Statistical significance of non-reproducibility of cross sections measured in dissipative reactions $^{19}F+^{93}Nb$

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Abstract Two independent measurements of cross sections for the $^{19}F+^{93}Nb$ dissipative heavy-ion collision (DHIC) have been performed at incident energies from 100 to 108 MeV in steps of 250 keV. Two independently prepared targets were used respectively with all other experimental conditions being identical in both experiments. The data indicate non-reproducibility of the non-self-averaging oscillation yields in the two measurements. The statistical analysis of this non-reproducibility supports recent theoretical predictions of spontaneous coherence, slow phase randomization and extreme sensitivity in highly excited quantum many-body systems.

Keywords DHIC, Non-reproducibility, Probability distribution, Nuclear reaction cross section, Excitation function

CLC numbers O571.41$^+$3, O571.6

1 Introduction

It is well-known that an intermediate dinuclear system (IDS) is formed at the early stage in dissipative heavy ion collision (DHIC). The IDS does not attain a complete statistical equilibrium within its lifetime. Some statistical non-equilibrium characteristics of IDS manifest themselves by measuring the excitation function of the reaction products in DHIC.[1-9] It is especially interesting that the oscillation energy structure is not washed out in spite of the high intrinsic excitation of IDS and the enormous number of the final microstates contributing to the observable cross section,[1-9] that an anomalous large long-range angular correlation exists[2,8] and that there is a marked indication of non-reproducibility of cross sections in two independent measurements.[9] All of these features are unable to understand in view of the conventional statistical theory.[10,11] Several theoretical efforts[12-18] have been undertaken to develop the statistic theory on nuclear reaction by taking into account the angular momentum coherent effects[12-15] and the slower phase randomization.[16-18] In this paper we devote to present an experimental result and the related discussion about the non-reproducibility of cross sections in two independent measurements for the same system of $^{19}F+^{93}Nb$ DHIC.

2 Experiment and results

Two independent measurements of excitation functions for the strongly dissipative collision for the same reaction system of $^{19}F+^{93}Nb$ have been carried out at the China Institute of Atomic Energy (CIAE), Beijing. In these measurements, the $^{19}F^{8+}$ beam was provided by the HI-13 tandem accelerator. The beam incident energies were varied from 102 to 108 MeV in steps of 250 keV. For both measurements the same accelerator parameters and the same electronic and acquisition systems were employed. The same two sets of gas-solid (ΔE - E) telescopes, with a charge resolution $Z/\Delta Z \geqslant 30$ and an energy resolution $\leqslant$ 0.4 MeV, were set at $\theta_{\rm lab} = 38^{\rm o}$ and 53º. The ΔE detector is an ionization chamber filled with P10

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gas at a pressure of 1.03×10^4 Pa, the residual energy E is deposited in a Si position sensitive detector with a thickness of 1000 μm and a size of 8 mm $\times$ 47 mm.

In Fig.1 we present a typical (ΔE - E) scatter-plot obtained at $E_{\rm lab}$ (^{19}F) = 100.25 MeV. It is seen that the projectile-like fragments from the ^{19}F+^{93}Nb reaction can be separated. For the F fragments direct and quasi-elastic processes constitute the major contribution to the cross section. For the Ne fragments there was no a sufficient statistics. Therefore we restrict our analysis to the cross sections of the N and O products of the ^{19}F+^{93}Nb DHIC.

