DINUCLEAR SYSTEM PHENOMENA IN NUCLEAR STRUCTURE AND NUCLEAR REACTIONS*

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Properties of states of the alternating parity bands, as well as super- and hyper-deformed states are analyzed within a cluster model.

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1. Introduction

The relevant collective degrees of freedom of the dinuclear system (DNS) are the internuclear distance R and the mass (charge) asymmetry coordinate defined as $\eta = (A_1 - A_2)/(A_1 + A_2)$ $(\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2))$ where A_1 (Z_1) and A_2 (Z_2) are the mass (charge) numbers, respectively, of the clusters [1]. The mass (charge) asymmetry degree of freedom was successfully used to describe fusion and quasifission processes and to predict cross sections for producing superheavy nuclei [2]. Mass asymmetry coordinate can be also used in description of nuclear shape. The DNS potential energy as a function of η and η_Z in touching configuration region has a few local minima. The stationary eigenstates of this potential are localized in these minima. The characteristics (multipole moments and moment of inertia) of these states which are related to the oscillations in η (η_Z) and to rotation of a nucleus are close to those for the low-lying negative parity states, high- and low-spin super- (SD) and hyper-deformed (HD) states [3–5]. One can populate these SD and HD states in induced fission reactions and in heavy ion reactions by choosing appropriate reaction partners and bombarding energy.

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2. Alternating parity states

Our model is based on the assumption that the reflection-asymmetric shapes are produced by the collective motion in the mass asymmetry coordinate [3]. The ground state wave function in η can be thought as a superposition of different cluster-type configurations including the mononucleus configuration with $|\eta|$=1. The calculations in [3] have shown that in some nuclei the DNS configuration with an alpha cluster has a potential energy which is close or even smaller than the energy of the mononucleus at $|\eta| = 1$. The total wave function of a system

$$\Phi_L(\eta,\theta) = \left(\frac{2L+1}{8\pi^2}\right)^{1/2} D^L_{0M}(\theta)\left[1 \pm (-1)^L\right] \Psi_L(\eta)$$

is determined by solution of the stationary Schrödinger equation $H\Phi_L = E_L \Phi_L$, with the collective Hamiltonian

$$\hat{H} = -\frac{\hbar^2}{2B_\eta}\frac{d^2}{d\eta^2} + \frac{\hbar^2 \hat{L}^2}{2\Im(\eta)} + U(\eta)\,,$$

where B_η is the effective inertia of a nucleus with respect to η and $U(\eta) = B_1(\eta) + B_2(\eta) - B + V(\eta)$ is the potential [3]. Here, L, V, B, B_1 and B_2 are the spin of system, nucleus–nucleus interaction at the zero rotational energy and touching distance, binding energy of the mononucleus, experimental binding energies of the clusters forming the DNS at given η, respectively.

TABLE I

Comparison of experimental ($E_L^{\rm exp}$) and calculated ($E_L^{\rm calc}$) energies of states of the alternating parity bands in ^{222}Ra, ^{242}Pu, ^{146}Ba and ^{148}Nd. Energies are given in keV. Experimental data are taken from [6].

	^{222}Ra		^{242}Pu		^{146}Ba		^{148}Nd	
L^π	$E_L^{\rm exp}$	$E_L^{\rm calc}$	$E_L^{\rm exp}$	$E_L^{\rm calc}$	$E_L^{\rm exp}$	$E_L^{\rm calc}$	$E_L^{\rm exp}$	$E_L^{\rm calc}$
1^-	242	224	781	778	739	664	1023	734
2^+	111	96	45	45	181	143	302	279
3^-	317	324	832	843	821	818	999	943
4^+	302	287	147	146	514	469	752	776
5^-	474	486	927	958	1025	1078	1242	1261
6^+	550	550	306	304	958	958	1280	1280
7^-	703	728		1122	1347	1424	1645	1647
8^+	843	843	518	514	1483	1491	1856	1788
9^-	992	1014		1578	1778	1841	2132	2084
10^+	1173	1166	779	773	2052	2028	2472	2286

The relative contribution of each cluster component is determined by the eigenfunction Ψ_L which has a well defined parity with respect to the reflection $\eta \to -\eta$. In order to justify the interpretation of low-lying states as oscillations in mass asymmetry of the DNS, we described all observable characteristics [3] (parity splitting and electric dipole, quadrupole, octupole transition moments) of even–even nuclei $^{218-226}$Ra, $^{220-232}$Th, $^{230-238}$U, $^{236-244}$Pu, $^{142-146}$Ba, $^{144-148}$Ce and $^{146-150}$Nd for which the experimental data are available. The results of calculations agree well with the experimental data [6], especially of the variation of the parity splitting with A at low L and of the value of the critical angular momentum at which the parity splitting disappears (Table I).

