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Clustering phenomena in radioactive and stable nuclei and in heavy-ion collisions

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Abstract. A theory for clustering formation in nuclei and in heavy-ion collisions has been worked out in terms of the quantum-mechanical fragmentation process. Treating the mass fragmentation and relative separation coordinates as weakly coupled, the spontaneous cluster-decay of radioactive nuclei has been considered as a two-step process of clustering formation and tunnelling of the confining nuclear interaction barrier. This model has also been applied to "stable" nuclei, lighter than lead. The effects of adding more and more neutrons to colliding $N = Z$, $A = 4n$ nuclei are studied for the α-clustering transfer phenomenon.

Keywords. Cluster-radioactivity; cluster-transfer; heavy-ion-collisions; quantum-mechanical fragmentation.

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1. Introduction

Clustering is known to have played an important role in understanding the structural properties of some light nuclei. Nuclei, such as ^{8}Be, ^{12}C, ^{16}O, etc were considered to be made up of two-, three-, four- and more alpha-particles, respectively. Such an alpha-clustering model attained a reasonable success only for nuclei upto $s-d$ shell (see e.g. a recent review by Bromley 1984). More recently, Iachello and Jackson (1982) proposed that a similar α-clustering may also be important for the structure of heavy nuclei. For example, they proposed that the ^{224}Th nucleus consisted of ^{220}Ra + α, ^{216}Rn + ^{8}Be and ^{212}Pb + ^{12}C, etc (Iachello 1985; Engel and Iachello 1987). Since sequences of three α-particles often occur in radioactive decay chains, one may reasonably expect the preformation probabilities of ^{8}Be, ^{12}C and ^{16}O to be considerably higher than for other non-α particle configurations. However, the recent experiments of Rose and Jones (1984) and other subsequent experiments (Aleksandrov *et al* 1984; Gales *et al* 1984; Săndulescu *et al* 1984; Price *et al* 1985; Barwick *et al* 1985; Kutschera *et al* 1985; Tretyakova *et al* 1985a, b, and Hourani *et al* 1985), have established conclusively the spontaneous emission of ^{14}C cluster from $^{222-224,226}$Ra and ^{24}Ne from ^{230}Th, ^{231}Pa and ^{232,233}U. Also heavier clusters like ^{30}Mg, ^{34}Si and ^{48}Ca are expected from ^{237}Np, ^{241}Am and ^{252}Cf, respectively (Tretyakova *et al* 1985a; Hourani *et al* 1985; Ortlepp *et al* 1985). Notice that all of these observed, or expected to be observed, clusters are non-α nuclei. On the other hand, there is as yet no such direct experimental evidence for heavier α-nuclei ($N = Z$, $A = 4n$ nuclei like ^{8}Be, ^{12}C, ^{16}O etc.) emission, though for the α-particle configuration alone (like ^{218}Rn + α for ^{222}Ra) some experimental evidence exists (Gai *et al* 1982) and theoretical model calculations (Iachello and Jackson 1982; Iachello 1985; Daley and Barrett 1986; Daley and Nagrajan 1986; Engel and Iachello 1987) seem to work well for the structural properties of some heavy nuclei in both rare-earth and actinide regions. Similarly, these experiments also suggest the existence of $^{14}C + \alpha$ molecular band in non-α light nucleus ^{18}O (Gai *et al* 1983). The need for extension of the theoretical calculations to include clusters heavier than α-particle is already indicated by the data available on 0^+ excited states (van der Berg *et al* 1984). It is, therefore, very important to know the nature of clustering phenomena in other nuclear studies also.

Betts and collaborators (Betts 1981, 1984; Kutt *et al* 1985) have recently made an extensive experimental study of collisions between $s-d$ shell nuclei. These authors use bombarding energies ranging from 1·5 to 2 times the Coulomb barrier where the experiments do not distinguish between inelastic and transfer reactions, the latter being presumably very weak at these energies. Nevertheless some data on transfer process are still recorded which present an interesting result (Betts 1981). Whereas the measured mass spectrum of $^{16}O + {}^{40}Ca$ reaction at 75 MeV (and also at 80·6 MeV) shows an explicit preference for α-particle transfer, the $^{16}O + {}^{44}Ca$ reaction at 80·6 MeV does not indicate any such preferred α-resonance structure. The same result is obtained for the excitation functions for elastic and inelastic scattering between various other $s-d$ shell nuclei ($^{24}Mg + {}^{24}Mg$, $^{28}Si + {}^{28}Si$, $^{28}Si + {}^{30}Si$, $^{30}Si + {}^{30}Si$ and $^{32}S + {}^{32}S$). Specifically, as two neutrons are added to the α-particle target, or to the projectile or to both the reaction partners, the occurrence of resonance structure in the excitation functions for elastic and inelastic scattering is suppressed. Notice that $^{16}O + {}^{40}Ca$ and $^{16}O + {}^{44}Ca$ form the same compound nuclei, $^{56}Ni^*$ and $^{60}Ni^*$, as $^{28}Si + {}^{28}Si$ and $^{30}Si + {}^{30}Si$, respectively. We have shown earlier (Saroha *et al* 1985; Malik and Gupta 1986) that such a resonance-like structure observed in the α-cluster transfer process of collisions between the α-particle $s-d$ shell nuclei ($N = Z$, $A = 4n$) and its suppression on adding neutrons to the target or to the projectile (or both), is a collective mass transfer, given lucidly by the dynamical fragmentation theory. We shall show in the following that an extension of this calculation predicts that further addition of neutrons to either or both the reaction partners lead gradually to a complete disappearance of the α-resonance structure and new non-α clusters appear which might have relevance to those already observed, the above mentioned cluster radioactivity or to the predicted cluster-decay of "stable" heavy nuclei. In other words, the α-clustering resonance structure in heavy-ion collisions is predicted to be limited to the colliding $N = Z$, α-nuclei or in its immediate neighbourhood (N or Z differing by ~ 2 neutrons only), and as the N/Z ratio becomes much larger than one, the clusters transferred in light heavy-ion collisions will perhaps be of the same type as are observed in the decay of radioactive nuclei or predicted for heavy "stable" nuclei.