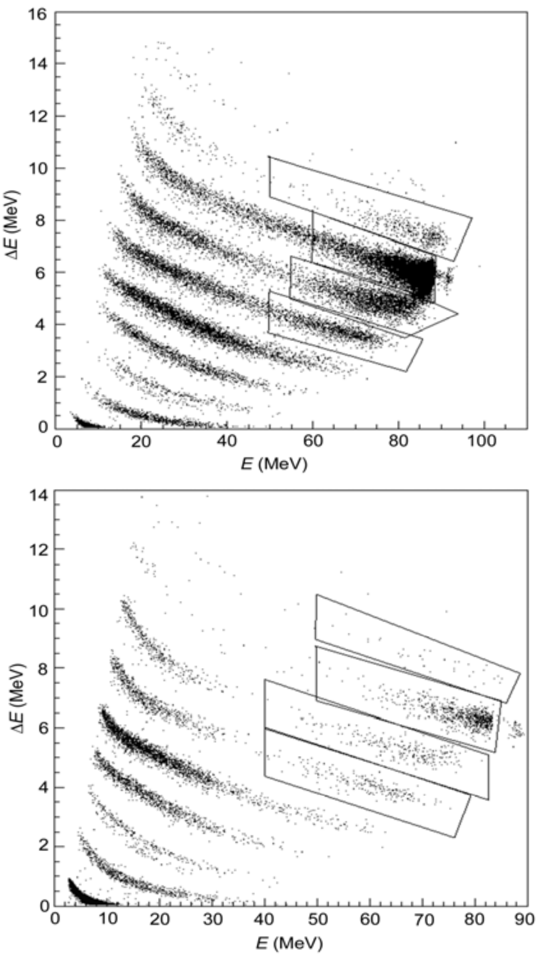

Fig.1 ΔE - E scatter-plots obtained in the ^{19}F+^{93}Nb dissipative heavy-ion collision at $\theta_{\rm lab}$ = 38° (upper panel) and $\theta_{\rm lab}$ = 53° (lower panel) at $E_{\rm lab}$ =100.25 MeV. The figure also shows energy gates used in the analysis.

To avoid a possible effect of the carbon build-up in the target, we analyze events with $E_{\rm lab}$ (N) $\geqslant$ 50 MeV and $E_{\rm lab}$ (O) $\geqslant$ 55 MeV for $\theta_{\rm lab}$ = 38° and with $E_{\rm lab}$ (N) $\geqslant$ 40 MeV and $E_{\rm lab}$ (O) $\geqslant$ 40 MeV for $\theta_{\rm lab}$ = 53° (see Fig.1). In Fig.2 we present a (ΔE - E) scatter-plot for the fragments from the ^{19}F+^{12}C reaction at $E_{\rm lab}$ (^{19}F) = 100.25 MeV. Our measurement shows that the cross sections are negligible for the N and O outgoing energies $\geqslant$ 45 MeV for $\theta_{\rm lab}$ = 38°, and $\geqslant$ 40 MeV for $\theta_{\rm lab}$ =53°. We also note that, for $E_{\rm lab}$ (^{19}F) = 108 MeV and $\theta_{\rm lab}$ = 53°, the production of the N and O fragments with the outgoing energy $\geqslant$ 39 MeV in the ^{19}F+^{12}C reaction is kinematically forbidden. Since the energies of the N and O yields in our measurements $\geqslant$ 50 MeV for $\theta_{\rm lab}$ = 38° and $\geqslant$ 40 MeV for $\theta_{\rm lab}$ = 53°, we conclude that the carbon build up does not produce uncontrolled errors and does not affect our data for the cross sections of the N and O products of the ^{19}F+^{93}Nb DHIC.

