acta physica slovaca vol. 45 No. 6, 711 – 716 December 1995

MEMORY EFFECTS IN THE EXCITATION FUNCTION VARIATIONS IN HEAVY-ION AND NUCLEAR REACTIONS[1]

S.Yu. Kun[2]
Theoretical Physics Department, RSPhysSE, Institute of Advanced Studies, ANU, Canberra ACT 0200, Australia

Received 23 October 1995, accepted 27 October 1995

We briefly discuss the stochastic modelling of the statistical reactions with memory. The effect of the S-matrix spin and parity correlations on the cross section energy variations is reviewed. We also discuss the coherent rotation of the spherical highly excited nucleus.

1. The stochastic modelling of the statistical reactions with memory is based on the theories [1–4] of the fluctuating S-matrix. The idea of the stochastic modelling of the dissipative heavy-ion collisions (DHIC) was introduced in Ref. [5]. The characteristic feature of the statistical ($\langle S(E)\rangle_E = 0$) reactions with memory ([6–12] and Refs. therein) is that bilinear combinations of the fluctuating S-matrix elements with different orbital momenta (l), total spins (J) and parities (π) are permitted to survive energy averaging. This is in contradiction with the standard assumptions that are accepted in the modern quantum-mechanical theories of compound and precompound, *i.e.* time-delayed, reactions. The only exception is the model of leading particle [13]. The relationship between the model [13] and that of [6–12] is beyond the scope of this contribution. In the modern S-matrix approach to nuclear reactions it is accepted to allocate all memory effects to the energy-averaged S-matrix elements (provided they do not vanish, i.e. the interaction time does not exceed the kinematical flight-time of the space wave packet). These energy-averaged S-matrix elements are associated with the direct or multistep-direct reactions [4].

2. The possible motivation for introducing the statistical reactions with memory is given in Refs. 6–12 and Refs. therein. The principle question is: What kind of experimental data should be appropriate to disprove or support the existence of the statistical reactions with memory? The statistical reactions with memory affect both — the energy-averaged differential cross sections [7,10,11] as well as excitation function fluctuations [6–12]. In this contribution, for lack of the space, we briefly discuss mainly

[1]Presented at the International Symposium on Pre-Equilibrium Reactions, Smolenice Castle, 23 – 27 October, 1995
[2]E-mail address: KSU105@PHYVS0.ANU.EDU.AU

 © Institute of Physics, SAS, Bratislava, Slovakia

the effect of the spin and parity correlations between fluctuating S-matrix elements on the cross section energy fluctuations. The choice seems to be rather favourable. Indeed, in the absence of the statistical reactions the interaction mechanism is direct or multistep-direct. Therefore, the characteristic energy scale of the cross section variations is about a few MeV or more. Thus a few hundreds keV energy structures in the excitation function are due to the fluctuating amplitude. Once one accepts that such fluctuations around energy-averaged cross section are due to the statistical mechanism, *i.e.* fluctuating S-matrix, the next steps are: (i) To develop the statistical reactions with memory to analyze the excitation function fluctuations; (ii) To compare the results of the above approach with experimental data as well as with the predictions of the Ericson theory [14–16] of compound nucleus (statistical reactions without memory) fluctuations.

3. Since the discovery [17] of fluctuations in the excitation functions of DHIC, further experiments [18–26] have confirmed the universality of this phenomenon. There have been already a number of works (see Refs. in Ref. 12) focussed on the interpretation of the excitation function fluctuations in DHIC. However the central question, why fluctuations are not washed out in spite of the high intrinsic excitation of the intermediate system and enormous number of uncorrelated final micro-states contributing to the observable cross section, has not yet been answered. The nonself-averaging of excitation function fluctuations in DHIC is the intriguing puzzle [27] of heavy-ion interactions. The phenomenon is of particular interest, since the attempts to search for a selective population of special final states (for example giant resonances), which could reduce the effective number of final micro-channels in DHIC, have failed [28,29].

