

COMPETITION BETWEEN QUASI-MOLECULAR RESONANCES AND FUSION-FISSION IN LIGHT DINUCLEAR SYSTEMS*

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The results presented in this paper clearly suggest that a coherent framework may exist which connects the topics of heavy-ion molecular resonances, hyperdeformation effects, and fission shape isomerism. New data on particle-particle- γ triple coincidences of the $^{28}\text{Si}+^{28}\text{Si}$ reaction at a beam energy corresponding to the population of a conjectured $J^\pi = 38^+$ resonance in ^{56}Ni are presented. The absence of alignment of the spins of the outgoing fragments with respect to the orbital angular momentum is found to be in contrast with the alignment as measured for the $^{24}\text{Mg}+^{24}\text{Mg}$ resonances. A molecular-model picture is presented to suggest a “butterfly” motion of two oblate ^{28}Si nuclei interacting in a equator-to-equator molecular configuration.

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The interplay between the reaction dynamics and the nuclear structure of the interacting nuclei in light heavy-ion systems ($A_{cn} \leq 60$) has been the focus of a number of experimental and theoretical studies over the last decade [1–6]. It has been established that the fusion-fission (FF) process in such light dinuclear systems has to be taken into account when exploring the limitations of the complete fusion process at high excitation energies and large angular momenta [2]. The detailed analysis of mass distributions and the systematic investigation of different entrance channels populating a given compound nucleus (CN) supports the FF picture. This is the case for the ^{47}V nucleus as formed in statistical way by three different reactions [3]. Another example is given in Fig. 1 for the neighbouring ^{48}Cr CN as populated by two different entrance channels: $^{36}\text{Ar}+^{12}\text{C}$ [4] and $^{24}\text{Mg}+^{24}\text{Mg}$

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[5] the third reaction $^{32}\text{S}+^{24}\text{Mg}$ [6] leads to the ^{56}Ni CN which will be further investigated in this paper. The data [4–6] are plotted as solid points, whereas the histograms are FF model predictions as calculated by using the scission-point picture [7]. Transition-state model (TSM) calculations using the saddle-point picture [6] give very similar results. Typical excitation-energy spectra for the $^{32}\text{S}+^{24}\text{Mg}$ reaction are displayed for two bombarding energies in Fig. 2 and well compared with TSM calculations [6]. The FF mechanism is known to play a significant role at spins above the grazing angular momentum so that the nuclear configuration leading to the resonance behavior is only slightly more extended than that of the nuclear scission (saddle) point. In this paper we will report on very recent results showing for the first time that there exists a strong overlap between the FF process and the quasi-molecular resonant behavior in the interaction between two light nuclei.

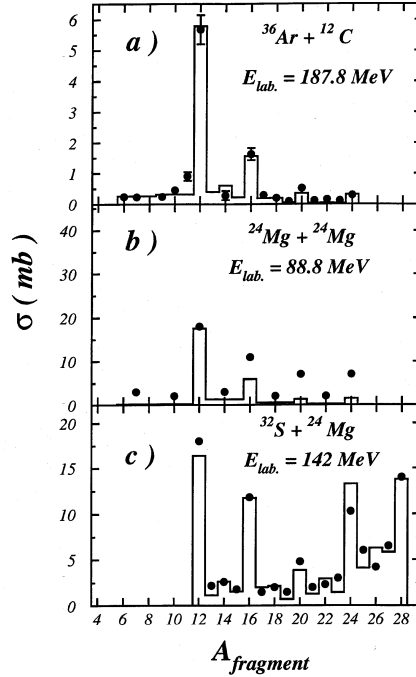


Fig. 1. Experimental mass distributions (solid points) as measured for (a) $^{36}\text{Ar}+^{12}\text{C}$ at 188 MeV [4], (b) $^{24}\text{Mg}+^{24}\text{Mg}$ at 88.8 MeV [5], (c) $^{32}\text{S}+^{24}\text{S}$ at 142 MeV [6] and compared to scission-point model calculations (histograms) using the Extended Hauser–Feshbach Method [7]. The input parameters were taken from complete fusion data and from the FF systematics [1,3,14].

Narrow-width resonances in excitation functions of $^{28}\text{Si} + ^{28}\text{Si}$ [8] and $^{24}\text{Mg} + ^{24}\text{Mg}$ [9] elastic and several inelastic scattering yields were found to be correlated among these channels and they were believed to be associated with quasi-stable configurations with extreme deformation. These very striking quasi-molecular resonant structures are possibly connected to a rather unusual subset of high-spin states stabilized against the mixing into the more numerous CN states by some special symmetry.

