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Damped oscillations in the energy autocorrelation functions of the ^{58}Ni+^{46}Ti elastic and ^{58}Ni+^{62}Ni elastic and inelastic scattering cross sections

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Abstract. Structures of non-statistical character, recently observed in ^{58}Ni +^{46} Ti elastic and ^{58}Ni +^{62} Ni elastic and inelastic excitation functions, produce damped oscillations in the cross section energy autocorrelation functions. The analysis of these damped oscillations in terms of S-matrix spin and parity decoherence indicates, as a possible interpretation, damping of the coherent rotational motion of the intermediate dinuclear system formed in the reaction.

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1 Introduction

Measurements of excitation functions in heavy-ion scattering were recently stimulated by the search for resonant-like mechanisms in the nucleus-nucleus interaction [1]. In fact the analysis of such excitation functions is a powerful tool due to their sensitivity to the time evolution of the collision process. So far, these measurements have been mainly restricted to relatively light colliding systems [1]. A recent extension of measurements to higher mass and energy regions [2,3,4], however, has demonstrated some features which are different from those observed in light systems. In particular, clear fluctuations have been observed in the excitation functions of ^{58}Ni+^{46}Ti elastic scattering ($E_{c.m.}$ = 95.6 − 106.1 MeV) and of ^{58}Ni +^{62} Ni elastic and inelastic scattering ($E_{c.m.}$ = 113.7 − 118.8 MeV).

As the measured angular distributions are strongly asymmetric about 90° in the c.m. system, one might assume that the dominant interaction mechanism is direct. However the interpretation in terms of a purely direct mechanism can not, from our point of view, be consistent because the width of the fluctuations observed in the measured excitation functions is 1.2-1.5 MeV for the ^{58}Ni+^{46}Ti scattering and $\simeq$ 1.0 MeV for the ^{58}Ni +^{62} Ni scattering (see Fig. 1). These widths indicate that the characteristic time scales of the reaction processes involved are longer than that of a direct process (10^{-22} s) which would give rise to broader ($\geq$ 6 MeV) energy structures. A purely statistical mechanism, however, as described by the Ericson theory [5], also cannot explain the observed phenomena. Indeed the conventional statistical treatment is not consistent with the following evidence: (i) the strong channel-channel correlations observed in the ^{58}Ni +^{62} Ni elastic and inelastic scattering, (ii) the measured angle-dependence of the differential cross sections, and (iii) the observed spacing and width of the fluctuations in the excitation functions.

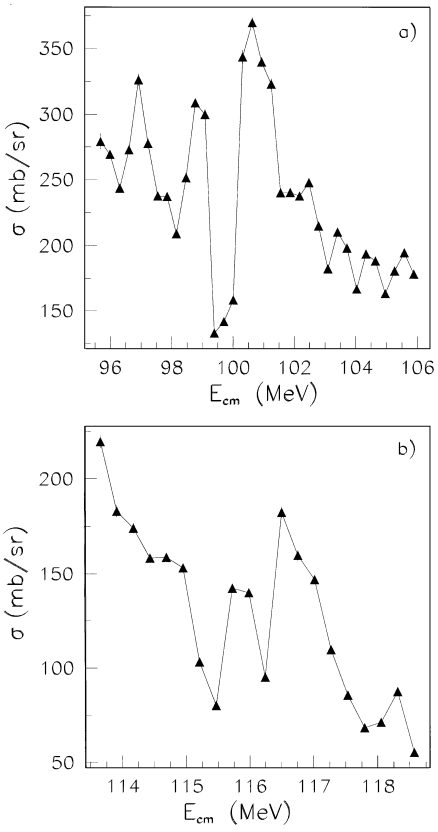

Fig. 1. Excitation function: **a** ^{58}Ni +^{46} Ti elastic channel, **b** ^{58}Ni +^{62} Ni sum of the elastic and inelastic channels

