Eur. Phys. J. A **7**, 435–440 (2000)

THE EUROPEAN
PHYSICAL JOURNAL A

Multiparticle correlations in resonance-matter formation

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Received: 29 December 1998 / Revised version: 20 December 1999
Communicated by A. Schäfer

Abstract. The effect of multiparticle correlations on resonance and pion populations, in relativistic nuclear reactions, is calculated in the context of an intranuclear cascade model which includes N-body (N > 2) collisional processes. The resonance-matter population present in the highly-compressed phase of nucleus-nucleus collisions is investigated, in reactions between different intermediate-mass nuclear systems.

PACS. 25.75.Dw Particle and resonance production – 25.75.Gz Particle correlations – 25.75.-q Relativistic heavy-ion collisions – 24.10.Lx Monte Carlo simulations (including hadron and parton cascades and string breaking models)

1 Introduction

Resonance-matter formation is expected to give an important contribution to the strangeness enhancement and the subthreshold antiproton production in relativistic heavy-ion reactions at intermediate energies [1–6]. The interest on this subject has increased once the presence of a dense resonance matter can affect several observables, mainly those related to the in-medium particle production mechanism [7,8]. Many different models have estimated the abundance of Δ-resonances and pions in the nuclear medium, in relativistic nucleus-nucleus reactions at incident energies in the range 1–10 GeV per nucleon [4–6]. However, the study of relativistic heavy-ion reactions at intermediate energies still claims for a theoretical approach that includes properly particle correlations in the interacting nuclear system. In what concerns the inclusion of particle correlations in the dynamical evolution of the system, the models based on the intranuclear cascade (INC) method seem to be the best candidates among the dynamical microscopic approaches [9,10], since models based on transport equations deal only with the one-body phase space distribution function [11–13].

The present calculation follows our previous relativistic model, already discussed in [10] and applied here to the study of many-body effects on the formation of resonance matter as well as on the pion production. The importance of N-body (N > 2) correlations for the description of the heavy-ion reaction mechanism was firstly pointed out by Kodama et al. [9], by using Monte Carlo simulations in the INC model. In that work, it was demonstrated that non-binary particle collisions due to dynamical density fluctuations cannot be neglected. In this context of improved INC models, we discussed recently the relevance of multibaryonic collisions to the particle production mechanism [10], by introducing two different criteria for the specification of the collision-correlated cluster of baryons participating in the intranuclear dynamics; the calculations have shown that the pion production is strongly sensitive to many-body intranuclear processes. Furthermore, new data for the negative pion multiplicity in heavy-ion collisions at incident energies between 1 and 2 GeV per nucleon, and an experimental inference of the delta matter formation, were recently reported by Hong et al. [14,15].

In the present work we study the resonance-matter formation by applying a microscopic dynamical calculation to different colliding nuclear systems. The time evolution of the density of the baryonic environment of the formed resonance matter is also determined, and the effect of the dynamics of particle correlations on these results is discussed.

2 The model

For the sake of completeness, we present here the most relevant aspects which have been taken into account in the calculation, concerning the inclusion of many-body collisions. The model considers that multiparticle correlations affect the usual binary collision through an inter-

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fering neighborhood. For the two interacting baryons i and j, separated by the distance d_{ij}, the simplest way to decide on whether a generic third particle k is in the geometric interfering neighborhood of the i-j pair or not, is by comparing the effective ranges for the k-i and k-j interactions to the distances r_{ki} and r_{kj}, respectively. Namely, if any of the following conditions

$$r_{ki} < \sqrt{\frac{\sigma_{ki}(s)}{\pi}} \qquad \text{or} \qquad r_{kj} < \sqrt{\frac{\sigma_{kj}(s)}{\pi}} \tag{1}$$

is satisfied, the particle k is considered as interacting with the primary baryons i and j. The above criterion will be called henceforth large-cluster criterion (LCC).

A more restrictive criterion for the definition of the neighborhood interfering on the primary entrance channel, and consequently on the particle production, results by imposing that the particle k only interferes in the i-j collision if, in addition to condition (1), one is also required that

$$r_{ki} < d_{ij} \qquad \text{or} \qquad r_{kj} < d_{ij} \, . \tag{2}$$

With the additional condition (2), the number of particles involved in the many-body processes results smaller than in the previous situation (see [10]). In contrast to the first criterion mentioned above, this second criterion will be hereafter referred to as small-cluster criterion (SCC).