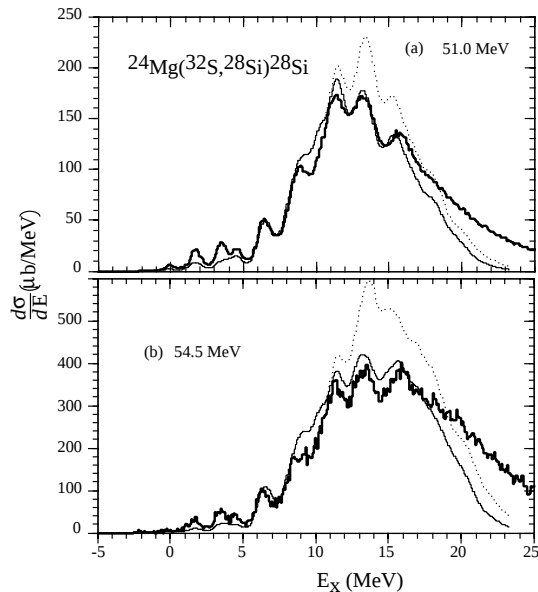


Fig. 2. Excitation-energy spectra for the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel for the $^{32}\text{S} + ^{24}\text{Mg}$ reaction at (a) 119.1 MeV and (b) 129.0 MeV [1,6]. The curves correspond TSM calculations [1] for fission decay to particle-bound states (solid curve) and for all decays (dotted curve).

This interpretation is supported by theoretical investigations indicating that shell-stabilized “hyperdeformed” shapes may exist in the ^{56}Ni and ^{48}Cr nuclei with large angular momenta [10]. Spin-alignment measurements [11] for the resonant $^{24}\text{Mg} + ^{24}\text{Mg}$ system [9] allow us to suggest a deformed configuration (with an axis ratio of 3:0) for the ^{48}Cr compound system that corresponds to two prolate deformed ^{24}Mg nuclei in a pole-to-pole arrangement. Due to the complexity of the resonance structure, where several narrow resonances are found to be described by the same resonance spin, their decay properties are difficult to be analysed within the Nilsson-Strutinsky approach [10] alone. This resonant behavior might be, however, understood in the framework of a molecular picture developed by Uegaki and Abe [12] using the strong-coupling limit. The motion of the two interacting ^{24}Mg nu-

clei in the $^{24}\text{Mg} + ^{24}\text{Mg}$ collision is here described with different vibrational excitations about the deformed equilibrium shape leading to a fragmentation of the resonance strength for a given spin value. Similar calculations have been done for the $\text{Si} + \text{Si}$ system [13], however with differences arising because of the oblate deformation of the ^{28}Si nucleus in its ground state. To explore these differences and to further develop the properties of the $^{28}\text{Si} + ^{28}\text{Si}$ resonances, an experimental study of the $^{28}\text{Si} + ^{28}\text{Si}$ collision at an energy corresponding to a conjectured $J^\pi = 38^+$ resonance in ^{56}Ni [8] has been undertaken. This study was motivated in part by the development of a new generation of state-of-art 4π γ -ray detector arrays that allows the high-precision measurements needed to determine the resonance properties.

Fragment-fragment- γ triple coincidence events of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction have been measured [14] at the VIVITRON Tandem facility at a resonance energy [8]. TSM model calculations [6] have been performed in order to well separate the resonant yields from a strong FF “background” as shown in Fig. 3 for the excitation-energy spectrum of the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel. The full spectroscopy [14] of the ^{28}Si exit-fragments shows that the resonant “signal”, as extracted from the Q -value spectra, is related to a long-lived di-nuclear system stabilized by a favorable oblate-oblate configuration before scission. Unexpected spin-alignment results are shown in Fig. 4 for the measured angular distributions (elastic, inelastic, and mutual excitation channels) which are well described by a single Legendre polynomial squared of order $L = 38$.