Another characteristic feature of both the $^{58}Ni + ^{46}Ti$ and the $^{58}Ni + ^{62}Ni$ scatterings is the smooth behaviour of the angular distributions. This implies two intimately related consequences: (i) a Legendre-polynomial analysis is unsuitable and (ii) at each energy (in particular at the excitation function maxima) the shape of the angular distribution is due to the contribution of a few partial waves rather than of a single one. In other words, the maxima in the excitation functions are not associated with the excitation of isolated resonances with single spin and parity values, but would appear to be due to the interference of, possibly overlapping, resonant states with different spin and parity values. Thus the preferential excitation of dinuclear rotational states as described in [3] can be assumed as a possible reaction mechanism, consistently with the observed phenomena in the $^{58}Ni + ^{46}Ti$ and $^{58}Ni + ^{62}Ni$ scatterings. Such a suggestion is supported by the results of [3] in which the energy autocorrelation functions of $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{62}Ni$ scattering are compared with a simplified approximate theoretical expression [6] which takes into account correlations between fluctuating S-matrix elements with different total spin and parity values. The calculated values agree fairly well with the data although this simplified formula is valid only in a restricted interval of the parameters involved and neglects the effects of S-matrix spin and parity decoherence [7]. The formula used in [3] results in exactly periodic energy autocorrelation functions and is unable to reproduce the decreasing magnitude of the oscillations experimentally observed. In this paper we extend the interpretation of [3] by employing the generalized expression for the energy autocorrelation function [8]. This generalized formula takes into account the effects of S-matrix spin and parity decoherence and damping of the coherent nuclear rotation [7]. This leads to damping of the oscillations in the energy autocorrelation functions and improves the description of the data [2,3].

2 Analysis of the energy autocorrelation of the cross section

For the relatively low excitation energy (about 2-5 MeV above the yrast line) overlapping levels of a rotational nature with an intrinsic wave function relatively stable to small variation of the angular velocity, give rise to an angular-momentum coherence of the pole form [6,8-10]. Such a coherence also occurs at high excitations, when the collective rotational motion is strongly damped [7]. The S-matrix spin correlation gives rise to time-space localization of the dinucleus in the region of isolated [10], partially overlapping [6,8,9] as well as strongly overlapping resonances [7] of the intermediate system. The time-space localization implies that the dinucleus rotates as a classical object, which is associated with the *light-house effect* [10]. This phenomenon was originally obtained for isolated dinuclear resonances, due to excitation of the main rotational band and states close to the yrast line. The effect of the time evolution of the dinucleus can be observed in the excitation function and, consequently, in the energy autocorrelation function $C(\varepsilon,\theta)$. An analytical expression for $C(\varepsilon,\theta)$ was deduced in Ref. [6]. It is convenient to write it in the following form:

$$C(\varepsilon,\theta) = C(\varepsilon = 0,\theta)\bar{C}(\varepsilon), \tag{1}$$

where

$$C(\varepsilon = 0,\theta) = \exp(-\pi\Gamma/\hbar\omega)\cosh(2(\pi-\theta)\Gamma/\hbar\omega)/ [2\cosh(\pi\Gamma/\hbar\omega)\cosh((\pi-\theta)\Gamma/\hbar\omega)] \tag{2}$$

is the normalized variance and

$$\bar{C}(\varepsilon) = (1-\exp(-2\pi\Gamma/\hbar\omega))\mathrm{Re}[\exp(2\pi i\varepsilon/\hbar\omega)/(1-\exp(-2\pi(\Gamma-i\varepsilon)/\hbar\omega))] \tag{3}$$

is the normalized ($\bar{C}(\varepsilon = 0) = 1$) energy autocorrelation function which does not depend on the scattering angle θ. In (2,3), Γ is the average total decay width of the intermediate dinucleus and ω its angular velocity. Note that the expression (2) for the normalized variance is correct for the whole range of the parameters involved and it differs from (10) of [6] due to a misprint in the latter. Equation (3) is a periodic function of the c.m. energy ε with period $\hbar\omega$. Equations (1,2,3) were obtained for the condition that S-matrix elements with different total spin values are correlated. The extension of the standard statistical model by taking into account the spin S-matrix correlation results in the focussed, strongly asymmetric angular distributions [11].