After having established which are the baryons composing the interacting cluster, i.e. the colliding pair and the baryons in the interfering neighborhood, the next task is the processing of the N-body collision. However, due to the lack of information about the cross sections of N-body collisional processes, we have treated them as binary collisions sunk in a heat bath generated by the interfering baryons; this procedure defines an energy-momentum redistribution mechanism among the N particles of the cluster. In the present calculation, we have adopted an energy-momentum redistribution prescription that preserves strictly the total energy and momentum. As a matter of fact, we have picked out equally-probable configurations in the many-body phase-space constrained by energy-momentum conservation [9,16]. After this redistribution, the resulting energies and momenta of the baryons i and j are then used as input for the processing of their binary interaction. By using this prescription we are imposing a local thermalization mechanism, similar to the one adopted in [12] to define an effective cross section for the many-body processes.

We emphasize that the first step of the process is represented by a microcanonical phase-space choice of new momenta and energies for the particles involved. Namely, with equal probability in N-body phase-space, a new momentum-energy configuration is picked up, strictly preserving the total four-momentum of the N-baryons involved; as the total number of particles and their characteristics are maintained, the time reversibility and the unitarity of the process are both respected in this first step. In the second step, the binary collision between the original two baryons is processed by taking into account the modified four-momentum of each particle, and preserving the extended detailed balance relation for binary reactions, mentioned previously.

Concerning the resonance production, three excited states of the nucleon are considered: the P_{33} (Δ), P_{11} (N^*) and S_{11} (N') resonances. We list below all the elementary reactions included in the present version of the model:

$$B_1B_2 \to B_1B_2 \tag{3}$$
$$NN \rightleftharpoons N\Delta \tag{4}$$
$$NN \rightleftharpoons NN^* \tag{5}$$
$$NN \rightleftharpoons NN' \tag{6}$$
$$\Delta \rightleftharpoons N\pi \tag{7}$$
$$N^* \rightleftharpoons N\pi \tag{8}$$
$$N' \rightleftharpoons N\pi \tag{9}$$
$$N' \to N\eta \, , \tag{10}$$

where B means any baryon, N means a nucleon, and Δ, N^* and N' are the baryonic resonances.

The cross section for the elastic baryon-baryon process, (3), has been taken from a compilation of experimental data [17]. The direct reactions (4), (5) and (6) are the Δ, N^* and N' production processes, respectively. The cross sections for all possible isospin channels in the first two of these reactions are given in terms of the parametrization of the data for the NN single pion production by VerWest and Arndt [18]. The N' production cross section is obtained by considering that N' decays into a pion (9) or an eta (10) with the same probability [19]. From the elementary process

$$pp \to pp\eta \, , \tag{11}$$

which can be interpreted as $pp \to pN'^{+}$ followed by $N'^{+} \to p\eta$, the cross section for the N'^{+} formation can be established. The other isospin states are obtained by using isospin symmetry. The resonance-recombination processes, inverse reactions in (4), (5) and (6), were calculated by using the extended detailed balance relation [20–22], which takes into account the finite width of the resonances. Although other versions of the extended detailed balance relation have been used [21], an experimental analysis carried out more recently [23] showed that the version by Wolf et al. [20] reproduces better the available data for the delta-recombination cross section.

The resonances decay into a pion-nucleon pair through the direct reactions in (7), (8) and (9). The decay time of a resonance is chosen from the characteristic exponential law with a lifetime given by $\tau = \hbar/\Gamma$, where $\Gamma_\Delta = 115$ MeV, $\Gamma_{N^*} = 200$ MeV, and $\Gamma_{N'} = 150$ MeV. Note that pion absorption effects —inverse reactions in (7), (8), and (9)— are explicitly included; their cross sections are taken from [24]. Finally, in our model the pion production may occur only through a resonance decay, since we disregard the direct s-state pion production.

