Longitudinal momentum of projectile-like residues: a new tool to investigate the EOS

J. Pereira[a] *, M.V. Ricciardi[b], T. Enqvist[b] †, J. Benlliure[a], M. Bernas[c],
E. Casarejos[a], V. Henzl[b], A. Kelic[b], J. Taieb[c] ‡, K.H. Schmidt[b]

[a] Universidad Santiago de Compostela, 15706 Santiago de Compostela, Spain
[b] Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany
[c] Institut de Physique Nucléaire, 91406 Orsay Cedex, France

Abstract

A systematic investigation of the longitudinal-velocity distribution of projectile-like residues produced in the reactions ^{238}U (1 A GeV) + Ti and ^{238}U (1 A GeV) + Pb has been performed with the high-resolution magnetic spectrometer FRS at GSI. With increasing mass loss, the velocities first decrease, then level off, and finally increase again. Light fragments are even faster on the average than the projectiles. This apparent re-acceleration is interpreted as the response of the spectator to the participant blast and can be exploited as a new tool to investigate the equation of state of nuclear matter.

1 Introduction

One of the main motivations of nuclear physics is the determination of the nuclear equation of state. Besides many astrophysical phenomena such as supernovae explosions or neutron stars, heavy-ion reactions provides an ideal tool to investigate the thermodynamical properties of nuclear matter. The major advantage of these reactions with respect to other natural scenarios is the possibility to deal with samples of compressed nuclear matter at different conditions of density and temperature.
The experimental observables associated with heavy-ion reactions are usually analyzed with theoretical models based on different assumptions [1, 2, 3]. The essence of these models relies on a set of microscopic parameters such as scalar mean field or nucleon-nucleon cross sections which are defined to properly describe the interaction between the constituents of the colliding nuclei. Those parameters are adjusted with the model calculations to reproduce the experimental observables measured in heavy-ion reaction. In addition, they are directly related to a set of macroscopic [3] variables which are used to define the thermodynamical properties of nuclear matter (pressure, temperature, etc.) in such a way that it is possible to extract information of the

* E-mail: jorgepc@usc.es
† Present address: University of Jyväskylä, 40351 Jyväskylä, Finland
‡ Present address: CEA/Saclay DM2S/SERMA/LENR, 91191 Gif / Yvette CEDEX, France

thermodynamical properties of nuclear matter from the experimental observables measured in heavy-ion reactions.

Figure 1 shows the results of a simulation of a typical relativistic heavy-ion reaction between two nuclei of ^{124}Sn. During the sequence of the reaction we distinquish two geometrical regions: the so-called participant and spectators which evolve in time in a completely different way. In the initial stage of the reaction the violent collision induces a fast raise of the nuclear density in the overlaping region between the two colliding nuclei (the participant), while the density of the outer region of the system remains constant (spectator). The fast compression of the participant gives rise usually to its total disintegration accompanied by the production of many objects (p, n, d, π, t, ^{3}He, etc.). On the other hand, the spectators, in a rather low excited state follow their initial trajectories almost undisturbed. The impact parameter of the collision determines the size of these two regions -large participant sizes correspond to low impact parameters-.

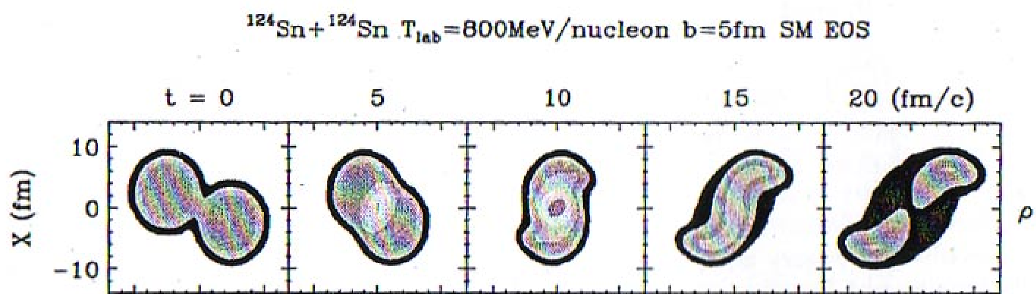

Figure 1: Contour plots of the calculated system-frame baryon density in the ^{124}Sn+^{124}Sn reaction at 800 A MeV and b=5 fm, at times t=0, 5, 10, 15 and 20 fm/c [5].