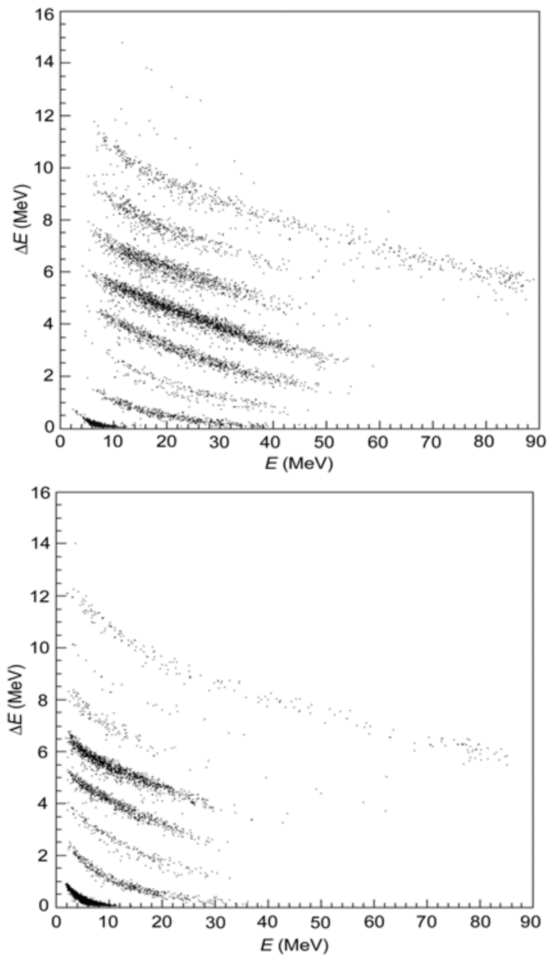

Fig.2 ΔE - E scatter-plots obtained in the ^{19}F+^{12}C reaction at $\theta_{\rm lab}$ =38° (upper panel) and $\theta_{\rm lab}$ =53° (lower panel) at $E_{\rm lab}$ =100.25 MeV.

In the two measurements we used different, independently prepared self-supporting ^{93}Nb target foils with the nominal thickness ≈ 70 μg/cm^2. It was found that the difference in thickness of the two foils was $\leqslant$ 5 μg/cm^2. This difference results in different stopping energy losses in the two different targets. This itself should not affect reproducibility of the cross sections as this difference of ~15 keV in stopping energy losses is smaller than the energy spread of ~50 keV in the beam and additional energy spread of ~150 keV in the target.

Absolute cross sections were not determined, though great care was taken to ensure no spurious sources of oscillations were introduced into the relative cross sections. Stability of the beam direction was controlled as follows: (i) TV monitor screen was used before each energy step to check and correct position of beam spot on the target. (ii) Two silicon detectors were placed at $\theta_{\rm lab} = \pm 12^{\rm o}$. (iii) The beam charge was collected using a Faraday cup placed at $\theta = 0^{\rm o}$ and was compared with the counting rates of the silicon detectors. The data were normalized with respect to both the count rates of each silicon detector and the integrated beam current. All the three normalizations produced the relative cross sections, for each individual experiment, which agree within the statistical errors, $1/N^{1/2}$, where N is the count rate. We have taken 5 repeat points (one repetition for 5 different energies measured) for the first experiment (target) and 21 repeat points (one repetition for 21 different energies) for the second experiment (target). Before repeating each point the TV monitor screen was used to check and correct position of beam spot. All the repeated points demonstrated reproducibility, within the statistical errors, for both individual experiments (targets). This reproducibility is demonstrated in Fig.3 for the two runs in the second experiment. Such a reproducibility for the two runs for the same target indicates that no damages of the targets, which could bring about uncontrolled spurious effects, occurred in our experiments. All the above procedures indicate that the systematic uncertainties do not seem to be present and the data errors can be evaluated as statistical only.

