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Coherently rotating hyperdeformed quasimolecules in ^{12}C+^{24}Mg scattering?

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We present an interpretation of oscillations in the energy autocorrelation functions for ^{12}C+^{24}Mg scattering assuming that the scattering process can be treated in terms of formation and decay of a dinucleus with strongly overlapping resonances. It is shown that these oscillations can be interpreted in terms of a slow spin decoherence and time-space localization of a coherently rotating hyperdeformed intermediate system. This coherent rotation allows us to reconstruct the time evolution of the long-lived intermediate dinucleus back into the past as far as the moment of its formation. Our analysis indicates that for spin values $\simeq 20-25\hbar$ and at $\simeq$50 MeV excitation energy hyperdeformation (3:1) of ^{36}Ar terminates and is replaced by (2:1) deformation. New experiments are proposed to test our interpretation. [S0556-2813(99)50102-7]

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The structures observed in excitation functions for relatively light heavy-ion scattering are often associated with the excitation of isolated molecular resonances with fixed total spin J and parity π values [1,2]. However such an interpretation is no longer applicable for heavier colliding systems [3] where the maxima in the excitation functions occur due to the interference between overlapping molecular levels with different (J,π). Yet the departure from the picture of isolated resonances occurs not only for heavy systems. For example, the data for ^{12}C+^{24}Mg elastic and inelastic scattering [4] do not correlate: the maxima in the excitation functions for different channels appear at different energies. Also the analysis of angular distributions corresponding to the maxima of back-angle excitation functions in the ^{12}C+^{24}Mg scattering revealed [5] the presence of many partial waves rather than a single spin value. At first sight, these experimental results indicate a statistical origin of the energy structures in the ^{12}C+^{24}Mg scattering [4] suggesting an interpretation within the conventional statistical model [6] and the Ericson theory [7]. However such an interpretation is not consistent because the oscillating cross section energy autocorrelation functions (EAFs) are non-Lorentzian, resembling the oscillations in the correlation functions for the magnetoconductance of quantum dots [8] due to the relatively slow dephasing of the electron wave function.

In this paper we analyze the quasiperiodic oscillations in the ^{12}C+^{24}Mg back-angle scattering within the approach [9] developed originally to interpret the forward peaking of evaporating particles [10] and the nonself-averaging of excitation function oscillations [11,12] in dissipative heavy-ion collisions [13]. This approach suggests that in the region of strongly overlapping resonances of the intermediate system the correlations between the fluctuating S-matrix elements with different (J,π) values are generated spontaneously.

Our basic assumption is that the heavy-ion scattering can be treated in terms of the formation and decay of a strongly deformed intermediate system [14,15]. This assumption can be justified within the two-center shell model [14,15] provided the ion-ion potential has a pocket. Potentials of this type have been successfully applied to describe the excitation of isolated quasimolecular resonances in light-heavy-ion scattering [1,2,14,15]. The calculation demonstrates the existence of a pocket in the double-folding potential for the rotating ^{12}C+^{24}Mg system [16]. As the relative kinetic energy transfers into intrinsic excitation the pocket is expected to deepen [16], and the ions drop into this pocket forming a dinucleus with overlapping resonances [14–16]. The formation of a rotating dinucleus in heavy-ion collisions is also supported by TDHF calculations [17].

Since at $\theta=\pi$ the relative contribution of potential scattering into the cross section amounts to $\simeq$70% [4], the oscillations in the excitation functions originate from the interference between the energy averaged and oscillating amplitudes. This allows us to reconstruct the time power spectrum (TPS) of the collision. The TPSs, which are similar for both elastic and inelastic scattering, consist of two noticeable peaks indicating slow spin decoherence and coherent rotation of the hyperdeformed intermediate nucleus. This is a manifestation of the previously suggested orbiting [18] and lighthouse [19] effects. Our analysis also indicates that for $J\simeq 20-25$ and at $\simeq$50 MeV excitation energy in ^{36}Ar the hyperdeformation (3:1) terminates and is replaced by a (2:1) deformation supporting the prediction [20].