In this paper, we advance the mechanism of quantum-mechanical fragmentation process for the clustering formation in nuclei (naturally occurring or man-made through heavy-ion reactions, including the intermediate excited compound nucleus) and give an analytical method for the final step of tunnelling of the confining nuclear interaction barrier (see e.g. a review by Gupta 1987). The model is applied to the clustering and decay of both "stable" and radioactive nuclei.

2. Theory of clustering formation and of spontaneous cluster-decay

Many theoretical attempts have been made to understand the phenomenon of spontaneous cluster emission observed in the decay of many radioactive nuclei. The early calculations are made simply for the one-dimensional WKB penetration probability through a barrier, assuming the preformation factor to be unity for all the clusters (Poenaru *et al* 1984, 1985a, b; Shi and Swiatecki 1985a, b). One such fission calculation was also applied to "stable" nuclei, lighter than lead (Poenaru *et al* 1985c). Interestingly enough, in some cases, the cluster emission rates are predicted to be larger than for α-decay. More recent studies also include the clustering formation factor and decay into excited states of the daughter nucleus (Iriondo *et al* 1986; Landowne and Dasso 1986; Greiner and Scheid 1986; Blendowske *et al* 1987).

Our model consists of coupled motions in mass-asymmetry and relative separation coordinates, which in decoupled approximation represents the two steps of (i) the clustering formation and (ii) tunnelling of the confining nuclear interaction barrier. The decoupling is justified since the coupling effects in potential are shown to be very small, atleast for fission charge distributions and α-particle transfer resonances (Saroha and Gupta 1986; Malik *et al* 1986; see also figure 4) and the coupling cranking masses are found to be very small compared to the masses in the two degrees of freedom (Maruhn and Greiner 1974; Gupta *et al* 1975). Thus, if P_0 is the clustering formation probability (in ground state) and P, the barrier penetration probability after making ν number of attempts per second, the decay constant or half-lifetime for a metastable system, in decoupled approximation, is

$$\lambda = P_0 \nu P \quad \text{or} \quad T = \ln 2/\lambda. \tag{1}$$

Introducing the dynamical collective coordinates of mass and charge asymmetries (Maruhn and Greiner 1974; Gupta *et al* 1975)

$$\eta = (A_1 - A_2)/A \quad \text{and} \quad \eta_Z = (Z_1 - Z_2)/Z \tag{2}$$

the quantum-mechanical probability for finding the clusters A_1 and A_2 (with fixed charges Z_1 and Z_2, respectively), at a fixed relative separation R, is given by the solution of the following stationary Schrödinger equation in η:

$$\left[-\frac{\hbar^2}{2(B_{\eta\eta})^{1/2}} \frac{\partial}{\partial \eta} \frac{1}{(B_{\eta\eta})^{1/2}} \frac{\partial}{\partial \eta} + V(\eta) \right] \psi^{(\nu)}_{R\eta_Z}(\eta) = E^{(\nu)}_R \psi^{(\nu)}_{R\eta_Z}(\eta). \tag{3}$$

Then, on proper scaling and normalizing the solution of (3), the formation probability in the ground state is

$$P_0 = |\psi^{(0)}_{R\eta_Z}(\eta)|^2 [B_{\eta\eta}(\eta)]^{1/2} \frac{4}{A}. \tag{4}$$

The fragmentation potential $V(\eta)$ in (3), in the approximation of two touching (or overlapping) spheres, is defined as the sum of the experimental binding energies, the Coulomb interaction and the proximity potential (Blocki *et al* 1977).

$$V(\eta, R) = -\sum_{i=1}^{2} B_i(A_i, Z_i) + \frac{Z_1 Z_2 e^2}{R} + V_P, \tag{5}$$

Here the charges Z_i are fixed by minimizing the sum of the two binding energies and Coulomb interaction in η_Z coordinate. The two-sphere approximation is justified, since our earlier calculations show that the general shape of $V(\eta)$, including the positions of all the potential energy minima, is independent of the choice of R-value (Săndulescu *et al* 1976; Gupta 1980; Malhotra *et al* 1986).

For the mass parameters $B_{\eta\eta}$, we use here the classical model of Kröger and Scheid (1980) which gives a simple analytical expression whose predictions are shown to match with microscopic cranking model calculations.

For the assault or escape frequency ν, we use the simple relation

$$\nu = v/R_0 = (2E_2/\mu)^{1/2}/R_0 \quad \text{with} \quad E_2 = (A_1/A)Q, \tag{6}$$

where R_0 is the radius of the parent nucleus and E_2 the kinetic energy of the emitted cluster. $Q = E_1 + E_2$, since the clusters are assumed to be produced in the ground state.

