4.1 Introduction:

Betts in 1981 /3/ reported a measured mass spectrum of 75 MeV $^{16}_0 + ^{40}_0$Ca reaction, indicating an explicit preference for the $\alpha$-particle transfer. More recently, reactions between various other s-d shell nuclei ($^{16}_0 + ^{44}_0$Ca, $^{24}_0$Mg + $^{24}_0$Mg, $^{28}_0$Si + $^{28}_0$Si, $^{28}_0$Si + $^{30}_0$Si, $^{30}_0$Si + $^{30}_0$Si and $^{32}_0$S + $^{32}_0$S) have been studied extensively /41,42/, which present an interesting result. Whereas the measured mass spectrum of $^{16}_0 + ^{40}_0$Ca reaction at 75 MeV (and also at 80.6 MeV) shows an explicit preference for $\alpha$-particle transfer, the $^{16}_0 + ^{44}_0$Ca reaction at 80.6 MeV does not indicate any such preferred $\alpha$-resonance structure. Furthermore, for Si + Si reaction as two neutrons are added to the $\alpha$-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. This phenomenon occurs at bombarding energies ranging from 1.5 to 2.0 times the Coulomb barrier where the experiments do not distinguish between inelastic and transfer reactions, the latter being presumably very weak at these energies. Notice that $^{16}_0 + ^{40}_0$Ca and $^{16}_0 + ^{44}_0$Ca form...
the same compound nuclei, $^{56}_{28}$Ni$^*$ and $^{60}_{28}$Ni$^*$, as $^{28}$Si + $^{28}$Si and $^{30}$Si + $^{30}$Si respectively.

Saroha et al /44/ have shown that such a resonance-like structure, observed in the $\alpha$-cluster transfer process of collisions between $^{16}$O + $^{40}$Ca at 75 MeV, is a collective mass transfer, given lucidly by the dynamical fragmentation theory. In this Chapter, we report our calculations made for $^{56-68}_{28}$Ni$^*$, $^{48,50,52}_{28}$Cr$^*$ and some other $N=Z$ compound systems, produced in the reactions of $^0 + Ca$ (or Si + Si), $Mg + Mg$ reactions etc. We shall see that addition of neutrons to either or both the $\alpha$-nucleus reaction partners lead gradually to a complete disappearance of the $\alpha$-resonance structure and new non-$\alpha$ clusters appear which might have relevance to the observed cluster radioactivity (as discussed in Chapter 3). In other words, the $\alpha$-clustering resonance structure in heavy-ion collisions is predicted to be limited to the colliding $N=Z$, $\alpha$-nuclei or in its immediate neighbourhood ($N$ or $Z$ differing by $\sim 2$ neutrons only), and as the $N/Z$ ratio becomes much larger than one, the clusters transferred in light heavy-ion collisions are perhaps going to be of the same type as are observed in the decay of radioactive nuclei.

More recently, Iachello and Jackson /79/ have proposed that a similar alpha-clustering may also be
important for the structure of heavy nuclei. The study of $\alpha$-clustering effects in heavy nuclei is made difficult by the fact that these nuclei involve a mixture of collective aspects (as evidenced by the rotational nature of the spectra) and particle aspects (as evidenced by the $\alpha$-decay probabilities). For this reason, Iachello and Jackson based their discussion on the interacting boson model (IBM) /80/, where both aspects are to a certain extent present.

In order to investigate the $\alpha$-clustering effects in heavy nuclei, some calculations on rare earth nuclei, such as $^{156}$Gd, $^{160}$Dy and $^{164}$Er, are also presented in this thesis. We find that all the predicted clusters are non-\alpha-nuclei. Though theoretical model calculations /79-81/ based on $\alpha$-clustering picture seem to work well for the structural properties of some heavy nuclei in both rare-earth and actinide regions, as yet there is no such direct experimental evidence for heavier $\alpha$-nuclei ($N = Z, A = 4n$ nuclei like $^8$Be, $^{12}$C, $^{16}$O etc.) emission. Need for extension of such theoretical calculations to include clusters heavier than $\alpha$-particle is already indicated by the data available on $0^+$ excited states /82/. Thus, it seems important to know the nature of clustering phenomena expected in rare earth and actinide regions.

