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Shape Resilience of Nuclear Matter in Light Ion Induced Reactions

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Abstract

Wake (or cavitation) phenomena in the first instances of ^{3}He-induced collisions in the GeV/u range are investigated in the frame of an intranuclear cascade model for the formation of this structure and in a stochastic one-body approach for its evolution. It is found that nuclear matter shows a strong resilience : the target recovers a spherical shape rather quickly before decaying. Conditions to overcome to resilience and to have decay from exotic shapes are briefly discussed.

1. Introduction

Heavy ion collisions in the incident energy range stretching from ~ 100 MeV/A to ~ 2 GeV/A are usually assumed to lead to the formation of one, two or three thermalized sources, except for the so-called pre-equilibrium emission which can quite often be isolated from the former processes. This scenario is supported by microscopic transport calculations. So, a two step picture has emerged : (a) the first step corresponds to the formation of the sources and can usually be tackled by a hard scattering model ; (b) the second step assumes that the sources have a <u>spherical</u> shape and decay statistically, either at once [1,2] or sequentially [3]. This scenario has been challenged recently, since it has been suggested that thermalized sources with exotic shapes could be formed or that sources could decay non statistically. However, the standard scenario seems to be largely valid, by far.

The formation of transient uneven shapes can also occur in the first moments of proton-induced reactions [4] in the GeV range. This is also true for the case of light ion induced reactions, as was emphasized by the recent work of ref. [5]. The projectile drills a somehow conical hole (one should rather speak of a wake, see below) in the target. In the works of ref. [4,5], the hole closes after some relatively short time span, which seems to depend upon the detail of the calculations. However, these models do not possess the necessary ingredients to handle correctly the dynamics of the mean field [6] and especially the possible spinodal instabilities linked to this dynamics.

Three questions may be raised : (1) does the system recover a spherical shape before decaying or does the system decay from an exotic shape ? (2) what

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are the frequency of the special events corresponding to the decay of uneven shape, if this is possible ? (3) when the system recovers a thermalized spherical shape, is the intranuclear nuclear cascade (INC) + evaporation model (often used to successfully describe the data), still valid ? This model has in general an intrinsic criteria to stop the cascade and to evaluate the parameters of the source [7]. The third question can thus be rephrased as follows : are the source parameters provided by the INC model, the same as those given by a more realistic approach, as the one described below ?

In this paper, we investigate question (1) and, to some extent, question (2) raised above, for ^{3}He induced reactions. This choice is motivated by the existing good quality data that have been obtained by the IUCF-Saclay collaboration [8,9] and that are consistently described by the INC + evaporation model. More about questions (2) and (3) can be found in ref. [10].

2. Wake phenomena

2.1. Early stages of the collision

We use here the INC model of ref. [11] to study this problem. We show in fig. 1 the average density in the reaction plane for b = 0.1 fm collisions of 1.6 GeV/A ^{3}He ions with ^{nat}Ag nuclei.