The tunnelling probability P is calculated analytically by using the WKB approximation. The interaction potential $V(R)$ is obtained from (5) by normalizing it to the sum of the binding energies. This is illustrated in figure 1 (solid lines) for $^{222}\mathrm{Ra} \rightarrow {}^{14}\mathrm{C} + {}^{208}\mathrm{Pb}$. For the overlap region, we simply join smoothly the potential calculated at touching configuration $R = R_t = R_1 + R_2$ to the Q-value at the parent nucleus radius $R = R_0$. We are not interested in this part of the potential since our calculations below suggest the use of $R = R_t$ for evaluating the pre-formation factor. In other words, the first (inner) turning point in the WKB penetrability integral is chosen at $R = R_t$. The second (outer) turning point, $R = R_b$ is taken to give the Q-value of the reaction i.e. $V(R_b) = Q$. With this choice of the turning points, figure 1 shows that our transmission probability P consists of three contributions: the penetrability P_i from R_t to R_i, the de-excitation probability W_i at R_i and then the penetrability P_b from R_i to R_b. Thus

$$P = P_i W_i P_b. \tag{7}$$

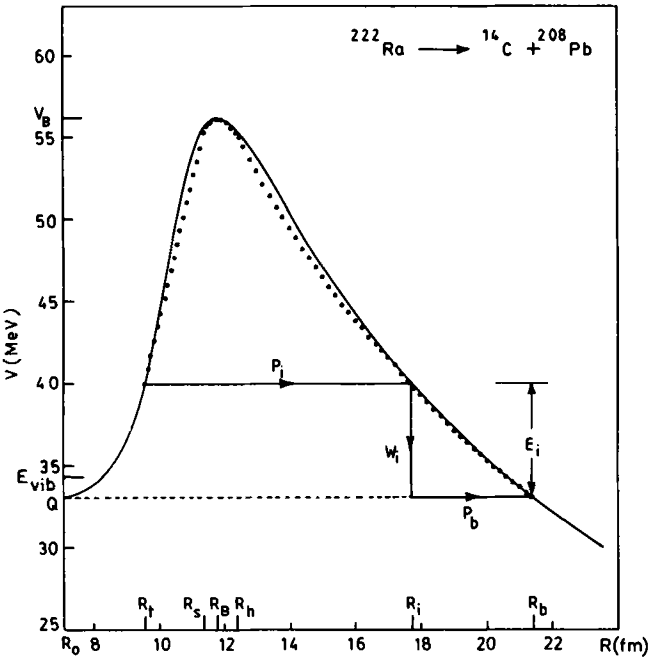

Figure 1. Nuclear interaction potential for $^{222}\mathrm{Ra} \rightarrow {}^{14}\mathrm{C} + {}^{208}\mathrm{Pb}$, calculated as a sum of Coulomb and proximity potentials (solid lines). The dots show the parametrized fit to equation (12). The path of tunnelling is also indicated.

Greiner and Scheid (1986) have suggested scaling of the de-excitation probability W_i, exponentially with the excitation energy:

$$W_i = \exp(-bE_i). \tag{8}$$

The parameter b is obtained by applying this ansatz to α-decay of ^{222,224}Ra and ^{232}U. It is shown that for R_i-values of interest, b must be very small such that for heavy cluster emission, these authors use $b = 0$, which means $W_i = 1$. This reduces (7) to

$$P = P_i P_b, \tag{9}$$

where in the WKB theory, the penetrabilities P_i and P_b are defined as

$$P_i = \exp\left(-\frac{2}{\hbar}\int_{R_t}^{R_i} \{2\mu[V(R) - V(R_i)]\}^{1/2}\,\mathrm{d}R\right), \tag{10}$$

$$P_b = \exp\left(-\frac{2}{\hbar}\int_{R_i}^{R_b} \{2\mu[V(R) - Q]\}^{1/2}\,\mathrm{d}R\right). \tag{11}$$

The integrals in (10) and (11) are solved analytically by parametrizing $V(R)$ as follows:

$$V(R) = \begin{cases} V(R_t) + s(R - R_t) & R_t \leqslant R \leqslant R_s \\ V_B - \frac{1}{2}k(R - R_B)^2 & R_s \leqslant R \leqslant R_h \\ V(R_h) - C_1(R - R_h)/R & R_h \leqslant R \leqslant R_i \\ V(R_i) - C_2(R - R_i)/R & R_i \leqslant R \leqslant R_b \end{cases}. \tag{12}$$

This is illustrated in figure 1 (dots). Then, using the fact that

$$\int_{R_t}^{R_i} f(R)\,\mathrm{d}R = \int_{R_t}^{R_s} f(R)\,\mathrm{d}R + \int_{R_s}^{R_h} f(R)\,\mathrm{d}R + \int_{R_h}^{R_i} f(R)\,\mathrm{d}R, \tag{13}$$

we obtain P_i and P_b, which on substituting in (9) gives the analytical expression for the tunnelling probability P.

2.1 *Calculations*

We first look at our calculated fragmentation potentials $V(\eta)$ at various R-values, starting from touching configuration to a large overlap of two spheres (figure 2, illustrated for ^{222}Ra). Apparently, the positions and depths of all the potential energy minima are almost independent of the R-value. Following this result, $V(\eta)$ were calculated only at $R = R_t$ for a number of nuclei (Gupta *et al* 1987). In each case, deep potential energy minima are found to occur at the usual fission fragments (e.g. ^{88}Kr and its complementary fragment ^{134}Te in ^{222}Ra) and at ^{4}He, ^{10}Be, ^{14}C and $^{46-50}$Ca clusters. For ^{232}U, ^{237}Np and ^{241}Am, additional deep minima occur at ^{24}Ne, ^{30}Mg and ^{34}Si, respectively. Adding of proximity potential does not bring any alternation in these minima, though the minima at large mass asymmetry then become somewhat deeper. This means that though the proximity potential V_P would contribute significantly to the yield of large mass-asymmetry fragments, the potential energy minima, determining the possible cluster formation (and decay) channels are due to