The theoretical basis used for the clustering formation in nuclei is already discussed in Chapter 3.
Based on this formalism, we give our calculations for the PES and the mass distribution yields in sections 4.2 and 4.3, respectively. The results are summarized in section 4.4.

4.2 Calculations of Potential Energy Surfaces:

Fig. 4.1 shows the calculated mass fragmentation potentials, as a function of $A^2$, the mass of the light fragment, for some $\alpha$-particle, $A = 4n$, $N = Z$ composite systems ($^{48}\text{Cr}$, $^{52}\text{Fe}$, $^{56}\text{Ni}$, $^{60}\text{Zn}$, $^{64}\text{Ge}$, $^{72}\text{Kr}$ and $^{80}\text{Zr}$), calculated at the touching configurations (see also Fig. 4.2(a)). Here, the $V_q$ term is taken to be zero since Saroha et al. /44/ have shown that for light nuclei, this term is negligibly small. We notice in Fig. 4.1 that these fragmentation potentials show the $\alpha$-cluster structure in all the cases. The minima in the fragmentation potentials lie only and exactly at the $\alpha$-particle transfer, thereby supporting the earlier calculations of Saroha et al. /44/ for the $N = Z = 28$ compound system.

Figs. 4.2 (a) and 4.2(b) show the PES for $N \neq Z$ composite systems, as compared to that for $N = Z$ systems ($^{56-60}\text{Ni}$ and $^{48-52}\text{Cr}$). We notice that as two neutrons are added to $N = Z$ systems (refer to the PES for $^{58}\text{Ni}$ and $^{50}\text{Cr}$) the depths of the minima at the $\alpha$-particle transfer are reduced and new minima appear at two nucleon or non-$\alpha$-particle transfer. Furthermore, on adding four neutrons to the targets or projectiles or
alternatively two neutrons each to the targets or projectiles (refer to PES for $^{60}$Ni and $^{52}$Cr), the $\alpha$-clustering effect is almost lost. The minima now become shallower for $\alpha$-particle transfer and deeper for non-$\alpha$-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 $\alpha$-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 $\alpha$-particle itself and the lighter $\alpha$-nuclei ($^8$Be and $^{12}$C), which were not measured in this experiment $^{41}$. The interesting result of this calculation is that a further addition of neutrons suppresses the $\alpha$-clustering further and strongly and leads to the formation of new clusters like $^{10}$Be, $^{14}$C, $^{24}$Ne etc. This is shown in Fig. 4.2(c). Specifically, when six neutrons are added to the $\alpha$-particle, $N = Z$ nucleus $^{56}$Ni to form $^{62}$Ni, the depths of the potential minima at $\alpha$-nuclei are greatly reduced and new clusters like $^{14}$C, $^{18}$O, $^{22}$Ne, etc. appear. Similarly, when eight neutrons are added to form $^{64}$Ni, deeper minima for $\alpha$-nuclei, occur only upto $^8$Be and depths of the potential minima at $^{14}$C and $^{22,24}$Ne get further enhanced. The minima for $^{14}$C and $^{24}$Ne become further deeper as more and more (twelve) neutrons are added (i.e. for $^{68}$Ni) and in this case a new minima at $^{10}$Be also appear to be very deep.
Thus, the mass fragmentation potentials reveal that \( \alpha \)-cluster model picture is predominant in \( N = Z, A = 4n \) nuclei up to at least mass number \( A \approx 80 \) and that this picture breaks down slowly as we go away from the \( N = Z \) stability line. For \( N \neq Z \) nuclei, as neutrons are added, the non-\( \alpha \)-nuclei, like \(^{10}\text{Be}, {^{14}\text{C}} \) and \(^{22,24}\text{Ne} \) are obtained as the decay products, which might have relevance to the cluster radioactivity, discussed in Chapter 3.