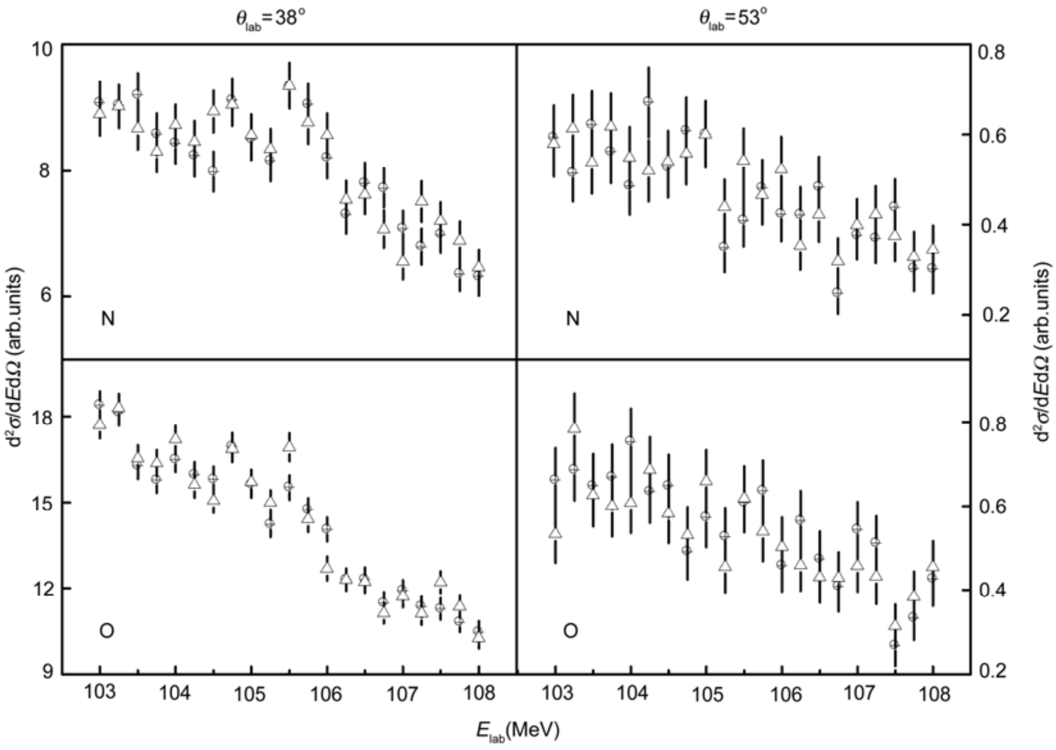

Fig.3 Excitation functions for the N and O yields of the ^{19}F+^{93}Nb strongly dissipative heavy-ion collisions obtained in two runs (triangles and crossed circles) for the same single target foil in the second experiment. The error bars are statistical only.

The cross sections $\sigma(E)$ for the products N and O in the ^{19}F+^{93}Nb DHIC are presented in Fig.4, where the error bars are statistical only. Although Fig.4 presents energy integrated yields over the wide, ~25 MeV, ranges of the dissipative spectra (i.e. these yields are summed over huge number of different final micro-channels of the highly excited collision products) the characteristic non-self-averaging oscillating structures of the excitation functions in DHIC can be visually identified. From Fig.4 we notice that, for some incident energies, the cross sections measured for two different target foils are different. A statistical significance of this non-reproducibility is discussed in next section.

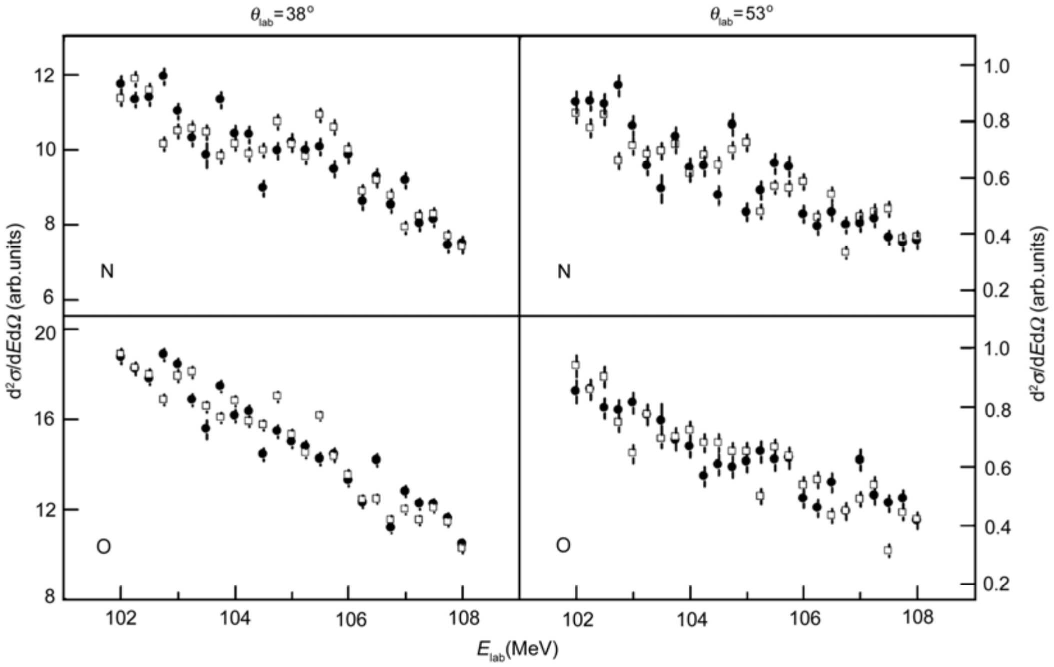

Fig.4 Excitation functions for the N and O yields of the $^{19}F+^{93}Nb$ strongly dissipative heavy-ion collisions obtained in two independent experiments. Full dots correspond to the first experiment and open squares to the second one. The error bars are statistical only.

