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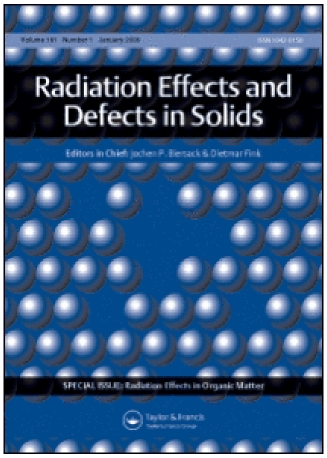

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Thermalized non-equilibrated matter and high temperature superconducting state in quantum many-body systems

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Thermalized non-equilibrated matter and high temperature superconducting state in quantum many-body systems

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A characteristic feature of thermalized non-equilibrated matter is that, in spite of energy relaxation-equilibration, a phase memory of the way the many-body system was excited remains. As an example, we analyse data on a strong forward peaking of thermal proton yield in the Bi(γ, p) photonuclear reaction. A new analysis shows that the phase relaxation in highly-excited heavy nuclei can be eight orders of magnitude or even much longer than the energy relaxation. We argue that thermalized non-equilibrated matter resembles a high temperature superconducting state in quantum many-body systems. We briefly present results on the time-dependent correlation function of the many-particle density fluctuations for such a superconducting state. It should be of interest to experimentally search for manifestations of thermalized non-equilibrated matter in many-body mesoscopic systems and nanostructures.

Keywords: Thermalized non-equilibrated matter; High temperature superconductivity

1. Introduction

Consider a beam of photons or electrons directed on a many-electron quantum dot. Let the quantum dot be three-dimensional with spherically symmetric or two-dimensional with circularly symmetric confining potential. Upon the interaction of the incoming radiation with the electrons inside the dot and because of the inter-dot electron–electron interaction, the total energy of the system eventually gets redistributed among many electrons – the quasi-bound many-electron quantum dot reaches a thermally equilibrated state. Then, after a certain period of time, due to the strong electron–electron interaction, a sufficient energy may be concentrated on a single electron for its escape from the dot. Such a thermal emission can also be

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viewed as an evaporation process usually described by the statistical reaction theory or phase space theory [1].

We ask the questions: Do angular distributions for the thermal emission carry any information of the way the quantum dot was excited? Is there any memory about a direction of the beam of incoming radiation for the thermal emission? More specifically, are angular distributions of the thermal emission necessarily symmetric about 90° in the center of mass system (c.m.) with respect to the direction of the incident beam? These questions have never been addressed experimentally. Indeed, in many fields of modern physics the notion 'thermalization' or 'energy equilibration' are considered to be equivalent to the notion 'statistical equilibrium'. This equivalence seems so obvious that it has never been questioned for highly-excited quantum many-body systems.

While, for the above stated reasons, the problem has never been addressed either theoretically or experimentally for mesoscopic systems, *e.g.,* for many-electron quantum dots, it turns out that there are many well-documented nuclear data sets that reveal unexpected and counterintuitive forward peaking for a thermal emission from highly excited quantum many-body systems. Curiously, some of these data sets have been available for longer than 50 years. Yet, the fact that thermal emission from a compound nucleus can demonstrate a strong angular asymmetry around 90° c.m. has never been recognized by nuclear physicists. Accordingly, the effect has been unknown to a wide physics community. As an illustration, we present an extended analysis of the data on a strong forward peaking of thermal proton yield in the Bi(γ, p) photonuclear reaction. The effect is described in terms of anomalously slow phase relaxation in highly-excited quantum many-body systems. This effect is of significant implications for multi-qubit (n $\simeq$ 100–1000) quantum computers, since it can extend the time for quantum computing far beyond the quantum chaos border [2, 3]. The effect of anomalously slow phase relaxation has also been revealed for heavy ion collisions [4–12] and bimolecular chemical reactions [12, 13]. We find that the phase memory in highly-excited heavy nuclei can be eight orders of magnitude or even much longer than the energy relaxation. We argue that a new form of matter – thermalized non-equilibrated matter – introduced by one of us [14, 15], resembles a high temperature superconducting state in quantum many-body systems. It should be of interest to experimentally search for manifestations of thermalized non-equilibrated matter in many-body mesoscopic systems and nanostructures.

In the Appendix, we briefly outline the results on time-dependent correlation function of the many-particle density fluctuations in such a high temperature superconducting state of the thermalized non-equilibrated matter.

