Investigation of the nuclear mean field by precision measurements of the spectator response to the participants blast

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Abstract: The longitudinal re-acceleration phenomenon of the fragmentation residues, as found recently in projectile fragmentation of uranium [1,2], has been interpreted [3] as the postulated spectator response to the participants' blast [4]. According to transport calculations, the longitudinal momenta of the surviving residues yield a direct access to the momentum-dependent properties of the nuclear mean field (MF), little affected by the uncertainties in nuclear incompressibility [4]. Therefore, we propose an experiment in which the more detailed investigation of the re-acceleration phenomenon will be performed. We plan to explore the re-acceleration dependence on the initial beam energy as well as the importance of the isospin effects on the evolution and strength of the participants blast, thus directly addressing the characteristics of the momentum dependent MF. We propose to measure longitudinal momenta of the final residues in the systems of ^{197}Au+^{197}Au at 250, 500, 750 and 1000 *A* MeV, ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn at 1000 *A* MeV at the Fragment Separator (FRS), GSI Darmstadt.

KEYWORDS: re-acceleration, nuclear mean field, momentum dependence, isospin dependence, spectator, fragmentation, equation of state

I. Introduction

The equation of state (EOS) of nuclear matter, ruling how nuclear pressure responds to temperature and density, belongs to the key topics of nuclear physics. It also constrains the nucleon-nucleon interactions in the nuclear medium [5] represented by the mean-field (MF) potential, and it remains an important ingredient for a detailed understanding of astrophysical and cosmological phenomena such as supernovae explosions [6], stability of neutron stars under gravitational pressure [7], and the evolution of the early Universe [8].

The determination of the nuclear equation of state with use of high-energy heavy-ion reactions turned out to be more difficult than was initially anticipated. Thus, early on, it seemed to be possible to describe early single-particle observables using the cascade model [9,10] with an ideal gas EOS, with the potential energy term needed for binding nuclei missing. Only the failure to describe the results from the first 4π experiments [11-14] drew the attention to the importance of including the mean-field potential felt by the nucleons in the reaction dynamics.

During that time, several theoretical papers were published that described the collective effects from a semiclassical microscopic viewpoint, emphasizing either the importance of the short-range nature of the nuclear force [15] or the density-dependent mean field aspect [16]. Later it had been demonstrated [17-20] that the effects of the soft EOS with included momentum-dependent MF are comparable with the effects of a stiff EOS with a static mean field. Although the nonlocality of the optical potential has been long known from elastic nucleon scattering [21,22], it has been difficult to demonstrate this nonlocality in heavy-ion collisions. Further ambiguities were associated with the effective NN cross sections which have been expected to be lower in the nuclear medium [23,24] than those in free space.

This complex puzzle of heavy-ion reactions, where many effects related to different properties of matter compete in generating observables, calls for the search of experimental observables or their combinations which would be reasonably sensitive only to individual features of nuclear matter rather than their interconnected manifestations. Joint effort of more and more elaborate comparisons of theoretical predictions with systematical results of (not only) new generation full-acceptance detectors has led to a significant progress. The stopping observables, such as linear momentum transfer, balance energy and $ERAT=E_{\perp}/E_{\parallel}$ ($E_{\perp}$ and $E_{\parallel}$ are transverse and longitudinal energy respectively) have been linked to the in-medium cross section reduction [25,26,27]. The giant monopole resonance excitation [28,29], the sideward flow [30], and strangeness production have been shown to be connected to the nuclear incompressibility [31,32]. On the other hand, the elliptic flow seems to exhibit preferential sensitivity to the momentum dependence of the mean field [33], and the shadowing effects of the spectator on the particle emission anisotropy are suggested as the timer of the nuclear collision, especially when looking at the energy dependence of created secondary particles [34,35].

Unfortunately, as can be found in all recent articles [36-39], despite the steady progress due to the enormous amount of experimental results as well as new theoretical approaches, the final conclusion on the nuclear EOS cannot be made. Until that is possible still a large systematic effort delivering data of higher diversity and better quality to constrain many unknown parameters, (not forgetting independent confirmations of already established knowledge) will be required.

For this very reason stated above, we want to address the characteristics of the momentum-dependent nuclear mean field with a recently established experimental probe – the spectator response to the participant blast.

II. Motivation

1. Theoretical background

Although the influence of the large spectator fragments on the evolution of the participants decompression has long been considered [40,41], it has not been until very recent times that the heavy reaction residues have been investigated in terms of sensitivity to the nuclear equation of state [4].

When nucleons of a projectile are decelerated in the participant region (region of overlap with the target nuclei), the longitudinal kinetic energy brought in by the initial colliding nuclei is converted into thermal and potential compression energy. In the subsequent rapid expansion, the collective transverse energy develops [42,43,44,36], and many particles from the participant zone get emitted in the transverse directions. The particles emitted towards the reaction plane can encounter the cold spectator pieces and, hence, get redirected or absorbed. On the other hand, since the spectators serve to deflect particle emissions toward the reaction plane, their properties may be significantly changed.

The analysis of Shi et al. [4] utilizes a set of BUU transport equations in order to demonstrate the sensitivity of the spectator observables to the compressibility and momentum dependence of the nuclear MF. The most interesting quantity turned out to be the average center-of-mass momentum change per nucleon of the surviving spectator Δ|<**P**/A>|. In **Fig.1**, taken from the work of Shi [4], the calculated net momentum change is plotted as the function of the impact parameter for two symmetric systems differing by the mass at comparable incident beam energies, for four different types of the EOS, including soft and hard with and without momentum dependent MF. In the figure, we can see the clear sensitivity of Δ|<**P**/A>| to the momentum dependence of the MF contrasted by the very weak sensitivity to the stiffness of the EOS.