The cross section of $\sigma(E,\pi)$ for elastic scattering at $\theta=\pi$ has the form $\sigma(E,\pi)=|\langle f(E,\pi)\rangle+\delta f(E,\pi)|^2$. The energy (E) averaged amplitude $\langle f(E,\pi)\rangle$ describes the potential scattering corresponding to a very short ($\simeq 10^{-22}$ sec) time duration of the collision. There is also a time-delayed reaction mechanism associated with the formation of a relatively long-lived intermediate system. It is described by the energy oscillating amplitude $\delta f(E,\pi)=\Sigma_J(2J+1)\exp[i(\Phi+\pi)J]\delta S^J(E)$, where Φ is the deflection angle due to the J dependence of the potential phase shifts. The fluctuating S-matrix elements, $\delta S^J(E)=W(J)^{1/2}\delta\underline{S}^J(E)$, give rise to the energy dependence of $\sigma(E,\pi)$, where $W(J)=\langle|\delta S^J(\underline{E})|^2\rangle$ is the average partial probability of the process and $\delta\underline{S}^J(E)$ is the normalized fluctuating S-matrix. In the region of strongly

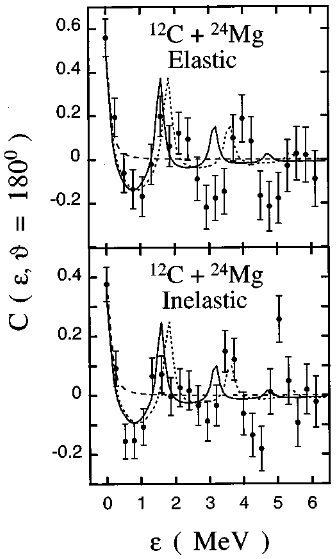

FIG. 1. Experimental $C(\varepsilon,\pi)$ and theoretical fits (solid and dotted lines) for $^{12}\mathrm{C}+^{24}\mathrm{Mg}$ elastic and inelastic scattering on the $E_{\mathrm{c.m.}}=24$–35 MeV energy interval (see text). Dashed lines are Lorentzians with $\Gamma=130$ KeV.

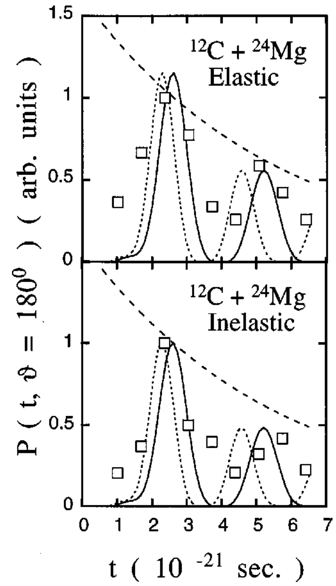

FIG. 2. Experimental $P(t,\pi)$ and theoretical fits (solid and dotted lines) for $^{12}\mathrm{C}+^{24}\mathrm{Mg}$ elastic and inelastic scattering on the $E_{\mathrm{c.m.}}=24$–35 MeV energy interval (see text). Dashed lines correspond to the exponential decay.

overlapping resonances of the intermediate system the energy dependence of $\sigma(E,\pi)$ is studied in terms of the cross section EAF [7] $C(\varepsilon,\pi)=[|\rho(\varepsilon,\pi)|^2+2\sigma_{\mathrm{dir}}\,\mathrm{Re}\,\rho(\varepsilon,\pi)]/\langle\sigma(E,\pi)\rangle^2$, where $\rho(\varepsilon,\pi)=\langle\delta f(E+\varepsilon,\pi)\,\delta f(E,\pi)^*\rangle$, $\sigma_{\mathrm{dir}}=|\langle f(E,\pi)\rangle|^2$, $\langle\sigma(E,\pi)\rangle=\sigma_{\mathrm{dir}}+\langle\sigma_{\mathrm{osc}}(E,\pi)\rangle$, and $\langle\sigma_{\mathrm{osc}}(E,\pi)\rangle=\rho(\varepsilon=0,\pi)$. The Ericson theory yields $\langle\delta S^J(E+\varepsilon)\,\delta S^{J'}(E)^*\rangle=\delta_{JJ'}(1-i\varepsilon/\Gamma)$ and, therefore, $|\rho(\varepsilon,\pi)|^2\propto\mathrm{Re}\rho(\varepsilon,\pi)\propto C(\varepsilon,\pi)\propto(\varepsilon^2+\Gamma^2)^{-1}>0$, where Γ is the total decay width of the intermediate system.