2. Experimental evidence for a formation of thermalized non-equilibrated matter in Bi(γ, p) photonuclear proton evaporation

We analyse the proton yield of the Bi(γ, p) photonuclear reaction, produced by 24 MeV bremsstrahlung. The properly scaled angle-integrated spectrum for the proton energy $\varepsilon \leq$ 8 MeV has an exponential shape with a slope of 0.55 MeV [3]. This is characteristic for the decay of thermalized compound nucleus with a 'temperature' $T = 0.55$ MeV of the residual nucleus. The average excitation energy of the compound nucleus can be evaluated as $\bar{E}^* = 14$ MeV, *i.e.,* slightly above the center of the dipole giant resonance peak at 13.5 MeV [16]. Then, the experimentally determined nuclear 'temperature' is in a good agreement with the statistical model calculations [3].

In figure 1, we present experimental proton angular distributions from the Bi(γ, p) photonuclear reaction for $\varepsilon = 2$–8 MeV [17]. We observe that, in spite of complete energy relaxation in the thermalized compound nucleus, the angular distributions are strongly asymmetric about

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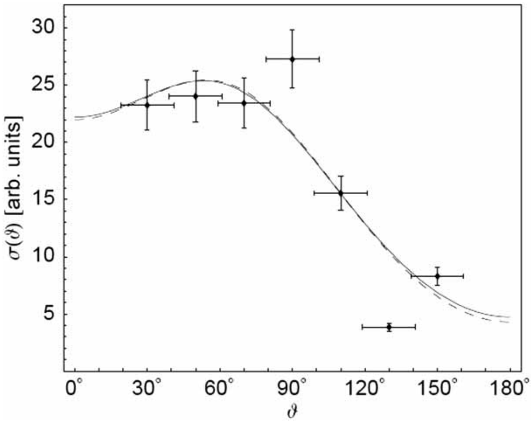

Figure 1. Experimental proton angular distributions (in arbitrary units) from the Bi(γ, p) photonuclear evaporation process for $\varepsilon = 2 - 8$ MeV [17]. The solid curve is a fit to the experimental data with $\beta/\Gamma_{\rm cn} = 0.11$, and the dashed curve is a fit with $\beta/\Gamma_{\rm cn} \to 0$, (see text).

90°, *i.e.,* memory of the direction of the incident γ-ray beam is clearly retained. Therefore, even though the compound nucleus is in a thermalized state, it is far from being fully equilibrated.

3. Theoretical interpretation of the forward peaking of evaporating protons in the Bi(γ, p) photonuclear reaction

Clearly, a description of the decay of thermalized but yet non-equilibrated matter requires a major modification of the conventional picture of the compound nucleus (see *e.g.* ref. [18]), originally formulated by Bohr, Bethe, Weisskopf, Wigner, Dyson, and others. The basic idea behind the conventional picture is that thermalization of the compound nucleus guarantees a complete loss of memory of initial phase relations. A modification of this conventional picture of the compound nucleus was proposed by one of us in Refs. [14, 15]. Unfortunately, there has been no other interpretation of an angular asymmetry around 90° c.m. in evaporation processes. The key element in the description of the asymmetry of angular distributions around 90° c.m. for evaporating particles is the total spin off-diagonal correlation between compound nucleus partial width amplitudes. Such correlation is neglected in a conventional picture of compound nucleus. Following [14, 15], we have

$$\frac{\overline{\gamma_{\mu_1}^{J_1 a_1}\gamma_{\mu_1}^{J_1 b_1}\gamma_{\mu_2}^{J_2 a_2}\gamma_{\mu_2}^{J_2 b_2}}}{\left[\overline{\left(\gamma_{\mu_1}^{J_1 a_1}\right)^2}\;\overline{\left(\gamma_{\mu_1}^{J_1 b_1}\right)^2}\;\overline{\left(\gamma_{\mu_2}^{J_2 a_2}\right)^2}\;\overline{\left(\gamma_{\mu_2}^{J_2 b_2}\right)^2}\right]^{1/2}} = \frac{(1/\pi)D\beta\,|J_1 - J_2|}{\left(E_{\mu_1}^{J_1} - E_{\mu_2}^{J_2}\right)^2 + \beta^2\,(J_1 - J_2)^2}, \qquad (1)$$