Some details of the stochastic modelling of excitation function oscillations in DHIC will be reported elsewhere [12]. Here we briefly present the main result.

For concreteness, we consider the case $\hbar\omega \gg \Gamma \simeq \beta$ (where ω and $\beta/\hbar$ are the real and imaginary parts of the angular velocity of the coherent nuclear rotation, and Γ is the total width of the intermediate nucleus. We also consider the region of backwards angles. We calculate the Fourier components $R^{(\pm)}(\tau,\theta)$ of the cross section variations summed over the very large ($N \to \infty$) number of exit microchannels:

$$R^{(\pm)}(\tau,\theta) = (1/\hbar\omega)\int_{\bar{E}-\mathcal{I}}^{\bar{E}+\mathcal{I}} \mathrm{d}E \exp(i(E-\bar{E})\tau/\hbar)(\sigma^{(\pm)}(E,\theta) - \langle(\sigma^{(\pm)}(E,\theta)\rangle_E), \quad (1)$$

where the indices ($\pm$) correspond to the near- and far side contributions, θ is the scattering angle and $\langle(\sigma^{(\pm)}(E,\theta)\rangle_E$ are the energy-averaged cross sections. The Fourier components (1) are considered on the finite energy interval $(\bar{E}-\mathcal{I},\bar{E}+\mathcal{I})$, where $\bar{E}$ is the average energy, $2\mathcal{I} \leq d\hbar\omega$, and $d \geq 5$ is the spin-window width. We obtain

$$R^{(\pm)}(\tau,\theta) = (2\pi/d)N\langle\sigma(E,\theta)\rangle_E(\Gamma/\hbar\omega)(\beta/\hbar\omega)\sin(\mathcal{I}\tau/\hbar) \quad (2)$$
$$\sum_{M,N=0(1)}^{\infty} (\theta_M^{(\pm)}+\theta_N^{(\pm)})\exp[-(\theta_M^{(\pm)}+\theta_N^{(\pm)})\Gamma/2\hbar\omega](\tau\omega+2(\theta_M^{(\pm)}-\theta_N^{(\pm)}))/$$
$$\{[(\theta_M^{(\pm)}-\theta_N^{(\pm)})^2+(\theta_M^{(\pm)}+\theta_N^{(\pm)})^2\beta^2/(\hbar\omega)^2][(\tau\omega+\theta_M^{(\pm)}-\theta_N^{(\pm)})^2+(\theta_M^{(\pm)}+\theta_N^{(\pm)})^2\beta^2/(\hbar\omega)^2]\},$$

where $M,N \geq 0$ for $R^{(+)}(\tau,\theta)$, $M,N \geq 1$ for $R^{(-)}(\tau,\theta)$, $\theta_M^{(\pm)} = \Phi \pm \theta + 2\pi M$ and Φ is the average deflection angle due to the spin dependence of the potential phase shifts in

the entrance and exit channels. In Eq. (2), $\langle\sigma(E,\theta)\rangle_E = \langle\sigma^{(+)}(E,\theta)\rangle_E + \langle\sigma^{(-)}(E,\theta)\rangle_E$. In Eqs. (2), the modulation factor $\sin(\mathcal{I}\tau/\hbar)$ appears due to the fact that the Fourier components (1) are calculated on a finite energy interval. These finite energy range modulations can be easily separated from the effect of a finite β-width by proper data analysis.

