Oscillating-Correlated Nonstatistical Structures, Slow Spin Decoherence, and Hyperdeformed Coherent Rotational States in ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si Scattering

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Nonstatistical structures observed in ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si elastic and inelastic excitation functions produce channel-channel correlations and damped oscillations in the cross section energy autocorrelation functions. We present an interpretation of these nonstatistical effects assuming the formation of a highly excited dinucleus with strongly overlapping resonances in these scattering processes. We show that the essential features of the nonstatistical behavior of the excitation functions can be reproduced in terms of a slow spin decoherence of $\simeq$(4:1) hyperdeformed coherent rotational states excited in ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si scattering.

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Excitation functions for heavy-ion scattering generally demonstrate the presence of three basic energy scales [1]. Gross structure with width $\simeq$3–5 MeV is due to potential scattering and direct reactions. Intermediate nonstatistical structure with width $\simeq$0.5–1 MeV is often associated with the excitation of isolated molecular resonances [2–7]. The intermediate structure manifests itself in a strong ($\simeq$100%) channel-channel correlation and non-Lorentzian cross section energy autocorrelation functions (EAF). Fine statistical structure with width $\leq$0.1 MeV is usually presumed to originate from the decay of a hot intermediate system with strongly overlapping resonances. It is generally assumed that in the region of strongly overlapping resonances involving a large number of open channels the conventional statistical model [4], the theory of chaotic scattering [8–11], and the random-matrix theory [12] are applicable leading to Lorentzian EAF and the absence of channel-channel correlations. Since the three distinct energy scales correspond to different reaction mechanisms, the S-matrix elements with total spin J are usually represented [1] as $S^J(E) = \langle S^J(E)\rangle + \Delta S^J(E) + \delta S^J(E)$. Here the energy averaged S-matrix elements, $\langle S^J(E)\rangle$, are associated with potential scattering, the $\Delta S^J(E)$ correspond to the excitation and decay of isolated molecular resonances, and fluctuating around zero the $\delta S^J(E)$ produce statistical fluctuations.

The current understanding of heavy-ion scattering implies that the presence of intermediate ($\simeq$0.5–1 MeV) regular correlated structures in the excitation functions is an unambiguous indication that the $\Delta S^J(E)$, originating from the excitation and decay of isolated molecular resonances, are nonvanishing. In this Letter we demonstrate that the nonstatistical oscillating-correlated intermediate structures can also be generated by fluctuating $\delta S^J(E)$ even in the absence of isolated resonances [so that $\Delta S^J(E) = 0$], provided the heavy-ion scattering can be treated in terms of the formation of a hot strongly deformed dinucleus. For the ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si systems, which are analyzed in this Letter, the formation of a dinucleus is supported by the two-center shell model [$\simeq$(2:1) deformation] [13], the rotating liquid drop model [$\simeq$(2:1) deformation] [14], the cranked cluster model [$\simeq$(3:1) deformation] [15] for ^{48}Cr, and calculations in the framework of a deformed rotating shell model for both ^{48}Cr [$\simeq$(3:1) deformation] and ^{56}Ni [$\simeq$(2:1) deformation] intermediate systems [16]. Yet, in the region of strongly overlapping resonances of the intermediate system, strong deformation alone is obviously not sufficient to reproduce the nonstatistical oscillating-correlated structures observed in heavy-ion scattering. We show that the additional necessary conditions for these nonstatistical effects to occur in the region of strongly overlapping resonances are (i) correlations between $\delta S^J(E)$ with different J values and (ii) slow but finite spin decoherence. These off-diagonal spin correlations are generated spontaneously [17], allowing one to interpret [18] the non-self-averaging of the excitation function oscillations in strongly dissipative heavy-ion collisions [19]. We demonstrate that our approach reproduces both the channel-channel correlations and the nonstatistical oscillating intermediate ($\simeq$0.8 MeV) structures observed in the excitation functions for ^{24}Mg + ^{24}Mg [20] and ^{28}Si + ^{28}Si [21] elastic and inelastic scattering.