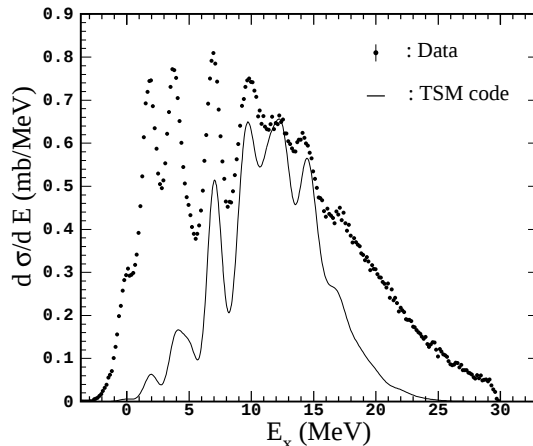


Fig. 3. Excitation-energy spectrum for the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at 111.6 MeV [14]. Efficiency corrected experimental data (solid points) are given as absolute cross sections. The curve corresponds to TSM calculations [1] for fission decay.

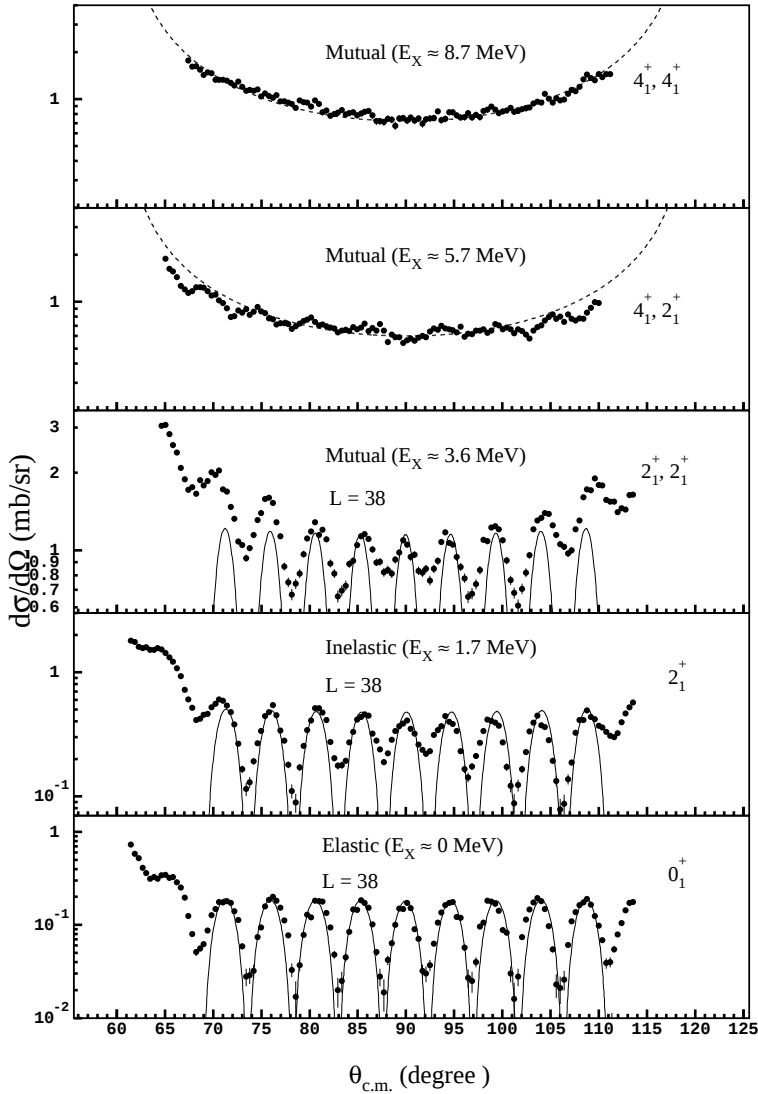


Fig. 4. Experimental angular distributions of the elastic ($E_x \approx 0$ MeV), inelastic ($E_x \approx 1.7$ MeV), mutual inelastic ($E_x \approx 3.6$ MeV) and mutual excitations ($E_x \approx 5.7$ and 8.7 MeV) for the $^{28}\text{Si} + ^{28}\text{Si}$ symmetric exit-channel [14]. The solid curves represent squared Legendre polynomial of order 38. The dotted curve corresponds to a $1/\sin \theta_{\text{c.m.}}$ behavior.

Fragment-fragment- γ coincidence data of the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel have been measured for the low-lying excitation states (single inelastic 2_1^+ and mutual inelastic $(2_1^+, 2_1^+)$ exit-channels) by using Eurogam Phase II.

