Chapter 5

Isospin effects in the decay of $^{114-122}$Ba* nuclei

5.1 Introduction

Barium nuclei have been of much interest from time to time. First, as an extension of the phenomenon of exotic cluster radioactivity to parents other than radioactive, the $^{12}$C emission from various $^{112-120}$Ba nuclei (with $^{100}$Sn and its heavier isotopes as daughter nuclei) has been the subject of several investigations, both theoretically [7–10] and experimentally [12, 13]. However, the ground state decay of Ba is not yet observed. Then, a new phenomenon of intermediate mass fragments (IMFs, with $3 \leq Z \leq 9$), also referred to as ‘clusters’ or ‘complex fragments’, emitted from excited compound systems, was observed in $^{58}$Ni+$^{58}$Ni→$^{116}$Ba* reactions at both the medium (E$_{c.m.}$ = 174, 185.5, 187.5 and 197 MeV) [14, 15] and high (E$_{c.m.}$ = 315 MeV) [16, 98] energies. The IMFs cross-section, $\sigma_{IMF}$, is known [42, 80, 82] to be small, of the order of 5-10% of the light particles (LPs, $Z \leq 2$) cross-section, referred to as the fusion-evaporation cross-section $\sigma_{ev}$. The fusion-evaporation cross-section for the $^{116}$Ba* compound system at these energies is not measured as yet. The measured $\sigma_{IMF}$ for the $^{116}$Ba* decay at all the above-mentioned medium and high energies are so far understood only on the preformed-clusters based dynamical cluster-decay
Figure 5.1: Scattering potentials $V(R, \ell)$ for $^{114}\text{Ba}^*$ to $^{12}\text{C}^{+102}\text{Sn}$ at fixed temperature $T=2.57$ MeV (equivalently, $E_{c.m.}=142.81$ MeV) and different angular momentum $\ell$-values. The decay path, defined by $V(R_{\ell}, \ell) = Q_{\text{eff}}(T, \ell)$ for each $\ell$, is shown to begin at $R_{\ell} = C + \Delta R$, fixed for the $\ell=0$ case, with extrapolated $\Delta R=1.55$ fm a best fit to data [100] for $^{118}\text{Ba}^*$ and $^{122}\text{Ba}^*$ model (DCM) [25]. The DCM describes the $^{116}\text{Ba}^*$ data on $\sigma_{IMF}$ reasonably well, and predicts an additional fusion-fission of $^{116}\text{Ba}^*$ which consists of fragments at the heavy end of symmetric and near symmetric division ($14\leq Z\leq 28$), very recently observed at GANIL [100] for the decays of $^{118,122}\text{Ba}^*$ nuclei, also analyzed successfully by some of us on DCM [109]. With the availability of neutron rich $^{82}\text{Kr}$ beam, the above mentioned GANIL experiment [100] is made at a still lower energy of 5.5 MeV/A for $^{78,82}\text{Kr}$ on $^{40}\text{Ca}$ target ($E_{c.m.}=145.42$ and 147.87 MeV, respectively), and the cross-sections, kinetic energies and angular distributions of fragments are measured for charges $6\leq Z\leq 28$ emitted from $^{118,122}\text{Ba}^*$. This cross-section is referred
Figure 5.2: Fragmentation Potential \( V(\Lambda_i) \) for compound system \(^{118}\text{Ba}^*\) formed in \(^{74}\text{Kr} + ^{40}\text{Ca}\) reaction at 5.5 MeV/A of bombarding energy, calculated on DCM for use of different \( \Delta R \) (and \( \ell_{\text{max}} \)).

to as the fusion-fission cross-section \( \sigma_{\text{ff}} \), taken as the sum of cross-section due to intermediate mass fragments (IMF2), the heavy mass fragments (HMF), the near-symmetric fission (nSF) and symmetric fission fragments (SF). To this must also be added the, not yet measured cross-section due to light mass fragments \( Z=3-5 \) (IMF1), denoted \( \sigma_{IMF1} \).

