# Chapter 8

# Summary and Outlook

In the previous chapters the details of the experiment performed and the results were presented. The basic motivation of performing these experiments was to understand how the fusion probability of heavy ions is affected by the structure of the interacting nuclei. In chapters 1 and 2, the role of other reaction channels like inelastic excitations and particle transfer in influencing the fusion process was discussed. As the two fusing nuclei approach each other, they undergo transitions from the ground state to the excited states and transfer particles between themselves, before going close enough to form a compound nucleus. The coupled channels formalism discussed in chapter 3 presents an elegant way of treating the influence of other reaction channels on the fusion mechanism. However a clear identification of the reaction channels which are important is not possible in most of the cases. The concept of 'barrier distribution' has been very useful in this regard as it is very sensitive to the channels which couple strongly to the ground state. The barrier distribution is extracted from precisely measured fusion excitation function as was discussed in chapter 4, where the utility of displaying the data in the form of barrier distribution was also highlighted.

The experiments reported in this thesis tried to isolate specific effects like coupling to multi-phonon states in target and projectile and the role of particle transfer channels on the fusion process. The measurements performed are the fusion excitation function for the systems $^{37}$Cl + $^{116}$Sn, $^{16}$O + $^{112,116}$Sn and $^{32}$S + $^{112,116,120}$Sn. Quasi-elastic cross sections at a laboratory angle of 180° were also measured for the systems $^{16}$O + $^{120}$Sn and $^{32}$S + $^{120}$Sn to obtain an alternative representation of the barrier distribution. Details of the experiment were discussed in chapter 5. The emphasis of the experiments was to achieve a high level of precision so that the second derivative can be extracted. We were successful in reducing the random errors to the minimum which is reflected in the well defined barrier distributions obtained for the different systems. The time of flight technique using pulsed beam was extremely useful in discriminating against the beam background and we could measure very low cross sections without difficulty.

The experimental results have been analysed in the framework of coupled channels formalism. The computer code CCFULL was used, which is an exact coupled channels code solving the coupled equations numerically. The coupling potential in this case is not expanded in terms of the deformation parameter, hence it includes coupling to all orders. The detailed analysis of the experimental data was discussed in chapter 7. A realistic nuclear potential was used in all the calculations.

Let us look at the important points which emerged from the analysis:

The influence of coupling to surface vibrations or 'phonons' on the fusion process was explored in detail through the study of the $^{16}$O + $^{112,116}$Sn systems. Here both the targets and projectile are closed shell spherical nuclei and transfer of particles is not significant here. It was observed that the experimental excitation function and barrier distribution for both the systems could be explained by the coupled channels calculations incorporating up to two phonons of Sn excitations in the vibrational coupling scheme. The calculations performed in the harmonic approximation limit revealed that though the gross features of both the systems could be explained reasonably well by the calculations, there remained differences for the experimental data of $^{116}$Sn, similar effect was also observed for the $^{16}$O + $^{120}$Sn system. All Sn isotopes have similar low lying collective states which maintain their phonon character, however the phonon character of the multi-phonon states gradually reduces as one moves away from the middle of the neutron sub shell (N = 64). These differences in the collective nature of the two phonon states may be the cause of the residual disagreement of the calculations with the experimental data, as the fusion barrier distribution is found to be very sensitive to the departure of the transition strengths from the harmonic limit. Detailed calculations taking into account the anharmonic behaviour of the multi-phonon states need to be performed to address this issue.