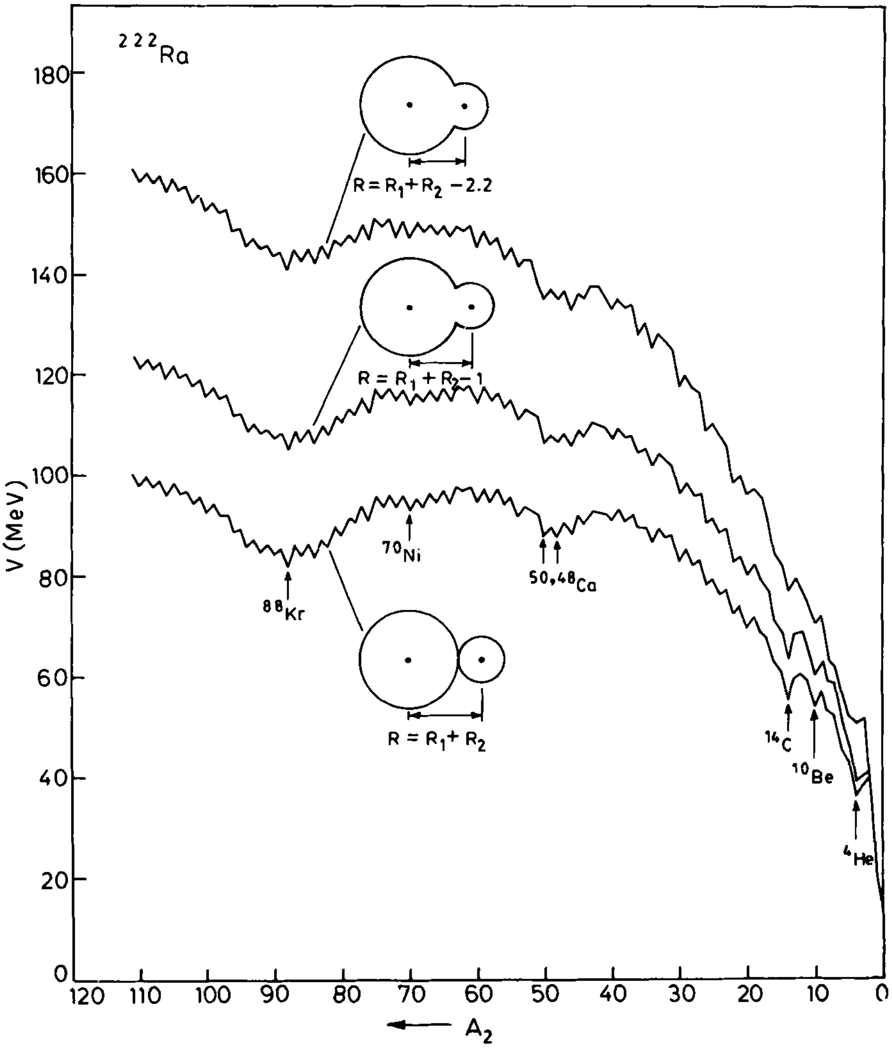

Figure 2. Fragmentation potential $V(\eta)$ for ^{222}Ra at various $R \leqslant R_1 + R_2$, calculated by using equation (5) with $V_P = 0$.

shell effects only (Gupta *et al* 1987). The importance of adding V_P was seen earlier (Malhotra *et al* 1986) for heavy nuclei ($Z \geqslant 102$).

Table 1 gives our calculations of the clustering formation probability relative to α-particle, $P_0(^{14}\mathrm{C})/P_0(\alpha)$, at different $R \leqslant R_1 + R_2$ for ^{222}Ra. We notice that for a very large overlap ($R = R_1 + R_2 - 2{\cdot}2$) the formation probability for ^{14}C is zero. However, as the overlap decreases, this ratio remains constant up to the touching configuration. Interpreted in terms of the zero-point vibration energy E_{vib}, introduced empirically by Poenaru *et al* (1984) to fit the cluster decay half-lifetimes in their model, we find that the configuration of larger overlap ($R = R_1 + R_2 - 2{\cdot}2$) refer to an excitation energy below their E_{vib} but the ones with smaller overlap above it. This suggests that clustering formation in our model also begins at R-value corresponding to $V(R) \approx Q + E_{\mathrm{vib}}$. However, since the relative clustering formation probability

Table 1. Cluster preformation probabilities, P_0(cluster), relative to one, and their ratios for ^{222}Ra, at various relative separations.

$R_{(fm)}$	$P_0(^{14}C)$	$P_0(\alpha)$	$P_0(^{14}C)/P_0(\alpha)$
$R_1 + R_2$	$1{\cdot}40 \times 10^{-14}$	$9{\cdot}93 \times 10^{-8}$	$1{\cdot}41 \times 10^{-7}$
$R_1 + R_2 - 0{\cdot}5$	$4{\cdot}12 \times 10^{-15}$	$1{\cdot}12 \times 10^{-7}$	$0{\cdot}37 \times 10^{-7}$
$R_1 + R_2 - 1$	$2{\cdot}33 \times 10^{-6}$	$9{\cdot}33 \times 10^{-1}$	$0{\cdot}25 \times 10^{-7}$
$R_1 + R_2 - 2{\cdot}2$	0	$3{\cdot}93 \times 10^{-10}$	—

Table 2. Relative clustering formation probabilities with respect to α-particle, P_0(cluster)/ $P_0(\alpha)$.

