at Berkeley and Dubna.

Table 1

Projectile and target combinations for the productions of elements Z = 104 and Z = 106, corresponding to the potential energy minima and its neighbourhood. Only those combinations are given where both the partners of the reaction are stable in nature

Element Z	|η|	Projectile and Target Nuclei		Quadrupole Deform.[a]		Experiment performed
		A_1	A_2	A_1	A_2	
104	0.039	$^{124}_{50}Sn$	$^{134}_{54}Xe$	0.0	0.0	No
	0.054[d]	$^{122}_{50}Sn$	$^{136}_{54}Xe$	0.0	0.0	No
	0.360	$^{82}_{34}Se$	$^{176}_{70}Yb$ [m]	0.052	0.183	No
	0.610	$^{50}_{22}Ti$	$^{208}_{82}Pb$	0.0	0.0	Yes [b]
106	0.031	$^{126}_{52}Te$	$^{134}_{54}Xe$	0.037	0.0	No
	0.046	$^{124}_{50}Sn$	$^{136}_{56}Ba$	0.0	0.0	No
	0.062 [d]	$^{122}_{50}Sn$	$^{138}_{56}Ba$	0.0	0.0	No
	0.338 [d]	$^{86}_{36}Kr$	$^{174}_{70}Yb$	0.0	0.185	No
	0.369	$^{82}_{34}Se$	$^{178}_{72}Hf$ [m]	0.052	0.173	No
	0.585	$^{54}_{24}Cr$	$^{206}_{82}Pb$	0.047	0.0	Yes [c]

a) Ref. 18
b) Ref. 5
c) Ref. 6
d) values that correspond to the minima in $V(R,\eta,\eta_2)$
m) stable isomer

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