Also, the evaporation residues cross-section \( \sigma_{\text{evr}} \) is identified in another attempt of the same experiment [101] and the total fusion cross-section \( (\sigma_{\text{total}} = \sigma_{\text{evr}} + \sigma_{\text{ff}}) \) given as 640 and 670 mb for \(^{78}\text{Kr} + ^{40}\text{Ca} \rightarrow ^{118}\text{Ba}^*\) and \(^{82}\text{Kr} + ^{40}\text{Ca} \rightarrow ^{122}\text{Ba}^*\) reactions, respectively. Note that only charged fragments are measured in this experiment, i.e. \( Z=1 \) and 2 for \( \sigma_{\text{evr}} \) and \( Z=6-28 \) for \( \sigma_{\text{ff}} \).
Figure 5.3: $\Delta R$ fitted to experimental data of $^{118}$Ba* and $^{122}$Ba*, extrapolated down to $^{114}$Ba* and interpolated for $^{120}$Ba*.

The measured characteristics are compatible with binary emission from a compound nucleus. An interesting result of these measurements is that the yields for symmetric division of $^{118}$Ba* are higher by about 30%, compared to that for $^{122}$Ba*. Also, for both the compound systems, a strong odd-even effect is observed for light fragments ($Z \leq 10$), which persists to some extent for higher-Z fragments with highly reduced amplitude. Furthermore, cross-sections for even-Z fragments are higher for $^{118}$Ba* but that for odd-Z are higher for $^{122}$Ba*. Here it may be relevant to recall that this suppression of even-Z fragments with the addition of neutrons to the compound system was also observed in the very early experiments on the decay of $^{56,58,60}\text{Ni^*}$ [115, 116]. More recently, experiments are being planned [117] to study the entrance channel effects, i.e., for forming the same compound nucleus $^{116}$Ba* with reaction partners other than $^{58}\text{Ni+58Ni}$, and for the neighboring isotopes $^{114,116,118}\text{Ba^*}$ for the iso-spin ($N/Z$ ratio of the compound nucleus) dependence of the emission of the IMFs, while we move from neutron rich to neutron deficient nuclei. With the availability of exotic proton and neutron-rich beams, $^{72}\text{Kr}$ and $^{82}\text{Kr}$, respectively, it
Figure 5.4: Preformation probability $P_\theta$ as a function of fragment mass $A_L$ for energetically favored fragments $A_L$, minimized in charge coordinate $Z_L$, calculated on DCM for the compound system $^{114}\text{Ba}^*$ at $E_{\text{c.m.}}=142.81$ MeV (equivalently $T=2.57$ MeV) and $^{116}\text{Ba}^*$ at $E_{\text{c.m.}}=144.14$ MeV (equivalently $T=2.59$ MeV) calculated at $R=R_a=C_t+\Delta R$, $\Delta R=1.16$ fm (arbitrary) and for different $\ell$-values.

has now become possible to see how the IMFs production yields may vary with N/Z ratio of the compound nucleus. In this context, it may be relevant to remind again that for light compound nuclei $^{56,58,60}\text{Ni}^*$, it was already shown [115,116] that the alpha-nucleus spectrum, observed for $N=Z$, $^{56}\text{Ni}^*$, nearly disappeared for its $N>Z$ isotopes. This result was rather well understood within the general framework of the fragmentation theory [118–121], which is also the basis of the dynamical cluster-decay model [20–24] studied here. However, the role of N/Z ratio on IMFs spectrum, rather “IMFs window”, for heavier compound systems still remains to be seen. The statistical model code BUSCO seems to show [117] the same result for $\text{Ba}^*$ nuclei as is observed for $\text{Ni}^*$ isotopes, i.e., the enhancement of IMFs yields as the $N/Z$ ratio decreases towards unity.