Nucleus	Emitted cluster	Present work	Rose-Jones (1984)	Landowne-Dasso (1986)	Iriondo *et al* (1986)	Blendowske *et al* (1987)
^{222}Ra	^{14}C	$1{\cdot}41 \times 10^{-7}$		$\sim 10^{-7}$	$1{\cdot}09 \times 10^{-5}$	$3{\cdot}05 \times 10^{-10}$
^{223}Ra	^{14}C	$5{\cdot}46 \times 10^{-8}$	$7 \times 10^{-5} - 4 \times 10^{-7}$		$9{\cdot}61 \times 10^{-6}$	$2{\cdot}78 \times 10^{-10}$
^{224}Ra	^{14}C	$1{\cdot}69 \times 10^{-8}$			$7{\cdot}29 \times 10^{-6}$	$1{\cdot}94 \times 10^{-10}$
^{232}U	^{24}Ne	$1{\cdot}92 \times 10^{-11}$			$4{\cdot}00 \times 10^{-10}$	

remains constant up to the touching configuration $R = R_t$, we choose R_t as our starting point for the tunnelling process.

Table 2 gives a comparison of our relative cluster formation probabilities at $R = R_t$, with those obtained by other workers. Our calculations agree, within an order of magnitude, with these other studies, except with those obtained by Blendowske *et al* (1987). Further, in agreement with Iriondo *et al* (1986), our calculations show a decrease in pre-formation probability with increase of the cluster size.

Tables 3 and 4 give our calculations for half-lifetimes T for the decay of some radioactive and "stable" ($Z \leqslant 64$) nuclei, respectively and their comparisons with other available calculations and experimental data. We notice in table 3 that for ^{14}C decay, our calculations and that of Blendowske *et al* (1987), using both the steps of clustering formation and barrier penetration, are in better agreement with experiments than the fission calculations of Poenaru *et al* (1985b). On the other hand, for heavier clusters like ^{24}Ne, ^{30}Mg, ^{34}Si and ^{48}Ca, the fission calculations (Poenaru *et al* 1985b) compare better with experiments. Our preliminary calculations using the fragmentation theory of nuclear fission (Maruhn and Greiner 1974), also support this result. Further, it may be relevant to note that for ^{24}Ne decay of ^{232}U, the measured spontaneous fission (Jaffey and Hirsch unpublished see Vandenbosch and Huizenga 1973) branching ratio $\lambda(^{24}\mathrm{Ne})/\lambda(\alpha) = 1{\cdot}2 \times 10^{-12}$ is comparable with the recently measured cluster decay ratio $\lambda(^{24}\mathrm{Ne})/\lambda(\alpha) = (2{\cdot}0 \pm 0{\cdot}5) \times 10^{-12}$.

Finally, in table 4 for "stable" nuclei, we notice that in agreement with other available calculations (Poenaru *et al* 1985c), the half-lifetimes for some cluster decays are even smaller than for α-decay and in some cases, whereas the nucleus is stable against α-decay, it is in fact metastable with respect to heavy cluster decay.

Table 3. Calculated and experimental half-lifetimes for cluster-decay of radioactive nuclei.

	Experiments	Calculated values of log(T)			
Decay	log(T)	Present work	Blendowske *et al* (1987)	Poenaru *et al* (1985b)	de Carvalho *et al* (1986)
$^{222}Ra \rightarrow {}^{14}C + {}^{208}Pb$	10·9–11·1	11·2	11·0	12·6	12·4
$^{223}Ra \rightarrow {}^{14}C + {}^{209}Pb$	14·9–15·5	14·1	15·2	14·8	14·5
$^{224}Ra \rightarrow {}^{14}C + {}^{210}Pb$	15·8–16·0	15·0	15·9	17·4	17·1
$^{226}Ra \rightarrow {}^{14}C + {}^{212}Pb$	21·2	21·2		22·4	22·0
$^{230}Th \rightarrow {}^{24}Ne + {}^{206}Hg$	24·6	21·2		24·8	
$^{231}Pa \rightarrow {}^{24}Ne + {}^{207}Tl$	23·2	19·3		22·0	
$^{232}U \rightarrow {}^{24}Ne + {}^{208}Pb$	21·3–21·5	16·5		20·4	
$^{237}Np \rightarrow {}^{30}Mg + {}^{207}Tl$	> 27·2	21·0		25·4	
$^{241}Am \rightarrow {}^{34}Si + {}^{207}Tl$	> 21·6	16·3		22·6	
$^{252}Cf \rightarrow {}^{48}Ca + {}^{204}Pt$	> 15·9	11·3		21·5	

Table 4. Calculated half-lifetimes for cluster decay of "stable" nuclei.

	Calculated log(T)					
	Present work				Poenaru *et al* (1985c)	
Nuclide	α	^{14}C	^{16}O	^{18}O	α	^{16}O
^{154}Gd	52·1	53·8	49·2	66·2	60·4	48·5
^{156}Gd	stable	70·4		64·1		
^{160}Dy	89·4	81·7		69·0		
^{164}Er	38·2	86·9	69·0	73·7		

3. Clustering in heavy-ion reactions

The theory of clustering formation in nuclei, outlined in equations (2)–(5), is also applicable to the compound nucleus formed in heavy-ion reactions (Saroha *et al* 1985; Malik and Gupta 1986). Since a compound nucleus always carries an excitation energy E^*, the cluster formation yield is then defined as follows, by including the nuclear temperature effects through a Boltzmann-function,

$$Y(A_2) = |\psi_{R\eta_Z}(\eta)|^2 [B_{\eta\eta}(\eta)]^{1/2} \frac{2}{A} \tag{14}$$

with

$$|\psi_{R\eta_Z}|^2 = \sum_{\nu=0}^{\infty} |\psi_{R\eta_Z}^{(\nu)}|^2 \exp(-E_R^{(\nu)}/\theta), \tag{15}$$

where the nuclear temperature θ (in MeV) is related to the excitation energy as

$$E^* = \tfrac{1}{9} A\theta^2 - \theta. \tag{16}$$

3.1 *Calculations*

We have made calculations for a large number of cases and discuss here first the cases of colliding $N = Z$, α-nuclei.