In conventional versions of the INC model [25–28], the Pauli-blocking effect has been taken into account through prescriptions which adopt some sort of energy cutoff for *soft-collisions*, i.e., collisions with relative kinetic energy lower than the local Fermi energy are not processed. In our model, the prescription for the Pauli-blocking represents an improvement over the previously adopted treatments; we have used phase-space exclusion volumes attached to each fermion. For every elementary interaction processed, we check whether the exclusion volume associated with the final state of each colliding fermion includes more than 2S+1 similar fermions, where S is the spin of that fermion. Whenever this happens, the collision is not allowed. The exclusion volume corresponds to a hypercubic cell in phase space, with the spatial size equal to typical nucleon dimension ($\Delta x_\alpha = 1.13$ fm), and the momentum size given by the uncertainty relation $\Delta x_\alpha\, \Delta p_\alpha = h$, with $\alpha = x, y, z$. Recently, Cugnon and coworkers have introduced a similar treatment for the Pauli-blocking in an improved intranuclear cascade model for photonuclear reactions [29].

3 Multiparticle correlation in resonance-matter formation

Current experimental and theoretical studies have explored the possibility of resonance-matter formation in heavy-ion reactions at intermediate energies [4–6]. In this section we discuss the effect of many-body correlations on resonance-matter formation in the following colliding systems: $^{12}C + {}^{12}C$, $^{20}Ne + {}^{20}Ne$, $^{40}Ca + {}^{40}Ca$ and $^{58}Ni + {}^{58}Ni$.

In Fig. 1, the maximum number of resonances reached during the dynamical evolution of these colliding systems is shown as a function of incident energy. Calculations performed with the standard INC model —one that includes only binary collisions— are displayed in part (a); the results of the present model, which includes also multiparticle collisions under the two different particle-correlation criteria SCC and LCC, are displayed in parts (b) and (c), respectively. As a background information we also display the *model-dependently* extracted delta population for the $^{58}Ni + {}^{58}Ni$ reaction inferred in [14]. The resonance population includes the number of Δ-, N^*-, and N'-resonances. The main contribution to the resonance population obtained in the present work comes from the lowest-mass nucleonic excitation; the Δ-resonance accounts for at least 85% of the total number of resonances in the system. On the other hand, the number of N^*-resonances is about 14% of the total resonance population, and the number of N'-resonances is roughly smaller than the N^* population by a factor of 10; these details are not exhibited in the figure. For incident energies higher than 2 GeV per nucleon we expect an enhancement in the population of N^*, N', and even heavier resonances, as one moves to energies beyond their thresholds.

Figure 1 clearly shows a decrease in the maximum number of resonances present in the system, as one increases the range of correlation from the SCC to the LCC procedure for inclusion of N-body processes, i.e. as one goes from (b) to (c) in the figure. This can be understood as the interplay of two effects included in the present work: the correlation imposed by the cluster formation criterion, and the mechanism of redistribution of energy among the