After a successful analysis [109] of the first preliminary results of GANIL data
[100] on $\sigma_{ff}$, here in this chapter we further calculate the total fusion cross-section $\sigma_{evr} + \sigma_{ff}$ [101] of $^{118}$Ba* and $^{122}$Ba* to investigate the influence of the compound nucleus N/Z ratio on the various channels of $^{114-122}$Ba* nuclei formed in the low energy heavy-ion reactions $^{74,76,78,80,82}$Kr+$^{40}$Ca. Here $^{74,76,78,82}$Kr are exotic neutron deficient and neutron rich beams available at SPIRAL and LNS, proposed to be used in near future experiments [117]. Our calculations and results towards a study of the effects of X/Z ratio on the decay of compound nuclei $^{114,116,118,120,122}$Ba* are presented in the following section. Finally, our results are summarized in Section 5.3.

5.2 Calculations and discussion of the results

5.2.1 Fusion-evaporation and fusion-fission cross-sections for $^{74,76,78,80,82}$Kr+$^{40}$Ca reactions

As already mentioned above, preliminary results of GANIL fusion-fission ($ff$) data [100] has been analyzed with DCM [109] and an interesting result was that the light particles (LPs) ($A_L=1-5$ or $0\leq Z \leq 2$), the light mass fragments ($A_L=6-14$) denoted IMF2, the heavy mass fragments ($A_L=15-27$ and $A_L=28-41$) denoted HMF, and the near symmetric fission (nSF) and symmetric fission (SF) fragments ($A_L=42-48$ and $A_L=49-59$) show different characteristic behaviors (see Fig.1 of [109]), which guide us to take different $\Delta R$ ($\ell_{max}$) values for different mass regions, which successfully reproduce the results of GANIL $\sigma_{ff}$ data. In the initial measurements [100] since, only angular distributions of fission fragments of charges $6\leq Z \leq 28$, was measured, there were no data available for evaporation-residue and hence in [109] $\Delta R$ for LPs ($A_L=1-5$, $0 \leq Z \leq 4$) was taken to be the same as for IMF2 ($A_L=6-14$) (see Fig. 5.1). Now with the new analysis of the available data [101], evaporation-residue cross-section and hence the total fusion cross-section is obtained by summing-up $\sigma_{evr}$.
Table 5.1: Calculated fusion-evaporation cross-sections $\sigma_{\text{cal}}^{\text{evr}}$, 0f LPs ($1 \leq Z \leq 2$, $A=2-4$ for $^{114,116}\text{Ba}^*$ and 5 for $^{118,120,122}\text{Ba}^*$ ), compared with the experimental $\sigma_{\text{expt}}^{\text{evr}}$, ($=\sigma_{\text{total}}^{\text{evr}}-\sigma_{\text{ff}}^{\text{evr}}$) (6 $\leq Z$ $\leq 28$)) data of Ref. [101]. Also listed are the calculated IMFs cross-sections $\sigma_{\text{IMF}}^{\text{cal}}$ ($Z=3-5$), which is not observed experimentally. $\sigma_{\text{IMF}}^{\text{cal}}$, and HMFs cross-sections $\sigma_{\text{HMF}}^{\text{cal}}$ due to light-mass and heavy-mass fragments, the near symmetric-fission component $\sigma_{\text{nsf}}^{\text{cal}}$, the symmetric-fission component $\sigma_{\text{sf}}^{\text{cal}}$, and their sums, the fusion-fission cross-section $\sigma_{\text{ff}}^{\text{cal}}$ ($=\sigma_{\text{IMF}}^{\text{cal}}+\sigma_{\text{HMF}}^{\text{cal}}+\sigma_{\text{nsf}}^{\text{cal}}+\sigma_{\text{sf}}^{\text{cal}}$), compared with the experimental fusion-fission cross-section $\sigma_{\text{ff}}^{\text{expt}}$ ($6 \leq Z \leq 28$) data of Ref. [100], also the total cross-section calculated on DCM $\sigma_{\text{ff}}^{\text{cal,1}}$ ($=\sigma_{\text{evr}}^{\text{cal}}+\sigma_{\text{ff}}^{\text{cal,1}}$) is compared with total experimental cross-section $\sigma_{\text{ff}}^{\text{expt, total}}$ ($=\sigma_{\text{evr}}^{\text{expt}}+\sigma_{\text{ff}}^{\text{expt}}$ $(Z=6-28)$). In DCM calculations, IMFs, HMFs, nSF and SF windows are described separately for different CN in the literature. The neck-length parameter $\Delta R$ used for different regions are different as are determined in Fig. 5.3 by fitting the experimental $\sigma_{\text{total}}^{\text{expt}}$.