3 Statistical significance of the data

A possibility to find out if the oscillations in the individual excitation functions measured for each of the two different targets (Fig.4) are true oscillations should be verified by calculating the experimental normalized variances of the oscillations, $C(\varepsilon=0)$. Here $C(\varepsilon) = <\Delta\sigma(E+\varepsilon)\Delta\sigma(E)>$ is a cross section energy autocorrelation function, $\Delta\sigma(E)=(\sigma(E)/<\sigma(E)>-1)$ is a relative oscillating yield, and $<\sigma(E)>$ is an energy averaged smooth cross section which is obtained from the best second order polynomial fit of the original data. For the two independent measurements of the N oscillating yields (Fig.4) at $\theta=53°$ we obtain $C(\varepsilon=0)=0.015\pm0.0035$ for the first target and $C(\varepsilon=0)=0.017\pm0.004$ for the second one, where the uncertainties are due to the finite data range only.[19] For the O oscillating yields at $\theta=53°$ we have $C(\varepsilon=0)=0.012\pm0.003$ for the first target and $C(\varepsilon=0)=0.016\pm0.0037$ for the second one. This is to be compared with the quantities $1/N$, which represent $C(\varepsilon=0)$ corresponding only to statistical uncertainties due to the finite average counting rate N. For the N yield we have $1/N=0.004$ and for the O yield $1/N=0.0035$. Therefore, for $\theta=53°$, the experimental values of $C(\varepsilon=0)$ are larger by a factor of ~3 than $1/N$ expected based on finite statistics. Similarly, for the two independent measurements of the N oscillating yields (Fig.4) at $\theta=38°$ we obtain $C(\varepsilon=0)=0.0024\pm0.0006$ for the first target and $C(\varepsilon=0)=0.0028\pm0.0007$ for the second one. For the O oscillating yields at $\theta=38°$ we have $C(\varepsilon=0)=0.0024\pm0.0006$ for the first target and $C(\varepsilon=0)=0.0022\pm0.00055$ for the second one. These values are larger by a factor of ~3 than corresponding average inverse counting rates ($1/N=0.0008$ for the N products and $1/N=0.0007$ for the O products) at $\theta=38°$. The above analysis indicates that the oscillations shown in Fig.4 are true oscillations and do not result from insufficient statistics.

Another indication for the statistical significance of the oscillations in Fig.4 can be revealed from the analysis of probability distributions of the properly scaled cross section relative deviations, $(\sigma_i/<\sigma_i>-1)/(1/N_i)^{1/2}$, from the energy smooth background $<\sigma(E)>$. Here, $\sigma_i=\sigma(E_i)$, $<\sigma_i>=<\sigma(E_i)>$ is an energy averaged smooth cross section obtained from the best second order polynomial fit of the data, and N_i is the counting rate for the E_i energy step. Suppose that the cross section energy oscillations in Fig.4 are not true oscillations but originate from the finite count rate. If this would be the case then the probability distribution of

$(\sigma_i/<\sigma_i>-1)/(1/N_i)^{1/2}$ should be a Gaussian distribution with zero expectation and unit standard deviation (variance). Gaussian distributions and the actual probability distributions of absolute values of the measured cross section deviations from the energy smooth background are presented in Fig.5. One observes that the experimental probability distributions are systematically wider than Gaussian distribution with unit standard deviation. Also 21% of all the deviations exceed three standard deviations.