The fragmentation potentials calculated for rare earth nuclei, \(^{156}\text{Gd}, {^{160}\text{Dy}} \) and \(^{164}\text{Er} \), and are shown in Fig. 4.3. We notice that in each case deep minima lie at \( \alpha \)-particle, \(^{10}\text{Be}, {^{14}\text{C}}, {^{18}\text{O}} \) and \(^{22,24}\text{Ne} \) and not at \( \alpha \)-nuclei like \(^{8}\text{Be}, {^{12}\text{C}} \) etc. Thus, it seems more plausible to base the structure of these nuclei on the newly observed clusters rather than on \( \alpha \)-nuclei.

4.3 Mass Distribution Yields:

The mass fragmentation yields are calculated for the compound systems \(^{56-60}\text{Ni} \) and \(^{48-52}\text{Cr} \) (Fig. 4.4 - full lines), using the fragmentation potential given in Figs. 4.2(a) and 4.2(b) and constant mass parameter \( B_{\eta \eta} \). For \( B_{\eta \eta} \), we notice from the work of Maruhn and Greiner /24/, that the adiabatic cranking masses \( B_{\eta \eta} (\gamma) \) oscillate between \( 10^3 \) to \( 10^5 \) M fm\(^2\). Therefore, we use an average constant value of \( B_{\eta \eta} = 1.0 \times 10^4 \) M fm\(^2\), which means the neglect of the dynamical effect of the mass.
parameter. The choice of temperature, $\Theta = 2\text{MeV}$ (or equivalently $E^* = 22.9\text{ MeV}$), is made in view of the interaction barrier being $24\text{ MeV}$ for $^{160} + ^{40}\text{Ca} \rightarrow ^{56}\text{Ni}$ system. It is interesting to observe in Fig. 4.4 (full lines) that, in agreement with the experiments on $^{160}\text{MeV}^{160} + ^{40}\text{Ca} \rightarrow ^{56}\text{Ni}^*$ and $^{160} + ^{44}\text{Ca} \rightarrow ^{60}\text{Ni}^*$ reactions, the calculated mass fragmentation yields for compound systems $^{56,58}\text{Ni}$ and $^{48,50}\text{Cr}$ are peaked only at $\alpha$-particle nuclei with greatly reduced amplitudes in the cases of $^{58}\text{Ni}$ and $^{50}\text{Cr}$, and the non $\alpha$-particle resonances occur equally predominantly for $^{60}\text{Ni}$ and $^{52}\text{Cr}$. This effect is, perhaps, more vivid for Cr isotopes. We have also studied the effect of varying the mass parameter $Bn^p(\eta)$, obtained empirically by fitting the measured mass distribution of $^{160} + ^{40}\text{Ca} \rightarrow ^{56}\text{Ni}^*$ at $75\text{ MeV}$. This is shown in Fig. 4.5. The calculated mass distribution for $^{56}\text{Ni}^*$ compare reasonably well with experimental mass spectrum. The mass distribution yields for $^{58}\text{Ni}^*$ and $^{60}\text{Ni}^*$ are also recalculated by using this variation of $Bn^p(\eta)$. The result of this calculation is shown by broken lines in Fig. 4.4(a). Apparently, the effect of a gradual reduction of $\alpha$-particle transfer resonances by adding two and four neutrons to $N = Z$, $A = 4n$ compound systems, formed in collisions between $s$-$d$ shell nuclei, is now given equally neatly for Ni-isotopes as for Cr isotopes with a constant value of $Bn^p$. 
The mass yields are also calculated for other systems and in each case similar results are obtained.

4.4 Summary of Results:

The calculated fragmentation potentials for the composite systems formed due to $N = Z$, $A = 4n$ nuclei, show deep minima only at the $\alpha$-particle transfer of the nucleons. As two neutrons are added ($A = 4n+2$, $N = Z+2$) the depths of the potential energy minima decreases but $\alpha$-clustering picture seems to be still valid. On further increasing the N/Z ratio, the $\alpha$-clustering effect is almost lost.

