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Clustering aspects in ^{20}Ne Alpha-conjugate Nuclear System

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Abstract The clustering aspects in alpha-conjugate nuclear system ^{20}Ne has been investigated comparatively within microscopic and macroscopic approaches of relativistic mean field theory (RMFT) and quantum mechanical fragmentation theory (QMFT), respectively. For the ground state of ^{20}Ne, the matter density distribution calculated within RMFT, depict the trigonal bipyramidal structure of 5α's and within QMFT, the equivalent α+^{16}O cluster configuration is highly preformed. For excited state corresponding to experimental available energy, the QMFT results show that in addition to α+^{16}O clusters, other xα-type clusters (x is an integer) are also preformed but in addition np-xα type (n, p are neutron and proton, respectively) ^{10}B clusters are having relatively more preformation probability, due to the decreased pairing strength in liquid drop energies at higher temperature. These results are in line with RMFT calculations for intrinsic excited state which show two equal sized fragments, probably ^{10}B clusters.

Keywords: Clusters, Alpha conjugate nuclear system, Preformation probability

1. INTRODUCTION

Nuclei are complex entity constituted by nucleons, in which under the mean field depiction nucleons are considered as independent while few of them conglomerate to form clusters leading to an enhancement in binding energy of nuclear system. In other words, the high abundance, large binding energy of 4n nuclei (e.g. ^{4}He, ^{12}C and ^{16}O) and α-decay of heavy nuclei are the manifestations of clustering in nuclei. Another evidence is the cluster radioactivity, discovered in 1980's. The preponderance of α-clustering in light mass alpha conjugate nuclei (N = Z) has long standing history [1, 2]. The pioneering work by Ikeda, in form of diagrams for clustering in light alpha conjugate nuclei, reveal that α-clusters are not apparent in ground state rather they appear near decay threshold energy [2]. The cluster structures are also predicted for non-alpha conjugate nuclei (N $\neq$ Z) in extended Ikeda diagram. Even after couple of decades of work in this direction, the studies are still progressing in this field to investigate the cluster structure in stable as well as exotic nuclei [3,4].

In order to explore the nuclear structure and reaction mechanism, the nuclear reactions involving the capture or emission of nucleon clusters are significant spectroscopic tools [4, 5]. Several attempts have been undertaken on the theoretical modeling front e.g. Antisymmetrized Molecular Dynamics (AMD) [6], Fermionic Molecular Dynamics (FMD) [7], mean field approach etc. which have been developed to explain the clustering in nuclei, particularly in lighter nuclei. Two of the authors have explored the clustering effects in lighter nuclei within relativistic mean field theory (RMFT) [8]. Recently, the clustering effects in light mass N = Z and N $\neq$ Z nuclei have been explored comparatively, within collective clusterization approach of quantum mechanical fragmentation theory (QMFT) based dynamical cluster-decay model [9].

At low temperature the mean field effect is not strong enough to break the cluster correlation [10]. Therefore, it is quite important to explore the evolution of cluster structure with rise in temperature or excitation energy and to dig out information about α-clustering from excited, decaying alpha conjugate nuclear systems. In the present work, the clustering aspects in ^{20}Ne nuclear system is studied, comparatively, within microscopic and macroscopic approaches of RMFT and QMFT, respectively, to explore further, existence as well as the impact of rising temperature on clustering within alpha conjugate nuclear system ^{20}Ne.

2. METHODOLOGY

2.1 Relativistic Mean Field Theory (RMFT)

The RMFT Lagrangian, with the NL3 parameter set [11, 12], is used to calculate the nuclear matter density, which is reasonably useful for both stable and drip lines nuclei. The Lagrangian contains the terms of interaction between mesons and nucleons and also self-interaction of isoscalar scalar sigma meson.