For relatively short-lived configurations ($\Gamma \geq \hbar\omega/2$) Eq. (1) reduces to

$$C(\varepsilon,\theta) \simeq \exp(-(\pi+\theta)\Gamma/\hbar\omega)\cos(2\pi\varepsilon/\hbar\omega). \tag{4}$$

In [3], the data for $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{62}Ni$ elastic and inelastic scattering were analysed using an approximate expression of the type of (4), implying exact periodicity of $C(\varepsilon)$. The exact periodic behaviour of the energy autocorrelation function (1-4) is associated with the regular coherent rotation of the dinuclear system so that the time-space dispersion of the rotating wave packets does not increase with time. In other words, the dinuclear system does not experience time-space delocalization. The precondition for the regularity (absence of time-space delocalization) is that the S-matrix spin correlations do not decay as time proceeds.

While the fit with the expression used in [3], accounts very well for the oscillating behaviour of the experimental energy autocorrelation functions (see Figs. 16 and 17 of [3]), it fails to reproduce the decrease in the magnitude of the oscillations with the increase of the center of mass energy ε. This is especially visible in the $^{58}Ni + ^{62}Ni$ data. A hypothesis that could explain this disagreement is the slow spin *decoherence* [7,8] during the time evolution of the intermediate dinuclear system. Following this hypothesis the spin decoherence width (β) should be different from zero and an order of magnitude smaller than $\hbar\omega$. In fact for $\beta \simeq \hbar\omega$ oscillations in the autocorrelation function should fully disappear. Moreover, the quasi-exact periodic behaviour of $C(\varepsilon,\theta)$ indicates that the S-matrix spin decoherence does not strongly affect the regular rotation of the dinucleus and consequently $\beta \ll \Gamma$.

Calculating $C(\varepsilon,\theta)$ for $\beta \ll \hbar\omega$ one obtains Eqs. (1,2) [8] with

$$\bar{C}(\varepsilon) = (1-\exp(-2\pi\Gamma/(\hbar\omega - i\beta))) \times\mathrm{Re}[\exp(2\pi i|\varepsilon|/(\hbar\omega - i\beta))/ (1-\exp(-2\pi(\Gamma - i|\varepsilon|)/(\hbar\omega - i\beta)))] \tag{5}$$

instead of the expression (3). One can see that, in the limit $\beta \to 0$, (5) transforms into (3). For relatively short-lived configurations ($\Gamma \geq \hbar\omega/2$) one obtains, from (1,2,5), a simplified expression for the energy autocorrelation function

$$C(\varepsilon,\theta) \simeq \exp(-(\pi+\theta)\Gamma/\hbar\omega) \times \exp(-2\pi|\varepsilon|\beta/(\hbar\omega)^2)\cos(2\pi\varepsilon/\hbar\omega), \quad (6)$$

which explicitly shows the damping of the oscillations in $C(\varepsilon,\theta)$ for a finite value of β, in contrast with the exact periodicity resulting from (3,4).

In what follows we use the more general (1,2,5) to analyse the data for $^{58}Ni+^{46}Ti$ elastic scattering [2] and the $^{58}Ni+^{62}Ni$ elastic and inelastic scattering [3].

$^{58}Ni+^{46}Ti$ *elastic scattering*

The measured energy autocorrelation function for the $^{58}Ni+^{46}Ti$ elastic scattering [3] is presented in Fig. 2a as a histogram. The fitting procedure consists of the following steps.

1. We notice that, for a given θ, $C(\varepsilon=0,\theta)$ depends only on the $\Gamma/\hbar\omega$-ratio (see Eq. (2)). Accordingly, we take $\theta=\theta_{cm}=95°$, which is the mean scattering angle in the interval of measurement ($89°-114°$). Having the experimental value of $C(\varepsilon=0,\theta)$=0.035 (see Fig. 2a), we uniquely find that, for $\theta_{cm}=95°$, $\Gamma/\hbar\omega$=0.677.