3. SD and HD states

The moments of inertia and quadrupole deformations of certain DNS given in Table II are in a good agreement with experimental ones of SD and HD nuclei. Calculations were done taking into consideration the static polarization of nuclei in the DNS, due to the interaction between the nuclei. It is found that the SD states in ^{190,192,194}Hg and ^{192,194}Pb are connected to the dinuclear systems ^{8}Be+ ^{182,184,186}Os and ^{8}Be+ ^{184,186}Pt, respectively.

TABLE II

The calculated $\hbar^2/(2\tilde{\Im})$ (keV) ($\tilde{\Im} = 0.85\Im^{rb}$, $\Im^{rb}$ is rigid-body moment of inertia [3–5]), Q_2 ($10^2 e$ fm^2) and Q_3 ($10^3 e$ fm^3) rotational parameter, charge quadrupole and octupole moments, respectively, for different DNS corresponding to the SD nuclei, SD and HD fission isomers. $\hbar^2/(2\Im^{\rm exp})$ (keV), $Q_2^{\rm exp}$ ($10^2 e$ fm^2) are experimental data [7].

Cluster Config.	$\hbar^2/(2\tilde{\Im})$	$\hbar^2/(2\Im^{\rm exp})$	Q_2	$Q_2^{\rm exp}$	Q_3
^{194}Hg→^{8}Be+^{186}Os	6.06	$5.56^{+0.07}_{-0.07}$	14.2	$17.7^{+0.4}_{-0.4}$	8
^{194}Pb→^{8}Be+^{186}Pt	6.11	$5.65^{+0.47}_{-0.47}$	14.3	$20.1^{+0.19}_{-0.19}$	8
^{236}U→^{30}Mg+^{206}Hg	3.30	$3.36^{+0.01}_{-0.01}$	31	32^{+5}_{-5}	27
^{238}U→^{32}Mg+^{206}Hg	3.11	$3.27^{+0.03}_{-0.03}$	33	29^{+3}_{-3}	29
^{236}Pu→^{28}Mg+^{208}Pb	3.33		33	37^{+14}_{-8}	30
^{239}Pu→^{30}Mg+^{209}Pb	3.26	$3.36^{+0.01}_{-0.01}$	32	36^{+4}_{-4}	28
^{240}Pu→^{32}Mg+^{208}Pb	3.08	$3.343^{+0.003}_{-0.003}$	34		29
^{240}Am→^{32}Al+^{208}Pb	3.16		34	32.7^{+2}_{-2}	29
^{230}Th→^{50}Ca+^{182}Yb	2.1	$2.0^{+0.2}_{-0.2}$	73		42
^{231}Th→^{50}Ca+^{181}Yb	2.2	$2.0^{+0.2}_{-0.2}$	73		42
^{233}Th→^{50}Ca+^{183}Yb	2.1	$2.0^{+0.2}_{-0.2}$	74		43
^{234}U→^{50}Ca+^{184}Hf	2.1	$2.1^{+0.2}_{-0.2}$	73		43
^{236}U→^{50}Ca+^{186}Hf	2.1	$1.6^{+1.0}_{-0.4}$	73		43

The low-lying alternative parity states in the SD and HD structures are expected. One can explain the parity splitting by tunneling in η. In fission, the nuclear system passes through the cluster isomeric SD and HD states localized in the corresponding deep minima in the potential energy as a function of η (or η_Z). The work on these problems is in progress.

At the scission point in fission the system looks like DNS where both nuclei are highly deformed with respect to their equilibrium deformations. This interpretation of scission was checked by calculating the TKE and angular momenta of fission fragments [8]. The dependences of the TKE on the mass splitting are well described in the fission of ^{232}Th, ^{234,236}U, ^{240}Pu, ^{250,252}Cf and ^{258}Fm [9].

3.1. How to observe HD states populated in reactions

In order to form the HD states directly (without the stage of compound nucleus formation) in the heavy ion reactions the colliding nuclei must be trapped into the quasibound states (resonance states) of the nucleus–nucleus potential [5]. A long survival of the DNS (molecular type states) in the quasibound states against the decay in R or the evolution in η_Z (η) are fulfilled on the following conditions:

(1) The formed DNS must be cold (the internal excitation energy of system is practically zero), *i.e.* the optimal bombarding energy has to be taken (1–2) MeV below the Coulomb barrier (defined with taking the centrifugal potential into account) which means that the nuclei are captured into a quasibound state via the quantum tunneling effect;

(2) The initial DNS must be kept in a local minimum to prevent a motion in η (η_Z) asymmetry. This is possible if the DNS has a large angular momentum L;

(3) Target and projectile should be spherical and stiff with respect to deformation magic or double magic nuclei to satisfy (1) and(2).