$$
\begin{aligned}
L = {} & \bar{\psi}_i \left\{ i\gamma^\mu \partial_\mu - M \right\} \psi_i + \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma{}^2 \sigma - \frac{1}{3} g_2 \sigma^3 \\
& - \frac{1}{4} g_3 \sigma^4 - g_s \bar{\psi}_i \psi_i \sigma - \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu} + \frac{1}{2} m_\omega{}^2 V^\mu V_\mu + \frac{1}{3} c_3 (V^\mu V_\mu)^2 \\
& - g_\omega \bar{\psi}_i \gamma^\mu \psi_i V_\mu - \frac{1}{4} \vec{B}^{\mu\nu} . \vec{B}_{\mu\nu} + \frac{1}{2} m_p{}^2 \vec{R}^\mu . \vec{R}_\mu - g_\rho \bar{\psi}_i \gamma^\mu \vec{\tau} \psi_i \vec{R}^\mu \\
& - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - e\bar{\psi}_i \gamma^\mu \frac{(1-\tau_{3i})}{2} \psi_i A_\mu
\end{aligned}
\tag{1}
$$

The field for the σ meson is denoted by σ, that for the ω meson by V_μ, and that for the isovector ρ meson by R_μ. A^μ denotes the electromagnetic field. The ψ_i are the Dirac spinors for the nucleons whose third component of isospin is denoted by τ_{3i}. Here g_s, g_w, and g_ρ and ε2/4π = 1/137 are the coupling constants for σ, ω, ρ mesons and photons, respectively. g_2, g_3 and c_3 are the parameters for the non-linear terms of σ and ω mesons, respectively. M is the mass of the nucleon and m_σ, m_ω, and m_ρ are the masses of the σ, ω, and ρ mesons, respectively. $\Omega^{\mu\nu}$, $B^{\mu\nu}$, and $F^{\mu\nu}$ are the field tensors for the V^μ, R^μ, and the photon fields, respectively.

From the relativistic Lagrangian the field equations for the nucleons and mesons are obtained. These equations are solved by expanding the Dirac spinors and the boson fields in a deformed harmonic oscillator basis, starting with an initial deformation. The set of coupled equations is solved numerically by a self-consistent iteration method to obtain the nuclear matter density.

2.2 Quantum Mechanical Fragmentation Theory (QMFT)

The QMFT [13, 14] is based on the fact that the fragments are pre-born prior to the decay of the excited nucleus. The quantum mechanical preformation probability P_0 of the decaying clusters or fragments formed in the mother nucleus is calculated by solving a stationary Schrodinger equation in mass fragmentation coordinate. QMFT is worked out in terms of collective co-ordinates of :

(i) mass asymmetry co-ordinate $\eta = (A_1 - A_2)/(A_1 + A_2)$
(ii) the relative separation co-ordinate R
(iii) the multiple deformations β_{λ_i} ($\lambda = 2, 3, 4$) and orientations θ_i ($i = 1, 2$) of two nuclei.

The cluster preformation probability is given as:

$$P_0(A_i) = |\psi(\eta(A_i))|^2 \, (2/A) \sqrt{B_{\eta\eta}} \tag{2}$$

which is the solution of stationary Schrödinger equation in η, at fixed R= R_a (the first turning point of penetration path through interaction barrier)

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V_R(\eta)\right\}\Psi_R^{(\nu)}(\eta)=E_R^{(\nu)}\Psi_R^{(\nu)}(\eta) \tag{3}$$

with $R_a = R_1(\alpha_1,T) + R_1(\alpha_1,T) + \Delta R(\eta,T) = R_t(\alpha_1,T) + \Delta R(\eta,T)$, with the radius vectors

$$R_i(\alpha_i,T) = R_{0i}(T)[1+\sum_{\lambda}\beta_{\lambda i}Y_{\lambda}^{(0)}(\alpha_i)] \tag{4}$$

here, $R_{0i}(T)$ are the T-dependent nuclear radii given as

$$R_{0i}(T)=\left[1.28A_i^{\frac{1}{3}}-0.76+0.8A_i^{-\frac{1}{3}}\right](1+0.0007T^2) \tag{5}$$

with T calculated from the excitation energy of resonant state (E*), using $E^* = (A/8)T^2 - T$. In Equation (3), $\nu = 0, 1, 2, 3...$ referring to ground-state ($\nu = 0$) and excited-states solutions. The mass parameters $B_{\eta\eta}$ are the smooth classical hydrodynamical masses [15]. For clustering effects in nuclei we look for the maxima in $P_0(A_i)$ or energetically favored minima in the fragmentation potential $V_R(\eta, T)$ which is calculated as