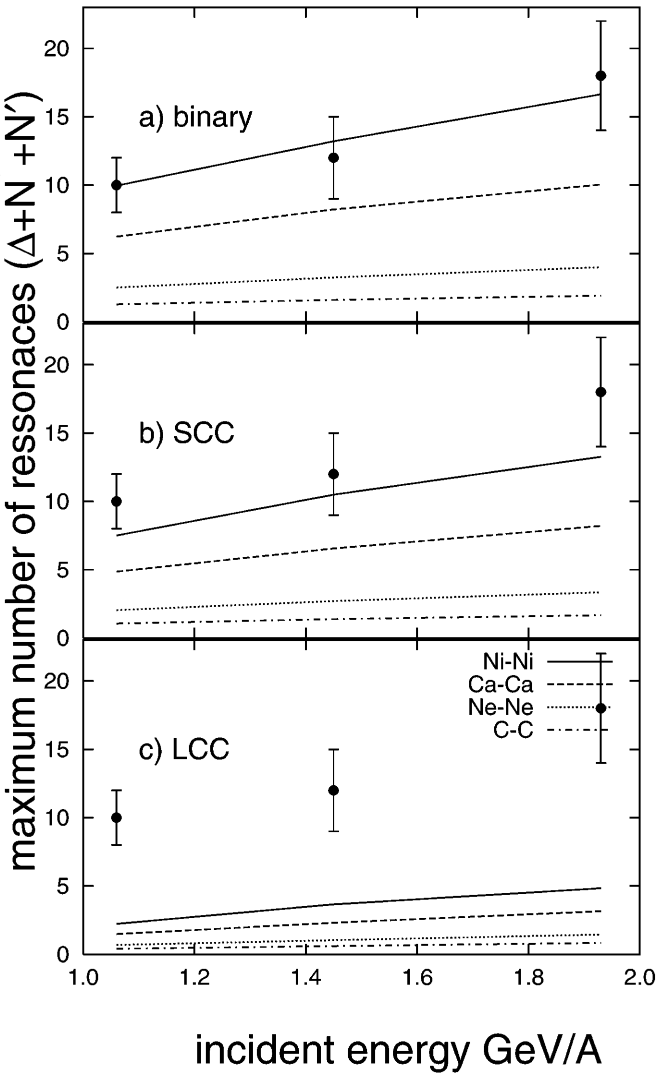

Fig. 1. Maximum number of resonances ($\Delta + N^* + N'$) as a function of the incident energy, for different nucleus-nucleus reactions. The line conventions (included only in part (c)) are as follows: the solid, dashed, dotted, and dot-dashed lines represent the results for Ni + Ni, Ca + Ca, Ne + Ne, and C + C reactions, respectively. Calculations performed with the binary model are displayed in part (a); the results of the present model under the small-cluster criterion (SCC) and the large-cluster criterion (LCC) are shown in parts (b) and (c), respectively. The model-dependent extraction of [14] for the population of Δ-resonances in Ni+Ni reactions is shown by solid circles

particles inside a cluster. As the SCC model (2) correlates less particles than the LCC model (1), the mechanism of redistribution of energy adopted in the present work (see Sect. 2) leads to a more efficient redistribution of beam energy among participants when using LCC than when using the SCC. As a consequence, the collision between the two interacting baryons is softened, resulting in fewer particles produced. In addition, the role played by the resonance-recombination processes, inverse reactions in (4), (5), and (6), is enhanced. These latter reactions, being particularly important for small values of the relative kinetic energy,

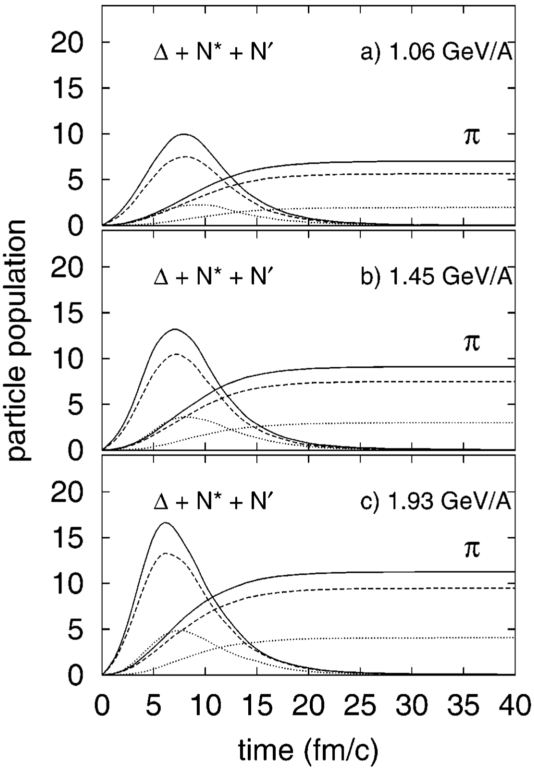

Fig. 2. Total number of resonances and pions, as a function of time, in quasi-central Ni + Ni reactions at three different energies: 1.06 GeV/A (a), 1.45 GeV/A (b), and 1.93 GeV/A (c). For each incident energy, the dynamical evolution of the particle population has been obtained with the three models discussed in the present work: binary model (solid lines), SCC model (dashed lines), and LCC model (dotted lines)

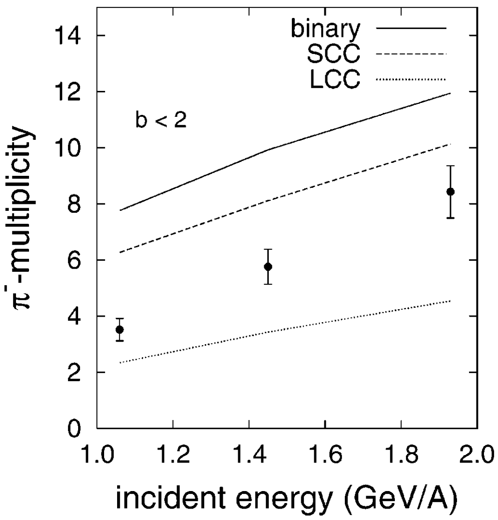

Fig. 3. Incident-energy dependence of the negative-pion multiplicity in quasi-central (b < 2 fm) Ni + Ni reactions. The conventions are the same as in Fig. 2. The solid circles are the data from [14]

will also contribute to a decrease in the number of resonances present in the system.

