Cross Section Coherence Energy and Interaction Time in Heavy Ion Dissipative Collisions

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A recent formulation of the cross section autocorrelation function, specially developed to take into account the angular momentum effects, is compared to the experimental results concerning the 28Si + 48Ti and 28Si + 64Ni reactions. The possibility of determining the mean lifetime of the dinucleus excited states populated in dissipative collisions is also discussed.

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1. Introduction

Since the early years of nuclear physics the statistical properties of the cross section were a main source of information on the reaction mechanism as well as on the time evolution of the complex system formed after the collision. Until the development of heavy ion beams the major part of experimental data could be described in terms of an incoherent sum of direct (DI) and compound nucleus (CN) reaction amplitudes due to the very different interaction times of these reaction mechanisms. In this context Ericson theory [1] was developed which, in conjunction with the Feshbach unified theory of nuclear reactions [2], allowed to understand the main features of CN formation and decay as well as the interplay between the two extreme models of CN and DI.

Heavy ion experimentation increased the importance of preequilibrium reactions owing to the difficulty of reaching the CN equilibrium stage or complete fusion in heavy ion interactions. A renewed interest has been devoted to the statistical features of the cross section after the discovery of angular [3] and energy [4] coherence in dissipative reactions. Statistical analysis performed by means of different methods allowed the extraction of coherence energies and intermediate system state lifetimes [4, 5]. The inadequacy of the standard Ericson theory for fluctuation analysis in dissipative reactions arises from the non complete equilibration of the intermediate system degrees of freedom and from the many unresolved final channels contributing to the cross section. These features generate coherence between partial waves, hence asymmetric angular distributions and fluctuation damping in the excitation functions.

Some special formulations [6, 7] of the correlation function have been proposed to overcome the above difficulties. All of them take into account the angular momentum effects in determining coherence between partial waves. The angular momentum role was also considered on a more experimental ground pointing out the correlation between coherence energy angular dependence and angular distribution features.

In this paper the autocorrelation function in the formulation of [7] is compared to the very few existing data on dissipative reactions suitable for a statistical analysis. The angular distributions and the coherence energies have been analyzed in a comprehensive way starting from the definition of amplitude autocorrelation function. The possibility of determining the mean lifetime of the intermediate system excited states by means of the features of the power spectrum of the correlogram is also considered.

2. Beyond Ericson Theory

In the standard Ericson theory the most important quantity to be compared to the experimental data is the cross section autocorrelation function:

$$C(\varepsilon) = \frac{\langle \sigma(E+\varepsilon) \sigma(E) \rangle - \langle \sigma \rangle^2}{\langle \sigma \rangle^2}$$

(1)
where \( \varepsilon \) is a variable energy step.

Under the condition that the correlations follow a normal bivariate distribution with zero mean, the cross section autocorrelation function defined in (1) is related to the amplitude correlation function:

\[
C(\varepsilon) = \frac{|c(\varepsilon)|^2}{c(\varepsilon)}
\]

by the expression:

\[
C(\varepsilon) = \left| \frac{c(\varepsilon)}{c(\varepsilon)} \right|^2.
\]

According to the Feshbach unified theory of nuclear reactions, the scattering amplitude can be put in the form:

\[
\delta f(E) = \frac{1}{2i \hbar} \sum_i \frac{\gamma_i \times \gamma_i}{E - E_i + i \Gamma/2}
\]

being \( \gamma_i \) the partial width amplitude and \( \Gamma \) the constant average decay width of CN overlapping excited states. Under the hypothesis of uncorrelated and stochastic \( \gamma_i \), the amplitude correlation function corresponding to (4) is:

\[
c(\varepsilon) = \frac{i \Gamma}{\varepsilon + i \Gamma}
\]

which using (3) gives:

\[
C(\varepsilon) = \frac{\Gamma^2}{\Gamma^2 + \varepsilon^2}.
\]

By taking into account the possible presence of DI and the contribution of \( N \) unresolved channels expression (5) can be generalized in the form:

\[
C(\varepsilon) = \frac{1}{N} \left( 1 - \frac{\sigma_{\text{DI}}}{\langle \sigma \rangle} \right)^2 \frac{\Gamma^2}{\Gamma^2 + \varepsilon^2}
\]

where

\[
\sigma_{\text{DI}} = \frac{\sigma_{\text{DI}}}{\langle \sigma \rangle}
\]

is the relative contribution of DI to the reaction cross section.

On the expression (7), or equivalently on relation (6), lies the possibility of extracting \( \Gamma \) values from a statistical analysis of the experimental data. Fitting the experimental values of \( C(\varepsilon) \) (1) by means of a Lorentz curve determines \( \Gamma = \varepsilon_{1/2} \) as the HWHM of relation (6). This result is not affected by the presence of DI and of many unresolved final channels, however the fluctuation observability could become very questionable. This is the case of dissipative heavy ion reactions where, due to experimental conditions, an intrinsic average is performed over many unresolved exit channels. However in the last few years several papers have been published showing oscillations in excitation functions which resemble statistical fluctuations. Attempts have been made to analyze these in the framework of the standard Ericson theory so cross section coherence energies \( \Gamma_{\exp} \) have been determined for several ejectiles and different emission angles.

Up to now available \( \Gamma_{\exp} \) values exhibit a more or less marked dependence both on the fragment atomic number and on the emission angle. The latter feature is unexpected at the extent in which fluctuations are generated by the energy coherence introduced in the cross section by the width of intermediate system excited levels which in turn is related to their mean lifetime through the indetermination relation:

\[
\Gamma = \frac{\hbar}{\tau}.
\]

Then, being the mean lifetime of an excited state a quantum property, its measure should be independent on the angle at which the decay is observed.

The above considerations point out that the relations

\[
\Gamma_{\exp} = \varepsilon_{1/2} = \Gamma = \frac{h}{\tau}
\]

can be stated only if the hypotheses for the applicability of the Ericson theory are fulfilled. This is not the case with the dinucleus formed in heavy ion collisions for which the Bohr independence hypothesis is not satisfied and correlation between partial waves, introduced by the angular momentum, gives rise to asymmetric angular distributions.

A new formulation of the autocorrelation function which takes into account the effects of the rotational motion has been very recently developed by Kun [8]. The underlying hypothesis is that the radial motion is weakly perturbed by the dinucleus rotation. Then the correlation function for the partial fluctuating amplitude can be put in the form:

\[
\langle \delta a_l(E + \varepsilon) \delta a_l(E) \rangle = \left[ W(l, E) W(l', E) \right]^{1/2} \frac{i \Gamma}{\varepsilon + \hbar \omega (l - l') + i \Gamma}
\]

being \( \omega \) the rotation velocity of the intermediate system.

To derive expression (11) a procedure similar to the Ericson formulation is followed, starting from the