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Authors: CHEREVKO Kostyantyn, SU Jun, BULAVIN Leonid, SYSOEV Volodymyr, ZHANG FengShou

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Abstract

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Full Text

Preamble

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On Ring and Bubble Formations in Heavy Ion Collisions

CHEREVKO Kostyantyn[1],[2],[3], SU Jun[1],[2], BULAVIN Leonid[3], SYSOEV Volodymyr[3], ZHANG Feng-Shou[1],[2], ,*

[1]College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
[2]Beijing Radiation Center, Beijing 100875, China
[3]Physics Department, Taras Shevchenko National University of Kyiv, 4 Glushkova av., Kyiv 03022, Ukraine
 Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China

Abstract

This work is devoted to implementing hydrodynamic laws to head-on heavy ion collisions within the energy range of 50–100 MeV/A. The hydrodynamic mechanisms of bubble and ring structure formation are investigated. It is shown that there is a possible hydrodynamic explanation for the different structures formed in the case of soft ($K = 200$ MeV) and stiff ($K = 400$ MeV) equations of state. Within the suggested approach, the final geometry of the system is defined in the initial stage of the collision and is highly dependent on the sound velocity in nuclear matter. The obtained results are in good correspondence with Boltzmann-like transport theory calculations and experimental data for the selected energy range.

Key words: Nuclear incompressibility, Head-on collisions, Hydrodynamics

Introduction

Knowledge of the nuclear equation of state (EOS) represents one of the fundamental goals in nuclear physics that has not yet been achieved. The possibility of extracting information on the EOS at high baryon density is restricted to two research fields: observations of astrophysical compact objects and studies of hot nuclear systems created in high-energy proton-induced reactions or heavy-ion collisions (HIC). This likely explains the intensive studies of heavy ion collisions over the last several decades.

Among the most exciting aspects are investigations of nuclear multifragmentation (MF), when multiple intermediate mass fragments with $3 < Z < 20$ (IMF) are formed from the compressed and excited system. IMFs may provide a unique probe to study reaction mechanisms and hot nuclear matter properties. Despite this interest, many questions remain unanswered. A serious challenge in these studies is the inclusiveness of heavy ion collision experiments. While modern detectors are sophisticated and allow high detection rates, some data are still missing. At this stage, computer simulations serve as a powerful and important tool. Numerous transport theories for simulating collisions and statistical decay models provide interesting microscopic results and predictions regarding possible MF mechanisms.

Within the Boltzmann-Uehling-Uhlenbeck (BUU) model, it was shown that in the energy range of 60–75 MeV/A, “bubble” or “doughnut” structures can be formed depending on the stiffness of the nuclear EOS. Later, the formation of “doughnut” structures was confirmed experimentally. Unfortunately, up to now there is no model describing in detail the underlying physical mechanisms of exotic shape formation in head-on HIC. Different possible approaches exist to seek an explanation.

One approach is to continue with computer simulations, though one should bear in mind that we are still far from having models that are formally well-founded, practically applicable, and sufficiently realistic to be quantitatively useful. Another approach is to consider the qualitative similarity between Van der Waals and nucleon-nucleon interactions and seek explanation in thermodynamics or hydrodynamics, which are well-developed for ordinary liquids. In that case, numerous possible physical mechanisms responsible for these phenomena can be suggested. Among them are mechanisms involving shockwave formation and interference, and those studying thermodynamic properties of the system (temperature, surface tension) together with the influence of angular momentum on system behavior. Other possibilities include capillary effects with "capons" formed on nuclei surfaces and spinodal decomposition of the system. Therefore, deep analysis of these phenomena is needed to choose the appropriate decay channel.

The first step toward better understanding the process is analysis of the qualitative picture that emerges from BUU calculations and available experiments. First, the expanding velocity of the outer surface of the system is much smaller than that of the inner surface, suggesting the importance of surface effects. Second, BUU calculations predict simultaneous breakup with few fragments of similar masses and low kinetic energies, indicating that dynamic processes might be responsible for system evolution, though Coulomb forces seem to be of great importance at the breakup stage. Third, the angular distribution of fragments is almost isotropic for soft EOS, while for stiff EOS fragments are concentrated in the plane perpendicular to the beam direction.

From all the above, the hydrodynamic approach seems quite attractive as it allows explanation of the observed system behavior. In this work, we report an attempt to develop a hydrodynamic approach with a shockwave mechanism that can explain the observed phenomena and reveal their physical nature.

2 Model Description

When studying the system from a hydrodynamic point of view, the question arises whether such a macroscopic theory works for nuclear systems. The idea of applying such a macroscopic theory to nuclei was originally introduced in the 1970s–1980s by Siemens and Stocker. Their studies focused on a higher energy range than we are interested in; nevertheless, existing confirmation for the applicability of hydrodynamics to nuclear systems suggests that it should be possible to use it for the energy range in focus.