Figure 3 shows the calculated potential energy surfaces (PES) for a number of composite systems ^{16}O, ^{28}Si, ^{40}Ca, ^{52}Fe, ^{60}Zn, ^{64}Ge, ^{72}Kr and ^{80}Zr formed due to collisions between $N = Z$, α-nuclei. We notice that in every case deep minima lie only (and exactly) at the α-particle transfer of the nucleons. Thus the PES reveal the α-cluster structure beyond $s-d$ shell and the observed resonance-like structure of the mass yields in the 75 MeV $^{16}O + {}^{40}Ca \rightarrow {}^{56}Ni^*$ reaction is expected to be

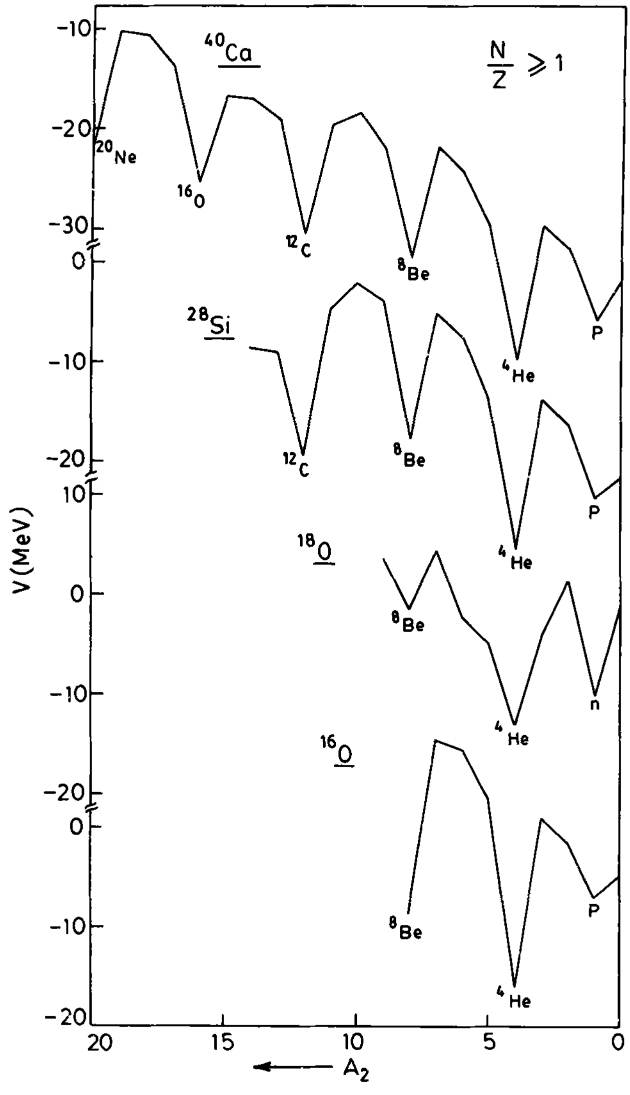

Figure 3a. Fragmentation potentials at $R = R_1 + R_2$ for $N = Z$, α-nuclei. Also the case of ^{18}O is included in this figure.

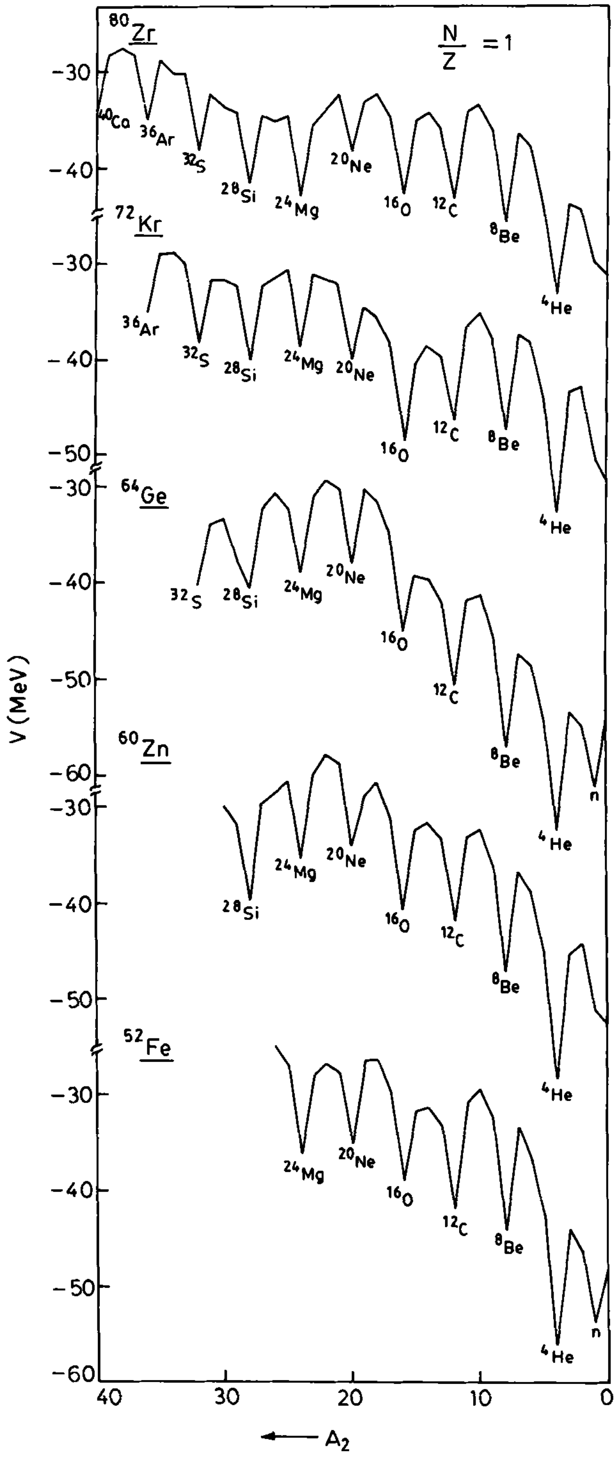

Figure 3b. Fragmentation potentials at $R = R_1 + R_2$ for $N = Z$, α-nuclei.

