Thermalized Non-Equilibrated Matter: Compound Processes and Beyond

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A characteristic feature of thermalized non-equilibrated matter is that, in spite of energy relaxation (thermalization), a phase memory of the way the strongly interacting many-body system was excited remains. In this contribution we analyze a low energy evaporating proton data in nucleon induced reactions at \( \simeq \) 62 MeV incident energy with \(^{197}\text{Au}, ^{208}\text{Pb}, ^{209}\text{Bi}\) and \(^{nat}\text{U}\). Our analysis demonstrates that the thermalized non-equilibrated matter survives a cascade of several evaporating particles. Thus the experiments show that the effect of the anomalously slow phase relaxation, with upper limits of the phase relaxation widths in the range \( 1-10^{-4} \) eV, is stable with respect to the multi-step evaporating cascade from the thermalized compound nuclei. We also briefly mention manifestations and implications of the thermalized non-equilibrated matter for some other fields.

I. INTRODUCTION

The basic idea of the modern theory of highly excited strongly interacting quantum many-body systems is that the phase relaxation time is much shorter than the energy relaxation time \([1]\). Application of this idea to the theory of pre-compound and compound reactions implies the absence of correlations between energy fluctuating around zero S-matrix elements carrying different total spin and parity quantum numbers. However the assumption of a very fast phase relaxation is in a conflict with many data sets on complex quantum collisions. In particular, the anomalously long-lived spin off-diagonal S-matrix correlations have been revealed from the data on forward peaking of evaporating protons in nucleon induced \([2, 3]\) and photonuclear \([4, 5]\) reactions. These long-lived correlations reflect an anomalously slow phase relaxation, which is many orders of magnitude longer than the energy relaxation. This provides a manifestation of a new form of matter: thermalized non-equilibrated matter introduced by one of us \([6, 7, 8]\). The problem is of a primary importance for the nuclear technology applications.

The previous analysis \([2, 3, 4, 5]\) dealt with the data obtained for relatively low, \( \simeq 15-20 \) MeV, excitation energies of the compound nuclei. For such energies a second chance proton evaporation is either forbidden or negligible. In this contribution we analyze the data sets for the higher energy when there is a high probability for evaporation up to three and even four nucleons from the thermalized compound nucleus. The data demonstrate that, after evaporation of nucleons, the residual compound nuclei are in (i) a coherent superposition of the strongly overlapping resonance states with different total spins and parities, and (ii) the phase relaxation between the strongly overlapping resonance states with different total spins and parities is still anomalously long in these highly-excited residual compound nuclei.

II. ANALYSIS OF THE DATA

In Figs. 1-6 we present the scaled low energy proton spectra, for forward and backwards angles, produced in nucleon induced reactions with the incident energy \( \simeq 62 \) MeV. The spectra are in arbitrary units and are scaled with (i) the outgoing proton energy \( \epsilon \), and (ii) the cross section, \( P(\epsilon) \), of the inverse process of the capture of the proton with energy \( \epsilon \) by the residual compound nucleus. The latter quantities are taken from \([9]\) for \( r_{0}=1.3 \) fm.