We consider first the scattering of identical spinless bosons neglecting the intrinsic spins of the reaction fragments. Using the asymptotic form of the Legendre polynomials for $J \gg 1$ we represent the cross section in the form $d\sigma(E,\theta)/d\theta \equiv \sigma(E,\theta) = \sigma_d(\theta) + \delta\sigma(E,\theta)$ with $\delta\sigma(E,\theta) = \delta\sigma^{(+)}(E,\theta) + \delta\sigma^{(-)}(E,\theta)$, $\delta\sigma^{(\pm)}(E,\theta) = |\delta f^{(\pm)}(E,\theta)|^2$, and $\delta f^{(\pm)}(E,\theta) = \sum_J (2J+1)W(J)^{1/2} \times \delta\tilde{S}^J(E)\exp[iJ(\Phi \pm \theta)]$, where only even J values contribute to the sum. In these expressions, $\sigma_d(\theta) = |F_d(\theta)|^2$ is the energy independent potential scattering cross section, Φ is the average deflection angle due to the J dependence of the potential phase shifts in the entrance and exit channels, $W(J)$ is the average partial

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reaction probability, and $\delta\bar{S}^J(E)$ are the normalized $[\langle|\delta\bar{S}^J(E)|^2\rangle = 1]$ fluctuating S-matrix elements. In the expression for $\sigma(E,\theta)$ we have dropped (i) the highly angle oscillating interference term between the $\delta f^{(+)}(E,\theta)$ and $\delta f^{(-)}(E,\theta)$ amplitudes, and (ii) the interference terms between the $F_d(\theta)$ and $\delta f^{(\pm)}(E,\theta)$ amplitudes. This is because the excitation function data for both ^{24}Mg + ^{24}Mg [20] and ^{28}Si + ^{28}Si [21] scattering were obtained by integration over a $\Delta\theta_{\mathrm{c.m.}} \simeq 65°–95°$ angular range. The diminishing of the interference terms between $F_d(\theta)$ and $\delta f^{(\pm)}(E,\theta)$ upon angle averaging for elastic ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si scattering is supported by optical model calculations [7,14]. These calculations demonstrate that the period of the angular oscillations due to potential scattering is about (1.5–2) times larger than the period of the observed near-grazing oscillations which originate presumably from the decay of a quasistationary strongly deformed intermediate system.

We calculate the EAF of $\sigma(E,\theta)$ and obtain $C(\varepsilon) = (1 - y_d)^2\delta C(\varepsilon)$, where $\delta C(\varepsilon) = \langle\delta\sigma(E + \varepsilon,\theta)\delta\sigma \times (E,\theta)\rangle/\langle\delta\sigma(E,\theta)\rangle^2 - 1$, $y_d = \sigma_d(\theta)/\langle\sigma(E,\theta)\rangle$ is the relative contribution of direct processes to the energy averaged cross section, and the brackets $\langle\cdots\rangle$ stand for energy averaging. It should be noted that due to the absence in $\sigma(E,\theta)$ of the interference terms between the energy averaged and fluctuating amplitudes, the direct reaction damping fluctuation factor, $(1 - y_d)^2$, in the above expression for $C(\varepsilon)$ differs from the Ericson result, $(1 - y_d^2)$, obtained in the presence of these interference terms.

In calculating $\delta C(\varepsilon)$ we take into account the S-matrix spin autocorrelation [17] $\langle\delta\bar{S}^J(E + \varepsilon)\delta\bar{S}^{J'}(E)^*\rangle = \Gamma/[\Gamma + \beta|J - J'| + i\hbar\omega(J - J') - i\varepsilon]$, where ω is the angular velocity of the coherent rotation, and β is the spin decoherence width. A similar expression, with $\beta = 0$, was obtained in Ref. [22]. However, in spite of the high dinuclear excitations, the derivation [22] relied on (i) a strong ($\simeq$100%) positive correlation between the partial width amplitudes with different J values, and (ii) an introduction of collective rotational degrees of freedom of the intermediate dinucleus. Both these assumptions are in sharp contrast with the random-matrix theory of highly excited nuclear states which assumes the absence of cross-symmetry correlation between partial width amplitudes [12] and a strong overdamping of the coherent nuclear motion [23]. In contrast, the S-matrix spin correlations [17] are generated spontaneously due to the extremely small $[\simeq \pm (D/\beta)^{1/2} \to 0]$ correlation between the partial width amplitudes with different J values. Also the S-matrix spin correlations [17] were obtained without introducing collective rotational degrees of freedom. Indeed, while such an introduction is fully justified [2–7,13–16] for excitations near the yrast line, for high intrinsic excitations these collective rotational states have large spreading widths [23] $\Gamma_{\mathrm{spr}} \gg \Gamma \simeq 100$ keV. Most importantly, for finite β, the spontaneous origin of the S-matrix spin correlations naturally leads to microchannel S-matrix correlations [18]. In contrast, the theory of Ref. [22] does not lead to such a microchannel S-matrix correlation.