In order to obtain information about the nuclear equation of state from the compressed region of nuclear matter, intensive effort has been invested to analyze the participant region of the colliding system by measuring the flow of light particles emerging from this region [4]. This flow is believed to carry information on the initial high-density phase. On the other hand, since the spectators remain very close to the participant matter during its compression-expansion phase, their properties may be significantly modified.

In the present work, we performed a systematic investigation of the longitudinal velocity distributions of fragmentation residues produced in the reactions ^{238}U (1 A GeV) + Ti and ^{238}U (1 A GeV) + Pb. This experimental observable can be used to extract information on some fundamental properties of the equation of state of nuclear matter. The paper is organized as follows. A brief description of the underlying theory which motivates our work is given in section 2. The experimental results are described and discussed in section 3. The paper is summarized in section 4.

2 Theoretical framework

In a recent work published by L. Shi, Danielewicz and R. Lacey [5] it has been established that the kinematics of the spectators could be influenced by the participant blast, and thus some of their observables could carry valuable information on the equation of state. In that work, the authors simulate semi-central heavy-ion collisions by means of transport equations of the Boltzmann-Uhlenbeck-Uehling (BUU) type [2]. The reacting system was represented by a sample of quasi-particles moving withing a mean field representing the nuclear potential. In order to explore the sensitivity of the emerging spectator properties to the equation of state, different assumptions were used according to the momentum-dependence of the mean field and the stiffness of the equation of state. In particular, the calculations were carried out using strongly momentum-dependent and momentum-independent mean fields in combination with hard and soft coefficients of compressibility. With these four possibilities the authors examined the impact of the interplay between participant and spectator on the evolution of different physical characteristics of the spectators in order to establish which of these properties could be used as probes to study the compressed nuclear matter.

It is beyond the scope of this paper to enter into the details of the calculations; we will rather limit ourselves to mention that the most important spectator property in the light of our work is the longitudinal momentum. This experimental observable reaches its maximum value during the high-density stage in the participant matter and remains almost unmodified during the subsequent expansion. Figure 2 summarizes the results obtained by Shi and co-workers concerning the longitudinal momentum P_z of spectators for different impact parameters. Calculations done with momentum-dependent mean field significantly differ from those obtained with momentum-independent: The later leads to a more pronounced momentum loss. On the other hand, P_z exhibits no sensitivity on the stiffness of the equation of state. According to these results, the longitudinal momentum is a good experimental observable to investigate the momentum dependence of the mean field.

The left panel of figure 2 shows a systematic reduction of the longitudinal momentum for the most central collisions in the Sn+Sn system. This dependence of P_z on b might be understood as a signature of the friction between the spectators and the participant (lower impact parameters or equivalently more violent collisions undergo more friction). However, when examining the system Au+Au (figure 2, right) one finds an outstanding effect: For low impact parameters and momentum-dependent mean fields, the average spectator momentum increases. This speeding up of the spectator can be seen as an effect of the explosion of the participant matter: After its compression, the participant experiences an expansion which pushes the spectators out of the system. If the collision is strong enough, the subsequent push may overcome the friction effects giving rise to a net longitudinal acceleration of the spectator.

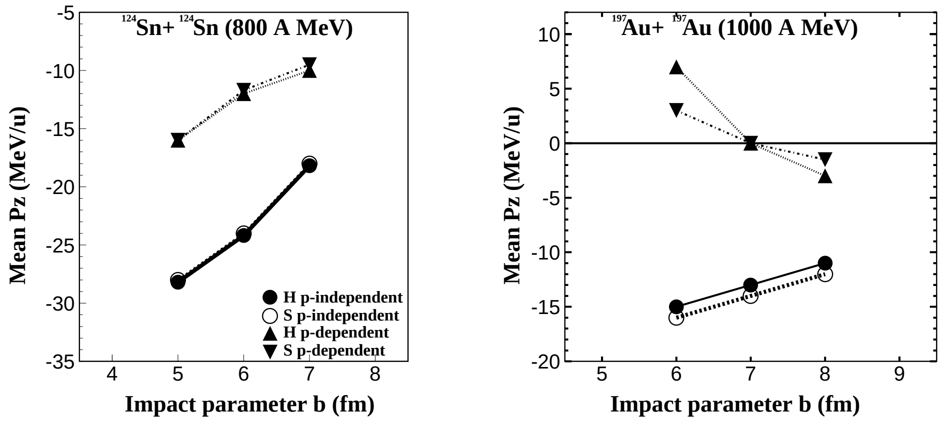

Figure 2: Longitudinal momentum of spectator as a function of impact parameter for the simulated reaction ^{124}Sn+^{124}Sn at 800 A MeV (left) and ^{197}Au+^{197}Au at 1000 A MeV (right) using different assumptions on the momentum dependence of the mean field and the stiffness of the equation of state [5].