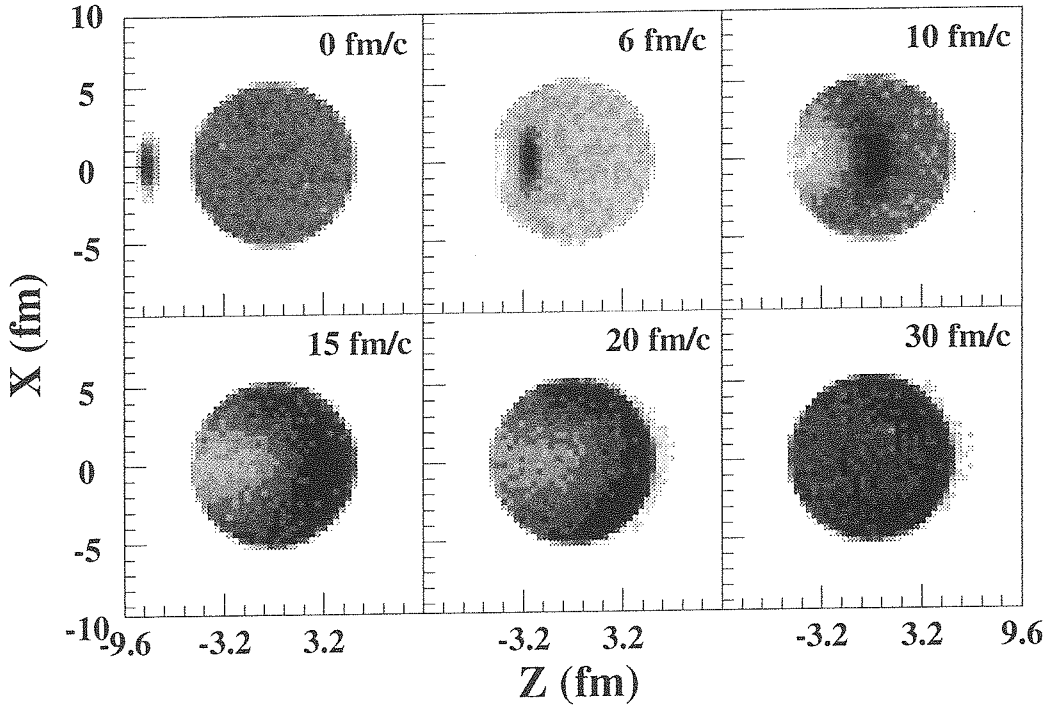

Fig. 1. Nucleon density distribution in the reaction plane for b = 0.1 fm collisions of 1.6 GeV/u ^{3}He projectiles on a Ag target, at various times, as given by the INC calculation. For $t \lesssim 15$ fm/c, the nuclear density ahead of the projectile is only slightly modified (the slightly lighter appearance of the target at t = 6 fm/c, compared to t = 0 fm/c is an artefact of the plotting routine). The wake left behind by the projectile is clearly visible. The average density at t = 30 fm/c is slightly less than normal nuclear matter density. For sake of clarity, particles outside the target volume are not displayed.

The wake left behind by the projectile is clearly visible. The density inside the wake goes down to about $\rho_0/2$. Incidentally, the larger depression obtained in the first calculation of ref. [5], called cavitation by the authors of this work, presumably comes from the too compact density distribution adopted for the ^{3}He projectile. In the calculation shown in fig. 1, the wake fades out after $t \approx$ 15-20 fm/c because nucleons are running into the partially empty space. At 30 fm/c, the target density is almost uniform again (this is roughly the time where the target excitation energy is more or less randomized and where the INC calculation is usually stopped). The filling of the wake is favoured, in the INC model, by the presence of a constant potential well : nucleons travelling backwards can be reflected by the potential wall. It is expected that, in reality, the potential wall is deformed, similarly to the density. Therefore, a more refined treatment is needed, for $t \gtrsim 15$ fm/c, to provide a satisfactory answer to question (1). This is investigated below, but before giving the results, let us speak a little bit about the impact parameter dependence of the wake phenomena. Basically, the importance of the wake is decreasing monotonously until $b \simeq 3$ fm, beyond which the damage to the nucleus is so small and heals so quickly that one can safely state that the wake does not exist. Therefore, we can define an upper limit for the cross-section for wake formation, in this particular system, as

$$\sigma_{\mathrm{wake}} \approx 270 \text{ mb} \approx \frac{1}{7}\,\sigma_{\mathrm{tot}} \,.$$

2.2. *Later stages of the collision*

INC calculations being questionable when hard collisions have ceased and when dynamical mean field effects are becoming important, we study the evolution of the wake (basically beyond 15-20 fm/c in the case of fig. 1) by a more accurate tool, namely a stochastic one-body approach (SOBA). A detailed description of this approach can be found in ref. [12]. Let us just mention that : (1) it is basically a Landau-Vlassov (test particle) model ; (2) a random noise is introduced at the beginning, to simulate thermal density fluctuations; (3) parameters are tuned to accurately describe phase space fluctuations and instabilities in the spinodal region [6,13,14]. In particular, this last requirement forces to adopt a width parameter σ = 0.9 fm for the gaussian profile used to generate the mean field from the test particle distribution [15] (alternatively, this parameter can be considered as the range of the underlying effective interaction). In fig. 2, we give an example of the results of such a calculation. The density distribution obtained in the INC calculation of fig. 1 around $t \sim 20$ fm/c has been idealized, assuming the removal of a cone from the original target (the clock is reset to $t = 0$ at the beginning of the calculation shown in fig. 2). A temperature of T = 8 MeV is assumed, corresponding roughly to the excitation energy in the

INC calculation after subtraction of the mass energy of the Δ-particles.

