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ARE HYPERDEFORMED NUCLEI NUCLEAR MOLECULES?

G. G. ADAMIAN[a], N. V. ANTONENKO[a] and W. SCHEID[b]

[a]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[b]*Institut für Theoretische Physik der Justus-Liebig-Universität, Giessen, Germany*

Paper devoted to honour the memory of Professor Nikola Cindro

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A study of the interpretation of hyperdeformed nuclei as dinuclear quasimolecular cluster configurations is presented. Under the assumption that hyperdeformed states are quasimolecular resonance states, it is suggested to excite them directly in heavy-ion collisions. Signatures of hyperdeformed states in such reactions could be γ-transitions between these states and their decay into the nuclei forming the hyperdeformed nucleus.

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1. Introduction

Nuclear molecular states were first observed in the ^{12}C+^{12}C collision by Bromley et al. [1] and then seen up to the system Ni + Ni by Cindro et al. [2]. Reviews on these activities can be found in the Proceedings of the Adriatic Conferences organized by Cindro [3]. The question arises whether heavier nuclear systems have excited states with the properties of molecular (or cluster) states. Such states could be the hyperdeformed (HD) states which are explained by nuclear shapes with a ratio of axes of 3 : 1 caused by a third minimum in the potential energy surfaces of the corresponding nuclei [4]. By using very effective 4π γ-ray spectrometers like EUROBALL and GAMMASPHERE, many high-spin superdeformed bands have been studied but no evidences were obtained for high-spin HD bands. An interesting observation in macroscopic-microscopic calculations was made that the third minimum of the potential energy surfaces of actinide nuclei belongs to a molecular configuration of two touching nuclei (clusters) [5], which is called dinuclear system (DNS) in the following. It was shown that dinuclear systems have the same quadrupole moments and moments of inertia as those measured for superdeformed states and estimated for HD states [6]. This similarity is already known for light α-particle-type nuclei where hyperdeformed and cluster-type states are seen as quasi-molecular states [7, 8].

The aim of this paper is to propose an experimental study proving whether hyperdeformed states can be interpreted as molecular resonance states. Such a possibility exists in collisions of heavy ions forming a dinuclear system decaying by characteristic γ-radiation or fissioning.

2. Dinuclear system model for molecular states

The concept of the dinuclear system [9] has manifold successful applications in the calculation of fusion cross sections for very heavy nuclei and of the mass and charge distributions in quasifission and in the investigation of nuclear structure effects involving cluster configurations [10]. The main coordinates of the DNS model are the relative distance R between the nuclei (clusters), and the mass and charge asymmetry coordinates defined as $\eta = (A_1 - A_2)/(A_1 + A_2)$ and $\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$, where A_1, A_2 and Z_1, Z_2 are the mass and charge numbers of the nuclei, respectively. The potential of the DNS is strongly repulsive for smaller distances and hinders the nuclei to amalgamate or fuse in the relative distance. Under the assumption of a small overlap of the nuclei in the DNS, the potential energy is semi-phenomenologically calculated [11]

$$U(R,\eta,L) = B_1 + B_2 + V(R,\eta,L) - [B_{12} + V'_{\mathrm{rot}}]. \tag{1}$$

Here, B_i ($i = 1,2$) are the asymptotic experimental mass excesses of the nuclei, $V(R,\eta,L)$ is the interaction between the nuclei,

$$V(R,\eta,L) = V_{\mathrm{C}}(R,\eta) + V_{\mathrm{N}}(R,\eta) + V_{\mathrm{rot}}(R,\eta,L), \tag{2}$$

consisting of the Coulomb potential, the nuclear part and the centrifugal potential $V_{\mathrm{rot}} = \hbar^2 L(L+1)/(2\Im)$. The nuclear part is calculated by a double folding procedure with a Skyrme-type effective density-dependent nucleon-nucleon interaction taken from the theory of finite Fermi systems [12]. The potential $U(R,\eta,L)$ is referred to the binding energy $B_{12} + V'_{\mathrm{rot}}(L)$ of the rotating compound nucleus. The moment of inertia of the DNS is calculated in the sticking limit

$$\Im = \Im_1 + \Im_2 + \mu R^2, \tag{3}$$

where μ is the reduced mass of relative motion, and the moments of inertia $\Im_i$ ($i = 1,2$) of the nuclei are calculated in the rigid body approximation for large angular momenta.

With these formulas we calculated the potentials $V(R, \eta, L)$ for the systems ^{48}Ca + ^{140}Ce and ^{90}Zr + ^{90}Zr as a function of the relative distance for various angular momenta. The potentials are shown in Fig. 1. They have a minimum around 11 fm at a distance which is $R_{\rm m} \approx R_1 + R_2 + 0.5$ fm where R_1 and R_2 are the corresponding nuclear radii. The depth of the minimum decreases with angular momentum and vanishes for $L > 100$ in the considered systems.