We consider the Fourier component of the constant

$$(1/\hbar\omega)\int_{-\mathcal{I}}^{\mathcal{I}} \mathrm{d}E \exp(iE\tau/\hbar) = 2\sin(\mathcal{I}\tau/\hbar)/\tau\omega. \quad (3)$$

Comparison of Eq. (2) and (3) supports our suggestion on the nonself-averaging of the excitation function oscillations in DHIC. Indeed, one observes that the Fourier components (2) and (3) are quite different. In particular, while Eq. (3) has a maximum at $\tau = 0$, Eqs. (2) vanish at $\tau = 0$. This suggests that $\sigma^{(\pm)}(E,\theta)$ are not constants. The characteristic feature of the Fourier components (2) is the presence of equidistant narrow minima with long-range tails. The magnitude of these minima is not reduced by the compound nucleus damping factors $(1/N)^{1/2} \to 0$ and $(D/\Gamma)^{1/2} \to 0$, where D is the average level spacing at the energy $\bar{E}$. This suggests that the oscillations survive the summation over very large $N \to \infty$ number of the exit uncorrelated microchannels and the level-level noncorrelation condition [12]. The nonself-averaging occurs in spite of the strong overlap $\Gamma/D \to \infty$ of the resonance levels due to the high excitations in DHIC.

The nonself-averaging energy structures are quasiperiodic with the quasiperiod $\hbar\omega$. Indeed the average values $\tau_L = 2\pi L/\omega$ of the leading harmonics are bigger than their dispersions $\Delta\tau_K^{(\pm)} \simeq (2\pi/\omega)(\theta \pm \Phi + \pi K)(\beta/\pi\hbar\omega)$ provided $\pi L(\hbar\omega/\beta) \geq \Phi \pm \theta + \pi K$. That it why we suggest that it is probably more adequate to refer the nonself-averaged energy structures in DHIC as the oscillations rather than the fluctuations. The quasiperiodicity of the nonself-averaging oscillations is supported by the data [18,26] on the $^{19}F+^{89}Y$ system. It manifests itself by the presence of the equidistant bumps in the energy autocorrelation functions of the oscillating cross sections [18,26]. The distance between bumps is about 1.7–1.8 MeV independent of the scattering angle and the charge of the projectile-like ejected reaction fragments. The quasiclassical estimate [30] of the average angular velocity of the intermediate system created in the $^{19}F+^{89}Y$ collision is $\hbar\omega \simeq 2$ MeV. This is consistent with the fluctuation data [18,26].

The necessary condition for the nonself-averaging of the cross section oscillations (within the present model) is finite β-width. It can be shown that in the limit $\beta/\Gamma \to 0$ and $\beta/\hbar\omega \to 0$ (the regime of the regular undamped coherent nuclear rotation), the oscillations are self-averaged. It also can be shown that in the compound nucleus limit, $\Gamma/\beta \to 0$, the fluctuations wash out since their relative magnitude become proportional to either $(1/N)^{1/2} \to 0$ or $(D/\Gamma)^{1/2} \to 0$.

4. In DHIC the observable cross section is inevitable summed over very large ($N \to \infty$) number of final microchannels. However studying elastic-inelastic scattering or reactions with excitation of low-lying states of the residual nuclei(us) one is able to measure the decay on the one final microchannel. In the Ericson theory of compound nucleus fluctuations the cross section energy autocorrelation function is Lorentzian independent of the scattering angle and the relative contribution y_d of direct reactions [14–16]. This is related to the fact that the time power spectrum of the statistical compound nucleus decay has exponential shape independent of the scattering angle and y_d. However the above results are modified under the switching on the orbital momentum, total spin and parity correlations between fluctuating S-matrix elements [6,11]. We consider the situation when the relative direct reaction contribution is significant: $y_d \geq 0.7 - 0.8$. This is often the case in the nucleon and light-heavy-ion induced reactions in the wide angular range. Then the cross section energy autocorrelation function $C(\varepsilon, \theta)$ is proportional to

$$C(\varepsilon, \theta) \sim \mathrm{Re}\ c(\varepsilon, \theta), \tag{4}$$

where $c(\varepsilon, \theta)$ is the amplitude energy autocorrelation function. Let us consider the time power spectrum $P(t, \theta)$ of the decay:

$$P(t, \theta) \sim \int_{-\infty}^{\infty} d\varepsilon \exp(i\varepsilon t/\hbar) c(\varepsilon, \theta). \tag{5}$$