2. With $\Gamma/\hbar\omega$=0.677 being fixed, we vary θ_{cm} from 89° to 114° and find that $C(\varepsilon=0,\theta)$ varies from 0.037 to 0.026. This is the maximum variation that can affect the values of $C(\varepsilon=0,\theta)$ calculated with (2). Thus, the uncertainty in the value of the scattering angle θ produces an uncertainty in the calculation of the absolute value of the energy autocorrelation function less than 30%. Such an uncertainty, however, does not have any influence on the damping of the oscillations and thus on the determination of the spin decoherence width β.

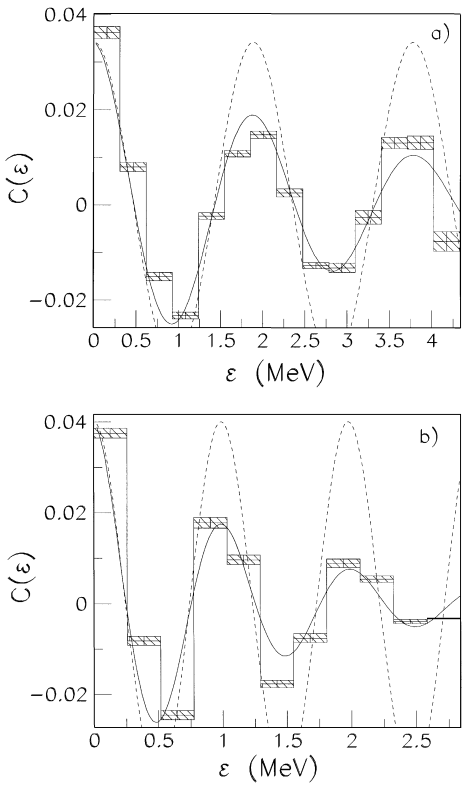

Fig. 2. Energy autocorrelation function $C(\varepsilon)$: **a** $^{58}Ni+^{46}Ti$ ($E_{c.m.}$ = 95.6 − 106.1 MeV) elastic channel, **b** $^{58}Ni+^{62}Ni$ ($E_{c.m.}$ = 113.7 − 118.8 MeV) sum of the elastic and inelastic channels. The *histograms* correspond to $C(\varepsilon)$ calculated from the data, the *dashed lines* to $C(\varepsilon)$ fitted with (1,2,3) and the *solid lines* to $C(\varepsilon)$ fitted with (1,2,5)

Table 1. Results of the two-parameter (ω and β) fit procedure of the energy autocorrelation function by using (1,2,5). Γ is uniquely determined from the values of $C(\varepsilon=0,\theta)$ and $\hbar\omega$

System	$\Gamma(MeV)$	$\hbar\omega(MeV)$	$\beta(MeV)$
$^{58}Ni+^{46}Ti$	1.28	1.89 ± 0.005	0.180 ± 0.006
$^{58}Ni+^{62}Ni$	0.67	0.99 ± 0.002	0.125 ± 0.003

Table 2. Results of the three-parameter (Γ, ω and β) fit procedure of the energy autocorrelation function by using (1,2,5)

System	$\Gamma(MeV)$	$\hbar\omega(MeV)$	$\beta(MeV)$
$^{58}Ni+^{46}Ti$	1.29 ± 0.015	1.89 ± 0.006	0.177 ± 0.011
$^{58}Ni+^{62}Ni$	0.65 ± 0.007	1.00 ± 0.002	0.130 ± 0.004

3. With $\Gamma/\hbar\omega$ fixed, the further fitting procedure is reduced to a two-parameter (ω and β) fit of the form of $C(\varepsilon,\theta)$ using (5). The numerical results of the fit are reported in Table 1. The fit to the measured autocorrelation function is shown in Fig. 2a as a solid line. In Fig. 2a we also present the best fit (dashed line) to the same data using (1,2,3), *i.e.* for β=0. One can see that the fit with (1,2,5) reproduces the data nicely and is clearly better than that obtained with (1,2,3), *i.e.* in the absence of the S-matrix spin and parity decoherence.