We take $W(J)$ in the J-window form [24] with the average spin close to the grazing orbital momentum. The J-window width is given by the effective number of partial waves, g, contributing to $\delta\sigma(E,\theta)$ at a given energy of the colliding ions. We estimate $g \simeq 2–3$, which is supported by the shape of the measured elastic scattering angular distributions [20,25] corresponding to the maxima of the excitation functions. Although these angular distributions show regular oscillations with a well-defined period they also clearly deviate from the square of single Legendre polynomials.

We calculate $\delta C(\varepsilon)$ under the conditions $g \simeq 2–3$, $\beta \leq \Gamma$, and $\beta \ll \hbar\omega$, and obtain $\delta C(\varepsilon) = \delta C(\varepsilon = 0)\delta\bar{C}(\varepsilon)$, where

$$\delta C(\varepsilon = 0) = \exp(-\pi\Gamma/2\hbar\omega)\cosh[(\pi - 2\theta)\Gamma/\hbar\omega]/\cosh(\pi\Gamma/2\hbar\omega)\cosh[(\pi/2 - \theta)\Gamma/\hbar\omega], \quad (1)$$

$$\delta\bar{C}(\varepsilon) = \mathrm{Re}[\exp\{i\pi\varepsilon/[\hbar\omega - i\,\mathrm{sgn}(\varepsilon)\beta]\}/(1 - \exp\{i\pi(\varepsilon + i\Gamma)/[\hbar\omega - i\,\mathrm{sgn}(\varepsilon)\beta]\})]/ \\ \mathrm{Re}[1/(1 - \exp\{-\pi\Gamma/[\hbar\omega - i\,\mathrm{sgn}(\varepsilon)\beta]\})], \quad (2)$$

with $\delta\bar{C}(\varepsilon = 0) = 1$. Putting $\beta \to 0$ in Eq. (2) yields $[\omega - i\,\mathrm{sgn}(\varepsilon)\beta/\hbar] \to \omega$. This indicates that $\beta/\hbar$ has the physical meaning of the imaginary part of the angular velocity signifying the space-time delocalization of the dinucleus and the damping of the coherent nuclear rotation [17]. For $\beta = 0$, $\delta\bar{C}(\varepsilon)$ is an oscillating periodic function with period $2\hbar\omega$. For finite β, the amplitude of the oscillations in $\delta\bar{C}(\varepsilon)$ decreases with increasing $|\varepsilon|$: the larger β the stronger the damping of the oscillations.

Although Eqs. (1) and (2) are obtained for spinless reaction fragments, they also hold for reaction products with intrinsic spins. This can be shown [17] using the helicity representation for the scattering amplitude.

In Fig. 1 we present EAFs for ^{24}Mg + ^{24}Mg elastic and inelastic scattering on the $E_{\mathrm{c.m.}} = 42–56$ MeV interval [20,26]. These $C(\varepsilon)$'s are obtained [26] from the trend reduced original data with the averaging interval $\Delta E_{\mathrm{c.m.}} = 1$ MeV. The experimental $C(\varepsilon)$'s are not Lorentzian but oscillate with a period $\simeq$0.85 MeV. The fit of the experimental $C(\varepsilon)$ for the elastic channel is obtained with $\Gamma = 0.2$ MeV, $\beta = 0.1$ MeV, $\hbar\omega = 0.42$ MeV, and $y_d = 0.55$. One observes that the value of y_d extracted using our expression for $C(\varepsilon)$ and Eq. (1) differs considerably from the estimate $y_d = 0.96$ [26]. In Fig. 1 we also present fits of the inelastic $C(\varepsilon)$'s. These fits are obtained with the same set of Γ, β, and $\hbar\omega$

