SUMMARY OF THE THESIS
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STUDY OF PREEQUILIBRIUM EMISSION
IN ALPHA PARTICLE INDUCED REACTIONS

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Nuclear research is aimed at obtaining an understanding of the properties of the nucleus as well as the nature of the forces that operate between sub-nuclear particles. Some of these aspects can be studied by bombarding the nucleus with energetic particles and observing the products formed in various nuclear reactions. The advancement of accelerator technology has not only provided a wide scope for systematic search of new experimental trends in fundamental research but also paved way to the study of various nuclear properties of applied interest.

The relation depicting the trend variation of the production cross section of a given isotope, with the bombarding energy of the incident particles, is known as the "excitation function" for the reaction producing that isotope. Beside giving useful information to optimise the production, the "excitation function" basically contains valuable information of the physics of interaction between the incident particle and the target nucleus resulting in the formation of the product isotope. It is necessary to compare the experimental results with theoretical predictions to infer the reaction mechanism. This implies, of course, the solution of the nuclear many body problem involved in the interaction of the incident particle with the target nucleus.

For a long time, two extreme models of nuclear reactions have received particular attention and enjoyed commensurate success. They are the direct reaction model and the compound nucleus model. These two are at the two extreme ends of a nuclear reaction time scale in which the direct reactions take place in a time scale of $10^{-22}$ s.
whereas compound nuclear reactions take place over a much longer time scale of $10^{-15}$s. So in the low energy studies, bulk of the particle emission can be attributed to the one of these processes.

However, there has been an increasing experimental evidence pointing out to new types of processes that lie in the complexity between above two models. The newly observed processes are called "pre-equilibrium" or "pre-compound" reactions as they occur in time sequence prior to the establishment of the equilibrium compound nucleus stage. The two completely different reaction theories - the direct and the compound nucleus theories have to be linked together for obtaining a satisfactory description of the experimental results. The success of the simple formulations used rests in the use of a statistical assumption applied to each configurational hierarchy as denoted by the projectile plus hole (or exciton) number. The number characterizes the initial exciton energy distribution engendered by the projectile entering the target nucleus at the start. The various preequilibrium theories differ appreciably in their flexibility and in mathematical rigour.

The importance of preequilibrium process increases with increasing excitation energy. Several models based on classical, semi-classical and quantum mechanical ideas were proposed during last three decades in order to explain the pre-equilibrium phenomena. All these models deal with the nuclear matter calculation. So they embody few of the details of nuclear structure. They take more general properties of a nucleus such as mean free path of nucleons in nuclear matter, densities of particle-hole states at different excitation, emission rates of nucleons from highly excited
nuclear systems etc. Several refinements and modifications were carried out in order to develop more accurate pre-equilibrium theories.

The semiclassical theories have been applied to a much wider range of reactions than the quantum mechanical theories in particular to those initiated by complex particle and those leading to the emission of many particles. By contrast, the quantum mechanical theories have so far been confined to nucleon interactions with not more than two emergent particles. For the interaction of a complex particle like an $\alpha$-particle the quantum mechanical picture is yet to come.

There is a growing demand for a systematic and accurate experimental data on the excitation functions to test the pre-equilibrium models. The presently available experimental information on the excitation functions is generally scanty with a large part of it measured with poor resolution detectors. In some cases, large discrepancies also exist among the various reported values for the same reactions measured by different investigators whereas in some cases, only single measurements are available.

So, in the present work, a systematic study of twenty six alpha particle induced reactions were carried out on typical elements $^{58,60}$Ni, $^{89}$Y, $^{103}$Rh, $^{159}$Tb, and $^{185,187}$Re using high resolution HPGe detector (2.0 keV FWHM for 1332 keV photons). Of these, fifteen reactions were measured for the first time. Experimental data were updated and extended for five reactions using high resolution HPGe detector which were measured with poor resolution detector and/or upto 40 MeV of bombarding energy. The cross-sections of six
reactions were re-investigated using high resolution HPGe detector which were earlier measured with Ge detector for which only single measurements were available.

Irradiation of the stack was carried out using 50 MeV alpha particles at Variable Energy Cyclotron Centre (VECC), Kolkata, India. The standard stacked foil activation technique and gamma ray spectroscopy method were employed in the measurement of $\gamma$-activities. Alpha particle flux was determined with the help of the current integrator and was also calculated using the well known standard (monitor)reaction cross-section. In general, two values agreed within 5%. The overall projected error of the measurements was less than 9% which do not include the uncertainties of the nuclear data used in the analysis.