where the overlines denote ensemble averaging. Here, $J_1 \neq J_2$ are the compound nucleus total spin values, E_μ^J are the resonance energies with μ being the running indices, D the average level spacing of the compound nucleus, and $\gamma_\mu^{J_a}$ the partial width amplitudes for the formation and decay of the compound nucleus. The a(b) indices specify the orbital momenta $l_{a_{1,2}}(l_{b_{1,2}})$, the channel spins $j_{a_{1,2}}(j_{b_{1,2}})$, and the microstates $\bar{a}(\bar{b})$ of the target and residual nucleus, respectively. Accordingly, $\bar{a}_1 = \bar{a}_2$ denotes the ground state of the target, and $\bar{b}_1 = \bar{b}_2$ specifies the microstates of the residual nucleus.The phase relaxation width β, introduced in refs. [14, 15, 19], determines a characteristic time, $\tau_{ph} = \hbar/\beta$, for the decay of the spin off-diagonal phase correlations. The above correlation between the partial width amplitudes leads

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to a correlation between fluctuating compound nucleus S-matrix elements carrying different total spin values,

$$\left\langle S^{J_1}_{a_1b_1}(E)^* S^{J_2}_{a_2b_2}(E)\right\rangle = \frac{\left[\left\langle \left|S^{J_1}_{a_1b_1}(E)\right|^2\right\rangle \left\langle \left|S^{J_2}_{a_2b_2}(E)\right|^2\right\rangle\right]^{1/2}}{1+|J_1-J_2|\,\beta/\Gamma_{\rm cn}}. \quad (2)$$

Here, $\Gamma_{\rm cn}$ is the compound nucleus decay width, $S^J_{a,b}(E)$ are compound nucleus S-matrix elements with total spin J and the brackets $\langle \dots \rangle$ denote the energy E averaging. For finite values of $\beta/\Gamma_{\rm cn}$, non-vanishing spin off-diagonal correlations in equation (2) reflect non-vanishing interference between resonance levels with different total spins upon energy averaging.

For the correlation between S-matrix elements carrying the same total spin values and the same microstates $\bar{a}_1 = \bar{a}_2$ and $\bar{b}_1 = \bar{b}_2$, but different orbital momenta and/or channel spins, we have [14, 15]

$$\left\langle S^{J}_{a_1b_1}(E)^* S^{J}_{a_2b_2}(E)\right\rangle = \left[\left\langle \left|S^{J}_{a_1b_1}(E)\right|^2\right\rangle \left\langle \left|S^{J}_{a_2b_2}(E)\right|^2\right\rangle\right]^{1/2}. \quad (3)$$

The above equation results from a strong correlation between the partial width amplitudes $\gamma_\mu^{J_{a_1(b_1)}}$ and $\gamma_\mu^{J_{a_2(b_2)}}$ with $\bar{a}_1 = \bar{a}_2$ and $\bar{b}_1 = \bar{b}_2$, but $l_{a_1} \neq l_{a_2}$, $l_{b_1} \neq l_{b_2}$, $j_{a_1} \neq j_{a_2}$, $j_{b_1} \neq J_{b_2}$. Such a correlation is referred to as the continuum correlation [14, 15].

For $\beta >> \Gamma_{\rm cn}$, the spin off-diagonal correlations in equation (2) result in the angular distributions symmetric around 90° c.m., recovering the conventional Bohr picture of the compound nucleus. However, if $\beta \approx \Gamma_{\rm cn}$, *i.e.*, the phase relaxation time $\tau_{\rm ph} = \hbar/\beta$ is comparable or longer than the average life-time of the compound nucleus $\hbar/\Gamma_{\rm cn}$, this allows us to describe a strong asymmetry of the angular distributions of the evaporating yield around 90° c.m.

We analyse the angular distribution of the thermal proton yield in figure 1 following ref. [3]. Without repeating details we note that the shape of the angular distribution has been found to depend on the four parameters: $A = T^{L=2}/T^{L=1}$, $B = T^{l'=1}/T^{l'=0}$, $C = T^{l'=2}/T^{l'=0}$, and $\beta/\Gamma_{\rm cn}$. Here, T^L are the entrance channel transmission coefficients for the formation of the compound nucleus with the total spins $L = 1$ and $L = 2$ due to the absorption of electric dipole and quadrupole radiation, accordingly. The exit channel transmission coefficients $T^{l'}$ with $l' = 0, 1, 2$ being orbital momenta of the evaporated protons, have been assumed to be independent of the compound nucleus spin L and the spin of the residual nucleus [18].