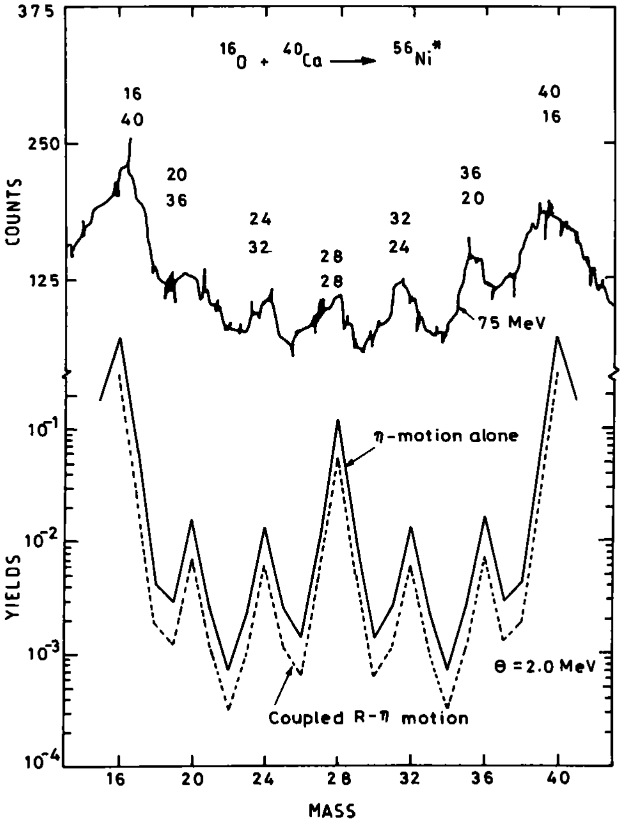

Figure 4. Calculated mass distribution yields for ^{56}Ni at $\theta = 2{\cdot}00$ MeV compared with the experimental data for 75 MeV $^{16}O + ^{40}Ca$ reaction. The full and broken lines refer, respectively, to cases without and with the coupling between R and η coordinates.

given by this model. This is shown in figure 4 for the temperature $\theta = 2{\cdot}00$ MeV ($E^* = 22{\cdot}9$ MeV) for a constant mass parameter $B_{\eta\eta} = 1{\cdot}2 \times 10^4$ M fm^2, together with the experimental data of Betts (1981). The choice of temperature is made in view of the fact that the interaction barrier for this system is ~ 24 MeV. The calculated yields peak only at the α-nuclei, in agreement with experiments. For a detailed comparison, however, we need to use $B_{\eta\eta}(\eta)$, as shown by Malik and Gupta (1986). The mass yields are also calculated for other systems and in each case a clear preference for α-cluster transfer, resonance-like structure, is predicted.

For collisions between $N \neq Z$ nuclei, we first add two neutrons ($N = Z + 2$) to either of the reaction partners. This is illustrated in figure 5 for Ni-isotopes (refer to the PES for ^{58}Ni). We notice that the depths of the minima for the heavy α-nuclei transfer are already reduced and the new minima appear at two-nucleon or non-α-particle transfer (the same is true of ^{18}O in figure 3). Further, on adding four neutrons to the target or projectile or alternatively two neutrons each to the target and projectile (refer to ^{60}Ni), the α-clustering effects at the heavier end ($A_2 > 12$) of the PES are almost lost. The minima now become shallower for α-particle transfer and deeper for non-α-particle transfer. In other words, the PES indicate the result of the 80·6 MeV $^{16}O + ^{44}Ca \rightarrow ^{60}Ni^*$ reaction that the resonance-like structure for α-cluster transfer is suppressed as one (or both) of the reaction partner is a $N \neq Z$ nucleus. However, our calculations still predict a preferred transfer of the α-particle and the lighter α-nuclei (^{8}Be and ^{12}C), which were not measured in the above experiment. The interesting result of this calculation is that a further addition of neutrons suppresses the α-clustering further (this happens gradually) and new clusters like ^{10}Be, ^{14}C and ^{24}Ne, etc are formed (refer to PES for ^{68}Ni). The calculated formation yields for a constant mass parameter $B_{\eta\eta}$ give the same result (Malik and Gupta 1986). Of course, the formation probability for the α-particle itself is still very large. This result might have consequences (i) for the structure models of heavy nuclei, based on the α-clustering picture (Iachello and Jackson 1982) and (ii) for the universality of the clusters involved in the transfer process of colliding $N \neq Z$ nuclei with $N \gg Z$ and the decaying "stable" and radioactive nuclei. For structure calculations it may be relevant to note that complete α-clustering picture is prevalent only in $N = Z$, $A = 4n$ nuclei and that this picture breaks down slowly as we go away from