For the initial moment $t = 0$, the above Eq. reads:

$$P(t=0, \theta) \sim \int_{-\infty}^{\infty} d\varepsilon c(\varepsilon, \theta) \sim \int_{0}^{\infty} d\varepsilon \mathrm{Re}\ c(\varepsilon, \theta) \sim \int_{0}^{\infty} d\varepsilon C(\varepsilon, \theta), \tag{6}$$

where the relation $c(\varepsilon, \theta) = c^*(-\varepsilon, \theta)$ has been used. Since, unlikely to the compound nucleus decay, in the presence of the spin and parity S-matrix correlations $P(t = 0, \theta)$ is exponentially suppressed in the region of backward angles θ_{back} [6,11], we obtain

$$P(t=0, \theta_{back}) \sim \int_{0}^{\infty} d\varepsilon C(\varepsilon, \theta_{back}) \to 0. \tag{7}$$

Therefore, since $C(\varepsilon = 0, \theta) > 0$, then $C(\varepsilon, \theta_{back})$ must be negative at certain ε, *i.e.* $C(\varepsilon, \theta_{back})$ is not Lorentzian. Among numerous experimental data demonstrating considerable deviations of the energy autocorrelations from Lorentzians, we refer to [6] (where the data [31] on the $^{27}Al(^{3}He, p)^{28}Si$ reaction are analyzed), and, for example, to the $^{56}Fe(p, p)$ scattering (see Fig. 17 from Ref. [32]).

5. As we have seen above, the S-matrix spin and parity correlations, i.e. comparable with Γ the spin and parity decoherence width β, result in the nonself-averaging of the excitation function oscillations in DHIC. It is of interest, from our point of view, to measure excitation functions in the compound and precompound reactions under the condition of highly excited residual nucleus. Then the residual nucleus is in the region of strongly overlapping resonances. It is well known that in the absence of the S-matrix spin and parity correlations the cross section summed over the very large ($N \to \infty$) number of final microstates is a smooth function of the incident energy. Therefore if the measurements show smooth excitation functions, then it means $\beta \gg \Gamma$, which does not support the memory effects in the statistical reactions. On the contrary, if the measurements demonstrate a few hundreds keV energy structures, this is in favour of the condition $\beta \simeq \Gamma$ and therefore supports the existence of the correlations between the fluctuating S-matrix elements carrying different spin and/or parity values. It would be of additional interest to measure (for example proton inelastic scattering) in the relatively high region of the outgoing spectrum. For example, if the initial proton energy is around, say, 65 MeV, then we suggest to measure excitation functions with the 20–25 MeV excitation of the residual nucleus. In this region, in accordance with the multistep models, the cross section is overwhelmingly given by the multistep direct (with energy smooth S-matrix elements) reactions, while multistep compound contribution is negligible. On the contrary, in accordance with the exciton model approaches, the whole cross section is formed due to the time-delayed mechanism, which originates from the fluctuating S-matrix elements.

Our preliminary consideration suggests that finite β-width (*i.e.* nonvanishing of the S-matrix spin and parity correlations) is a necessary condition for the nonself-averaging of the excitation function fluctuations in the compound-precompound decay to the very large ($N \to \infty$) number of final microchannels. The unanswered question is whether this is also sufficient condition? We would like to mention that excitation function fluctuation are affected not only by the β-width value, but also by the value of the angular velocity ω of the *coherent* nuclear rotation. Therefore, if the suggested above measurements of the compound and precompond excitation functions show a few hundreds keV fluctuations, then this, in principle, allows to find out whether the angular velocity of the *coherent* rotation of the spherical highly excited nucleus vanishes or not. Practically, the sensitivity of the effect of the nonself-averaging and other quantitative characteristics of the fluctuations in compound-precompound reactions to the angular velocity of the coherent nuclear rotation, is the crucial question.