From the best fit of the experimental angular distributions in figure 1 we obtain: $A = 0.082$, $B = 0.47$, $C = 0.37$, and $\beta/\Gamma_{\rm cn} = 0.11$. The compound nucleus decay width $\Gamma_{\rm cn}$ for Bi with an excitation energy of 14 MeV can be estimated from the systematics in figure 7 of ref. [20], which provides a good description of the experimentally determined $\Gamma_{\rm cn}$ for a wide range of mass numbers. From this estimation we obtain $\Gamma_{\rm cn} \approx 0.1$ eV yielding $\beta \approx 0.01$ eV. At the same time, the standard nuclear physics estimate for the spreading width of the Bi nucleus with the excitation energy 14 MeV is about 2 MeV (see figure 2.1 in ref. [21]). This is close to another estimate of $\Gamma_{\rm spr}$ as the width of a dipole giant resonance [22], which is about 4.5 MeV for Bi [16]. Notice that $\hbar/\Gamma_{\rm spr}$ is the energy relaxation time and $\hbar/\beta$ is the phase relaxation time. Therefore, we observe that the phase relaxation is at least eight orders of magnitude slower than energy relaxation.

In figure 1, we also present the best fit for $\beta/\Gamma_{\rm cn} \to 0$ (but still with $D/\beta \ll 1$ [15]). It is obtained with $A = 0.066$, $B = 0.42$, and $C = 0.39$. One can see that the two fits are practically undistinguishable. Therefore, the estimate, $\beta \approx 0.01$ eV, should be considered as the upper limit of β value. Thus, its actual value can be much less than 0.01 eV, though still much larger

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than the average level spacing of the compound nucleus [15], for which the statistical model calculations [18] yields $D \approx 10^{-10}$ eV.

We recall that the total spin off-diagonal S-matrix correlations for evaporation processes were justified in ref. [15] in the limit $N_{\rm eff} \to \infty$, where $N_{\rm eff}$ is an effective dimension of the Hilbert space of the quasi-bound intermediate system. For the analysed Bi(γ, p) photonuclear reaction, we estimate $N_{\rm eff} \approx \Gamma_{\rm spr}/D \approx 10^{16}$. Interestingly, the condition of the exponentially large $N_{\rm eff}$ for the anomalously slow phase relaxation is consistent with the experimental data on a proton thermal emission (evaporation) in proton induced nuclear reactions [23]. For heavy targets, Pt and Au, $N_{\rm eff} \approx 10^{20}$ [2] and the proton evaporating yields are strongly forward peaked revealing that $\beta/\Gamma_{\rm cn} \leq 1$. However, for lighter targets Cu, Fe, and Ni, $N_{\rm eff} \approx 10^{9}$ [2] and the proton evaporating yields are symmetric about 90° c.m. indicating that $\beta/\Gamma_{\rm cn} \gg 1$. Using the statistical model formalism [18], we obtain that $\Gamma_{\rm cn}$ for the Pt and Au targets is about 5 orders of magnitude smaller than $\Gamma_{\rm cn}$ for the Cu, Fe, and Ni targets. Accordingly, the value of β for $N_{\rm eff} \approx 10^{16}$ is at least six orders of magnitude or more smaller than the value of β for $N_{\rm eff} \approx 10^{9}$. The condition $N_{\rm eff} \to \infty$ for the anomalously slow phase relaxation also suggests that, with the decrease of the excitation energy and the compound nucleus temperature, $N_{\rm eff} \approx \Gamma_{\rm spr}/D$ also decreases exponentially, since D increases exponentially while $\Gamma_{\rm spr}$ is approximately constant. Then, such a decrease of $N_{\rm eff}$ is expected to lead to an increase of the phase relaxation width, $\beta \approx \Gamma_{\rm spr} \gg \Gamma_{\rm cn}$. This means that, for temperatures less than certain value, memory about the initial phase relations is completely lost and the compound nucleus is no longer in a superconducting state. This problem is worth an experimental study, *e.g.*, for $Pt(p, p')$ inelastic scattering [2].

There are many more data sets, including recent ones (see, *e.g.*, [2]) demonstrating a strong – a factor two or more – forward peaking for thermal emission in compound nucleus reactions. These nuclear data will be analysed in a future work. However, it should be of interest to experimentally search for manifestations of thermalized non-equilibrated matter in many-body mesoscopic systems and nanostructures. For example, one may try to search for an asymmetry around 90° in angular distributions of thermal electron yield originated from the interaction of the electron beam with many-electron quantum dots, often referred to as artificial nuclei.

It should be noted that while we have been able to determine an upper limit of the anomalously small value of β from the data analysis, its theoretical evaluation is an open problem.

