Spin Alignments in Heavy-ion Resonances

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Abstract

Recent particle-particle-$\gamma$ coincident measurements on a $^{28}$Si+$^{28}$Si resonance have suggested “vanishing spin alignments”. New analyses for spin alignments by using a molecular model are reported. Different aspects between di-nuclear systems with prolate deformed nuclei and those with oblate deformed nuclei are clarified.
1 Introduction

Resonances observed in heavy-ion scattering have offered intriguing subjects in nuclear physics. $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ resonances exhibit very narrow decay widths, with prominent peaks correlated among the elastic and inelastic channels, which suggest rather long lived compound nuclear systems. From the viewpoint of di-nuclear molecules, the present authors have studied normal modes around the equilibrium configurations, which are expected to be responsible to the observed resonances.

Very recently, $^{28}\text{Si} + ^{28}\text{Si}$ scattering experiment has been done on the resonance at $E_{\text{CM}} = 55.8\text{MeV}$ at IReS Strasbourg. Figure 1 shows angular distributions for the elastic and inelastic channels $2^+$, $(2^+, 2^+)$, respectively. The oscillating patterns are found to be in good agreement with $L = 38$, which suggests $L = J = 38$ dominance in the resonance, namely, misalignments of the fragment spins. Angular distributions of $\gamma$-rays from $^{28}\text{Si}$ first excited state to the ground state have been also measured in coincidence with two $^{28}\text{Si}$ nuclei detected at $\theta_{\text{CM}} = 90^\circ$. Figure 2 displays $\gamma$-ray intensities in the three panels, where quantizations are made for $z$-axis to be parallel to the beam direction in (a), $z$-axis parallel to normal to the scattering plane in (b) and $z$-axis parallel to the fragment direction in (c). The angular distribution in (b) shows characteristic "m=0" pattern, which suggests fragment spins $I_1$ and $I_2$ are on the scattering plane and is consistent with the misalignments observed in $^{28}\text{Si}$ angular distributions. Those features are much different from $^{12}\text{C} + ^{12}\text{C}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ systems, which exhibit spin alignments. The aim of the present paper is to clarify the mechanism of the appearance of spin misalignments in the resonance of $^{28}\text{Si} + ^{28}\text{Si}$ system.

![Figure 1: Experimental angular distributions for the elastic and inelastic scattering for $^{28}\text{Si} + ^{28}\text{Si}$ at $E_{\text{CM}} = 55.8\text{MeV}$. Solid curves show L=38 Legendre fits for comparison.](image1)

![Figure 2: $\gamma$-rays distributions obtained from particle-particle-$\gamma$ coincident measurements. Solid curves show $\chi^2$-fits. Dotted lines show the theoretical prediction obtained by the molecular model with tilting mode (K-mixings).](image2)
2 Di-nuclear Structure of $^{28}$Si + $^{28}$Si System

First, structures of the resonance states of $^{28}$Si + $^{28}$Si system and their normal modes around a stable configuration are briefly revisited. For simplicity, assuming a constant deformation and axial symmetry of the constituent nuclei, we have seven degrees of freedom $(q_i) = (\theta_1, \theta_2, \theta_3, R, \alpha, \beta_1, \beta_2)$, as illustrated in Fig. 3(a). Consistently with the coordinate system, we introduce a rotation-vibration type wave function as basis one,

$$\Psi_\lambda \sim D_{MK}^{IJ}(\theta_i) \chi_K(R, \alpha, \beta_1, \beta_2),$$

where $\chi_K$ describes internal motions. Dynamics of the internal motions have been solved around the equilibrium and various normal modes such as butterfly vibrations have been obtained, as is shown in Fig. 4(a).

Each mode has a characteristic feature with respect to the spin alignments. For example, butterfly motion shows the total intrinsic spin $I = 0$ dominance, namely, anti-alignment, which is very consistent with the fragments angular distributions. However the indication by the $\gamma$-ray measurements that the spin vectors $I_1$ and $I_2$ are both on the scattering plane provides more detailed information. In the following, we introduce a new mode in order to explain $\gamma$-rays data suggesting the fragments spin components $"m = 0"$. 

$\theta_3 = (\alpha_1 + \alpha_2)/2$

$\alpha = (\alpha_1 - \alpha_2)/2$

Figure 3: (a) Coordinate system of $^{28}$Si + $^{28}$Si. (b) Equilibrium configurations of di-nuclear systems. Upper panel is for $^{24}$Mg + $^{24}$Mg and lower panel for $^{28}$Si + $^{28}$Si.