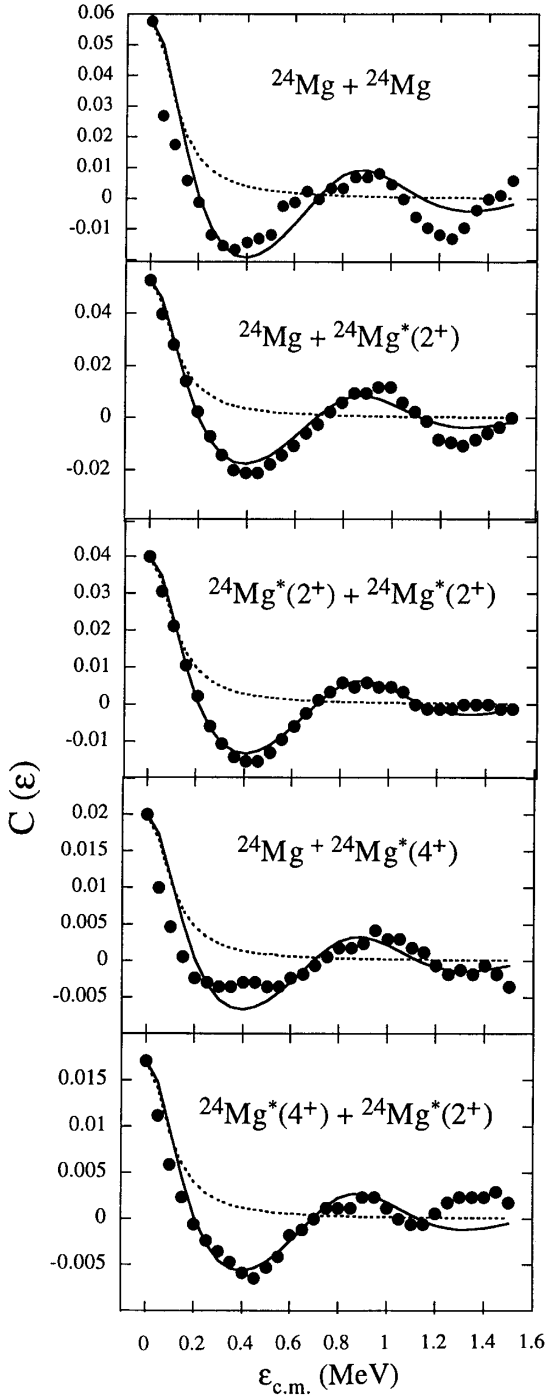

FIG. 1. Experimental (dots) and calculated (solid lines) $C(\varepsilon)$'s for ^{24}Mg + ^{24}Mg elastic and inelastic scattering on the $E_{\mathrm{c.m.}} = 42-56$ MeV energy interval (see text). Dashed lines are Lorentzians with $\Gamma = 0.11$ MeV.

as for the elastic channel, and the calculated $C(\varepsilon)$'s are normalized to the experimental EAFs at $\varepsilon = 0$. The extracted value of $\hbar\omega$ suggests an anomalous deformation of the intermediate dinucleus. Indeed, for $J \simeq 34-38$ [20], using the moment of inertia of a $\simeq$(2:1) superdeformed dinucleus yields $\hbar\omega \simeq 1.7-1.9$ MeV [6,14]. This suggests the excitation of $\simeq$(4:1) hyperdeformed coherent rotational states of ^{48}Cr.

We calculate the channel-channel correlation coefficient, k, following the same approach of Refs. [17,18] which has been used for the derivation of $\delta C(\varepsilon)$ (1) and (2). Using the above values of Γ, β, $\hbar\omega$, and taking $g = 3$, we obtain $k = 0.11$. We evaluate the experimental value of k by averaging over all the individual correlation coefficients [26] except for those corresponding to neighboring energy pairs of exit channels. These neighboring channels are not fully separated experimentally [14] which can lead to an overestimation of the effect of the correlation. We obtain $k_{\mathrm{exp}} = 0.19 \pm 0.05$. This is close to the theoretical estimate $k = 0.11$, supporting our interpretation in terms of strongly overlapping resonances of $a \simeq$ (4:1) hyperdeformed coherently rotating ^{48}Cr dinucleus. On the other hand, $k_{\mathrm{exp}} \simeq 1$ would support the interpretation of the nonstatistical correlated structures in terms of partially overlapping ($\Gamma \simeq D$) [27] or isolated ($\Gamma < D$) resonances.