In the light of this result, the experimental observation of this post-acceleration of the spectators may be associated with the momentum-dependence of the mean field.

3 Measurements of the longitudinal momentum of spectators

In order to observe experimentally the acceleration of the spectators two requirements must be fulfilled: First, the collision between the two nuclei must be strong enough to overcome the friction effects with the expansion of the participant. Secondly, the weak post-acceleration predicted by Shi and co-workers of about 0.25 cm/ns for the Au+Au system demmands a precision of the measured velocity of the same order. Velocity determinations based on time-of-flight measurements with an intrinsic resolution of 100 ps and a flight path of about 10 m provide a velocity resolution in the projectile frame not better than 0.5 cm/ns. This limit is rather far from the precision required to observe the acceleration of the spectator. On the other hand, the use of high-resolution magnetic spectrometers guarantees resolutions of the order of 0.05 cm/ns. According to this, we made use of the Fragment Separator (FRS) spectrometer at GSI to obtain experimental data on longitudinal momentum distributions of fully identified fragmentation residues produced in the reactions ^{238}U(1 A GeV)+Ti and ^{238}U(1 A GeV)+Pb [6].
The Fragment Separator (FRS) [7] is a two-stage spectrometer with a dispersive intermediate

image plane and an achromatic final image plane. Its angular and momentum acceptances are about 15 mrad (polar angle) and 3%, respectively. The detection equipment (see figure 3) consists of two plastic scintillators [8] placed at the dispersive and achromatic image planes, and an ionization chamber [9] at the exit of the spectrometer.

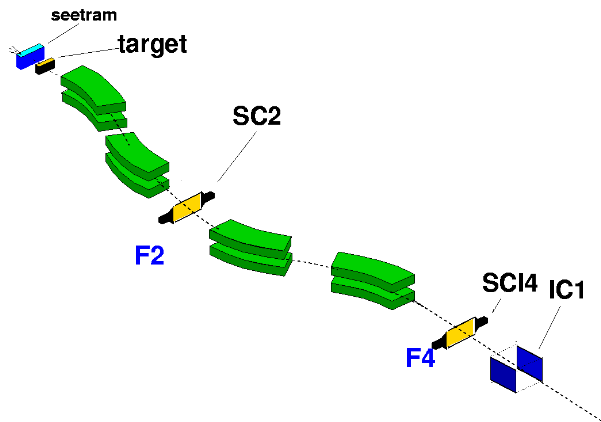

Figure 3: Layout of the FRS with its standard detection equipment: the secondary electron detector (seetram), the two plastic scintillators (SC2 and SCI4) placed at the intermediate F2 and final F4 image planes, and the ionization chamber IC1 at the exit.

In our experiment, the uranium beam, delivered by the heavy-ion synchrotron, SIS, at an energy of 1 A GeV and an intensity of 10^7 particles per second was monitored by a secondary electron detector (seetram) and focused on the target -a 36 mg/cm^2 titanium layer or a 50.5 mg/cm^2 lead layer-. The forward emitted projectile-like fragments were separated and identified in mass and nuclear charge with the FRS. According to the ion-optical properties of the apparatus, the mass-over-charge ratio of the selected fragment can be determined from the following equation:

$$\frac{A}{Z} = \frac{B\rho}{L} c \cdot ToF \sqrt{1 - \frac{L^2}{c^2 ToF^2}} \tag{1}$$

where c is the speed of light, ToF is the time-of-flight between the two plastic scintillators, L is the flight distance (36 m) and $B\rho$ the magnetic rigidity in the second half of the spectrometer. The nuclear charge was determined from the energy lost by the nucleus in the ionization chamber. Once each fragment is identified, its longitudinal momentum is deduced from the magnetic rigidity in the first stage of the spectrometer, according to:

$$\beta\gamma = \frac{Z}{A} B\rho = \frac{Z}{A} \cdot \left(1 - \frac{x_2}{D}\right) \tag{2}$$

being $\beta\gamma$ the reduced longitudinal momentum, x_2 the horizontal position in the dispersive plane and D the dispersion of the first stage. Due to the limited acceptance in momentum of the