4. Thermalized non-equilibrated matter as a high temperature superconducting state

Consider a proton beam directed on a heavy nucleus. Suppose the proton from the incident beam is captured by the nucleus. As a result, a thermalized compound nucleus, with strongly overlapping resonances, $\Gamma_{\rm cn} \gg D$, is formed. This compound nucleus can emit a proton either with the energy lower than the energy of the incoming proton or with the same energy as that of the incoming proton. The latter possibility is referred to as compound elastic scattering. Since the compound nucleus is formed due to the coherent contribution of partial waves with orbital momenta ranging from $J = 0$ to $J = J_{\rm max}$, only a fraction of the incoming plane wave contributes to the formation of the thermalized compound nucleus. The intensity of this fraction of the incoming plane wave is forward peaked with an angular dispersion $\approx 1/J_{\rm max}$. Suppose that $J_{\rm max}\beta/\Gamma_{\rm cn} \ll 1$, as it can be the case for the $Pt(p, p')$ compound nucleus scattering [24]. Then, the compound elastic proton yield emitted from the fully thermalized (since $\Gamma_{\rm spr} \gg \Gamma_{\rm cn}$ [2]) intermediate nucleus would have precisely the same forward-peaked angular distribution, with the same angular dispersion, as that for the fraction of the incoming

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plane wave contributing to the formation of the compound nucleus. This is because the phase relations between partial waves with different angular momenta (total spins) for the emitted proton are the same as for the incoming plane wave. In other words, the incident beam passes through the compound nucleus without any resistance. Such an ideal transparency takes place in spite of a complete thermalization of the intermediate compound nucleus having a high temperature. For this reason, such a state of the thermalized compound nucleus can formally be referred to as a high temperature superconducting state in strongly interacting quantum many-body system. It should be noted that, on the basis of arguments in ref. [15], such a superconducting state may be formed not only for the target nucleus being in a ground state but also for highly-excited target nucleus.

On the contrary, for $J_{\max}\beta/\Gamma_{\rm cn} \gg 1$, the phase relaxation – randomization is very fast, initial spin off-diagonal phase correlations are completely forgotten. This results in the conventional Bohr's picture of compound nucleus leading to symmetric angular distributions around 90° c.m. Within this picture, half of the initial forward-peaked incoming current would be emitted back implying an infinite resistance for a proton wave propagation through the thermalized compound nucleus – equal forward and backward emission intensities cancel each other resulting in zero net current.

5. Conclusion

The main purpose of this paper is not to promote the presented description of the anomalously slow phase relaxation, which is, many orders of magnitude, slower than the energy relaxation (thermalization). Rather, we intended to indicate a new field of research in quantum many-body physics. Our intention is motivated by an existence of nuclear data that reveal a clear physical picture for a new form of matter–thermalized non-equilibrated matter. The problem is of importance not only for nuclear physics (and applications for nuclear data evaluation), but it should be of interest to a wider physics community. Indeed, the fact that in highly excited many-body systems, the phase relaxation can be many orders of magnitude longer than energy relaxation is of significant implications for quantum computing [2, 3] as well as, *e.g.,* time-delayed 'statistical' ionization of many-electron quantum dots and atomic clusters (see, *e.g.,* [1] and references therein). A clear presence of the effect of anomalously slow phase relaxation in chemical reactions (see [12, 13] and references therein) would require a modification of the statistical theories, phase space, and transition state theories (see, *e.g.*, [25] and references therein). And, as has been discussed above, thermalized non-equilibrated matter may be viewed as high temperature superconducting state in highly-excited quantum many-body systems.

Yet, the nuclear data indicating the existence of anomalously slow phase relaxation, which is much slower than energy relaxation, have been completely unrecognized by nuclear physicists and, for this reason, are completely unknown outside the nuclear physics community. In many fields, including statistical physics, the notions of 'thermalization' or 'energy equilibration' are considered to be equivalent to the notion 'statistical equilibrium'.

The conventional idea of a very fast phase relaxation in quantum many-body systems is at the very foundation of the statistical model and random matrix theory. Accordingly, it is widely presented in the University courses on, *e.g.*, nuclear physics, molecular and atomic cluster physics, condensed matter, mesoscopic physics, etc. Yet, students should not be denied the opportunity and right to know that other possibilities exist. Namely, that a thermalized system is not necessarily in equilibrium due to the anomalously long phase memory. These concepts may be counterintuitive, despite of the sounding experimental evidence in their favor. Thus, a conceptual revision of the long-standing conventional physical picture is required.