For the comparison of the experimental excitation functions, semiclassical models such as hybrid model of Blann and index model of Ernst are used. Theoretical code ALICE/85/300 based on the hybrid model used Fermi gas level density of Bethe whereas code ALICE/90 which is also based on hybrid model used shell dependent level density option of Kataria, Ramamurthy and Kapoor (KRK). Code ALICE/90 is used for the comparison of experimental excitation functions where product nuclides are formed with closed or nearly closed shells. Above two codes are not designed to deal with the emission of alpha particles in the pre-equilibrium phase. However, the experimental excitation functions for $(\alpha,\alpha n)$ reactions are compared with the theoretical predictions using code COMPLET which is based on index model and includes the emission of $\alpha$-particles in the pre-equilibrium phase.
The following general conclusions are drawn from the overall comparison between experimental results and theoretical predictions for $(\alpha, xn), (\alpha, pxn), (\alpha, axn)$ and $(\alpha, apxn)$ reactions in light, medium and heavy nuclei studied in the present work.

1) The mechanism governing the emission of neutrons from light, medium and heavy nuclei is essentially the same.

2) For bombarding energies within about 10-15 MeV from the threshold energy of the reaction, single as well as multiple emission of neutrons is governed by the well known compound nucleus evaporation mechanism and is adequately accounted for by simple or multistep Weisskopf-Ewing formalism.

3) At increasing energies up to 50 MeV, the unambiguous evidence for increasing non-compound contributions in $(\alpha, xn)$ reactions particularly for decreasing neutron multiplicity.

4) The emission of neutrons from nuclear systems at excitation energies beyond a few tens of MeV is caused by the preequilibrium decay of the system in a time much shorter than the time for evaporation from an equilibrated compound nucleus. This is rather indirectly indicated by the "high energy tails" of the experimental excitation functions which signify a less rapid fall of the cross section than predicted by compound nucleus model.

5) The shape of the excitation functions in the preequilibrium dominated regions of energy is well reproduced by the improved version of hybrid model. As far as the magnitudes of the cross
sections are concerned, there is a reasonable agreement with
the predictions of this model using an initial exciton
configuration \( n_0 = 4(4p0h) \) i.e. pure particle state.

6) Physical interpretation of initial exciton configuration \( n_0 = 4(4p0h) \)
is that only four excitons initially share the excitation energy,
which is equivalent to the break-up of incoming alpha particle in the
field of nucleus and the nucleus occupying excited states above
the Fermi energy. This view is quite consistent with the basic
physics of the preequilibrium mechanism that only a few
degrees of freedom is initially excited in a nuclear reaction at
moderate energy.

7) It has been observed that reaction yields of nuclides with
closed or nearly closed shells are predicted well with shell
dependent level density option (ALICE/90) whereas Fermi gas
level density option (ALICE/85/300) is unable to predict the
experimental results. This indicates the effect of nuclear shell
structure on the reaction cross-sections.

8) The cross-sections for \((\alpha,\alpha xn)\) reactions are in general, one order
of magnitude smaller than those of \((\alpha, xn)\) reactions and shape
of excitation functions are significantly different for the two
types of reactions.

9) It is observed that the shape as well as magnitude of the
experimental excitation functions for \((\alpha,\alpha xn)\) reactions are
fairly well reproduced by COMPLET code, whereas ALICE code
underestimates the experimental results. This is because the
COMPLET code takes into account the emission of \(\alpha\)-particle in the
preequilibrium phase whereas ALICE code is not designed to deal with the emission of $\alpha$-particle in the preequilibrium phase.

10) For $Y(\alpha,\alpha n)$ reaction, the COMPLET code gives a rather satisfactory description of the shape and magnitude of experimentally observed excitation function whereas ALICE code underestimates experimental results by a factor of six at the peak. However, both the models failed to reproduce the slowly rising shape of the excitation function. It may be speculated that for this reaction, a direct inelastic scattering followed by neutron evaporation could be a contributing factor.

11) Due to the limitation of projectile energy ($E_a$) and the large effective threshold energies for $(\alpha,\alpha p n), (\alpha,\alpha 2n)$ and $(\alpha,\alpha 3n)$ reactions, only the predominant compound nucleus part of the excitation function could be investigated in the present work.

12) The difference in the shape which is conspicuous in the lower energy part of the excitation function can be attributed to the negative influence of Coulomb barrier on the emission of charged particle.

13) The fraction of preequilibrium particle emission ($f_{\text{PE}}$) has been calculated for $^{58}\text{Ni}$, $^{60}\text{Ni}$, $^{89}\text{Y}$, $^{103}\text{Rh}$, $^{159}\text{Tb}$, $^{185}\text{Re}$ and $^{187}\text{Re}$ isotopes as a function of bombarding energy $E_a$. It is inferred that $f_{\text{PE}}$ increases very fast as the energy of the alpha particle increases. The threshold for preequilibrium process is higher for the low mass number and $f_{\text{PE}}$ is higher for the system of higher mass number at a given alpha particle energy.