From the comprehensive analysis \([10]\) of the \(^{209}\text{Bi}(p,p')\) scattering at \( E_{p}=62 \) MeV it follows that the multi-step direct reaction contribution is negligible for \( E_{p'} \leq 10 \) MeV. From the structure of the multi-step direct reactions models it is clear that this should apply to all the data sets analyzed in this contribution. Our analysis, based on the exiton model \([1]\), shows that, for \( E_{p'} \leq 10 \) MeV, the multi-step compound reaction contribution is also negligible for all the data sets analyzed here (Figs. 1-6). Thus, for \( E_{p'} \leq 10 \) MeV, we deal exclusively with evaporation cascade from the chain of thermalized cooling down compound nuclei. Indeed the scaled spectra show locally exponential \( \epsilon \)-dependence, in agreement with the statistical evaporation model \([1]\). The slopes of the scaled spectra — the inverse nuclear “temperatures” — decrease with decrease of the energy of the evaporated protons. This reflects a process of cooling down of the compound nuclei by means of particle evaporation: the smallest energies of the evaporating...
protons correspond to the mainly last chance of evaporation. Notice that the slightly different slopes for forward and backward angles do not mean different “temperatures” but reflect different \( \varepsilon \)-dependence of the transmission coefficients for different exit channel orbital momenta of evaporating protons. Yet, in spite of a complete energy relaxation (thermalization) one observes that angular distributions of the evaporating protons are not symmetric around 90° up to the last chance thermal proton emission. The forward thermal emission intensities exceed the backward ones by factors of 2 to 6. The data [11, 12, 13, 14, 15] are in good agreement with each other and show that forward peaking is basically present for many angular distributions of \( d, t, {}^3\text{He} \) and \( \alpha \)-particles in the low energy, typically evaporation, domain of the outgoing spectra. In Ref. [12], a forward peaking of evaporating neutrons is also reported. Thus, the data in Figs. 1-6 demonstrate that thermalized non-equilibrated matter is stable with respect to a multi-step evaporation cascade. This also means that the phase relaxation widths \( \beta \), introduced by one of us [6, 7, 8], are about or less than compound nucleus total decay widths (defined as inverse average compound nucleus life-times), on each step of the cascade. The smallest compound-nucleus total-decay width corresponds to the last chance evaporation, i.e. to the smallest proton outgoing energy. From the slopes of the scaled spectra at the smallest energies in Figs. 1-6 we evaluate the “temperatures” of the residual compound nuclei. This allows us to evaluate excitation energies of the compound nuclei from which protons, with the lowest measured energies in Figs. 1-6, were evaporated. Finally, using the statistical model expression for the compound nucleus total decay width, which is in a good agreement with the data systematics [10], we find the upper limits for the phase relaxation widths for the data in Figs. 1-6. These upper limits are in the range from the maximal value of \( \simeq 1 \) eV for the data [11] (Fig. 3) (because of the lowest energy reported [11] is maximal among all the other data sets analyzed here) down to the value of \( \simeq 10^{-4} \) eV for the data [15] (Fig. 6). For a comparison, typical nuclear energy relaxation widths are evaluated as \( \Gamma_{spr} \geq 1 \) MeV [1]. We note that in all the data sets in Figs. 1-6, the excitation energy of the compound nuclei for the last chance proton evaporation is \( \geq 10 \) MeV. This means that the average level-spacing \( D \leq 10^{-16} \) MeV yielding effective dimensions of Hilbert spaces \( \Gamma_{spr}/D \geq 10^{16} \). Thus, the effect of anomalously slow phase relaxation for the data sets analyzed in this contribution is again revealed for exponentially large effective dimensions of Hilbert space [2, 4, 8]. Yet, for the upper limit of lowest \( \beta \simeq 10^{-4} \) eV obtained above, we have \( \beta/D \simeq 10^6 \).

FIG. 1: The scaled outgoing proton spectra, for different angles, from the \(^{197}\text{Au}(p,p')\) reaction. The lines connecting the data full points are for eye guide. The data errors reported are about of the size of the full dots. The data are from [11].
FIG. 2: The same as in Fig. 1 but for the $^{208}$Pb(p,p’) reaction. The data are from [12].

FIG. 3: The same as in Fig. 1 but for the $^{209}$Bi(p,p’) reaction. The data are from [11].
FIG. 4: The same as in Fig. 1 but for the $^{209}$Bi(n,p) reaction. The data are from [13].

FIG. 5: The same as in Fig. 1 but for the natU(n,p) reaction. The data are from [14].
III. DISCUSSION AND CONCLUSION

