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Non-reproducibility of the Cross Sections Measured in the Dissipative Collisions of $^{19}F + ^{93}Nb$*

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Abstract Two independent measurements of excitation functions for the $^{19}F + ^{93}Nb$ dissipative heavy ion collisions have been performed at incident energies from 100 to 108 MeV in steps of 250 keV. The two measurements differed by two target foils, 70 and 71$\mu g/cm^2$, respectively. All the other experimental conditions were kept to be identical in both experiments. The data indicate non-reproducibility of the non-self-averaging oscillating yields in the two measurements. This supports recent theoretical predictions of extreme sensitivity and chaos in complex quantum collisions.

Key words dissipative heavy ion collision, non-reproducibility of the cross sections, chaos

The cross section fluctuation phenomenon in dissipative heavy ion collision (DHIC) has been experimentally established since 1985[1]. Most remarkably, the cross section fluctuation are not washed out in spite of the high intrinsic excitations of the intermediate dinuclear system (IDS) formed in DHIC and the enormous number of final micro-channels contributing to measurable cross sections. The discovery of the fine excitation function structure in DHIC is as important as the discovery of DHIC itself. The phenomenon of the non-self-averaging of excitation function oscillations represents a unique challenge for distinguishing between numerous different concepts and models of DHIC, all of which have been equally successful in describing the energy averaged observables.

Modern understanding of quantum chaotic scattering and microscopic and mesoscopic complex quantum collisions is based on the assumption that the decoherence time, i.e. the time it takes to lose all the initial phase correlations, is the shortest time scale of the problem[2—4]. This implies the absence of a correlation between the partial width amplitudes carrying different resonance level and micro-channel quantum number for the collisions proceeding through the formation and decay of highly excited intermediate system (IS). The idea of a rapid phase randomization has been originally developed and successfully applied in the context of the random-matrix theory (RMT) of highly excited strongly interacting system[2]. However the domain of its applicability for many-body systems has been remained an open question. In DHIC the deviations from the predictions of RMT manifest themselves in persistence of a micro-channel correlation leading to the non-self-averaging of excitation function

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oscillations (EFO) in these complex microscopic collisions.

Recently the non-self-averaging of EFO in DHIC has been interpreted in terms of the spin off-diagonal micro-channel S-matrix correlations and quantum chaotic phenomenon of slow decoherence[5]. The coherence between the highly excited states of the IS occurs spontaneously resembling the spontaneous breaking of rotational symmetry. This results in the physical picture of the collapse of the initially delocalized incoherent superposition of the extended resonance states of the IS into the spacially localized coherently rotating many-body wave packets. The following slow decoherence, resulting in slow restoration of rotational symmetry and spreading of the rotating wave packets, is closely related to the localization within the infinite number of orthogonal subspaces of the Hirbert space. It has been shown that finite non-vanishing decoherence width, $\beta\neq0$, is a precondition for the non-self-averaging of EFO in DHIC. It has been recently argued that spontaneous micro-channel correlation and slow decoherence should be result in the cross sections for DHIC being sensitive to an infinitesimally small perturbation. This suggests a possibility that the cross sections of DHIC may not be reproducible in independent measurements of the same system.

Since the prediction of the non-reproducibility of the cross section in DHIC is in a sharp contrast with modern quantum theory of complex microscopic collisions, it is highly desirable to test this prediction experimentally. In our experiment we test the sensitivity by performing two independent measurements with the same reaction system using slightly different thickness of the targets. Use of the different targets results in, even though infinitesimally small but non-vanishing, different "target-environmental" perturbations into nucleus-nucleus Hamiltonian due to, e.g. different defect location, electronic structure, spacial distribution of electro-magnetic fields etc. in the two target foils. In this paper we briefly report the experimental results and their theoretical interpretation.

Two independent measurements of the excitation functions of the dissipative products have been carried out for the same reaction system of ^{19}F + ^{93}Nb at China Institute of Atomic Energy (CIAE), Beijing. In the two measurements, the beam ^{19}F^{8+} were provided by the HI-13 tandem accelerator in CIAE, the beam incident energies were from 100 to 108MeV in steps of 250keV. The same three sets of detector at $\theta_{\text{lab}} = 38°$, 45° and 53° were used as well as the same experimental parameters for the accelerator, the electronic and the acquisition system were selected. In other words, almost the same macroscopic experimental conditions have been chosen for the two measurements. The only difference in the two measurements has been that two different target foils of ^{93}Nb were used. The foil with thickness of $70\mu g/cm^2$ was used in the first measurement, and the foil with thickness of $71\mu g/cm^2$ was used in the second measurement.