The calculated yields for the fission of $^{56,58}$Ni and $^{48,50}$Cr show the resonance like structure for the $\alpha$-cluster transfer, with greatly reduced amplitudes in the case of $^{58}$Ni and $^{50}$Cr and this resonance structure gets completely lost for $^{60}$Ni and $^{52}$Cr. These results are in agreement with the experiments /3,41,42/. Thus the appearance of $\alpha$-cluster resonances in $A = 4n$, $N = Z$ nuclei and their suppression in $N \neq Z$ nuclei is a collective mass fragmentation process. Also, the transfer of clusters involved in the $N \neq Z$ nuclei containing large number of neutrons and in rare earth nuclei are $^{10}$Be, $^{14}$C, $^{24}$Ne etc. which might have relevance with the observed cluster radioactivity. Further experiments involving collisions of $N \neq Z$ light nuclei are needed.
Figure Captions:

Fig. 4.1 Fragmentation potentials for $N=Z$ (\(^{52}\)Fe, \(^{60}\)Zn, \(^{64}\)Ge, \(^{72}\)Kr, \(^{80}\)Zr) nuclei.

Fig. 4.2(a) Fragmentation potentials for \(^{56,58,60}\)Ni.
(b) Fragmentation potentials for \(^{48,50,52}\)Cr.
(c) Fragmentation potentials for \(^{62,64,68}\)Ni.

Fig. 4.3 Fragmentation potentials for \(^{156}\)Gd, \(^{160}\)Dy, \(^{164}\)Er.

Fig. 4.4 The calculated mass distribution yields for the fission of (a) \(^{56,58,60}\)Ni* and (b) \(^{48,50,52}\)Cr* at $\Theta=2$ MeV. The solid curves are for constant mass parameter $B_\eta=1\times10^4$ fm$^2$ and the dashed curves are for $B_\eta(\eta)$ of Fig. 4.5(c).

Fig. 4.5(a) The experimental data on mass distribution yields for the 75 MeV \(^{16}\)O+\(^{40}\)Ca $\rightarrow$ \(^{56}\)Ni* reaction /3/.
(b) The calculated mass distribution yields for the fission of \(^{56}\)Ni* at $\Theta=2$MeV for the $B_\eta(\eta)$ obtained empirically for the best fit to the data in (a). The calculations are not normalized to the data.
(c) The empirically obtained $B_\eta(\eta)$ for the best fit shown in (b) to the data in (a).
Fig. 4.1

\[ V(\text{MeV}) \]

\( N/Z = 1 \)

\( ^{80}\text{Zr} \)

\( ^{16}\text{O} \)

\( ^{12}\text{C} \)

\( ^{8}\text{Be} \)

\( ^{4}\text{He} \)

\( ^{36}\text{Ar} \)

\( ^{32}\text{S} \)

\( ^{28}\text{Si} \)

\( ^{24}\text{Mg} \)

\( ^{20}\text{Ne} \)

\( ^{16}\text{O} \)

\( ^{12}\text{C} \)

\( ^{8}\text{Be} \)

\( ^{4}\text{He} \)

\( ^{72}\text{Kr} \)

\( ^{64}\text{Ge} \)

\( ^{60}\text{Zn} \)

\( ^{52}\text{Fe} \)

\( A_2 \)
$^{58}_{\text{Ni}}$  $^{56}_{\text{Ni}}$  $^{60}_{\text{Ni}}$

$\frac{N}{Z} \geq 1$

Fig. 4.2(a)
$\frac{N}{Z} \geq 1$

$^{52}\text{Cr}$

$^{50}\text{Cr}$

$^{48}\text{Cr}$

$V(\text{MeV})$

$\Delta_2$

Fig. 4.2(b)
Fig. 4.2(c)