Figure 2 shows the calculated time evolution of the resonance and pion populations in ^{58}Ni + ^{58}Ni reactions at three incident energies: 1.06 GeV/A (a), 1.45 GeV/A (b), and 1.93 GeV/A (c), recently explored by Fopi collaboration [14,15]. In each figure, the curves are the results of the models here investigated: standard INC calculation (solid lines), SCC model (dashed lines), and LCC model (dotted lines). In all cases, after the resonance population has attained its maximum value it exhibits a rapid decreasing that results from the expansion of the highly-compressed colliding system. Also displayed in Fig. 2 is the pion population, whose asymptotic value, the pion multiplicity, can be measured directly. This latter quantity has been recently measured by Hong et al. [14,15], in quasi-central ^{58}Ni + ^{58}Ni reactions. The data were selected with a cut in the multiplicity of charged fragments (PM100 in [14]), corresponding to a cross section of 100 mb.

The main goal here is to use two different particle-correlation criteria to establish bounds to the effect of multiparticle correlations on the resonance and pion production. In Fig. 3 we display the incident-energy dependence of the negative-pion multiplicity in quasi-central (b < 2 fm) ^{58}Ni + ^{58}Ni reactions. We notice that the experimental data from [14] lie within the region delimited by the results of the LCC and SCC models, showing that the inclusion of multibaryonic collisional processes in the nucleus-nucleus dynamics is a key ingredient to reproduce the pion yields. One can also see in the figure that the SCC results are closer to the data than those obtained with the LCC model.

The effect of multiparticle correlations on the pion production is also evident in Fig. 4, in which the negative-pion multiplicity in Ni+Ni reactions is plotted as a function of the participant number, for the same three incident energies mentioned previously: 1.06 GeV/A, 1.45 GeV/A, and 1.93 GeV/A. In the figure, one can clearly see that the effect is energy dependent: for the lowest value of energy, more correlation than the one imposed by SCC seems to be necessary for reproducing the data; as the energy increases, less correlation is needed to reproduce the experimental results. These trends are consistent with what is observed in Fig. 3.

We now analyze the baryonic environment of the formed resonance matter. We have used the SCC criterion to determine the density evolution of the baryonic environment of the formed resonance matter. In Fig. 5, the calculated central baryonic density is displayed, as a function of time, for central nickel-nickel reactions at the incident energies 1.06 GeV/A (solid line), 1.45 GeV/A (dashed line), and 1.93 GeV/A (dotted line). By inspection of Figs. 2 and 5 one can see that the instants of maximum resonance population and maximum central baryonic density approximately coincide. Note that the maximum of resonance population occurs when the rate at which resonances are formed equals the rate at which they disappear, a situation that characterizes an instantaneous chemical equilibrium. At any time, the rate of formation of resonances is the sum of the individual rates of the processes of resonance production (direct reactions (4)–(6))