FRS, a combination of several $B\rho$ settings was needed in order to fully cover the momentum distribution of all residues [10, 11, 12]. The longitudinal momentum measured in the laboratory frame were transformed into the projectile frame. In order to provide the required accuracies energy losses of the primary beam in the target were accounted for.
The result of this experiment was the measurement of the velocity distributions of about 1000 nuclei produced in each system, ranging from vanadium (Z=23) to rhenium (Z=75) for the system ^{238}U+Pb and from oxygen (Z=8) to uranium (Z=92) for the system ^{238}U+Ti. Figure 4 shows the longitudinal velocity distributions in the beam frame for several isotopes produced in the reaction ^{238}U+Ti. As can be seen, the velocities follow a Gaussian distribution.

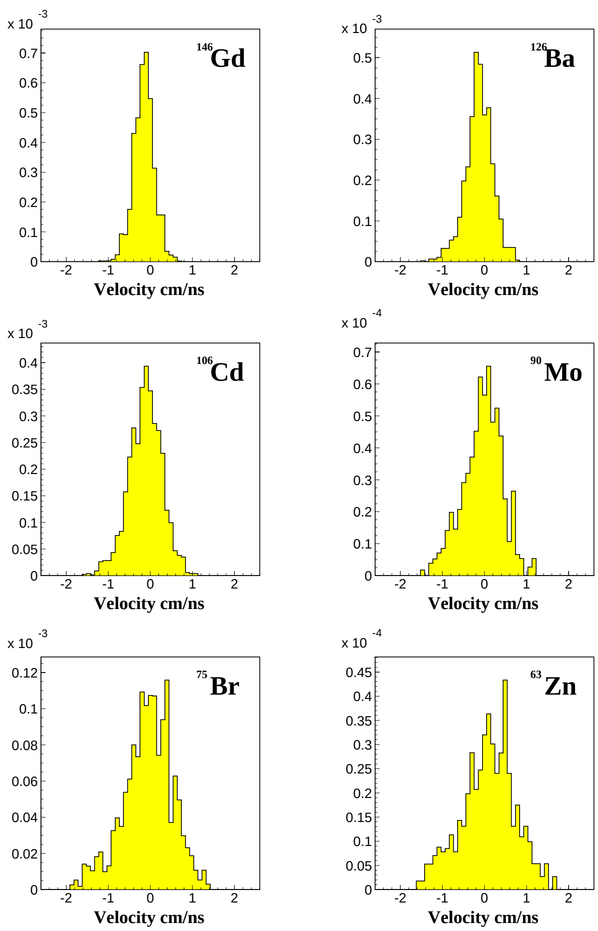

Figure 4: Velocity distributions of different nuclide produced in ^{238}U+Ti at 1 A GeV measured with the fragment separator (velocities are given in the frame of the projectile).

The mean velocity was deduced from the mean value of the corresponding Gaussian fit of the velocity distribution and averaged over each isobaric chain according to their cross sections. Fluctuations of these average values are within the statistical uncertainties of the results. In addition, the velocities were corrected for the small shift induced by the limited angular transmission. This correction was always very small compared with the absolute uncertainty of less than 0.05cm/ns for the final results. Figure 5 shows the mean velocity as a function of the mass number for the two reactions analyzed. As can be seen, the heavy fragments produced in the most peripheral collisions show a systematic reduction of the mean velocity with mass loss. This trend is associated with the friction between the spectator and the participant matter. However, the results show a surprising effect at intermediate masses: the velocities of the fragmentation products do not decrease any more when the mass loss becomes large (low impact parameters). For the lightest residues the velocities tend to increase, until they are even faster than the projectile; this effect is more pronounced for the reaction induced with lead. The observation of the acceleration of light spectator fragments is in clear disagreement with Morriseys systematics which predicts a continuous slowing down of the velocities with mass loss [13]. On the other hand, our results confirm the post-acceleration of the spectator fragments by the participant blast, postulated by Shi, Danielewicz and Lacey.