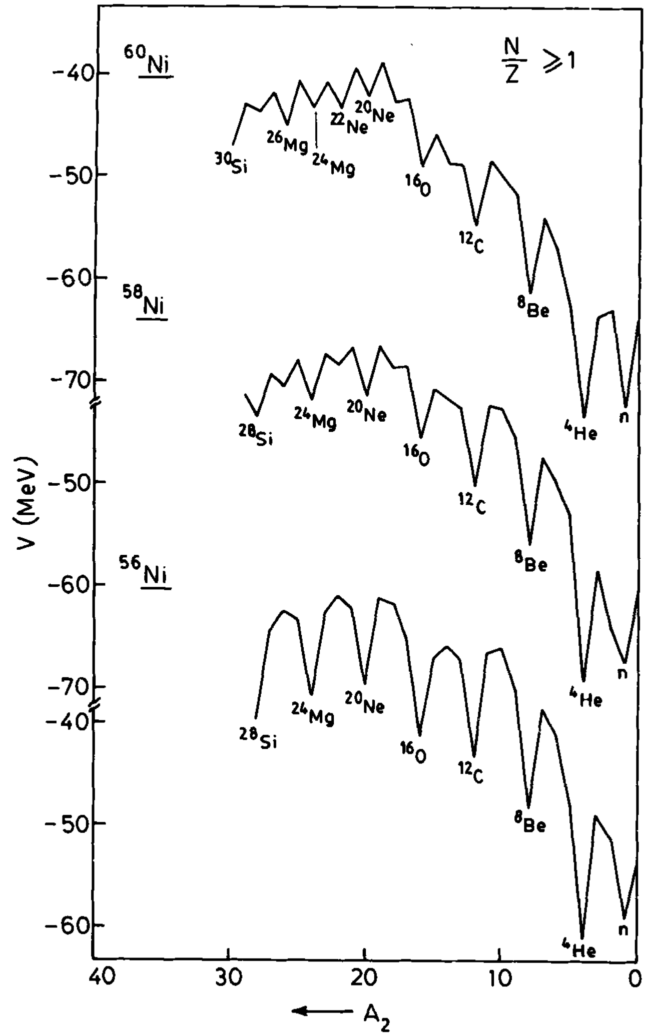

Figure 5a. Fragmentation potentials at $R = R_1 + R_2$ for various Ni-isotopes.

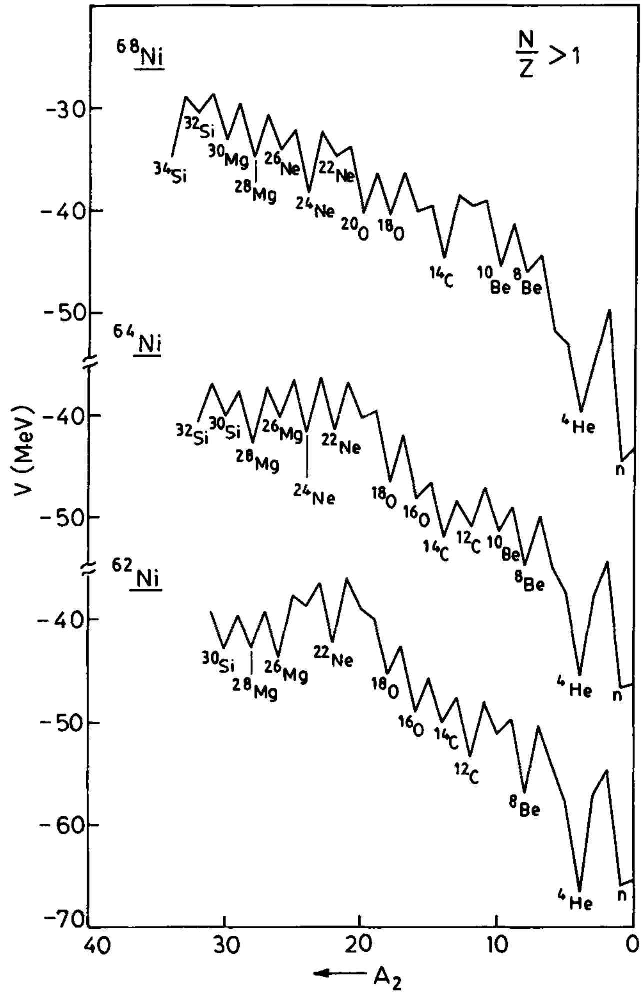

Figure 5b. Fragmentation potentials at $R = R_1 + R_2$ for various Ni-isotopes.

the $N = Z$ stability line. For the decay rates, it is relevant to point out that due to the coupling effects of relative motion (the penetrability P), some other new clusters may be preferred, as has been the case for "stable" rare-earth nuclei (table 4).

4. Conclusions

We have shown that clustering formation in nuclei as well as in heavy-ion transfer reactions is a similar phenomenon, given by the quantum-mechanical fragmentation process. The cluster-decay of the radioactive nuclei is best interpreted as a two-step mechanism of clustering formation and tunnelling of the confining nuclear interaction barrier, atleast for the lighter cluster like ^{14}C. For the heavier clusters like ^{24}Ne, ^{30}Mg, ^{34}Si and ^{48}Ca, perhaps the fission process is more predominant. Cluster-decay of "stable" nuclei in rare-earth region presents interesting possibilities of being stable against α-decay but metastable with respect to heavy clusters. In heavy-ion transfer reactions, a clear predominance is shown for α-nuclei transfer in collisions between $N = Z$, $A = 4n$ nuclei. However, such a picture breaks down slowly as neutrons are added to either or both of the reaction partners. As the neutron-proton ratio increases further, new clusters of the type obtained in radioactive and "stable" nuclei are shown to be transferred preferentially. Further experiments involving collisions of $N \neq Z$ light nuclei are needed.

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