Clustering in light nuclei

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Introduction

Clustering or more specifically α-clustering has been a topic of contemporary research since the discovery of α radiation. Many theoretical models assumed self-conjugate even-even nuclei as combination of Nα (N =1,2,3...) particles. The experimental results for ^{8}Be, ^{12}C etc. supported this conjecture [1]. However, verification of Nα states in heavier nuclei is still an open problem. Moreover, there is lot of ambiguities regarding the structure of these states; whether the αs are arranged in linear fashion, or forming a gas-like structure or a Bose-Einstein condensate. On the other hand, the presence of α-clustered states (nuclei) in the reaction process has somewhat indirect effect on the outcomes. This has been observed experimentally in the past few decades in various reaction mechanisms. For example, orbiting kind of phenomenon which is associated with α-clustered nuclei in the entrance channel, clearly indicates that there is some effect of α-clustering in the reaction dynamics.

Therefore, clustering phenomenon, which refers to spatial rearrangement of nucleons, can be probed either through populating the nuclei in their respective cluster states, or by looking at the influence of these nuclei on the reaction mechanism through some suitable observables. In this thesis, both these procedures have been adopted to investigate the clustering phenomenon in nuclei, particularly in the light mass region.

Effect of clustering on reaction dynamics

Two experiments have been carried out to study the effect of clustering in intermediate mass fragments (IMF, $2<Z_{IMF}<A_{CN}/2$) emission.

In the 1st experiment, the role of clustering has been studied in the binary complex fragment decay of fully energy relaxed composites ^{24,25}Mg, formed in reactions ^{12}C(80.0 MeV)+^{12}C and ^{13}C (78.5 MeV) + ^{12}C at an excitation energy ≈ 54 MeV. The experiment was performed at BARC-TIFR Pelletron-Linac facility, Mumbai and the emitted fragments were detected using two telescopes of ChAKRA [2]. The energy and angular distributions of the emitted fragments ^{6,7}Li and ^{7,8,9}Be have been measured. The ratio of the measured fully dissipative (fission-like) yields of each isotopic fragment obtained in the two reactions was compared with the corresponding statistical model prediction of the same. Unlike in the case of ^{6,7}Li fragments, the measured yield ratios of ^{7,8,9}Be fragments were found to deviate substantially from the statistical model predictions of the same. The observed deviations were due to the enhancement in the measured yields of ^{7,8,9}Be fragments (with respect to the respective statistical model predictions) only in specific exit channels containing either ^{16}O or ^{18}O, both well-known α-cluster nuclei, as the complementary binary fragment. The present data indicated, for the first time, the survival and sustained influence of cluster correlations on dissipative binary decay of hot composites ^{24,25}Mg* at excitation energy of ~2.25 MeV/nucleon [3].

In the 2nd experiment, the effect of weak binding of ^{9}Be (threshold for break up through different clusters ranges ~1.57-2.31 MeV) on complete fusion has been explored through the study of IMF emission in ^{20}Ne + ^{9}Be reaction. The yields of the fragments ^{6,7}Li and ^{7,9}Be emitted from the excited compound nucleus ^{29}Si* have been compared with the respective statistical model predictions. Emission of same fragments from another close-by compound nucleus ^{28}Si* at similar excitation energy, formed by the fusion of two strongly bound nuclei, ^{16}O + ^{12}C, has been studied for comparison. The experiments were performed at VECC, Kolkata, using ^{20}Ne (157.2, 193.0 MeV) and ^{16}O (135.9, 161.6 MeV) ion beams on ^{9}Be and ^{12}C targets, respectively. It has been observed that for the system ^{16}O + ^{12}C, the yields of $^{6,7}Li$ and $^{7,9}Be$ fragments are close to the predictions of the statistical model. However, for the ^{20}Ne + ^{9}Be system, although the experimental yield pattern follows the statistical model prediction, there is substantial reduction in yield for all detected fragments. The yields of IMFs produced in ^{20}Ne + ^{9}Be reaction are found to be reduced to ≈ 35-55(±12)% of the prediction of the statistical model normalised with respect to the fragment yields from ^{16}O + ^{12}C reaction at similar excitation energies. The large reduction of fragment yield seen here may be attributed to the suppression of complete fusion in ^{20}Ne + ^{9}Be system due to the weak binding of ^{9}Be, a dynamical effect which is not incorporated in the conventional statistical models. This is the first time, a clear signature of the suppression of complete fusion in light systems involving weakly bound nucleus has been observed via IMF emission from fully equilibrated composite produced in fusion well above the barrier [4].

Probing cluster resonance states

The most investigated clustered state to date is the Hoyle state of ^{12}C for its immense importance not only from structure point of view but also from astrophysical implications. Although the 3α nature of this state is well established, there are some ambiguities regarding the structure which can be probed by studying decay mechanism of this state. An experiment has been performed to populate the Hoyle state by bombarding 60 MeV ^{4}He beam from the K-130 cyclotron at VECC, on ~50 μg/cm^2 ^{12}C target. The α-particles emitted in the decay of the Hoyle state have been detected in coincidence with the inelastically scattered ^{4}He. The analysis shows that the direct decay ($^{12}C \rightarrow 3\alpha$) component of the Hoyle state is negligibly small compared to the sequential decay ($^{12}C \rightarrow {}^{8}Be + \alpha$) component. After fitting with simulation results, the upper limit of direct decay was found to be 0.019% with 95% upper confidence limit [5]. The present value is more than a factor of 2 lower than the limit obtained recently in similar high precision studies.

Like the Hoyle state of ^{12}C, one can find α-clustered states in other nuclei also, though no direct evidence has been observed experimentally in nuclei heavier than ^{12}C due to some inherent challenges. In the present work, the Hoyle analogue state has been explored in ^{16}O, predicted at 15.1 MeV (0^+_6) theoretically [6]. The experiment was performed at VECC, using 45 MeV α beam from the K130 cyclotron on a Mylar target. The break up 4αs of ^{16}O have been detected in coincidence with the inelastically scattered α beam particle to probe the Hoyle analogue state of ^{16}O in complete kinematics, for the first time. The data have been analysed for all possible configurations and the excitation function of ^{16}O has been reconstructed directly from 4α as well as for specific decay channels like $^{12}C(0^+_2)$ + α, $^{12}C(3^-_1)$ + α and ^{8}Be + ^{8}Be. A few new states have been observed above the 4α break-up threshold (14.44 MeV) in the above mentioned decay channels apart from several previously known states. However, none of the spectra could populate the 15.1 MeV state, convincingly. A Monte Carlo simulation has also been performed to calculate the detection efficiency of the detector setup used in this experiment. This study being first complete kinematical experiment [7], points to the further improvements required to efficiently probe this state in future.

Conclusion

Clustering in nuclei has been investigated indirectly through experiments on IMF emission and directly through resonance spectroscopy of ^{12}C and ^{16}O. The IMF emission studies show deviation of experimental yields from the theory whenever α-clustered nuclei are involved. The studies on the Hoyle and Hoyle analogue states produced some promising results which are important from the structure point of view.

References

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