The symmetry of the system allows simplification of the model. Namely, from the collision of two nuclei it is possible to transform to the collision of a spherical nucleus of radius R with a rigid wall that moves toward it with velocity v_0. The difference lies in viscous effects; therefore, a slip boundary condition on the wall surface should be added.

In our studies, we start from the acoustic approximation developed in the theory of liquid droplet collisions. Within this model, according to Huygens principle, the expanding nucleus edges emit wavelets that propagate with the sound velocity in all directions and constitute the only source of surface distortion. In that case, the compression stage when the nucleus remains spherical lasts until the contact point velocity (which can be found from the geometry of the system) is higher than the sound velocity v_s inside the nucleus. This first compression stage is characterized by uniform pressure along the z-axis and higher pressure near the contact edge compared to the central part. After that, lateral jetting occurs and the pressure gradually decreases while the shape of the nuclei changes.

In all calculations, a simple approximate relation between the sound velocity v_s and the particle velocity v_p is used:

$$v_s = kv_p + v_{s0}$$

where k is a coefficient used as an adjusting parameter in the model and v_{s0} is the ambient sound velocity.

The jetting time during the first stage of the collision can be calculated from the geometry of the system. This fact allows calculation of the anomalous behavior of the contact edge velocity, which decreases from infinity to some final value and after that starts increasing. Such a picture seems to be unphysical and the minimum should indicate the jetting time. The model is applicable until there is a shockwave due to the pressure difference and the existing particles flow inside the nucleus. In this case, assuming normal density ρ_0, it is possible to start with the hydrodynamic equations for the jet parameters that take into account work against the surface forces with surface tension coefficient σ.

From the system geometry characteristics, it is possible to calculate the density at the contact point ρ_{bound}:

$$\rho_{bound} = \frac{R_{jet}}{t_{jet} v_{jet}}$$

where R_{jet} and v_{jet} are the radius and particle velocity of the jet. The parameter $k = 0.77$ is adjusted in our calculations to check the hydrodynamic approach with the ^{93}Nb$+^{93}$Nb system at 400 MeV/A, which is the same as in the original BUU calculations. The comparison of jetting time and the size of the jet shows good agreement between our hydrodynamic model and BUU calculations for ^{80}Kr $+^{80}$ Kr at 400 MeV/A.

[Figure 1: see original paper]

3 Results and Discussion

All calculations are provided for the two types of EOS. The results are presented in Tables 1 and 2.

Soft EOS (Figure 3): The geometry allows the shockwaves reflected from the free surface of the nuclei to be focused on the symmetry axis of the system. In this case, rarefaction with cavity formation occurs along the symmetry axis.

The next steps in such a scenario are cavity collapse and bubble entrapment inside the system. This mechanism shows the possibility of bubble formation in the collision.

Stiff EOS (Figure 4): In this case, the system looks not like spherical nuclei with small side parts (as for soft EOS) but rather like an expanding "pancake." This picture has some similarity with the problem of an expanding liquid sheet. Therefore, we suggest that in this case the rarefaction along the symmetry axis does not play such an important role, but one rather observes the "pancake" becoming thinner and a thicker rim being formed due to surface and viscous forces.

Both mechanisms give low values of expanding velocities at the final state, corresponding to the low kinetic energies of fragments obtained in BUU calculations. The qualitative difference between the observed pictures originates in the initial stage when compression pressure and temperature are different for different incompressibility coefficients. At this stage, the only governing parameter is the sound velocity in the system. Viscous and surface forces come into play later when the geometry has already been defined and govern the fragment formation processes.

We would also like to mention the possibility of other geometries, such as uniform systems for different values of impact energy or intermediate values of the incompressibility coefficient. Defining the energy range where exotic topologies can be observed requires further studies of possible system splashing or recoil. Intuitively, the difference between observed qualitative pictures has its origin in the initial stage when compression pressure and temperature differ for different incompressibility coefficients.

Therefore, we suggest that exotic structure formation in head-on heavy ion collisions can be explained from a hydrodynamic point of view. To explain the breakdown of such structures and predict fragment mass distribution, it is necessary to consider possible Rayleigh-Plateau instabilities, capillary waves, and the influence of long-range Coulomb forces at the final stage of system evolution.

The suggested approach allows for a simple physical picture of exotic structure formation in head-on heavy ion collisions. The qualitative picture obtained within our model is in good correspondence with that observed in BUU calculations and experiments. The straightforward link between EOS and topology, combined with the hydrodynamic approach and microscopic calculations, reveals the physical nature of multifragmentation phenomena and offers the possibility to extract data on the EOS from head-on heavy ion collisions.

4 Conclusion

The suggested hydrodynamic approach provides a simple physical explanation for exotic structure formation in head-on heavy ion collisions. The qualitative results from our model correspond well with BUU calculations and experimental observations. The direct relationship between the equation of state and the resulting topology, combined with our hydrodynamic framework and microscopic calculations, illuminates the physical nature of multifragmentation and opens a pathway to extract equation-of-state data from head-on heavy ion collision experiments.

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Note: Figure translations are in progress. See original paper for figures.