Three quantization axes have been defined as follows : (a) corresponds to the beam axis, (b) axis normal to the scattering plane, and (c) axis perpendicular to the (a) and (b) axes. The fragment detectors are placed symmetrically with respect to the beam axis so that the ^{28}Si fragments are detected in the angular region $88^\circ \leq \theta_{\text{c.m.}} \leq 92^\circ$, then the (c) axis corresponds approximately to the molecular axis parallel to the relative vector between their two centers. The experimental results of the γ -ray angular correlations for the mutual excitation exit-channel 2^+-2^+ are shown in Fig. 5 as solid points. The minima observed in (a) and (b) at 90° imply that the intrinsic spin vectors of the 2^+ states lie in the reaction plane and are perpendicular to the orbital angular momentum. The value of the angular momentum remains close to $L = 38\hbar$ for the two exit channels, in agreement with the fragment-fragment angular distributions of Fig. 4. The feeding of the ^{28}Si states were also measured in this experiment [14]. The study of the feeding of the bands of ^{28}Si has revealed that the ^{28}Si is dominated by *oblate* deformation [14].

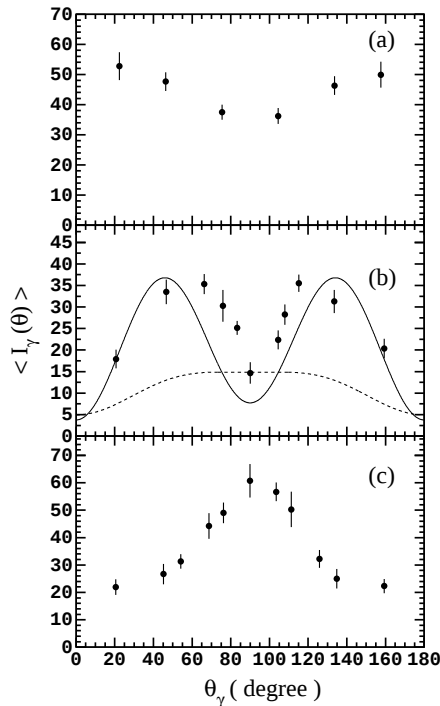


Fig. 5. Experimental γ -ray angular correlations of the mutual inelastic states $(2_1^+, 2_1^+)$ in the angular region $88^\circ \leq \theta_{\text{c.m.}}^{F.}(^{28}\text{Si}) \leq 92^\circ$ of the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel [14] for three quantization axes as defined in the text. The curves are molecular-model predictions discussed in the text.

The prolate-prolate system $^{24}\text{Mg} + ^{24}\text{Mg}$ has been shown to be characterised by spin alignment [11] in sharp contrast with the present results of the oblate-oblate system $^{28}\text{Si} + ^{28}\text{Si}$. Quasi-molecular resonances in the $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ collisions are examined in the framework of the molecular model [12,13]. The general ideas of the molecular model are based on the following considerations : the occurrence of elongated but stable dinuclear configurations and their characteristic normal-modes of motions at equilibrium may be linked to the observed resonant structures. A stable configuration of the $^{24}\text{Mg} + ^{24}\text{Mg}$ scattering is found to be a *pole-pole* configuration, due to the prolate shape of the interacting nuclei ^{24}Mg . Around the equilibrium various dynamical modes which may appear could be responsible for the observed narrow resonances. In an oblate-oblate system $^{28}\text{Si} + ^{28}\text{Si}$ (the ^{28}Si nucleus has an oblate shape) with high spins such as $38\hbar$, an equator-equator touching configuration is favored. In a Butterfly mode excitation, the interacting nuclei (fragments) move coherently, therefore the intrinsic spins of nuclei are always anti-parallel to each other, *i.e.*, the total intrinsic spin $I = 0$. On the other hand in an anti-butterfly mode, the spins are parallel in order to maximize the total spin.

Figs. 6 and 7 display molecular-model predictions on spin distributions of the normal-mode motions for $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ to the inelastic channel ($2_1^+, 2_1^+$). Fig. 6 shows (see panel B) that there is a concentration of the probabilities for channel spin of $I = 0$ for Butterfly motion. This is consistent with the experimental angular distributions with $L = J$ in Fig. 5. The curves in Fig. 5 correspond to the γ -ray angular distributions for the mutual inelastic channel of $^{28}\text{Si} + ^{28}\text{Si}$ obtained by using the molecular-model calculations [15] including the K -mixing and the "tilting" mode with $J = L = 38\hbar$ (solid curve) and $L = 34\hbar$ (dotted curve). The result of the $38\hbar$ curve exhibit strong concentration in " $m = 0$ " states, which appears to be in fairly good qualitative agreement with the experimental γ -ray distributions. The results of the calculations of Fig. 7 for $^{24}\text{Mg} + ^{24}\text{Mg}$ do not show a preference for the Butterfly mode which is consistent with experimental observation of spin alignment.