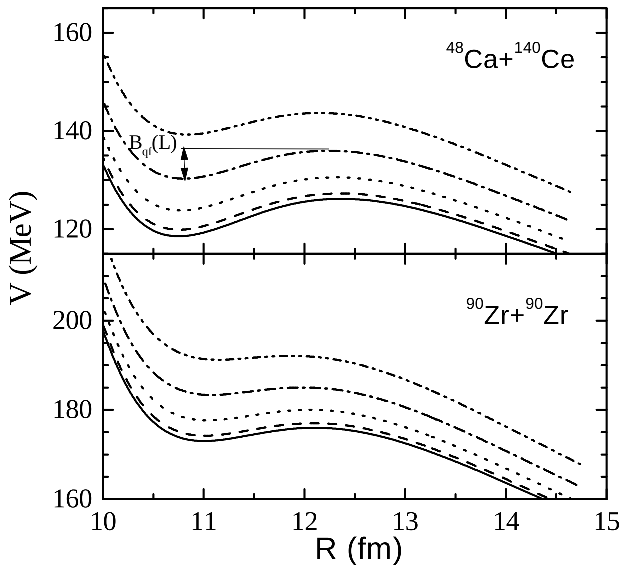

Fig. 1. The potential $V(R, L)$ for the systems ^{48}Ca + ^{140}Ce (upper part) and ^{90}Zr + ^{90}Zr (lower part) as a function of R for $L = 0$, 20, 40, 60, 80, presented by solid, dashed, dotted, dashed-dotted and dashed-dotted-dotted curves, respectively. $B_{qf}(L)$ depending on L is the height of the outer barrier with respect to the DNS minimum in the potential.

The potential pocket gives rise to virtual and quasibound states which are situated above and below the barrier, respectively. If we approximate the potentials around the minimum by a harmonic oscillator potential, we estimate an average energy of $\hbar\omega \approx 2.2$ MeV for $L > 40$. Therefore, these potentials have only one to three quasibound states. For example, in the ^{90}Zr + ^{90}Zr system we find the lowest quasibound state for $L = 50$ lying 1.1 MeV above the potential minimum.

3. Interpretation of quasibound states as hyperdeformed states and their formation in heavy ion collisions

The quadrupole moments of $(40 - 50) \cdot 10^2$ $e\,$fm^2 and the moments of inertia of $(160 - 190)$ $\hbar^2$/MeV of the quasibound dinuclear configurations ^{48}Ca + ^{140}Ce and ^{90}Zr + ^{90}Zr are close to those estimated for HD states. Therefore, we assume that it is justified to explain HD states by quasibound resonance states in the potentials shown in Fig. 1. The quasibound states have a long survival time against their decay through the quasifission barrier in the internuclear distance R and against mass transfer in the η coordinate. If the barrier in R is approximated by a parabola, the half-life of the DNS with respect to decay out of a quasibound resonance state can be calculated to be $T_{1/2} \geq 10^{-16}$ s which is equivalent to an escape width of $\Gamma \approx 10$ eV. In η coordinate, the potential $U(R = R_\mathrm{m}, \eta, L)$ has significant minima at $\eta = 0.49$ (^{48}Ca + ^{140}Ce) for the ^{188}Pt system and at $\eta = 0$ (^{90}Zr + ^{90}Zr) for the ^{180}Hg system (Fig. 2). These minima hinder the considered systems to exchange nucleons and to change the mass and charge asymmetries.

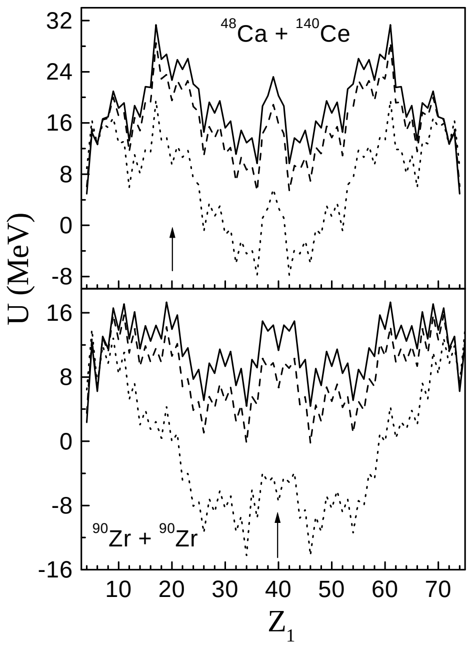

Fig. 2. The potential $U(R = R_\mathrm{m}(\eta, L), \eta_Z, L)$ of the dinuclear systems ^{188}Pt (upper part) and ^{180}Hg (lower part) as a function of the charge number of one of the clusters of the DNS. The calculated results for $L = 0$, 40, 80 are presented by solid, dashed and dotted curves, respectively. The arrows denote the DNS configurations ^{48}Ca + ^{140}Ce and ^{90}Zr + ^{90}Zr.