4. To check the reliability of the previous procedure we also fitted the experimental autocorrelation function by a three-parameter fit (Γ,ω and β) using (1,2,5). The numerical results are reported in Table 2 and do not differ significantly from the ones previously obtained. This is seen in Fig. 2a, where the behaviour of $C(\varepsilon,\theta)$ (solid lines) calculated with the set of two parameters is not distinguishable from the behaviour of $C(\varepsilon,\theta)$ produced by the set of three parameters. In fact the lines overlap completely.

$^{58}Ni+^{62}Ni$ *elastic and inelastic scattering*

Fig. 2b shows the energy autocorrelation function obtained for the sum of four channels - the elastic $(0^+,0^+)$ and the inelastic $(2^+,0^+)$, $(0^+,2^+)$, $(2^+,2^+)$ channels - for $^{58}Ni+^{62}Ni$ scattering. We analyse the summed excitation function because the errors due to the uncertainty in the separation of the single channels, greatly affected the excitation functions of the inelastic scatterings. This procedure is consistent with the underlying physical picture for the formation of an intermediate dinuclear system the angular velocity of which does not vary for the different reaction channels. In fact the values of the ω's and the Γ's extracted by means of an expression similar to (4) are very similar for all the studied reaction channels. Accordingly, the autocorrelation function in Fig. 2b, obtained from the summed excitation function, is very similar to the ones measured for each individual channel. The analysis of the summed excitation function is also intended to demonstrate that this summation does not reduce the relative amplitude of the damped oscillations in comparison with the amplitudes of the oscillations in each of the four channels. This means that oscillations in $C(\varepsilon,\theta)$ have the same period for each of the four individual channels.

The fitting procedure for the ^{58}Ni +^{62} Ni data was the same as for the ^{58}Ni +^{46} Ti data. The two-parameter fit to the measured autocorrelation function using (1,2,5) is shown in Fig. 2b as a solid line and the numerical results are reported in Table 1. In Fig. 2b we also show the fit (dashed line) obtained by using (1,2,3), *i.e.* for β=0. Again one can see that the fit with (1,2,5) nicely reproduces the damping of the oscillations and is clearly better than the exact periodic dependence given by (1,2,3). No appreciable difference in the behaviour of the calculated energy autocorrelation function is produced by the three-parameter fit the numerical results of which are summarized in Table 2.

3 Conclusion

The analysis of the energy autocorrelation functions for ^{58}Ni+^{46} Ti elastic and ^{58}Ni +^{62} Ni elastic and inelastic scattering has been extended using a recent formalism [8] which takes into account the effects of S-matrix spin and parity decoherence. Good agreement between results and experimental data has been obtained. In particular: (i) the calculated values of Γ are close to the widths of the structures observed in the excitation functions, (ii) the values of $\hbar\omega$ are close the spacing of the structures, (iii) the values of Γ are close the values of $\hbar\omega$, as expected for structures due to the partial overlap of resonant states and (iv) the values of the spin decoherence width β are much smaller than $\hbar\omega$ as expected in fast and weakly dissipative processes. The finite, non-zero, value of β extracted from the data analysis indicates the presence of S-matrix *spin and parity decoherence* and, therefore, time-space delocalization of the dinucleus during the scattering. The S-matrix spin and parity decoherence can be associated with *damping of the coherent dinuclear rotational motion* in heavy-ion reactions. Our analysis shows that these effects lead to damped oscillations in the energy autocorrelation functions for ^{58}Ni +^{46} Ti elastic and ^{58}Ni +^{62} Ni elastic and inelastic scattering. This damping could not accounted for by the less general analysis of [3]. The fact that autocorrelation functions calculated using data from two different experiments agree nicely with the expressions (1,2,5), shows the possibility of damping as the underlying physical mechanism. This is supported by recent results [12,13] suggesting that the effects of S-matrix spin and parity decoherence can explain the strong channel-channel correlation observed in heavy-ion elastic, inelastic scattering [2,3,14] and transfer reactions, as well as in strongly dissipative heavy-ion collisions (see, e.g., [15-20]). Alternatively, the channel-channel correlation can also be explained [18,19] as due to the partial overlap of resonant states of the intermediate system as suggested in the analysis reported in [3].

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