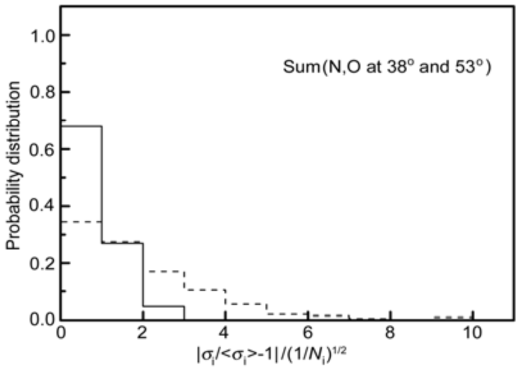

Fig.5 Probability distributions of absolute values of the cross section relative deviations from the energy smooth background obtained in the first measurement (dashed histograms). Solid histograms are Gaussian distributions with unit standard deviation expected based on the finite count rates only (see text).

Moreover, consider a probability distribution of the differences of cross sections for the two independent excitation function measurements

$$[\sigma_1(E)-\sigma_2(E)]/(\delta\sigma_1^2+\delta\sigma_2^2+2\rho\delta\sigma_1\delta\sigma_2)^{1/2} \tag{1}$$

where

$$\delta\sigma_{1,2}^2=(1/n)\sum_{i=1}^{n}(\sigma_i^{(1,2)}-<\sigma_i^{(1,2)}>)^2 \tag{2}$$

$$\rho=(1/n)\sum_{i=1}^{n}(\sigma_i^{(1)}-<\sigma_i^{(1)}>)(\sigma_i^{(2)}-<\sigma_i^{(2)}>)/(\delta\sigma_1\delta\sigma_2) \tag{3}$$

and indices (1,2) stand for the first and second measurement (target), respectively.

Suppose that non-reproducibility of the cross section energy oscillations in Fig.4 is not a true effect but originate from the finite count rates. If this would be the case then probability distribution of quantity (1) with

$$\delta\sigma_{1,2}^2=(1/n)\sum_{i=1}^{n}<\sigma_i^{(1,2)}>^2/N_i^{(1,2)} \tag{4}$$

should be a Gaussian distribution with zero expectation and unit standard deviation (variance). In Eq.(4) $N_i^{(1,2)}$ are the counting rates for the E_i energy step in the first and second measurements, accordingly. Gaussian distributions with unit standard deviation and the actual experimental probability distributions of absolute values of quantity (1) with $\delta\sigma_{1,2}^2$ given by Eq.(4) are presented in Fig.6. One observes that the experimental probability distributions are systematically wider than Gaussian distribution with unit standard deviation. A level of the non-reproducibility exceeds three standard deviations for 18% of all the cross section differences measured. This indicates that the non-reproducibility of the cross section energy oscillations (Fig.4) measured with different target foils of nominally the same thickness is of a statistical significance.

On the contrary, two runs for the same target foil (Fig.3) produce the reproducible cross section energy oscillations (see Fig.6).

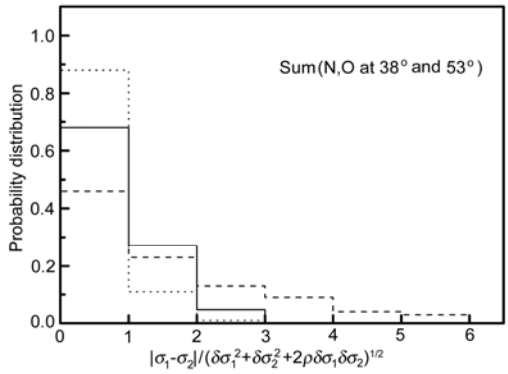

Fig.6 Probability distributions of absolute values of the properly scaled differences between the cross sections obtained in the two measurements with different target foils (dashed histograms). Dotted histograms are probability distributions of absolute values of the properly scaled differences between the cross sections obtained in the two runs with the same target foil for the second measurement. Gaussian distributions (solid histograms) with unit standard deviation expected based on the finite count rates only (see text).

4 Discussion

The necessary conditions for applying the statistical model, theory of Ericson fluctuations[9] and random matrix theory (RMT)[10,11] to interpret the data reported here must be (i) absence of oscillations in cross sections, i.e. energy smooth excitation functions for each of the individual measurements, and (ii) reproducibility of these energy smooth cross sections in the measurements with different target foils. But both of these conditions are not met for the data sets reported in this paper.