We briefly mention that the new form of matter — thermalized non-equilibrated matter — is of primary importance for many-qubit quantum computation since anomalously long-lived phase memory can extend the time for quantum computation far beyond the quantum chaos border [2, 4]. An effect of a very slow phase relaxation has also been strongly supported by numerical calculations for H+D$_2$, F+HD, and He+H$_2$ chemical reactions. In these calculations, a slow phase relaxation ($\beta \ll \Gamma_{spr}$) manifests itself in stable rotating wave-packets of the excited intermediate complexes [20]. Interestingly, this same effect of stable coherent rotation was originally revealed and described for heavy-ion elastic and inelastic scattering, e.g., for $^{12}$C+$^{24}$Mg, $^{24}$Mg+$^{24}$Mg and $^{28}$Si+$^{28}$Si, $^{58}$Ni+$^{46}$Ti and $^{58}$Ni+$^{62}$Ni scattering (see also [27]) as well as for strongly dissipative heavy-ion collisions, e.g., $^{19}$F+$^{89}$Y, $^{28}$Si+$^{64}$Ni and $^{28}$Si+$^{48}$Ti [30, 31] collisions. Slow phase relaxation has been found responsible for quantum-classical transition and Schrödinger cat states in heavy-ion collisions and chemical reactions [20, 32, 33, 34].

Another manifestation of the thermalized non-equilibrated matter is a strong channel-channel correlation in dissipative heavy-ion collisions [35]. The correlation has nothing to do with S-matrix unitary condition for fixed total spin and parity quantum numbers but originates from the correlation and slow phase relaxation between the strongly overlapping resonance states carrying different total spin and parity values. This correlation results in non-self-averaging of excitation function oscillations in these processes. This signifies that $\beta$ values are much smaller than $\Gamma_{spr}$ and yet requires finite $\beta$ values, comparable with the total decay width of the intermediate system [35]. Recently, a fine energy resolution measurement of excitation functions for $\alpha$-particle yields in $^{19}$F($110$-$118$ MeV)+$^{27}$Al with the energy step 250 keV in laboratory system has been performed [36]. For each incident energy, the $\alpha$-particle energy spectra have typical evaporation shape. Yet, in spite of a summation over the whole evaporation spectra for each energy step, the corresponding excitation functions show strong oscillations. This provides yet another demonstration that even though the intermediate system is thermalized it is not equilibrated [37]. Thermalization does not guarantee equilibrium!

There exists an indication that the anomalously slow phase relaxation and the thermalized non-equilibrated matter may lead to anomalous sensitivity of the cross sections in complex collisions [38]. The phenomenon is intimately related to the channel-channel correlation and non-self-averaging of the excitation function oscillations indicating deterministic randomness in complex collisions. So far the experiments [39, 40] have been supporting the theoretical conjecture [38].
The data analyzed in this contribution demonstrate that, after the evaporation cascade, the residual compound nuclei are in (i) a coherent superposition of the strongly overlapping resonance states with different total spins and parities, and (ii) the phase relaxation between the strongly overlapping resonance states with different total spins and parities in the highly-excited residual compound nuclei is still anomalously long corresponding to the upper limit of the phase relaxation widths to be in the range $10^{-4}$ eV. This is from 6 to 10 orders of magnitude less than typical nuclear energy relaxation (spreading) widths [1].

A possibly interesting aspect of the present discussion is the following. After emitting a first proton the highly excited residual nucleus is entangled with this proton. The thermally emitted proton is expected to readily interact with, say, atoms in the target, i.e. with “environment”. Therefore, this emitted proton very quickly (possibly quicker than the average time to complete the whole evaporation cascade) experiences decoherence. Accordingly, the reduced density matrix of the residual nucleus may also be expected to correspond to a fully mixed state unless it belongs to a decoherence free subspace of the highly excited strongly interacting many-body system. On the other hand, for the all data sets analyzed in this paper, it is not excluded that there is a considerable contribution of events when the proton is emitted on the last stage of the cascade only, while all the previous cascade steps proceeded through evaporation of neutrons. Then, since effective interaction of neutrons with the “environment” is much weaker than that of protons, the decoherence effects should be expected to be suppressed/postponed. It could be of interest to design experiments to try to find out which of the two possibilities may actually be realized, leading to the residual nucleus being in coherent superposition of strongly overlapping resonance states with different total spin and parity values (not to mention anomalously long phase relaxation of such a coherent superposition). One does not a priori exclude a possible relationship between the robust, against decoherence, quantum superpositions and their anomalously slow phase relaxation in a view that the latter was introduced by means of ensemble averaging over couplings of a given (fixed) intermediate system with continuum (“environment”).

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