$$\begin{aligned} V_R(\eta,T) &= \sum_{i=1}^{2}\left[V_{LDM}(A_i,Z_i,T)\right] + \sum_{i=1}^{2}\left[\delta U_i\right]\exp(-T^2/T_0^2) \\ &+V_c(R,Z_i,\beta_{\lambda i},\theta_i,T)+V_p(R,A_i,\beta_{\lambda i},\theta_i,T)+V_l(R,A_i,\beta_{\lambda i},\theta_i,T) \end{aligned} \tag{6}$$

where V_{LDM} is the T- dependent liquid drop energy, δU are the shell effects which are calculated in the "empirical method" of Myres and Swiatecki [16] and V_c, V_p, V_l are the temperature and orientation dependent Coulomb, nuclear proximity [17] and angular momentum dependent potentials, respectively. It is important to note that for α-clustering in nuclei, a modified temperature dependent pairing energy coefficient δ(T) is essential to be taken in temperature dependent V_{LDM} part as shown in Ref. [18].

3. RESULTS AND DISCUSSION

The results for clustering effects in the ^{20}Ne have been compared within microscopic approach of RMFT and macroscopic approach of QMFT. The nuclear matter distribution for ^{20}Ne in ground state using RMFT in Figure 1(a), shows trigonal bipyramidal configuration of 5α's. To make a comparative account of these microscopic calculations for ^{20}Ne nuclear system the same has been investigated using QMFT approach, within which for clustering effects we look for maxima in preformation (P_0) profile. Figure 1(b) for P_0 in ground state (T = 0 MeV) of ^{20}Ne nuclear system (with pairing constant $\delta(T) = 32.02$ MeV) reveal that xα-type (x is an integer) α+^{16}O cluster configuration ($\equiv$ 5α type) is dominant. This result is further supported by ground state density calculations for ^{20}Ne within DD-ME2 energy density functional, depicting the localization of density leading to formation of cluster structure [Figure 1 of Ref [3]].

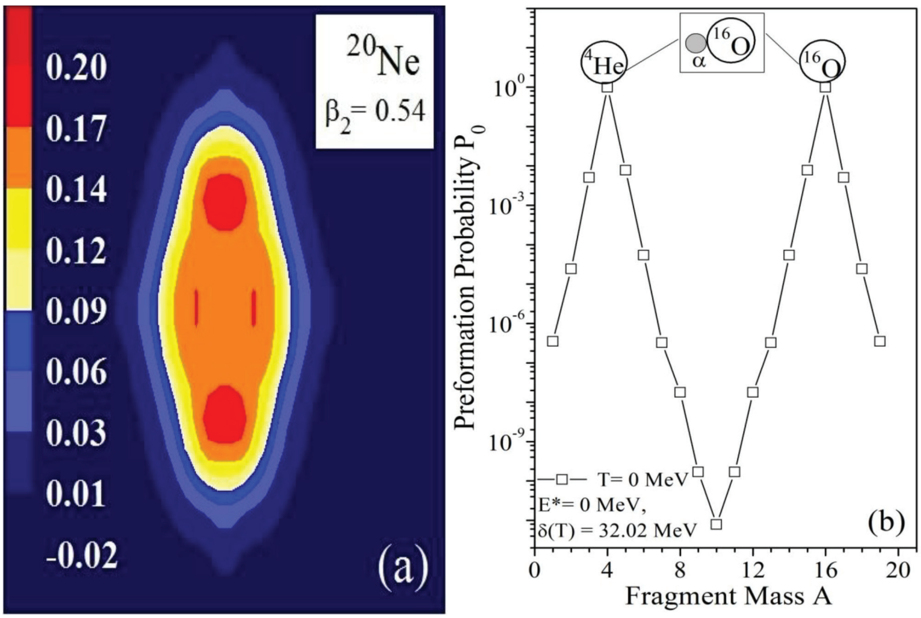

Figure 1: For ^{20}Ne nuclear system in ground state (a) the nuclear matter density calculated using RMFT (b) the quantum mechanical preformation probability P_0 of different clusters using QMFT.