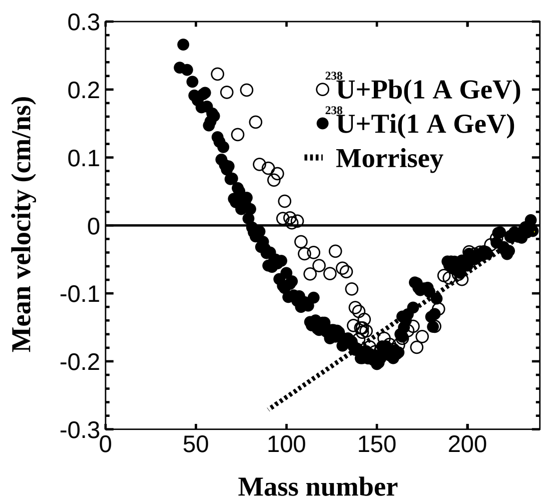

Figure 5: Mean values of the velocity distributions of fragmentation residues, produced in ^{238}U+Ti (dots) and ^{238}U+Pb (open circles) at 1 A GeV in the frame of the projectile. The absolute uncertainty amounts to less than 0.05 cm/ns for each system. The dashed line marks the Morrisey systematics [13].

The acceleration observed in the present work can only be qualitatively compared to the available calculations for the systems Sn+Sn and Au+Au (figure 3). These calculations estimates a post-acceleration of about 0.25 to 0.5 cm/ns in velocity in the projectile frame, for momentum-dependent mean fields. This is in the order of magnitude of the positive velocity values observed in the present experiments. In addition, the observation of a more pronounced acceleration for the heaviest system (uranium+lead) supports the idea that the more violent collisions will induce a stronger compression-expansion of the participant. According to Shi, Danielewicz and Lacey the major advantage of the longitudinal momentum (or velocity) of the spectators as an observable is its sensitivity to the momentum dependence of the mean field. In the light of this idea, the acceleration of the spectators observed in the present experiments can be interpreted as a signature of the momentum dependence of the mean field. For a more quantitative comparison, specific calculations of the systems analyzed are required.

4 Conclusions

In the present work, we have investigated the velocity distributions of projectile-like residues looking for experimental observables sensitive to the equation of state.
The high-resolution magnetic spectrometer FRS at GSI has been used to measure the longitudinal velocity distribution of projectile-spectator fragmentation residues produced in the reactions ^{238}U+Ti and ^{238}U+Pb. The results obtained show an outstanding deviation from the expected trend: rather than being reduced, the mean velocities of the lighter fragmentation residues tend to level off and increase again with mass loss. The lightest nuclei are even faster than the projectile.
The highly precise measurements required to observe this rather weak acceleration can not be attained with standard techniques based on thick-catchers [14, 15] or time-of-flight measurements [16]. Only in-flight separators seem to provide the required velocity resolution to observe this unexpected phenomena.
Following the ideas of Shi, Danielewicz and Lacey the major advantage of the longitudinal momentum (or velocity) as an observable is the sensitivity to the momentum dependence of the mean field. A qualitative comparison between the present experimental results and model calculations show that the measured velocity distributions can only be explained assuming a momentum-dependent mean field. However, specific calculation of the reactions studied are needed in order to provide quantitative conclusions.

References

[1] H. Stöcker, W. Greiner, Phys. Rep. 137 (1986) 277

[2] G.F. Bertsch, S. Das Gupta, Phys. Rep. 160 (1988) 189

[3] Nuclear decay modes, ed. D.N. Poenaru, IOP Publishing Ltd (1986)

[4] W. Reisdorf, H.G. Ritter, Annu. Rev. Nucl. Part. Sci. 47, (1997) 663

[5] L. Shi, P. Danielewicz, R. Lacey, Phys. Rev. C 64 (2001) 034601

[6] M.V. Ricciardi et al., submitted to Phys. Rev. Lett.

[7] H. Geissel et al., Nucl. Instr. and Meth. B70 (1992) 286-297

[8] B Voss, Nucl. Instr. and Meth. A 364 (1995) 150

[9] M. Pfützner, et al., Sci. Rep. GSI-91-1 (1991) 288

[10] M. de Jong et al., Nucl. Phys. A 628 (1998) 479

[11] T. Enqvist et al., Nucl. Phys. A 658 (1999) 47

[12] T. Enqvist et al., Nucl. Phys. A 686 (2001) 481

[13] D.J. Morrisey, Phys. Rev C 39 (1989) 460

[14] S.B. Kaufman et al., Phys. Rev. C 22 (1980) 1897

[15] W. Loveland et al., Phys. Rev. C 37 (1988) 1311

[16] V. Lindenstruth, PhD thesis (1993) University of Frankfurt