In Fig. 1 we present $C(\varepsilon,\pi)$ for $^{12}\mathrm{C}+^{24}\mathrm{Mg}$ elastic scattering. It is obtained by applying the linear approximation [12] of the Pappalardo trend reduction method [21] to the original data [4] on the $E_{\mathrm{c.m.}}=24$–35 MeV interval. For this interval $\sigma(E,\pi)$ resembles a quasistationary random process, while at $E_{\mathrm{c.m.}}\simeq35$ MeV $\sigma(E,\pi)$ abruptly decreases and undergoes a sharp transition to noticeably broader energy structures for all the elastic and inelastic measured channels. The experimental $C(\varepsilon,\pi)$ (Fig. 1) is not Lorentzian but oscillates taking negative values. This can also be seen from the Fourier transform (Fig. 2) of $C(\varepsilon,\pi)$, which consists of two distinct peaks instead of having the form $\exp(-\Gamma t/\hbar)$ typical for the decay of a fully equilibrated compound nucleus. Therefore, oscillations in $C(\varepsilon,\pi)$ indicate the existence of a stable mode of motion of the intermediate system. The study of medium weight heavy-ion collisions suggests [3,11,12] that coherent rotation is a stable nuclear mode. Coherent rotation originates from the spin correlation [9] $\langle\overline{\delta S^J}(E+\varepsilon)\,\overline{\delta S^{J'}}(E)^*\rangle=\Gamma/[\Gamma+\beta|J-J'|+i\hbar\omega(J-J')-i\varepsilon]$, where ω is the angular velocity of the coherent rotation and β is the spin decoherence width. This spin correlation can be obtained for both strongly overlapping [9] and partially overlapping [22] resonances of an intermediate system although its origin is essentially different for these two regimes. The underlying physical picture becomes more transparent if we study the Fourier transform of $C(\varepsilon,\pi)$, provided $C(\varepsilon=0,\pi)\leqslant0.5$. In this case $|\rho(\varepsilon=0,\pi)|^2\ll2\sigma_{\mathrm{dir}}\,\mathrm{Re}\,\rho(\varepsilon=0,\pi)$and $C(\varepsilon,\pi)\propto\mathrm{Re}\,\rho(\varepsilon,\pi)$.

Let us consider the TPS of the collision: $P(t,\pi)\propto\int_{-\infty}^{\infty}d\varepsilon\,\exp(-i\varepsilon t/\hbar)\rho(\varepsilon,\pi)$. Since $P(t,\pi)$ is real and $P(t<0,\pi)=0$, we have $P(t,\pi)\propto\int_0^\infty d\varepsilon\,\cos(\varepsilon t/\hbar)\mathrm{Re}\,\rho(\varepsilon,\pi)\propto\int_0^\infty d\varepsilon\,\cos(\varepsilon t/\hbar)C(\varepsilon,\pi)$, i.e., the Fourier transform of the experimental $C(\varepsilon,\pi)$ is the TPS of the collision. Taking $W(J)=W(|J-I|/d)$ in the J-window form, where I is the average spin and d is the J-window width, we obtain

$$P(t,\pi)\simeq\exp(-\Gamma t/\hbar)[1-\exp(-2\beta t/\hbar-2\Delta)]/|1-\exp[i(\omega t-\Phi-\pi)-\beta t/\hbar-\Delta]|^2 \tag{1}$$

independent of the actual shape of the $W(J)$. In Eq. (1) $\Delta\simeq1/d$ is the angular dispersion of the wave packets at $t=0$. For $d\to0$ (single spin value) and/or $\Gamma/\beta\to0$ (compound nucleus limit), $P(t,\pi)\to\exp(-\Gamma t/\hbar)$. However for finite Δ and Γ/β, $P(t,\pi)$ shows maxima at $t_m=(\Phi/2\pi+1/2+m)T$, where $T=2\pi/\omega$ is the period of one complete dinuclear revolution and $m=0,1,\ldots$. Since $\Phi\leqslant\theta_{gr}\simeq20°$ [5], $t_0\simeq T/2$ and $t_1\simeq3T/2$, i.e., $t_1/t_0\simeq3$ and $t_1-t_0\simeq2t_0\simeq T$. In contrast, the experimental TPS indicates $t_1/t_0\simeq2$ and $t_1-t_0\simeq t_0\simeq T/2$, i.e., the second peak appears earlier, after just one half of a revolution instead of after one complete revolution as follows from Eq. (1). Even though the indication of the second peak in the experimental TPS may not seem reliable the question arises of what additional assumptions are needed to account for its "wrong" position within the present interpretation. Let us take the decoherence width, $\beta_>$, between the strongly overlapping states with different J and different π (odd $|J-J'|$-values) to be greater than the decoherence width, $\beta_<$, between the states with different J but the same π (even $|J-J'|$-values). This yields $P(t,\pi)\propto P_{\mathrm{even}}(t,\pi)+P_{\mathrm{odd}}(t,\pi)$ with