In attempting to interpret the non-self-averaging of excitation function oscillations in DHIC one faces a non-straightforward task to modify the RMT of highly excited many-body systems. Such a possible modification has been presented in Refs.[16-18] in terms of spontaneous coherence and slow phase randomization in highly excited many-body systems. It has been argued[20] that the spontaneous origin of the micro-channel correlations (MC) should result in the cross sections for DHIC being sensitive to an infinitesimally small perturbation, although the discussion of Ref.[20] has not taken into account different distributed “target-environmental” perturbations within different independently prepared target foils.

According to Ref.[20], consider an experiment in which we do not determine which particular nucleus of the target participates in the single collision act. Then the measured cross section, per a single target nucleus and for a fixed single exit micro-channel $\bar{b}$ (microscopic states of the reaction products), is given by

$$\sigma_{\bar{b}}(E,\theta) = (1/\mathcal{N})\sum_{j=1}^{\mathcal{N}} \sigma_{\bar{b}}^{(j)}(E,\theta) \tag{5}$$

where $\sigma_{\bar{b}}^{(j)}(E,\theta) = \left| f_{\bar{b}}^{(j)}(E,\theta)\right|^2$, index (j) labels individual target nuclei participating in the collision, whose number is $\mathcal{N} \gg 1$, and $f_{\bar{b}}^{(j)}(E,\theta)$ is the amplitude of a collision involving (j) target nucleus. The difference between $f_{\bar{b}}^{(j)}(E,\theta)$ with different (j) originates from a nonuniform distribution of “target-environmental” perturbations. This introduces different local perturbations, $V_j \neq V_i$, in the purely nuclear Hamiltonian *H* of highly excited nuclear molecules created in the collision of the incident ion with different $(j \neq i)$ target nuclei. We evaluate the strength of the “target-environmental” perturbations to be of the order of the atomic electron effects[20] in DHIC. We employ the perturbation theory and use the decomposition $f_{\bar{b}}^{(j)}(E,\theta) = f_{\bar{b}}(E,\theta) + \delta f_{\bar{b}}^{(j)}(E,\theta)$, where $f_{\bar{b}}(E,\theta)$ is the collision amplitude in the absence of the “target-environmental” perturbations. We also drop the incoherent sum $(1/\mathcal{N})\sum_{j=1}^{\mathcal{N}}\left|\delta f_{\bar{b}}^{(j)}(E,\theta)\right|^2$, as this sum is about fourteen orders of magnitude smaller than $\sigma_{\bar{b}}(E,\theta)$. We therefore obtain

$$\sigma_{\bar{b}}(E,\theta) = \left|F_{\bar{b}}(E,\theta)\right|^2 - \left|(1/\mathcal{N})\sum_{j=1}^{\mathcal{N}} \delta f_{\bar{b}}^{(j)}(E,\theta)\right|^2 \rightarrow \left|F_{\bar{b}}(E,\theta)\right|^2$$

where $F_{\bar{b}}(E,\theta)$ is the collision amplitude corresponding to the Hamiltonian $(H+v)$ with $v = (1/\mathcal{N})\sum_{j=1}^{\mathcal{N}} V_j$.

It is reasonable to assume that a distribution of the local “target-environmental” perturbations V_j is random throughout the target. This means that $\delta f_{\bar{b}}^{(j)}(E,\theta)$ with different (j) have random phases. In this case we have

$$\left|F_{\bar{b}}(E,\theta) - f_{\bar{b}}(E,\theta)\right| \sim (1/\mathcal{N})^{1/2}\left|\delta f_{\bar{b}}^{(j)}(E,\theta)\right| \sim (1/\mathcal{N})^{1/2} 10^{-7}\left|f_{\bar{b}}(E,\theta)\right|$$

where we used the estimate $\left|\delta f_{\bar{b}}^{(j)}(E,\theta)\right| \sim 10^{-7}\left|f_{\bar{b}}(E,\theta)\right|$ from Ref.[20].