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Appendix A: Time-dependent correlation function of the many-particle density fluctuations for thermalized non-equilibrated matter

All known superconductors are solids. None are gases or liquids. Does our analysis of the nuclear data suggest a possibility of a high temperature superconducting state for highly excited boiling 'nuclear liquid'? In this Appendix, we briefly outline some results of ref. [26], which indicate that this is not quite so.

The wave function of the compound nucleus may be written as

$$\Psi(\mathbf{r}, t) = \sum_{J\mu} \gamma_\mu^{Ja} \exp(-i E_\mu^J t/\hbar) \phi_\mu^J(\mathbf{r}) \tag{A1}$$

Here, γ_μ^{Ja} are real partial-width amplitudes for the formation of the compound nucleus resonance level μ with the total spin J and energy E_μ^J from the channel a, $\phi_\mu^J(\mathbf{r})$ being the resonance eigenstates with $\mathbf{r}$ denoting the coordinates of all the particles, and t is the time.

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For each J value, the summation over μ includes $\approx \Delta E/D \gg 1$ terms with $\Delta E \approx \Gamma_{\rm spr} \gg \beta$, where D is the average level spacing of the compound nucleus. Summation over J-values goes from $J = 0$ to $J = J_{\rm max}$.

We consider the correlation between the density fluctuations, $\delta n(\mathbf{r}, t)$, for two different moments of time, t_1 and t_2. Here,

$$\delta n(\mathbf{r}, t) = n(\mathbf{r}, t) - \overline{n(\mathbf{r}, t)}^{\mathbf{r}}, \tag{A2}$$

with $n(\mathbf{r}, t) = (1/V)|\Psi(\mathbf{r}, t)|^2$, V being a multi-dimensional effective volume of the system, and $\overline{(\ldots)}^{\mathbf{r}}$ representing $(1/V)\int_V d\mathbf{r}(\ldots)$. For $\hbar/D > t_1, t_2 > \hbar/\Delta E$ and $\beta/D \gg 1$, we obtain [26]

$$\overline{\delta n(\mathbf{r}, t_1)\delta n(\mathbf{r}, t_2)}^{\mathbf{r}} \approx A \exp\left(\frac{-\Delta E|t_1 - t_2|}{\hbar}\right) + B \sum_{J_1 J_2 J_3 J_4} \exp\left(\frac{-\beta|J_1 - J_2|t_1}{\hbar}\right) \exp\left(\frac{-\beta|J_3 - J_4|t_2}{\hbar}\right) + R(t_1, t_2) \tag{A3}$$

where the summation runs over all spin values except for $J_1 = J_2$ and $J_3 = J_4$, and A and B are time-independent quantities. The first term in the r.h.s. of equation (A3) corresponds to a very quick decay of the density correlations on the very short period of time $|t_1 - t_2| \approx \hbar/\Delta E$. Yet, for $t_1 = t_2$, this term does not depend on t_1. This is characteristic of a liquid or gas phase. On the contrary, in the second term the dependence on t_1 and t_2 is factorized. Also, for $t_1, t_2 \ll \hbar/(J_{\rm max}\beta)$,), the second term does not depend on t_1, t_2 resembling the behavior of a solid (or glass). Pictorially, this may be viewed as a certain, not necessarily spherically symmetric, spatial configuration of ice put in a liquid or gas. Notice that on this time scale, $t_1, t_2 \ll \hbar/(J_{\rm max}\beta)$, the thermalized non-equilibrated matter resembles a high temperature superconducting state. As time goes on, the 'ice' slowly melts down and, for $t > \hbar/(J_{\rm max}\beta)$, the density fluctuations due to the 'solid' phase relaxes completely. This corresponds to the regime of complete phase relaxation (complete loss of the phase memory) recovering the conventional picture of the compound nucleus by Bohr. One also observes that if only states with a single total spin value are excited ($J_1 = J_2 = J_3 = J_4$) the second term in the r.h.s. of equation (A3) vanishes. Therefore, a formation of the 'solid' phase is essentially due to the coherent excitation of and a peculiar interference between the strongly overlapping ($t \ll \hbar/D$) states with different J-values in equation (A1).

The third term in the r.h.s. of equation (A3), which vanishes for $t_1, t_2 > \hbar/(J_{\rm max}\beta)$, corresponds to the interplay between the 'solid' phase and gas or liquid phase. This term will be analysed elsewhere.