The internal substructure of $^{112-122}$Ba* nuclei using the relativistic mean field formalism

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Introduction

Clustering is a very general phenomenon, which appears in atomic, nuclear, subnuclear, and the cosmic worlds [1]. In nuclear dynamics, similar to one in light stable nuclei, clustering is one of the essential features and various cluster structures have been known even in the low-energy reaction studies [2, 3], which describe well the structural properties of the ground as well as the excited states. Also, in the physics of unstable nuclei, clustering-features comprise one of the central role. In terms of the relativistic mean field theory, it is already well known [4–6] that clustering structures appear in the ground states of ordinary light nuclei with N = Z or in their neighbourhood. Even though this phenomenon has been studied for a long time, and many features on clustering revealed, but there are many things that still remain to be learned. In view of this, we investigate the clustering phenomenon in medium-heavy $^{112-122}$Ba* nuclei formed in heavy-ion reactions, with an additional first time attempt to calculate the actual number of protons and neutrons in the obtained clusters.

Theoretical Framework

We use the axially deformed relativistic mean field (RMF) formalism with NL3 parameter set to calculate the proton and neutron density distributions for the ground as well as the excited intrinsic states, including the highly deformed scission state. Knowing the density distributions of the spherical or deformed configuration, we calculate the number of nucleons by using the general formulla:

$$n = \int_{z_1}^{z_2} \int_{r_1}^{r_2} \rho(r_\perp, z) d\tau, \qquad (1)$$

with n as number of neutrons N, protons Z or mass A. Through a straight forward calculation, this is carried out here for the first time.

Result and Discussion

We first calculate the potential energy surfaces (PES) for ^{112,122}Ba nuclei, using the constrained RMF theory. The binding energy, the quadrupole deformation parameter β_2, and the root-mean-square radii of charge r_c and matter r_m for the ground state (g.s.) and 1st, 2nd, 3rd, etc., excited states (e.s.), including the scission state, are calculated and the result compared with Finite range droplet model (FRDM), Hartree-Fock-BCS (HFBCS) and experiment data whereever available, illustrated in TABLE I for ^{112}Ba .

Next, the density distributions for various solutions, with different deformation parameters β_2, of $^{112-122}$Ba are plotted, illustrated in FIG. 1 for their respective g.s. solutions.

From the density didtributions, we calculated the number of nucleons in different clusters formed inside the $^{112-122}$Ba nuclei, illustrated in the Table II for ^{112}Ba.

Summary and Conclusion

Analysing the nuclear density distributions, we get the internal or sub-structure of clusters in Ba isotopes. The first excited, oblate states of Ba isotopes consist of ^{12,13}C clusters. The ground-state solutions, in general, support the cluster configurations of heavier nuclei

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TABLE I: The RMF(NL3) results of binding energy, quadrupole deformation parameter β_2, the root-mean-square radii of charge r_c and matter r_m for the ^{112}Ba nucleus, ordered as the ground-state (g.s.) and 1st, 2nd, 3rd, etc., excited states (e.s.), including the scission state at the end, and compared with experimental data, the finite range droplet model (FRDM) and Hartree-Fock-BCS (HFBCS). The energy is in MeV, radii in fm.

Nucl.	BE		RMF		HFBCS	β_2		
	RMF	FRDM	r_m	r_c	r_c	RMF	Expt.	FRDM
^{112}Ba	895.4	894.9	4.62	4.74	4.72	0.24		0.21
	860.8		4.80	4.99	-0.39			
	882.4		5.35	5.48	1.24			
	897.3		12.17	12.21	10.71			

TABLE II: The number of nucleons $A_{clus.}$, the protons $Z_{clus.}$, and neutrons $N_{clus.}$ in clusters inside the ^{112}Ba nucleus for different solutions of deformations β_2 using the RMF(NL3) formalism. The clusters are listed as the ground state (g.s.), first excited state (e.s. I) and second excited state (e.s. II), etc., solutions. The ranges of integration in Eq. (1), i.e., $r_1, r_2; z_1, z_2$ (in fm), for each cluster are also given.

Nucleus	State	β_2	Cluster range $(r_1, r_2; z_1, z_2)$	$A_{clus.}$	$Z_{clus.}$	$N_{clus.}$	Cluster
^{112}Ba	g.s.	0.24	(1.9,4.5;-1.5,1.5)	36.0	17.7	18.3	^{36}Ar
			(-1.3,1.3;-2.6,-1.2)	13.0	6.3	6.7	^{13}C
	e.s.I	-0.39	(-0.7,0.7;-3.0,-1.7)	11.6	5.6	6.0	^{12}C
	e.s.II	10.71	(-6.3,6.3;-3.5,3.5)	1.6	0.7	0.8	^{2}H

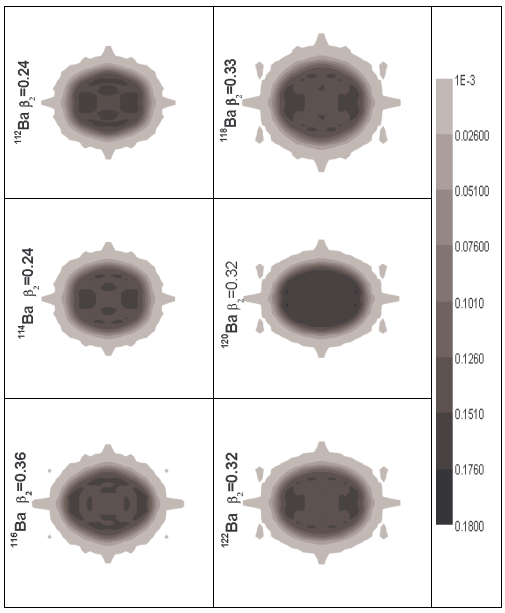

FIG. 1: The cluster confugurations of $^{112-122}$Ba for the ground-states in RMF(NL3).

such as Cl, Mg, Ar and Ca nuclei. With the increase of deformation to a fission stage (β_2 ∼10 or 11), the Ba nucleus breaks in to two fragments, releasing clusters of hydrogen isotopes $^{2,3}H$ or a ^{4}He nucleus from the neck region. This is an interesting result of the RMF(NL3) technique for nuclear structure physics.

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