Assuming that HD states are quasibound states, we propose to produce these states in heavy ion reactions like ^{48}Ca on ^{140}Ce or ^{90}Zr on ^{90}Zr [13]. The following conditions should be fulfilled: 1. The formed DNS should be cold, i.e. the quasibound states should be directly excited by tunneling through the potential barrier including the centrifugal potential. 2. The initial DNS should stay in the potential minimum without changing the mass and charge asymmetries. Spherical and stiff nuclei (magic and double magic nuclei) fulfill this condition.

Using the cluster approach, we can calculate the cross section for penetrating the barrier and populating quasibound states as

$$\sigma(E_{\rm c.m.}) = \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}} \sum_{L=L_{\rm min}}^{L_{\rm max}} (2L+1) T_L(E_{\rm c.m.}). \tag{4}$$

Here, $E_{\rm c.m.}$ is the incident energy in the center of mass system, $T_L(E_{\rm c.m.})$ the transmission probability through the entrance barrier which is approximated by a parabola

$$T_L(E_{\rm c.m.}) = 1/\left(1 + \exp[2\pi(V(R_{\rm b}, \eta, L) - E_{\rm c.m.})/(\hbar\omega)]\right) , \tag{5}$$

where the position of the barrier is denoted by $R_{\rm b}$, and $\hbar\omega$ is the energy corresponding to the parabola. The angular quantum numbers $L_{\rm min}$ and $L_{\rm max}$ in Eq. (4) define the interval of angular momenta which contribute to the excitation of HD states. With decreasing angular momentum, the excitation energy of the DNS increases and more reaction channels are open. To keep the initial DNS cold, we introduce the lower limit $L_{\rm min}$. The calculation of $L_{\rm min}$ is given in Ref. [13]. At smaller values of L, the complete fusion is the main process which contributes to the reaction cross section. The maximal value $L_{\rm max}$ is determined by the grazing angular momentum. The range of partial waves leading to the excitation of quasibound states constitutes the so called molecular window, well known in the theory of nuclear molecules with light-heavy ions [8].

In the reaction ^{48}Ca on ^{140}Ce, cold and long living DNS states can be formed at an incident energy $E_{\rm c.m.} = 147$ MeV and $90 < L < 100$, and in the reaction ^{90}Zr on ^{90}Zr at $E_{\rm c.m.} = 180$ MeV and $40 < L < 50$. For both reactions we estimate a cross section (4) of about 1 μb. Also other reactions, namely ^{48}Ca + ^{144}Sm ($E_{\rm c.m.} = 149$ MeV, $80 < L < 90$), ^{48}Ca + ^{142}Nd ($E_{\rm c.m.} = 148$ MeV, $80 < L < 90$), and ^{38}Ar + ^{140}Ce, ^{142}Nd, ^{144}Sm ($E_{\rm c.m.} = 137, 141$ and 145 MeV, respectively, $80 < L < 90$) can be thought to be investigated for a possible observation of cluster-type HD states.

The spectroscopic investigation of the HD structures is difficult because of the small formation cross section and the high background produced by fusion-fission, quasifisson and other reactions. However, the latter processes have characteristic times much shorter than the life-time of the HD states which is of the order of 10^{-16} s. Therefore, the HD states appear as sharp resonance lines as a function of the incident energy. Because of their small widths, it is impossible to see them experimentally as resonances in an excitation function. However, they could be identified by measuring short cascades of rotational γ–transitions with energies of 0.5-1 MeV in coincidence with decay fragments of the DNS.

4. Conclusions

The HD states are interpreted as quasimolecular resonance states. They are characterized by sharp resonances decaying by γ-emission and into the nuclei by which they are formed. Therefore, if these signatures would be observed in heavy-ion experiments, it would be a unique proof of the idea that HD states are cluster-type states, and further that quasimolecular configurations also exist in heavier nuclear systems. Then the concept of nuclear molecular states would be not restricted to light and medium nuclear systems, but spread over the whole range of nuclear systems.

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DA LI SU HIPERDEFORMIRANE JEZGRE NUKLEARNE MOLEKULE?

Razmatramo da li se hiperdeformirane jezgre mogu tumačiti kao dvonuklearni kvazimolekulski nakupinski sustavi. Pretpostavljajući da su hiperdeformirana stanja rezonantna stanja, predlaže se njihova uzbuda izravnim sudarima teških iona. Znaci hiperdeformiranih stanja u takvim reakcijama mogli bi biti γ-prijelazi među tim stanjima i njihov raspad u jezgre koje su proizvele hiperdeformiranu jezgru.