With extremely high spins such as $30 \sim 40 \hbar$, stable di-nuclear configurations tend to be "elongated systems by the strong centrifugal force". In the prolate-prolate systems, a stable configuration is pole-to-pole one, while in the oblate-oblate systems, it is an equator-to-equator one. The former has axial symmetry as a whole, but the latter has axial asymmetry, as is displayed in Fig. 3(b). What would be expected from the difference of the symmetries? Approximately a triaxial system rotates around the axis with the maximum moments of inertia. In the oblate-oblate systems, thus two pancakes-like objects touching side-by-side as in the lower panel of Fig. 3(b) rotate around $x$-axis which is parallel to the normal to the reaction plane. The axial asymmetry, however, gives rise to a mixing of $K$-quantum numbers, which is different from the axial symmetric prolate-prolate cases. In the high spin limit ($K/J \sim 0$), the diagonalization in the $K$-space is found to be equivalent to solving a differential equation of the harmonic oscillator with parameters given by the moments of inertia. Thereby, the solution is a gaussian, or a gaussian multiplied by an Hermite polynomial,

$$f_n(K) = H_n\left(\frac{K}{b}\right) \exp\left[-\frac{1}{2}\left(\frac{K}{b}\right)^2\right],$$
3 Spin Alignments

We define scattering waves and the collision matrix $U_{c'c}$ such as

$$\psi \sim (G_c - iF_c) - \sum_{c'} U_{c'c}(G_{c'} + iF_{c'}).$$

(3)

By using the $R$-matrix formula with one level approximation, we obtain $U_{c'c} = e^{-i\phi_{c'}}(-2\sqrt{2\gamma_{c'l}}\gamma_{c'l'}\sqrt{2\gamma_{c'd}}e^{-i\phi_d}/\Gamma_{\text{total}}$ for the inelastic scattering, where the reduced widths $\gamma_{c'd}$ are calculated from the model wave functions.

The scattering amplitudes with specified magnetic substates are given by

$$A_{m_1,m_2}(k',k) = \frac{2\pi}{ik} \sum_{L',S',M} (22m_1m_2|S'M'_{S'})(L'S'm'M'_{S'}|JM) x i^{J-J'}e^{i(\sigma_J+\sigma_{J'})U_{L'S'}Y_{JM}(\hat{k})Y_{L'M'}(\hat{k}')}.$$  

(4)

The transition amplitudes for the $\gamma$-ray emissions from the polarized nuclei are discussed by several authors (see for example Ref. 8). Note that in the experiment, only one of two emitted photons is detected in most cases, even with EUROGAM. Note also that the intensities of the detectors are averaged over the azimuthal angle $\phi_\gamma$ in the data shown in Fig. 2 and then are expressed as $W(\theta_\gamma) = \sum_m P_m W_m(\theta_\gamma)$, where $P_m$ denotes the probability in the $m$ magnetic substate.
Now we calculate $P_m$’s and $W(\theta_i)$’s with the molecular model. Combining with the lowest state of the tilting mode in Eq. (2), i.e., $f_0(K) \sim \exp(-K^2/2b^2)$, we introduce a refined wave function,

$$\Psi_{JM}^{\lambda} \sim \sum_K \exp(-K^2/2b^2)D_{MK}^{JM}(\theta_i)\chi_K(R, \alpha, \beta_1, \beta_2), \quad (5)$$

where in general, $\chi_K$ can be any excitation mode. A simple choice is that all the internal motions are zero-point ones. In Fig. 2, theoretical results for $b = 1.3$ are shown by dotted lines, which are seen to be in good agreement with the data, in all the three axes (a), (b) and (c). This value of $b$ is consistent with the di-nuclear configuration of $^{28}\text{Si} + ^{28}\text{Si}$ system.

4 Concluding Remarks

Differences between the oblate-oblate system($^{28}\text{Si} + ^{28}\text{Si}$) and the prolate-prolate system ($^{24}\text{Mg} + ^{24}\text{Mg}$) has been manifested. Corresponding to the axial asymmetry by the equilibrium shape of $^{28}\text{Si} + ^{28}\text{Si}$ system, we have introduced $K$-mixings and have succeeded to explain the characteristic features for the spin misalignments. Those $K$-mixings, namely, the tilting mode would be a new facet in nuclear resonance phenomena. Further experimental study is strongly desired.

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