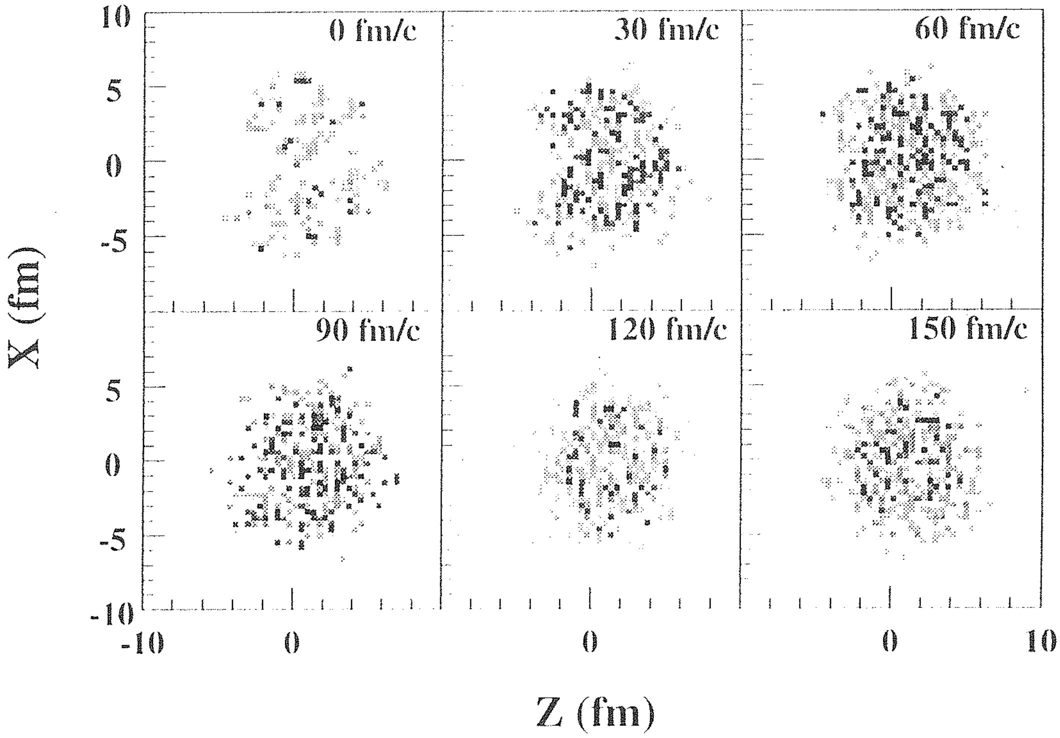

Fig. 2. Nucleon density distribution in the reaction plane at various times, as given by the SOBA calculation for a configuration corresponding to a Ag target at T = 8 MeV after removal of a cone. The gaussian parameter σ is taken as 0.9 fm. The system contains 91 nucleons. The density scale is arbitrary, but the darkest zones correspond to the largest values of the density.

It can be seen from fig. 2 that in less than 60 fm/c the system has recovered a spherical shape. This happens in all the 40 events we have studied, indicating strongly that, in these circumstances, nuclear matter is resilient to shape deformation.

We have also performed SOBA calculations for T = 6 MeV, superimposing the velocity field obtained by the macroscopic analysis of the INC results at $t \sim 15$ fm/c. Resilience is also observed, with the same frequency, although in this case the size of the target is oscillating. Finally, we also made calculations with $\sigma = 0.5$ fm. In this case, resilience is observed in only ~ 85 % of the events. Therefore, in this particular case (1.6 GeV/A ^{3}He + Ag), the cross-section for special events (decay before recovery of the spherical shape) is given by

$$\sigma_{sp} \approx 0.15\, \sigma_{wake} \approx 0.02\, \sigma_{tot}\ .$$

This cross-section is expected to increase with the energy, as the original damage is expected to increase. The possibility of having more and more excavated targets is underlined in refs. [5,10]. However, the importance of the surface is increasing for these exotic shapes and, therefore, their possible instability or resilience should be determined by studying the surface degrees of freedom accurately. The opportunity to realize such a study with high-energy ($\gtrsim$ 2 GeV/A) light ion projectiles should be underlined. Just to give a first, simple-minded guideline, let us study the stability of an incompressible system with an excavated spherical shape, obtained after the removal of a conical hole from the original sphere, as described in fig. 3.