The excitation functions of the dissipative products in ^{19}F + ^{93}Nb reactions are presented in Fig. 1, where the error bars are statistical only. It is obvious that the characteristic non-self-averaging structures of excitation functions in DHIC persist for all of the dissipative fragments produced in the two collisions. Most of the correlation coefficients between the products with different charge number Z are greater than 0.6 for each individual measurement. It is seen that for some energies the cross sections are clearly non-reproducible outside of the range of the experimental errors. And most of the correlation coefficients between the products with the same charge numbers in the two measurements are found to be small, about 0.1. As shown in Fig. 2, the relative magnitude of the oscillations for the differences $\sigma_1(E) - \sigma_2(E)$ is bigger than that for either $\sigma_1(E)$ or $\sigma_2(E)$. Both of the figures indicate that the cross sections for the two independent experiments with almost the same macroscopical conditions have non-reproducible oscillating component.

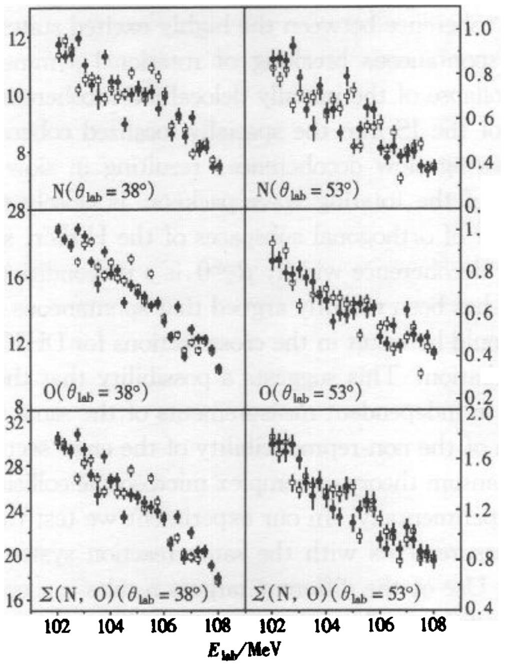

Fig. 1 Excitation functions in DHICs of $^{19}F + ^{93}Nb$

● 70μg/cm^2, ○ 71μg/cm^2.

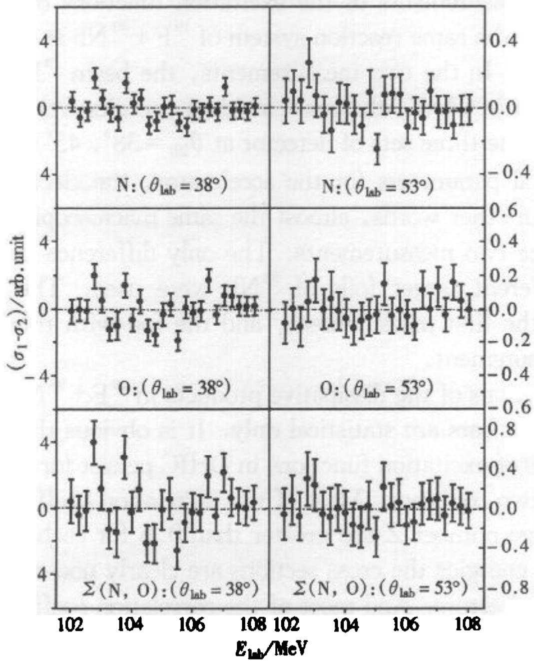

Fig. 2 The difference of oscillation amplitude in the two excitation functions of $^{19}F + ^{93}Nb$

The experimental data were carefully selected and checked. Only the nitrogen and oxygen outgoing fragments were chosen to avoid the possible contamination from carbon according to the two-body kinematics, and only the data coming from the scattering angles 38° and 53° were used for sufficient statistical counts. The experimental error due to the deviation of the incident beam was controlled by using two monitors placed at ± 12° with respect to the beam direction. It was found to be negligible. The beam directions were proofread and corrected before each energy step. The error of the target thickness evaluated by a spectrophotometry is about 5μg/cm^2. It has not influenced the result significantly. If the result was induced by the error of the thickness of the target, the excitation function behaviours for the two measurements should be evolved into some systematic outcome rather than being reproducible for some energies and non-reproducible for another energies.