Particle-particle-gamma coincident measurements in the decay of the $^{28}\text{Si} + ^{28}\text{Si}$ 38^+ resonance [8] provide informations on the orientations of the fragments spins in the resonance state being on the reaction plane. The molecular model [13] which includes the K -mixing and give rise to a tilting mode assumes that the dinucleus configuration of oblate-oblate systems is axially non-symmetric. This is different from prolate-prolate cases such as $^{24}\text{Mg} + ^{24}\text{Mg}$ for which the pole-pole configuration is axially symmetric. $K = 0$ gives the isotropic distribution with orientations of the fragments spins (pancakes) having the same distribution. The angular distribution of gamma-ray emitted from the fragments is calculated with this spin distri-

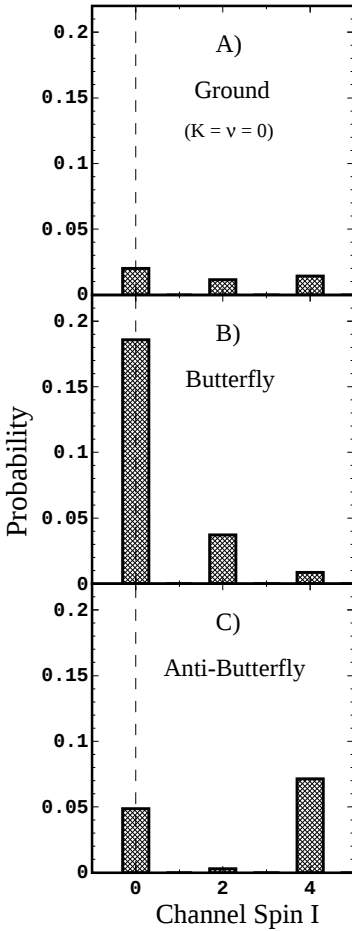


Fig. 6

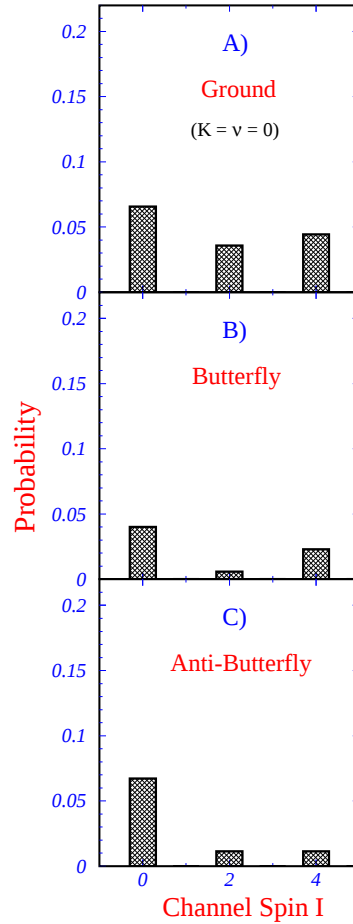


Fig. 7

Fig. 6. Molecular-model predictions [15] for the probability distributions of $^{28}\text{Si} + ^{28}\text{Si}$ ($[2_1^+ \otimes 2_1^+]$ with $L = J - I$) system versus channel spin I .

Fig. 7. Molecular-model predictions [15] for the probability distributions of $^{24}\text{Mg} + ^{24}\text{Mg}$ ($[2_1^+ \otimes 2_1^+]$ with $L = J - I$) system versus channel spin I .

bution and compared with the measurements in Fig. 5. The results exhibit strong concentration in “ $m = 0$ ” states, which may be in good agreement with the experimental γ -ray distribution. Work is in progress [15] for a reasonable comparison between the data and the calculated results. It seems that in the $^{28}\text{Si} + ^{28}\text{Si}$ system (oblate-oblate), the absence of spin alignment could result from a Butterfly motion and tilting mode.