$$P_{\rm even}(t,\pi)\simeq\exp(-\Gamma t/\hbar)[1-\exp(-4\beta_< t/\hbar-4\Delta)]/|1-\exp[2i(\omega t-\Phi-\pi)-2\beta_< t/\hbar-2\Delta]|^2,$$

$$P_{\rm odd}(t,\pi)\simeq 2\exp(-\Gamma t/\hbar)\cos(\omega t-\Phi-\pi)\times\exp(-\beta_> t/\hbar-\Delta)\times(1-\exp(-2\beta_> t/\hbar-2\Delta))/|1-\exp[2i(\omega t-\Phi-\pi)-2\beta_> t/\hbar-2\Delta]|^2, \quad (2)$$

which takes the form (1) for $\beta_>=\beta_<=\beta$. For sufficiently large $\beta_>$, $P_{\rm odd}(t\simeq T,\pi)$ is negligible, and, for $\Phi\leqslant 20°$, $P(t,\pi)\simeq P_{\rm even}(t,\pi)$ has the first maximum at $t_0=(\Phi+\pi)/\omega\simeq T/2$ and the second one at $t_1=(\Phi+2\pi)/\omega\simeq T$ so that $t_1-t_0=T/2$. However the value of $\beta_>$ is restricted from above: $\beta_><\hbar\omega/(\Phi+\Delta)$, to insure that $P(t=0,\pi)\to 0$. This suggests the following physical picture. At an early stage, $t\ll\hbar/\beta_>$, the coherently rotating asymmetric dinucleus is predominantly oriented along the $\theta\simeq\omega t$ direction. This corresponds to a single ''beam'' in the ''lighthouse'' effect [19]. As time proceeds, the dinuclear configuration gradually develops a reflection symmetry and, for $t\geqslant\hbar/\beta_>$, the asymmetric dinucleus is oriented in two opposite directions with equal probability. This corresponds to the appearance of the second ''beam of the lighthouse'' directed opposite to the first one.

The fit to the experimental TPS in Fig. 2 is obtained with $W(J)=\exp[-(J-I)^2/d^2]$, $d=2$ (so that the effective number of the partial waves $\simeq$3–4 [5]), $\Phi=0$, $\Gamma=0.13$ MeV, $\beta_<=10$ keV, $\beta_>=0.4$ MeV, $\hbar\omega=0.8$ MeV (solid line), and $\hbar\omega=0.9$ MeV (dotted line). $C(\varepsilon,\pi)$'s calculated with these sets of parameters are presented in Fig. 1. In Figs. 1 and 2 we also present the experimental EAF and TPS for $^{12}C+^{24}Mg$ inelastic (1.36 MeV 2^+ level of ^{24}Mg) scattering [4]. The corresponding fits are identical to those for the elastic scattering except for a rescaling factor which is the same for the TPS and EAF. One observes that in spite of the insignificant correlation between the elastic and inelastic excitation functions [4] their EAFs and TPSs are strongly correlated. However while the period ($\simeq$1.6–1.8 MeV) of oscillations in the experimental EAFs is reproduced the data are rather scattered around the fits. The effect of this discrepancy on the fit of the TPSs can be evaluated using Fig. 2. One can see that, for all t, $|D(t)|=|\int_0^\infty d\varepsilon\cos(\varepsilon t/\hbar)[C_{\rm data}(\varepsilon,\pi)-C_{\rm fit}(\varepsilon,\pi)]|$ does not exceed $P[t\simeq(4-4.5)\times 10^{-21}$ sec, $\pi]$ corresponding to the minimum between the peaks in the experimental TPSs. Therefore $|D(t)|$ does not exceed 25% of the height of the first peak and 50% of the height of the second peak in the experimental TPSs. This suggests that the background $|D(t)|$ does not influence the positions of the peaks in the experimental TPSs. A discrepancy between the data and fits could be due to the finite energy resolution ($\Delta E_{\rm res}=160$ keV c.m.) and finite energy step ($\Delta E_{\rm step}=266$ keV c.m.) [4] while the calculated $C(\varepsilon,\pi)$'s correspond to $\Delta E_{\rm res},\Delta E_{\rm step}\ll\Gamma=130$ keV. If this is the case then a measurement with $\Delta E_{\rm res}\simeq\Delta E_{\rm step}\leqslant 50$ keV will improve the fits to the data and reduce $|D(t)|$ without however changing the positions of the peaks in the experimental TPSs. Another possibility to check our interpretation arises from the θ dependence of TPSs and EAFs. For example, for $\theta=\pi/2$, the first peak in TPSs is predicted to appear at $t=(\Phi+\pi/2)/\omega\simeq(1.3–1.4)\times 10^{-21}$ sec and the second one at $t=(\Phi+3\pi/2)/\omega\simeq(3.9–4.2)\times 10^{-21}$ sec.