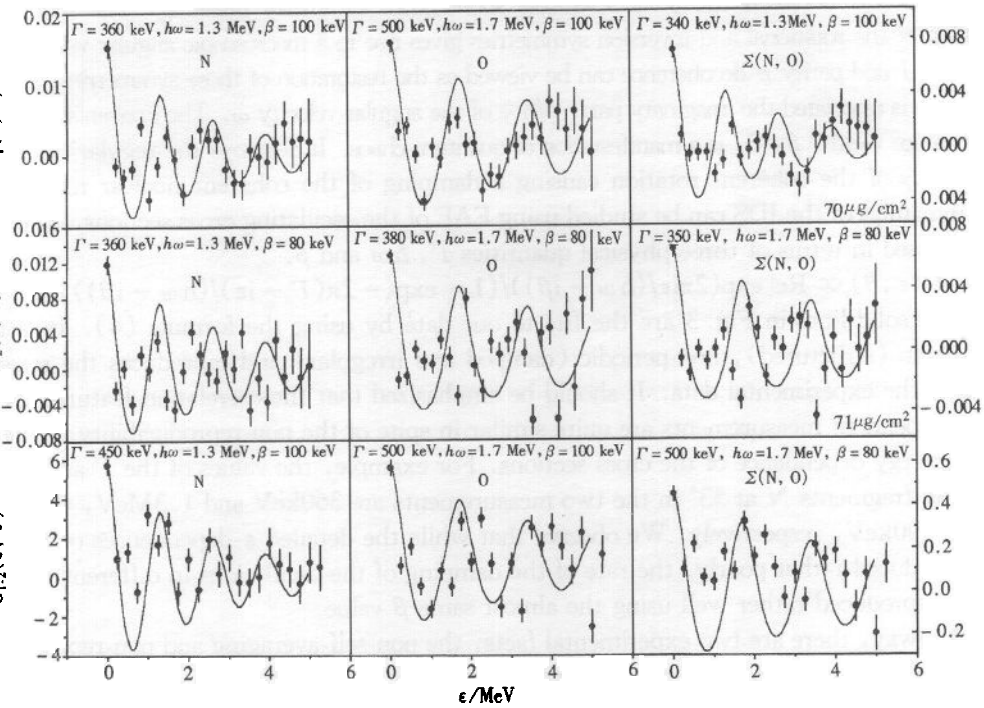

Fig. 3　EAF of the dissipative fragments emitted from reactions of ^{19}F + ^{93}Nb at $\theta_{\mathrm{lab}} = 53°$

The energy autocorrelation functions (EAFs) extracted from the experimental data as shown in Fig. 3. The errors are due to the finite size of the data sampling[6]. According to the statistical reaction with memory approach[5], the fluctuating S-matrix with total spin J and parity π can be represented in the form:

$$S_{ab}^{J\pi}(E) = [W_{ab}(J, I)]^{1/2} \exp[\mathrm{i}\phi(J - I)] \bar{S}_{\bar{a}\bar{b}}^{J\pi}(E), \tag{1}$$

where

$$\bar{S}_{\bar{a}\bar{b}}^{J\pi}(E) = \left(\frac{\Gamma D}{2\pi}\right)^{1/2} \sum_{\mu} \frac{\gamma_{\mu}^{J\pi a} \gamma_{\mu}^{J\pi b}}{E - E_{\mu}^{J\pi} + \mathrm{i}\Gamma/2}, \tag{2}$$

E is the total energy of the system, $W_{ab}(J, I)$ is the average partial reaction probability, ϕ is the average deflection angle due to the J-dependence of the potential phase shifts, Γ and D are the average total decay width and level spacing, $E_{\mu}^{J\pi}$ are the resonance energies of the intermediate system. The entrance(exit) channel indices a (b) specify intrinsic microstates $\bar{a}(\bar{b})$ of the reaction partners, orbital momentum and channel spin. The normalized partial width amplitudes.

$$\bar{\gamma}_{\mu}^{J\pi\bar{a}(\bar{b})} = \sum_{j} B_{\mu j}^{J\pi} \bar{\xi}_{j}^{J\pi\bar{a}(\bar{b})}, \tag{3}$$

where $B_{\mu j}^{J\pi}$ is the orthogonal matrix and normalized $\bar{\xi}_{j}^{J\pi\bar{a}(\bar{b})}$ are random Gaussian variables with zero mean value. The main result of the approach is that $\bar{\gamma}_{\mu}^{J\pi\bar{a}}$ and $\gamma_{\nu}^{J'\pi\bar{b}}$ with $J \neq J'$ and/or $\pi \neq \pi'$ are correlated variables. The correlation originates from the infinitely small entrance-exit off-diagonal ($J-\pi$)-correlation between $\bar{\xi}_{j}^{J\pi\bar{a}}$ and $\bar{\xi}_{j}^{J\pi\bar{b}}$. It also can be shown that switching off the correlation between the $\bar{\xi}$'s by means of a properly applied limiting procedure does not result in the vanishing of the correlation of the $\bar{\gamma}$'s. Therefore, the origin of the correlation between the $\bar{\gamma}$'s resembles spontaneous symmetry breaking. The spontaneous breaking of the rotational and inversion symmetries gives rise to a macroscopic angular velocity $\hbar\omega$. The spin J and parity π decoherence can be viewed as the restoration of those symmetries. The decoherence is associated the imaginary part, $\beta/\hbar$, of the angular velocity ω. The nonvanishing of the decoherence width, $\beta \neq 0$, is a manifestation of quantum chaos. It destroys the regularity and the periodicity of the coherent rotation causing a damping of the coherent nuclear rotation. A rich dynamics of the IDS can be studied using EAF of the oscillating cross sections. The EAF is expressed in terms of three physical quantities Γ, $\hbar\omega$ and β.