Another point that could be highlighted from the analysis of the data is regarding the influence of nucleon transfer reactions on the fusion dynamics. The comparative study of the fusion of Sn isotopes with the two projectiles $^{16}$O and $^{32}$S brought out the role of the neutron transfer channels in the sub-barrier fusion process. For the $^{16}$O + Sn systems it was observed that the excitation function as well as the barrier distribution were nicely reproduced by coupled channels calculations including coupling to the inelastic excitations of the target only. Transfer channels were not required to be considered in the calculations for explaining the data. The fact that for these systems all the transfer channels had negative Q-values corroborates the observation. The $^{32}$S + Sn systems have possible +Q-value neutron transfer channels and they are expected to affect the fusion process. From the discussion in chapter 7 it can be concluded that for systems where only one or two neutrons can be transfered with +Q-values, their effect on the fusion process is not very significant. It was seen that for $^{32}$S + $^{112,116}$Sn cases, the coupled channels calculations could reproduce the experimental excitation function and barrier distribution without including any transfer channels. The inclusion of coupling to transfer channels predicted shapes of the barrier distribution which could not be reconciled with the experimental ones indicating that in these cases it is the collective excitations which are important.

The situation was different for the $^{32}$S + $^{120}$Sn case where the experimental excitation function and barrier distribution could not be explained by the calculations. In this case, upto 6 neutrons can be transferred with +Q-values. The calculations performed cannot include multi-nucleon transfer so only the effect of pair transfer was explored which failed to give a good representation of the data. The shape of the experimental barrier distribution in this case was broad and flat and could not be reproduced by the calculations. This may be an evidence of the fact that multi-neutron transfer is occurring sequentially causing neutron flow which aids fusion as was suggested by Stelson. However in the absence of explicit calculations this can be treated as a qualitative signature only. The $^{32}$S + $^{112,120}$Sn systems that we have studied are comparable to the $^{40}$Ca + $^{90,96}$Zr systems studied by Timmers [NPA 633, 421 (1998)] as they have the same value of $Z_pZ_t$ (800) and similar situation regarding the possibility of neutron transfer. For the Ca + Zr systems a strong isotopic dependence was observed and the barrier distribution and excitation function for $^{96}$Zr case could not be explained by coupling to the inelastic states of target and projectile. In our case, we find that the calculations performed with the vibrational coupling come quite near to explaining the data for both the systems. Also the relative enhancement between the two systems is small compared to Ca + Zr case. Thus, the effects of transfer coupling appear to be less important in the fusion of S + Sn, the major contribution coming from the vibrational coupling. However it should be pointed out that the Sn isotopes are more similar structurally than the two Zr isotopes making the former a better candidate for bringing out the influence of transfer channels.

The barrier distribution was extracted from 180° scattering excitation function for the systems $^{16}$O + $^{120}$Sn and $^{32}$S + $^{120}$Sn and compared with the fusion data. It was found that for the $^{16}$O + $^{120}$Sn case their was good agreement between the two forms of the representation, however, there were significant differences for the

$^{32}S$ + $^{120}Sn$ case. This disagreement could not be understood, there is a need for further experiments and detailed analysis to get a consistent picture.

In the end it can be said that this thesis work was an effort to address the issues related to the understanding of the near and sub-barrier fusion process. In general, there has been remarkable progress made in the field of sub-barrier fusion. Sensitive ways of analysing data like barrier distribution, improved coupled channels calculations have been able to elucidate many important aspects of this process, though there are many unanswered questions. Most importantly a complete theory incorporating single and multi-nucleon transfer couplings is still to emerge. Fusion models which take into account transfer coupling effects would be instrumental in highlighting the influence of transfer on the fusion process. Understanding of the role of multi-nucleon transfer effects on fusion would also throw light on the macroscopic models of sub-barrier fusion like neck formation. The coupled channels calculations for fusion generally use a Woods-Saxon shape for the nuclear potential with parameters obtain from fitting high energy fusion data. However the real nuclear potential that should be used in the fusion calculations remains an uncertainty. A global analyses of high precision fusion data is required to get a complete picture which can describe both fusion and elastic and inelastic scattering. More refined coupled channels calculations incorporating the effects of the anharmonicities of the vibrational spectra of the nuclei are needed in light of the high precision data available.

*With these efforts, we should not be far away from a complete understanding of what happens as two heavy nuclei tunnel through a potential barrier to fuse.*