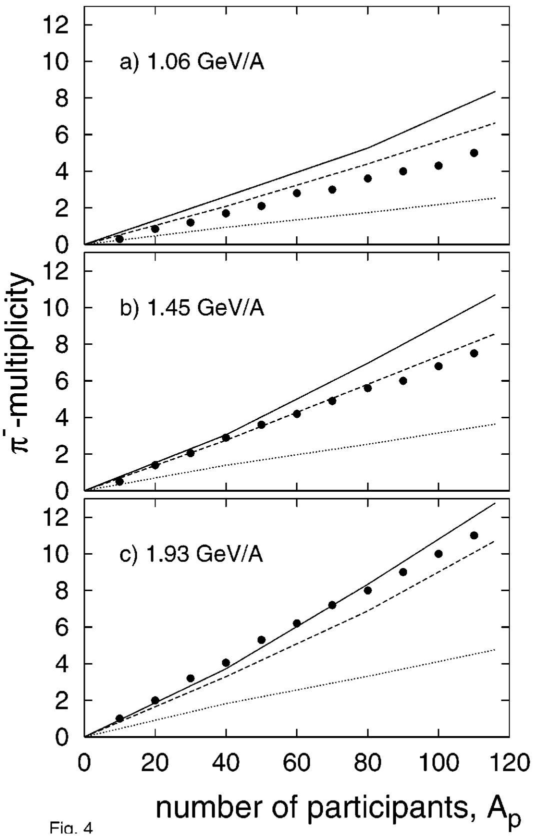

Fig. 4. Negative pion multiplicity as a function of participant number in Nickel-Nickel reactions at three incident energies: 1.06 GeV/A (a), 1.45 GeV/A (b), and 1.93 GeV/A (c). The conventions are the same as in Fig. 2. The solid circles are the data from [15]

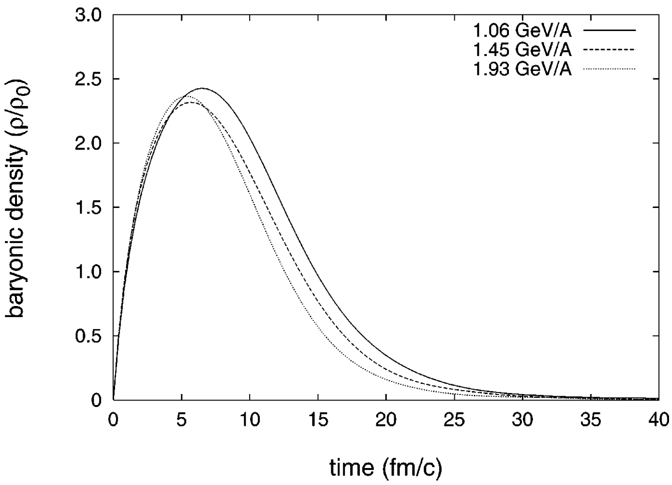

Fig. 5. Time evolution of the central density in quasi-central Ni + Ni reactions, obtained with the SCC model at three different incident energies: 1.06 GeV/A (solid line), 1.45 GeV/A (dashed line), and 1.93 GeV/A (dotted line)

and pion absorption (inverse reactions (7)–(9)). On the other hand, the rate at which the resonances disappear is the sum of the instantaneous individual rates of the processes of resonance recombination (inverse reactions (4)–(6)) and resonance decay (direct reactions (7)–(10)). Consequently, if some chemical equilibrium is reached, as it is claimed by models using the freeze-out concept, that should happen around the time of maximum resonance population. That's why our calculated results of maximum resonance population are presented, in Fig. 1, having the model-dependent inference of [14] as a background.

4 Conclusion and Final remarks

The results of the present calculations show that the inclusion of many-body correlations is a key ingredient to discuss the resonance abundance and the pion multiplicity observed in relativistic heavy-ion reactions. Also, by comparing the results obtained with our three different models (binary, SCC, and LCC), we end up with the conclusion that the effect of multiparticle correlations in the intranuclear dynamics plays a relevant role for resonance matter formation, and that this effect is more important at the lowest incident energies here investigated. However, the binary standard cascade has shown to be still useful at higher incident energies.

In summary, we have presented here two different models that include many-body effects on the intranuclear dynamics of a relativistic heavy-ion reaction. In order to assess the relevance of multiparticle collisional processes to resonance formation and pion production, we have explored some available data for the pion multiplicity as a function of incident energy and participant number.

We remark that the pion-absorption cross section used in the present work does not include multiparticle short-range correlations. This in-medium calculation of the cross section is available only for pions of low energy [30,31], far below the energy range here investigated.

The Pauli exclusion principle, which is taken into account in the present work by testing the phase-space availability for the final state of the colliding pair, is important also for the prolongation of resonance half-lives. Indeed, we had already shown, in [32], that in photonuclear reactions the pion production is sensitive to this improvement in the treatment of the Pauli exclusion principle.

M. Gonçalves and L. Castro would like to thank CNPq and FAPERJ for the partial financial support, and LNCC for the computational support.

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