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<td>119.70</td>
<td>111.67</td>
<td>609.60</td>
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†Note: Contribution of n ($Z=0, A=1$) is not included in $^{118,120,122}\text{Ba}^*$ though n is energetically favored. However n is energetically favored (see Fig. 5.4) and results in large contribution of the order $10^4$ mb, which apparently is not relevant for present experimental data. Also, the contribution of $^1\text{H}$ is not included in $^{114,116}\text{Ba}^*$ for the same reason as above.
and fusion-fission yields $\sigma_{ff}$ of the fragments with charge atomic number $6 \leq Z \leq 28$. Using these results we now fitted the total fusion cross-section i.e. both $\sigma_{evr}$ and $\sigma_{ff}$ of $^{118}$Ba* and $^{122}$Ba*, and the results obtained are given in the Table-5.1. Note that for the fitting of evaporation residue cross-section $\sigma_{evr}$, in the decay of $^{118,120,122}$Ba*, we have not included contribution of neutron (Z=0), minimised corresponding to mass number one ($A_L=1$) (see Fig. 5.2), as only charge distributions are observed in this experiment. However neutron (Z=0, $A_L=1$) contributes much to the cross-section ($\sim 10^4 mb$), compared to the observed data, and hence should be of interest for measurements. Also in cases of $^{114,116}$Ba*, contribution of fragment corresponding to mass number one ($A_L=1$) is not included, since the minimised fragment corresponding to mass one ($A_L=1$) is H (with Z=1) whose contribution is again very large ($\sim 10^4 mb$).

First of all we calculate the fragmentation potentials i.e. $V(A)$ minimised in $\eta_f$, taking same $\Delta R$ as in [109] except for LPs ($0 \leq Z \leq 2$), which is now fitted for $\sigma_{evr}$ data. This is illustrated in Fig. 5.2 for $^{118}$Ba* at $E_{cm}=145.42$ MeV, using different $\Delta R$ values in R coordinate $R_a=C_1+\Delta R$, fixed for different mass regions given above in the text and shown in Fig. 5.3, which shows the fitted $\Delta R$ to the experimental results for $^{118}$Ba* and $^{122}$Ba*, extrapolated upto $^{114}$Ba*, for different mass regions (LPs, IMFs, HIMFs, nSF and SF), which is well within the range of 2 fm, for all the regions, in all the compound systems. For mass 1, the energetically favored fragment in our calculation is neutron where in the experiment only the charge distribution is observed. Therefore in our calculations we have not included the contribution of neutron for mass number one case. We notice structure for different mass regions, independent of the $\ell$-value, but changing from an energetically favored LPs, IMFs and HIMFs (asymmetric) at $\ell=0$ and smaller $\ell$-values to a favorable nSF and SF (symmetric) at or near $\ell_{max}$. Naturally, this behavior of fragmentation potential will have consequences for preformation factor $P_0$ used in the calculation of cross-section, discussed latter. Fig. 5.2 shows, for $^{114,116}$Ba* the calculated $P_0(A_i)$. As for
Figure 5.5: The calculated cross-sections $\sigma$ compared with the experimental results as a function of charge $Z_L$ of the light fragments. (a) for $^{118}\text{Ba}^*$ at $E_{c.m.}=145.42$ MeV, (b) for $^{122}\text{Ba}^*$ at $E_{c.m.}=147.87$ MeV.