Optimal bombarding energy $E_{\rm c.m.}$=117 (147) MeV, angular momenta window $L_{\rm min}$=70 (90) and $L_{\rm max}$=80 (100) for finding the HD states in heavy ion reaction ^{58}Ni+^{58}Ni (^{48}Ca+^{140}Ce) are obtained [5]. The upper limit of cross sections for the formation of HD states is estimated to be about 1 μb.

Our calculations show that the half-life $T^{qf}_{1/2} \geq 10^{-16}$ s for the considered DNS. Thus, the cluster states have quite long lifetimes. A rotating cold DNS decays mainly by low-energy E2 transitions between the quasibound HD states. For high values of $L > 70$ ($L > 90$), these quasibound states in the ^{58}Ni+^{58}Ni (^{48}Ca+^{140}Ce) system have the energy difference of about 1.4–2 MeV (0.7–1.1 MeV). We expect spectra with rotational band structure.

During the emission of radiation, the HD states can decay into fragments. Therefore, we propose a new experimental method of identification of the HD states by measuring rotational γ-quanta in coincidence with decay fragments of the DNS (Fig. 1) [5]. The spectroscopic investigation of the HD structures turns out to be not easy because of the low cross section and high background produced by the fusion–fission, quasifission and other processes.

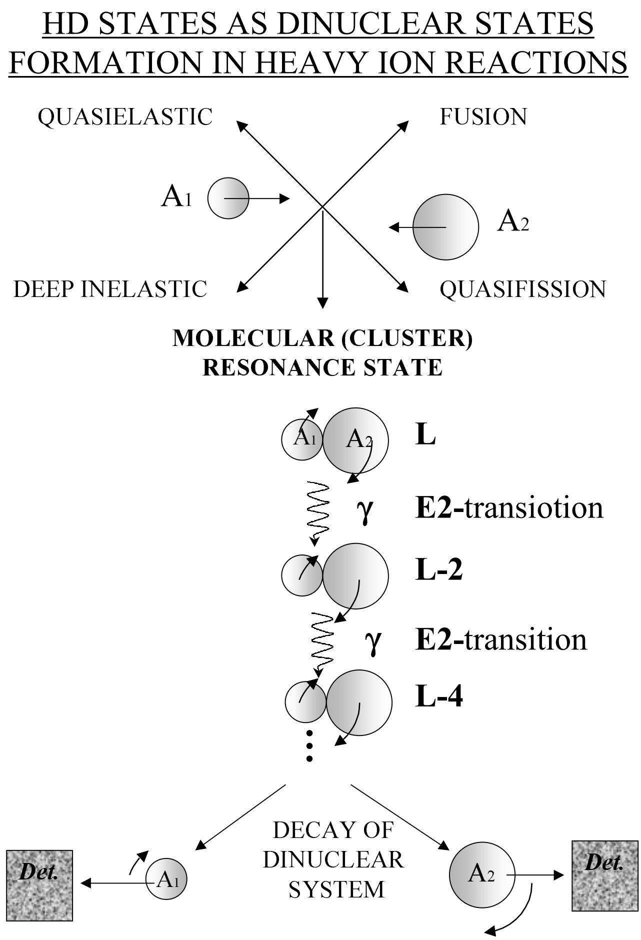

Fig. 1. Schematic picture of formation and identification of high-spin HD states.

3.2. Population of HD states in fission

The cold HD isomeric states may play a role of doorway-like states from which the fission can only occur through the limited number of paths in configuration space. After the evolution, the system decays mostly by configurations which are close to symmetric ones. There is a very small probability of decay of this initial doorway-like HD isomeric state. We can propose experimental method of identification of HD isomers by measuring the decay fragments of the isomeric DNS, where the light nucleus is ^{50}Ca (see Table II), at the energies of transmission resonances.

4. Summary

The manifestations of the cluster effects in the reactions and structure of heavy nuclei are illustrated within the framework of dinuclear system approach. A cluster interpretation of the properties of the alternating parity bands is suggested and justified by calculations in the different mass regions. In heavy nuclei the SD and HD states are interpreted as dinuclear-resonance states which can be formed directly in heavy ion and induced fission reactions. New experimental methods of the identification of HD states are proposed.

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