Suppose we perform two independent measurements with two different targets. The “target-environmental” perturbations V_j in the first target and $\widetilde{V}_j$ in the second one are different. The cross sections are given by the different amplitudes, $F_{\bar{b}}(E,\theta)$ and $\widetilde{F}_{\bar{b}}(E,\theta)$, corresponding to different Hamiltonians, $(H+v)$ and $(H+\tilde{v})$, accordingly. Let $\mathcal{N} \sim 10^{18}$, as it was the case in our experiment. Then we have $\left|F_{\bar{b}}(E,\theta) - \widetilde{F}_{\bar{b}}(E,\theta)\right| \sim 10^{-16}\left|F_{\bar{b}}(E,\theta)\right|$. Therefore one does not expect a detectable difference for the cross sections measured with two different targets. Indeed, such a detectable difference does not occur if one considers $\sigma_{\bar{b}}(E,\theta)$ for a single fixed $\bar{b}$ independently from the cross sections for the decay to other $\bar{b}' \neq \bar{b}$ micro-channels. However, as suggested in Ref.[20], the situation may change drastically for the cross sections summed over very large number of exit micro-channels. This is the case for DHIC where the collision products have high excitation energies and the measured cross section, $\sigma(E,\theta) = \sum_{\bar{b}} \sigma_{\bar{b}}(E,\theta)$, is the sum over very large number of micro-channels, $N_{\bar{b}} \gg 1$.

The above consideration suggests that the physical origin of the non-reproducibility of the cross sections for different targets is analogous to the origin of the atomic-electron effects in DHIC discussed in Ref.[20]. The key element in the interpretation of the spontaneous coherence, non-self-averaging and extreme sensitivity in complex quantum collisions is to introduce the infinitesimally small off-diagonal MC between different model transition amplitudes which couple model single-particle states (Slater determinants) of the quasi-bound IDS and the continuum states.[16-18,20] It has been argued that the limit of the vanishing of this infinitesimally small correlation properly supplemented by the limit of the infinite dimensionality of the Hilbert space does not destroy correlation between different physical transition amplitudes which couple the many-body configurations of the IDS and the continuum states. As a result, the highly-excited matter displays coexistence of two distinct phases. The decay of the disordered phase is associated with the $\Delta S_{\bar{b}}^{J}$ -matrix,[16] where J is the total spin of the IDS and, thereby, with the amplitude $\Delta F_{\bar{b}}(E,\theta)$ which is a linear combination of $\Delta S_{\bar{b}}^{J}$ with different J. Since $\Delta F_{\bar{b}}(E,\theta)$ with different $\bar{b}\neq\bar{b}'$ do not correlate, this disordered phase does not contribute to the MC producing the stable reproducible self-averaging, i.e. energy smooth, background in cross sections. The non-self-averaging, i.e. micro-channel correlations, and sensitivity originate from decay of the ordered phase corresponding to the micro-channel independent δS^{J}-matrix[20] and, thereby, the micro-channel independent $\delta F(E,\theta)$. It is this micro-channel independent $\delta F(E,\theta)$ which is so sensitive and, therefore, non-reproducible due to the spontaneous origin of the MC so that $\left|\delta F(E,\theta)-\delta\widetilde{F}(E,\theta)\right|\sim\left|\delta F(E,\theta)\right|\sim\left|F_{\bar{b}}(E,\theta)\right|$, where $\delta F(E,\theta)$ and $\delta\widetilde{F}(E,\theta)$ correspond to different targets with different distributions of “target-environmental” perturbations.

5 Summary

Two independent measurements with different target foils of nominally the same thickness indicate statistically significant non-reproducibility of the cross sections for the ^{19}F+^{93}Nb DHIC. The non-reproducibility is consistent with the recent theoretical arguments on spontaneous coherence, slow phase randomization and anomalous sensitivity in finite highly excited quantum systems. If this non-reproducibility is confirmed in more and further experiments it will signal that a realization of Wigner's dream,[21] a theory for the transition amplitude correlations, will require conceptual revision of modern understanding of microscopic and mesoscopic quantum many-body systems.

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