In the case of $^{114,116,120}\text{Ba}^*$ no data is available, we extrapolated and interpolated $\Delta R$ values (see Fig. 5.3) for different mass regions fitted for $^{118,122}\text{Ba}^*$ nuclei and then used these values for $^{114,116,120}\text{Ba}^*$. Note, here we fix $\ell = \ell_{\text{max}}$ for $\sigma_{LPs} \to 0$ for LPs, used earlier [25], and variable parameter, dependent on $\Delta R$ for $P \to 1$ at $\ell=\ell_{\text{max}}$ (see Fig. 5.1), for IMF1, IMM2, HMF, nSF and SF. For different mass regions, i.e. LPs, IMFs, HMFs, nSF and SF, $\Delta R$ (fm) (and $\ell_{\text{max}}(\hbar)$) values for $^{114}\text{Ba}^*$ decay are: $1.24$ (64), $1.55$ (50), $1.53$ (60), $1.53$ (65) and $1.47$ (70), for $^{116}\text{Ba}^*$ decay are: $1.43$ (67), $1.58$ (50), $1.44$ (66), $1.43$ (69) and $1.37$ (74), further for the case of $^{120}\text{Ba}^*$ decay are: $1.81$ (74), $1.62$ (56), $1.26$ (69), $1.25$ (76) and $1.17$ (84). For $^{114}\text{Ba}^*$ LPs: $A_L=1-5$, IMFs: $A_L=6-14$, HMFs: $A_L=15-32$, nSF: $A_L=33-43$ and SF: $A_L=44-57$.

For $^{116}\text{Ba}^*$ LPs: $A_L=1-5$, IMFs: $A_L=6-14$, HMFs: $A_L=15-38$, nSF: $A_L=39-52$ and SF: $A_L=53-58$ shown in Fig. 5.2, and for $^{120}\text{Ba}^*$ LPs: $A_L=1-5$, IMFs: $A_L=6-14$,
Figure 5.6: Comparison of the ratio of $\sigma^{118}\text{Ba}^*/\sigma^{122}\text{Ba}^*$ as a function of $Z_L$ for DCM calculations and experiments.

HMFs: $A_L=15-34$, nSF: $A_L=35-53$ and SF: $A_L=54-60$. In case of $^{118}\text{Ba}^*$ and $^{122}\text{Ba}^*$ compound nuclei for mass region $A_L=1-5$, $\Delta R$ (fm) (and $\ell_{\max}(b)$) are 1.62 (69) and 2.0 (76) respectively whereas for the rest of mass regions, it is same as that of in our earlier calculations [109].

Fig. 5.5 shows the comparison between the experimental [100,101] and calculated cross-sections, (a) for $^{118}\text{Ba}^*$ and (b) for $^{122}\text{Ba}^*$. Here we, successfully reproduced the results for nSF and SF fragments, with a dip for IMFS and HMFs, where the data are not reproduced because it may be due to a non-compound nucleus decay, as discussed in our earlier calculations [109]. However, we have now refitted the evaporation residue cross-section $\sigma_{evr}$ for both the compound systems not studied in [109]. Fig. 5.6 shows the ratio of cross-section for $^{118}\text{Ba}^*$ and $^{122}\text{Ba}^*$, as a function
Figure 5.7: Cross-section $\sigma_{evr}$ for LPs as function of N/Z ratio for $^{114,116,118,120,122}$Ba* nuclei. As discussed in text, for $^{114,116}$Ba*, $^1$H is not included and for $^{118,120,122}$Ba* n is not included. $Z_L$ for both DCM calculations and experimental data. For the light fragment even Z fragments have larger decay cross-section in case of $^{116}$Ba* and odd Z fragments have larger decay cross-section in case of $^{122}$Ba*. The cross-section around the symmetric splitting are observed to be large for neutron deficient compound nucleus $^{118}$Ba*, a result also seen in Fig. 5.6.