We would like to mention that the non-vanishing of the angular velocity of the *coherent* rotation of the spherical object does not contradict to the way it was introduced [11]. Indeed, the coherent nuclear rotation has been introduced without referring to the collective degrees of freedom related to the nuclear deformation. Therefore, it is clear that the coherent rotation [11] is principally different from the collective rotation.

6. To conclude, we have supported the existence of the memory effects in the statistical ($\langle S(E) \rangle_E = 0$) reactions and suggested further test of the phenomenon.

Acknowledgements The author is grateful to the Organizing Committee of the International Symposium on Preequilibrium Reactions for warm hospitality.

References

[1] H. Feshbach: *Ann. Phys. (N.Y.)* **5** (1958) 357 ;
H. Feshbach: *Ann. Phys. (N.Y.)* **19** (1962) 287

[2] C. Mahaux, H.A. Weidenmüller: *Shell Model Approach to Nuclear Reactions*. North-Holland, Amsterdam 1968

[3] D. Agassi, H.A. Weidenmüller, G. Mantzouranis: *Phys. Rep.* **22** (1975) 145

[4] H. Feshbach, A. Kerman, S. Koonin: *Ann. Phys. (N.Y.)* **125** (1980) 429

[5] T. Tomoda, H.A. Weidenmüller: *Phys. Rev. C* **28** (1983) 739

[6] S.Yu. Kun: *Phys. Lett. B* **319** (1993) 16

[7] S.Yu. Kun: *Z. Phys. A* **348** (1994) 273

[8] S.Yu. Kun: *Europhys. Lett.* **26** (1994) 505

[9] S.Yu. Kun: *Nucl. Phys. A* **583** (1995) 275c
[10] S.Yu. Kun, *submitted to* Z. Phys. A
[11] S.Yu. Kun, *submitted to* Z. Phys. A
[12] S.Yu. Kun, *submitted to* Z. Phys. A
[13] G. Mantzouranis, H.A. Weidenmüller, D. Agassi: *Z. Phys. A* **276** (1976) 145
[14] T. Ericson: *Ann. Phys. (N.Y.)* **23** (1963) 390
[15] T. Ericson, T. Mayer-Kuckuk: *Ann. Rev. Nucl. Sci.* **16** (1966) 183
[16] A. Richter: *in* Nuclear Spectroscopy and Reactions, part B, Academic Press, 1974, p. 343
[17] A. De Rosa *et al.*: *Phys. Lett. B* **160** (1985) 239
[18] T. Suomijärvi *et al.*: *Phys. Rev. C* **36** (1987) 181
[19] A. De Rosa *et al.*: *Phys. Rev. C* **37** (1988) 1042
[20] A. De Rosa *et al.*: *Phys. Rev. C* **40** (1989) 627
[21] A. De Rosa *et al.*: *Phys. Rev. C* **44** (1991) 747
[22] Wang Qi *et al.*: *Chin. Phys. Lett.* **10** (1993) 656
[23] Wang Qi *et al.*: *Chin. Phys. Lett.* **15** (1993) 113
[24] F. Rizzo *et al.*: *Z. Phys. A* **349** (1994) 169
[25] Wang Qi *et al.*: *High Energy Physics and Nuclear Physics* **18** (1994) 25
[26] D.J. Hinde *et al.*: *(unpublished)*
[27] H. Feshbach: *in Proc.* of Workshop on *Multistep Direct Reactions, Faure 1991 (Ed. R.H. Lemmer)*. World Sci., Singapore, 1992, p. 225
[28] N. Herrmann *et al.*: *Phys. Rev. Lett.* **60** (1988) 1630
[29] C. Agodi *et al.*: *Z. Phys. A* **340** (1991) 341
[30] M.C. Mermaz *et al.*: *Nucl. Phys. A* **456** (1986) 186
[31] R. Bonetti *et al.*: *Phys. Rev. C* **21** (1980) 816
[32] J. Ernst, H.L. Harney, K. Kotajima: *Nucl. Phys. A* **136** (1969) 87