$$C(\varepsilon,\theta) \propto \mathrm{Re}[\exp(2\pi i\varepsilon/(\hbar\omega - i\beta))/(1-\exp(-2\pi(\Gamma - i\varepsilon)/(\hbar\omega - i\beta)))]. \tag{4}$$

The solid lines in Fig. 3 are the fits to our data by using the formula (4). It is non-Lorentzian (structured), non-periodic (damped and irregular) and reproduces the essential trend of the experimental data. It should be emphasized that the correlation features for the two independent measurements are quite similar in spite of the non-reproducibility of the detailed energy dependence of the cross sections. For example, the values of the Γ and $\hbar\omega$ for outgoing fragments N at 53° in the two measurements are 360keV and 1.3MeV, the βs are 80 and 100keV, respectively. We observe that while the detailed ε-dependences of the data are reproduced rather poorly, the rate of the damping of the oscillations in different $C(\varepsilon,\theta)$ can be reproduced rather well using the almost same β value.

Anyway, there are two experimental facts, the non-self-averaging and non-reproducibility of the cross sections. The non-self-averaging of the cross sections in excitation functions implies that the summation over an extremely large unmber of exit micro-channels is not equivalent to the averaging over the ensemble of different uncorrelated individual cross sections. This suggests that in each particular independent measurement of the same system one observes a particular realization of $\sigma(E)$ rather than the excitation function averaged over the ensemble of all possible realization of the underlying process. This indicates the probabilistic nature of the underlying phenomenon. In other words, in the case of the non-equilibrium IDS, the reaction cross section at a fixed energy should be described in terms of a probability distribution rather than being considered as deterministic reproducible quantity. Such an interpretation is consistent with the non-self-averaging and non-reproducibility of the cross sections reported in this paper. The significant oscillations in EAF clearly indicate quasi-periodicity, i.e. the presence of strong leading harmonics in the energy dependencies of the cross sections. Therefore, it is appropriate to refer to such quasi-periodic structures as oscillation rather than fluctuations.

Our experimental data support the prediction of the theory about the extreme sensitivity and chaos in DHIC. Also, a clear physical picture on DHIC has been presented. An intermediate dinuclear system IDS formed in the DHIC of ^{19}F + ^{93}Nb was far from equilibrium state. The IDS with an average lifetime $\hbar\omega/\Gamma$ rotates coherently and this coherent rotation is damped and irregular due to the decoherence width $\beta \neq 0$. The coherence originate from the spontaneous breaking of rotational and inversion symmetries while the decoherence results in the restoration of these symmetries. The time evolution of IDS can be described by the three parameters, the decay width Γ, the angular velocity of coherent rotation ω and the decoherence width β. These physical quantities have been determined from the analysis of the EAF. The nonvanishing of β signifies the nonequilibrium quantum chaotic dynamics in highly excited many-body systems. Since the obtained the β-width is the about two orders of magnitude less than the characteristic nuclear spreading width[2,3], this implies that nuclear coherent motion is much more stable than the nuclear collective motion.

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^{19}F + ^{93}Nb 重离子耗散碰撞中截面测量的不可重复性*

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摘要　完成了^{19}F + ^{93}Nb重离子耗散碰撞激发函数的两次独立测量. 束流^{19}F^{8+}的入射能量100—108MeV，能量步长250keV；两次测量中分别使用了厚度为70和71μg/cm^{2}的^{93}Nb靶，其它宏观实验条件(例如，入射能量及能量步长，探测器及其探测角度，加速器、电子学以及数据获取系统的参数选取等等)则保持完全相同. 实验结果表明，两次测量所得到的耗散产物截面的激发函数的不平滑结构具有不可重复性. 这一实验结果支持了最近提出的理论预言："在复杂量子碰撞中存在对初始条件的极端敏感性与混沌运动."

关键词　重离子耗散碰撞　截面测量的不可重复性　混沌

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