5.2.2 Isospin dependence (N/Z ratio dependence) of the decay cross-sections of $^{114,116,118,120,122}$Ba*

In this section, we discuss the effect of isospin (N/Z ratio) on the evaporation residue cross-section ($\sigma_{evr}$) and fusion-fission cross-section ($\sigma_{ff}$) in $^{74,76,78,80,82}$Kr+$^{40}$Ca $\rightarrow$
Figure 5.8: Cross-section $\sigma$ for three fragments, one from IMFs (C), one HMFS (S), and one from SF (Ni) as function of N/Z ratio for $^{114,116,118,120,122}$Ba$^*$ nuclei.  

$^{114,116,118,120,122}$Ba$^*$ reactions. Fig. 5.7 shows the mass summed yield for charged light-fragments, the evaporation residue cross-section $\sigma_{evr}$ plotted as a function of N/Z ratio of compound nuclei. It is evident from this figure that the yield of light-fragments increases with increasing N/Z ratio, except for the case when we move from $^{118}$Ba$^*$ to $^{120}$Ba$^*$, where there is decrease and again it increases for $^{122}$Ba$^*$. Note, however, that for $^{114}$Ba$^*$, $^{116}$Ba$^*$, $^1$H fragment contribution is not included.

Fig. 5.8 shows the isotopic mass summed yield for some selected fragments, plotted as a function of N/Z ratio of compound nuclei. It is evident from this figure that the yield of Ni (Z=28), corresponding to half of the charge of the compound nucleus, is higher for all the compound nuclei, in comparison to the C and S, which is in accordance with experimental result [100]. Both the increasing and decreasing behavior are seen with increasing N/Z ratio, with the yields of most of the fragments...
Figure 5.9: Fusion-fission cross-section $\sigma_{ff}$ as function of N/Z ratio for $^{114,116,118,120,122}\text{Ba}^*$ nuclei. Experimental values for $^{118}\text{Ba}^*$ and $^{122}\text{Ba}^*$ are also shown in the figure.

emitted from $^{120}\text{Ba}^*$ being maximum, in contrast to low yield for LPs in the case of $^{120}\text{Ba}^*$.

Fig. 5.9 shows the mass summed yield for fission-fragments with Z=6-28 plotted as a function of N/Z ratio of compound nuclei compared with experimental data [100]. It is evident from this figure that the yield of fusion-fission decreases with increasing N/Z ratio, as is the case with data [100] for $^{118}\text{Ba}^*$ and $^{120}\text{Ba}^*$. Once again there is a small increase for $^{120}\text{Ba}^*$.
5.3 Summary of Results

Concluding, in this chapter, we have applied the preformed-cluster based dynamical cluster-decay model (DCM) to $^{114,116,118,120,122}$Ba$^*$, reached in $^{74,76,78,80,82}$Kr + $^{40}$Ca reaction at a relatively low laboratory energy of 5.5 MeV/A, in order to study the effect of N/Z ratio on the decay of compound nuclei, by making use of the available data of $^{118}$Ba$^*$ and $^{122}$Ba$^*$. Important result of DCM calculations is its in-built property of depicting different characteristics for different mass regions of decay products, a behavior accounted for via the neck-length parameter taken to be different for different mass regions of decay products, which fixes for $P \rightarrow 1$, the $\ell_{\text{max}}$ parameter for each region. As energetically favored fragment for mass one is neutron for $^{118-122}$Ba$^*$ and $^1$H for $^{114,116}$Ba$^*$, so there is call for the quantitative observation of evaporation-residue. DCM also supports the even-odd effect of fission fragment cross-sections and hence it will be interesting to see in future the experimental data for isospin dependence of both evaporation residue and fusion-fission processes.