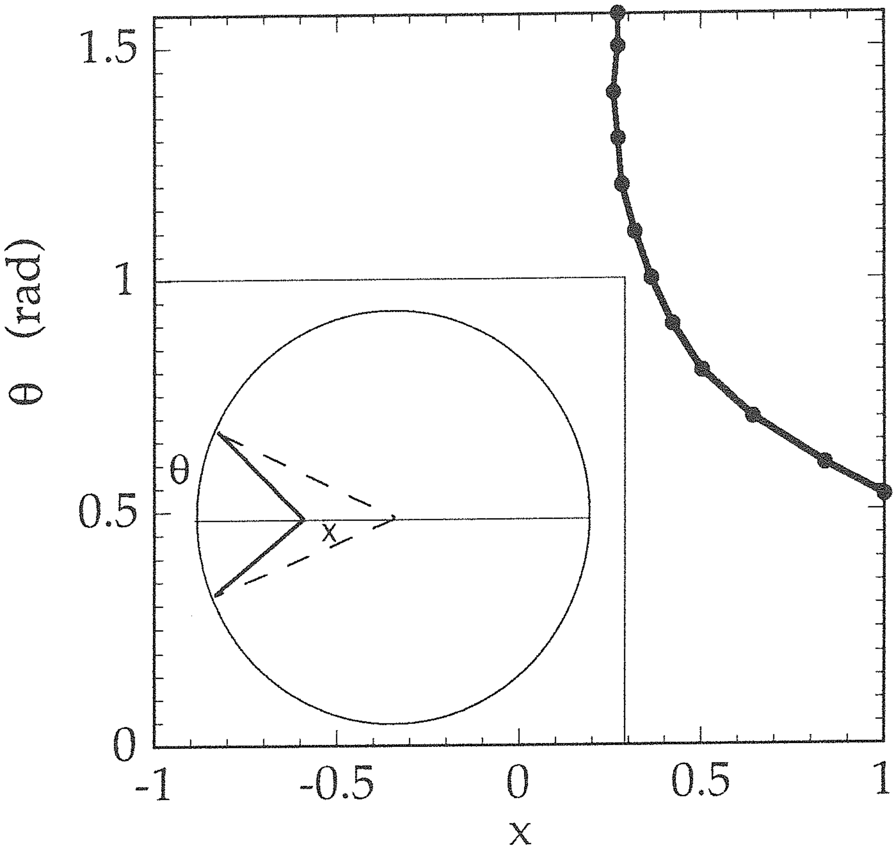

Fig. 3. Surface stability of a sphere (of unit radius) of incompressible fluid after removal of a cone of matter. The apex of the cone is located at a distance x from the center and θ is half the opening angle of this cone, as seen from the center of the sphere (see insert). The upper right corner gives the domain of the (x,θ) plane in which the splitting of the system in two spheres is energetically favorable. See text for detail.

Let x be the location (in radius units) of the apex of the cone with respect to the center of the nucleus and θ be half the angular opening of the cone. Disregarding Coulomb force, the stability of the configuration is determined by the area of the surface of the system. The upper right corner of fig. 3 gives the values of x and θ for which the splitting of the system into two spherical fragments is energetically favorable. The shape of the wake in fig. 1 roughly corresponds to $x \approx 0$ and $\theta \approx 0.5$. The instability zone is thus not too far and can presumably be probed in collisions at an incident energy of a few GeV/A's.

3. Conclusion

We have shown that light ion induced reactions under 2 GeV/A do produce transient uneven shapes of the interacting system. However, it seems that nuclear matter is rather resilient to these deformations and that the system recovers a spherical shape before decaying, presumably by ordinary evaporation [9]. Furthermore, the system may be quite excited. In the particular case of fig. 1, the target excitation energy after recovery of the spherical symmetry may reach 700 MeV. Therefore, in those reactions, the matter is also resilient to thermal excitations. In other words, nuclear matter seems to withstand shape and thermal stresses more easily than in heavy ion reactions. In the latter, multifragmentation is usually observed at such excitation energy [16]. Our interpretation is that heavy ion reactions lead to compression and subsequent expansion of the matter, which then is more unstable, whereas light ion collisions involve presumably no significant compression.

We also want to emphasize that even more exotic shapes are expected at a few GeV/A's (see ref. [10] for more indications). These configurations are characterized by a large surface to volume ratio and are expected to be less resilient. Their decay properties as well as the relationship of the latter with surface instabilities are interesting issues, deserving further investigations.

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