The observation of spin alignment has been first made in $^{12}\text{C} + ^{12}\text{C}$ quasi-molecular resonances [16]. In this case the correlation between the spin orientations of the two ^{12}C nuclei in the mutual inelastic scattering has been deduced from the measured directional correlations of the particle-coincident γ -ray. Resonances in the excitation functions were found to be associated with the mutually aligned component. Two years after the observation of the spin alignment in $^{12}\text{C} + ^{12}\text{C}$ molecular resonances, Wuosmaa and collaborators [11] have measured the single and correlated magnetic-substate population parameters for 2^+ and 2^+-2^+ excitations in $^{24}\text{Mg} + ^{24}\text{Mg}$ (prolate-prolate system) in the region of two strong resonances observed in inelastic scattering [7]. These data [11] have provided spectroscopic informations relatively uncontaminated by nonresonant amplitudes, and allow spin assignment of $J^\pi = 36^+$ for two resonances $E_{\text{c.m.}} = 45.70$ and 46.65 MeV. The angular correlation data for the mutual 2^+ inelastic scattering channel suggest a dominant decay ℓ value of $\ell = 34\hbar$ for both resonances. Correlated spin alignment data for this channel confirm the expectations for the relationship between angular momentum coupling and spin alignment for these resonances. The relatively high spin values suggest a resonance configuration in which the two ^{24}Mg nuclei interact pole-to-pole, allowing the system to sustain a large amount of angular momentum. This results is well corroborated by the molecular model [12]. The competition between quasi-molecular resonances and FF in the $^{24}\text{Mg} + ^{24}\text{Mg}$ reaction was also investigated very carefully at Argonne [4,5] and FF yields from the $^{28}\text{Si} + ^{28}\text{Si}$ reaction are presently being measured at the VIVITRON facility [17].

The present fragment-fragment- γ coincident data on the $^{28}\text{Si} + ^{28}\text{Si}$ scattering as performed at the 38^+ resonance energy shows for the first time the absence of spin alignment in a heavy-ion collision. This has been primarily shown in the measured angular distributions of the elastic, inelastic 2^+ , and mutual excitation channels 2^+-2^+ , which are dominated by a pure and unique partial wave with $L = 38\hbar$, and has been confirmed by measuring their particle-particle- γ angular correlations. The non-resonant high-energy structures in the experimental energy spectra are well described by a FF picture as shown by Figs. 2 and 3 for both the $^{32}\text{S} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ entrance channels which both populate the ^{56}Ni CN. Further experimental investigations (inclusive FF measurements as well as light charged particle — fragments correlations measurements) of the fusion process of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction are underway at the VIVITRON facility using the ICARE charged particle multi-detector array [17]. Within the molecular model the lack of spin alignment is taken to suggest an excitation of the Butterfly mode in the vibrational motion of the observed resonance. Therefore a stable configuration is inferred to be an elongated one, namely an equator-to-equator touching configuration. The comparison between the three symmetric sys-

tems $^{12}\text{C} + ^{12}\text{C}$, $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ shows an interesting contrast in the spin orientation at resonance energies. The $^{28}\text{Si} + ^{28}\text{Si}$ oblate-oblate system is expected to be characterised with essentially no spin alignment in contrast to the observed spin alignment for $^{12}\text{C} + ^{12}\text{C}$ oblate-oblate system and $^{24}\text{Mg} + ^{24}\text{Mg}$ prolate-prolate system. The molecular-model calculations explain the absence of alignment in the oblate-oblate $^{28}\text{Si} + ^{28}\text{Si}$ system by a Butterfly motion.

The question to understand why the orientations of spin in the two oblate-oblate systems $^{28}\text{Si} + ^{28}\text{Si}$ and $^{12}\text{C} + ^{12}\text{C}$ are so different and why the weak-coupling picture works well in the $^{12}\text{C} + ^{12}\text{C}$ system is still open. On the other hand it is interesting to observe how well the molecular model (strong-coupling picture) works for the $^{28}\text{Si} + ^{28}\text{Si}$ dinuclear system. This is, of course, considered to be due to a possible difference of interactions between the constituent nuclei. Actually, the experiments show that in heavier systems, such as $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$, the resonances are observed to be correlated among many inelastic channels, suggesting that the interaction is effectively strong and that the resonance states include many components (partial widths) over reaction channels. The situation appears to be different in the lighter dinuclear systems such as $^{12}\text{C} + ^{12}\text{C}$. This problem requires more systematic experimental and theoretical studies. Experiments with the EUROBALL and GAMMASPHERE arrays are planned or already accepted in order to measure precise excitation functions of the $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{24}\text{Mg} + ^{12}\text{C}$ reactions which results will help in developing the differences and possible relationships between the heavy-ion resonance and compound-nucleus fission processes in light-mass dinuclear systems.

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