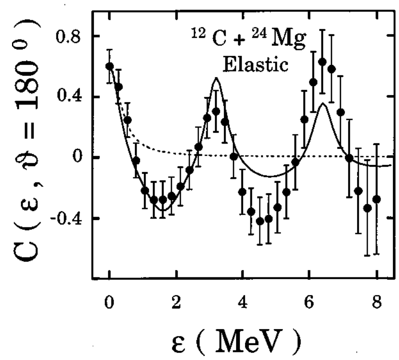

FIG. 3. Experimental $C(\varepsilon,\pi)$ and theoretical fit (solid line) for $^{12}C+^{24}Mg$ elastic scattering on the $E_{\rm c.m.}=35-43$ MeV energy interval (see text). Dotted line is Lorentzian with $\Gamma=0.4$ MeV.

Since the value of ω is determined by the position of the first peak in the TPSs the extracted value $\hbar\omega\simeq 0.8$ MeV is reliable. On the other hand, for $E_{\rm c.m.}\simeq 30$ MeV and $J\simeq 20-25$ [5], the use of the moment of inertia of two touching spheres, which corresponds to ~(2:1) deformation, gives $\hbar\omega\simeq$1.5–2 MeV [1]. This indicates that for the energy interval $E_{\rm c.m.}\simeq 24-35$ MeV the moment of inertia of the dinucleus is about a factor of two greater than that for $\simeq$(2:1) deformation suggesting the excitation of hyperdeformed $\simeq$(3:1) [20] excited coherent rotational states of ^{36}Ar.

In order to interpret an abrupt transition to broader energy structures at $E_{\rm c.m.}\simeq 35$ MeV we analyze the experimental $C(\varepsilon,\pi)$ (Fig. 3) and its Fourier components (TPS) (Fig. 4) for $^{12}C+^{24}Mg$ elastic scattering for the energy interval $E_{\rm c.m.}=35-43$ MeV. The fits in Figs. 3 and 4 are obtained with $d=3$, $\Gamma=0.4$ MeV, $\beta_<=10$ keV, $\beta_>=0.4$ MeV, $\Phi=0$, and $\hbar\omega=1.6$ MeV. This value of $\hbar\omega$ indicates that for $J\simeq 20-25$ and at $\simeq$50 MeV excitation energy hyperdeformation $\simeq$(3:1) of ^{36}Ar terminates and is replaced by the $\simeq$(2:1) deformation in remarkable agreement with the prediction [20].

In conclusion, we have extended the approach [9] to interpret the oscillations in the excitation functions of $^{12}C+^{24}Mg$ scattering under the assumption of the formation and decay of a dinucleus with strongly overlapping reso-

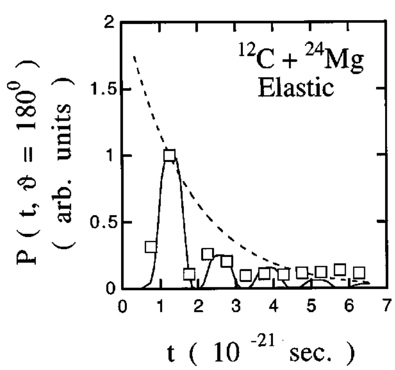

FIG. 4. Experimental $P(t,\pi)$ and theoretical fit (solid line) for $^{12}C+^{24}Mg$ elastic scattering on the $E_{\rm c.m.}=35-43$ MeV energy interval (see text). Dotted line corresponds to exponential decay.

nances. The analysis of the TPSs indicates the slow spin decoherence and strong time-space localization of a hyperdeformed coherently rotating ^{36}Ar. The time evolution of the collision has been traced back into the past as far as the moment of the formation of an intermediate system. Our analysis also indicates that for $J \simeq 20-25$ and at $\simeq 50$ MeV excitation energy hyperdeformation $\simeq(3:1)$ of ^{36}Ar terminates and is replaced by $\simeq(2:1)$ deformation. New experiments are proposed to test our interpretation.

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