^{20}Ne in intrinsic excited state corresponding to higher deformations using RMFT calculations present the configuration of two equal size fragments/

clusters, most probably the $^{10}B+^{10}B$ cluster configuration (Figure 2(a)). The results within QMFT, corresponding to experimental excitation temperature T = 4.94 MeV [19], by taking into account the modified temperature dependent pairing energy term in liquid drop energies, is shown in Figure 2(b). It is noted that in the decay of $^{20}Ne^*$ in addition to $\alpha+^{16}O$ cluster configuration other xα-type (x is an integer) clusters (shown encircled) are also preformed. These results are in agreement with Ikeda diagram [2], which reveal that more number of α-clusters appear with an increase in threshold energy. Furthermore, it is clear that ^{10}B which is np-2α (n, p are neutron and proton, respectively) type cluster (shown by boxes) is having dominant P_0 in comparison to xα-type clusters. It is due to decreased pairing strength at higher temperatures in the liquid drop energies. These results are in agreement with microscopic matter density calculations within RMFT (Figure 2(a)) which depict the formation of ^{10}B cluster, which is predicted to have α+np+α cluster structure as shown in recent work by Rogachev et al. [20].

It is clear from above discussion that relative P_0 of different clusters in the decay of $^{20}Ne^*$, formed in low energy heavy ion induced reactions, facilitate to put forth the role of α-clustering on the fragmentation process. It is mentioned here that although QMFT involves the macroscopic liquid drop energies in the calculation of collective potential energy surface/fragmentation potential [Eq.

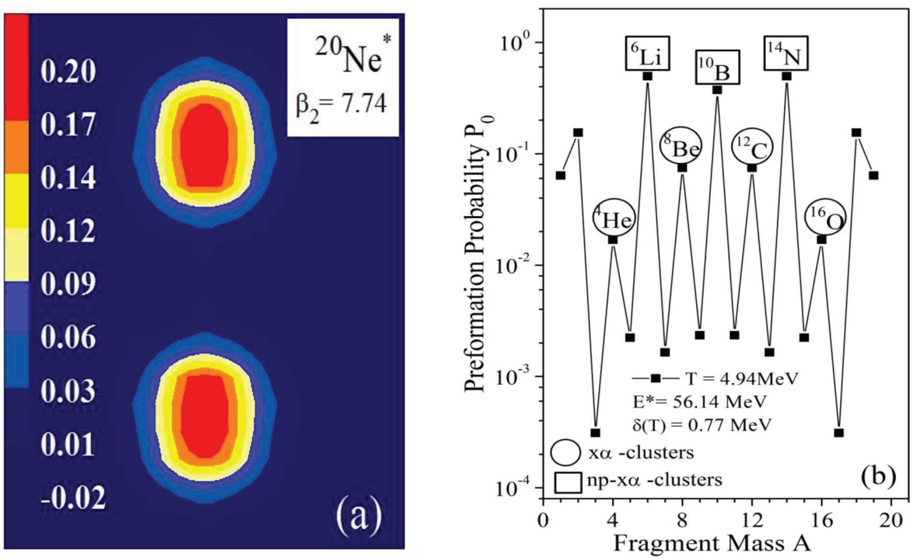

Figure 2: (a) The nuclear matter density, for $^{20}Ne^*$ nuclear system in intrinsic excited state, calculated using RMFT (b) preformation probability P_0 of different clusters for $^{20}Ne^*$ at experimental excited state using QMFT.

(6)], which in turn affect the cluster preformation probability P_0, while the results obtained within QMFT are in good comparison with RMFT results. On the other hand, the RMFT being microscopic approach, involve some inadequacies of mean-field approximation itself, RMFT parameters and shape degrees of freedom, but is able to explain successfully the clustering in light nuclei.

SUMMARY

The clustering prospects in ^{20}Ne nuclear system are explored within RMFT and QMFT i.e. microscopic and macroscopic approaches, comparatively. The results from these formalisms show that xα-clusters are prominent in ground state. The QMFT results for excited state of ^{20}Ne show that in addition to xα-clusters, the np-xα type clusters, particularly ^{10}B cluster is having quite dominant P_0 due to decrease in temperature dependent pairing strength at higher temperatures. The results within RMFT also present similar kind of scenario, showing that for intrinsic excited state of ^{20}Ne, ^{10}B clusters seems to be probable. The present work has scope to be extended further for investigating the clustering effects in non-alpha conjugate nuclei.

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