In Fig. 2 we present EAFs for ^{28}Si + ^{28}Si elastic and inelastic scattering on the $E_{\mathrm{c.m.}} = 52.5-60.5$ MeV interval [21]. We obtained these $C(\varepsilon)$'s from the trend reduced original data with an averaging interval $\Delta E_{\mathrm{c.m.}} = 1.5$ MeV [21]. The fit of the experimental $C(\varepsilon)$ for the elastic channel is obtained with $\Gamma = 0.05$ MeV, $\beta = 0.05$ MeV, $\hbar\omega = 0.4$ MeV, and $y_d = 0.81$. This value of y_d differs considerably from the estimate $y_d = 0.985$ [21]. In Fig. 2 we also present the calculated inelastic $C(\varepsilon)$'s obtained with the same set of Γ, β, and $\hbar\omega$ as for the elastic channel. The calculated inelastic $C(\varepsilon)$'s are normalized to the experimental EAFs at $\varepsilon = 0$. One can see that the agreement between the data and the calculated EAFs is not as consistent as for the ^{24}Mg + ^{24}Mg system. The data are rather scattered around the calculated curves. In order to further check our interpretation we construct the EAF for the cross section summed over the elastic and three inelastic channels. Such a summation is expected to enhance the correlated nonstatistical structure if it is present in all the channels. One can see in Fig. 2 that $C(\varepsilon)$ for the summed cross section does show a noticeable maximum at $\varepsilon = 0.8$ MeV supporting our interpretation. For $J \simeq 36-40$ [25] calculation of the moment of inertia of a superdeformed $\simeq$(2:1) ^{56}Ni dinucleus yields $\hbar\omega \simeq 1.6-1.8$ MeV [6]. Since our analysis gives $\hbar\omega = 0.4$ MeV this suggests the excitation of $\simeq$(4:1) hyperdeformed coherent rotational states of ^{56}Ni in ^{28}Si + ^{28}Si scattering. We also calculate the channel-channel correlation coefficient with the above values of Γ, β, $\hbar\omega$, and taking $g = 3$. We find $k = 0.14$ while $k_{\mathrm{exp}} = 0.18 \pm 0.06$. The nonvanishing of the channel-channel correlation is due to the finite spin decoherence width. This correlation is predicted [18] to vanish in both (i) the limit of the regular coherent rotation $\beta/\Gamma \to 0$ [17] and (ii) the compound nucleus limit $\Gamma/\beta \to 0$.

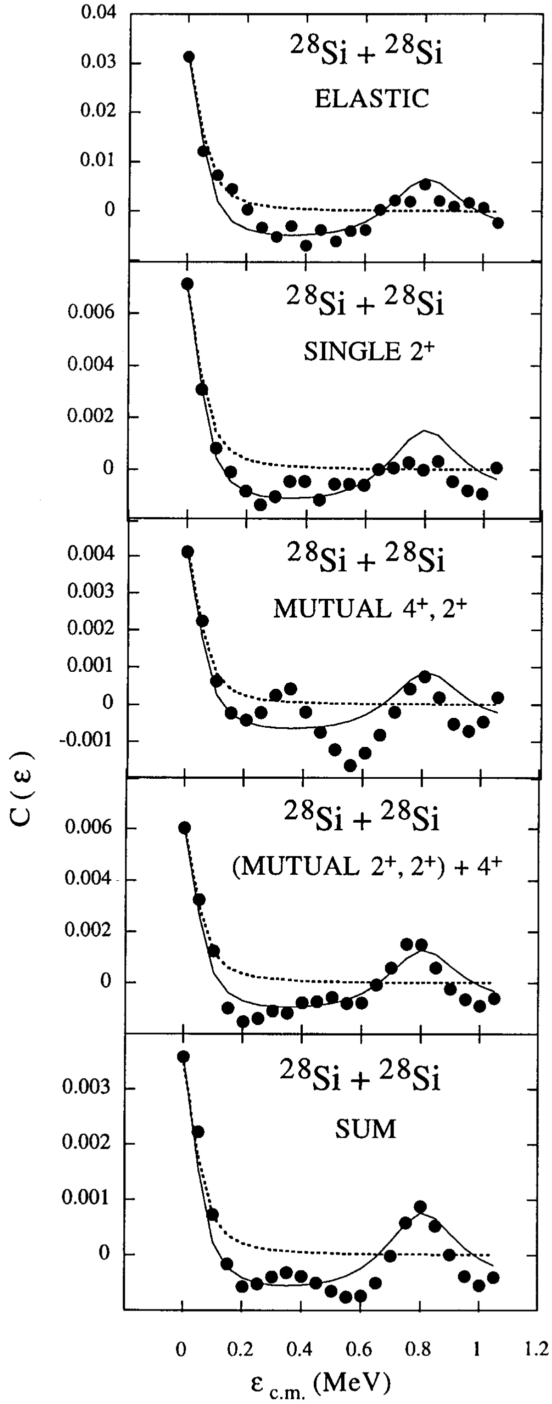

FIG. 2. Experimental (dots) and calculated (solid lines) $C(\varepsilon)$'s for ^{28}Si + ^{28}Si elastic and inelastic scattering on the $E_{\mathrm{c.m.}} = 52.5-60.5$ MeV energy interval (see text). Dashed lines are Lorentzians with $\Gamma = 0.05$ MeV.

In conclusion we have presented an interpretation of the oscillating-correlated intermediate ($\simeq$0.8 MeV) structures observed in ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si elastic and inelastic scattering. We have shown that the essential features of these nonstatistical effects can be reproduced in terms of the slow spin decoherence of hot coherently rotating $\simeq$(4:1) hyperdeformed quasimolecules formed in these scattering processes.

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