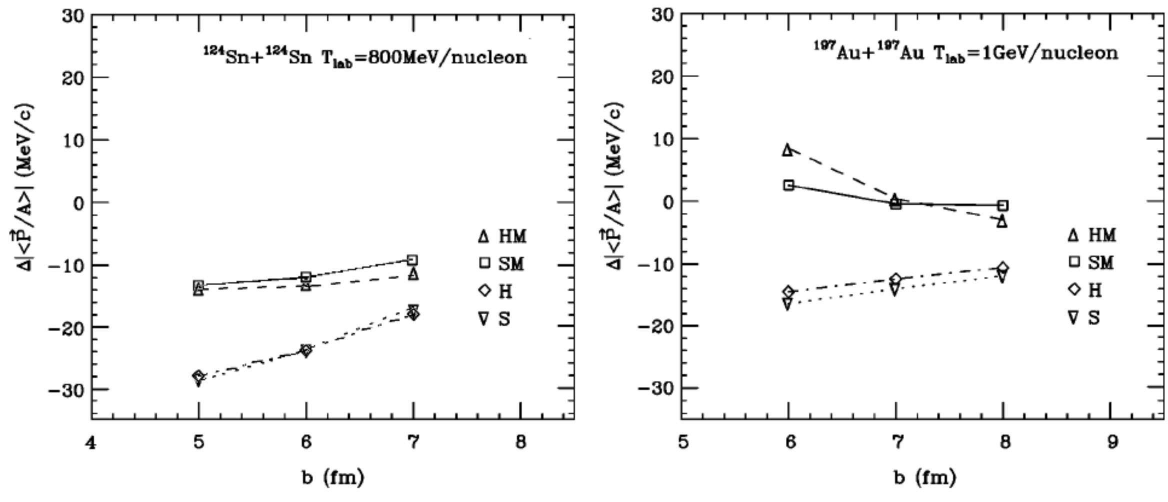

Fig. 1: Change in the average net c.m. momentum per nucleon Δ|<**P**/A>| as a function of the impact parameter for four representative EOS: hard momentum-dependent (HM), soft momentum-dependent (SM), hard momentum-independent (H), and soft momentum-independent (S) for the spectators of the system ^{124}Sn+^{124}Sn at 800 *A* MeV (left) and ^{197}Au+^{197}Au at 1 *A* GeV. Results of the BUU calculation reprinted from [4].

Moreover, the most striking feature of the calculations carried out with the momentum-dependent (MD) MF is the leveling off of the residue velocities with decreasing impact parameter in the system ^{124}Sn+^{124}Sn (in contrast to the non MD cases) and even rising to positive values for the heavier system ^{197}Au+^{197}Au. This means that the surviving spectator emerges from the reaction even with higher net average momentum per nucleon than the original momentum.

Considering the absolute values of the Δ|<**P**/A>|, which are in order of 1% of initial momentum per nucleon, one should not be surprised that only few indications of such effect (called longitudinal re-acceleration) had been found in the past studies [45-47].

2. Experimental evidence and possibilities

The first clear evidence of the re-acceleration phenomenon has appeared in the uranium fragmentation on lead, where the use of the inverse kinematics in combination with high-precision magnet spectrometer FRS allowed for complete identification of the reaction residues and measurement of their momentum distribution [1]. However, as there was still no suitable theoretical explanation available, this feature of that experimental observable has been left without interpretation.

The situation changed when the similar re-acceleration of the fragments with their decreasing mass has been observed in the uranium fragmentation on titanium under very similar experimental conditions [2,3]. As can be seen in the **Fig. 2** with the increasing mass loss, the mean velocities of the final reaction residues first decrease with the established systematics [47], then level off and finally increase again. Light fragments become even faster than the projectiles. The results have been interpreted [3] as the recently postulated spectator response to the participant blast [4]. According to our understanding, the ground for a new experimental approach has been laid.

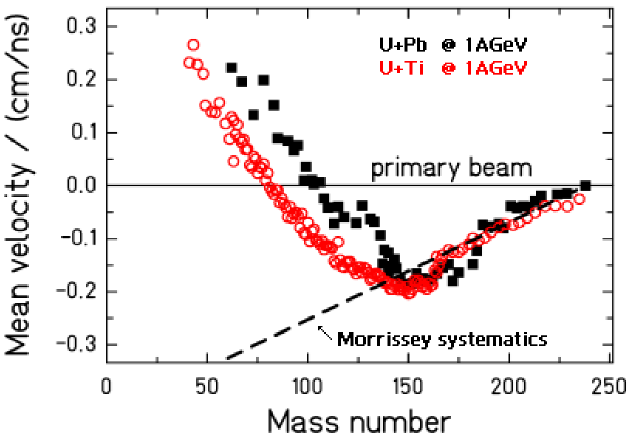

Fig. 2: Mean values of the velocity distributions of reaction residues, excluding fission, produced in ^{238}U+Pb (full squares [1]) and ^{238}U+Ti (open points [3]) at 1 *A* GeV in the frame of the projectile. The absolute uncertainty amounts to less than 0.05 cm/ns for each system, ^{238}U + Pb and ^{238}U+Ti, independently. The dashed line marks the Morrissey systematics [47]

The unique possibilities at the FRS allow for precise determination of the longitudinal momentum of all measured final reaction residues. The TOF resolution of 100ps on 36m allows determining $\beta\cdot\gamma$ with a relative uncertainty of $2.5\cdot10^{-3}$. Combining this with the $B\rho$ measurement, which is performed with a relative uncertainty of $5\cdot10^{-4}$, a mass resolution of $(A/\Delta A)$~400 is obtained, resulting in an unambiguous identification of all detected fragments in *A* and *Z*. A recursive calculation of $\beta\cdot\gamma$ from the known $B\rho$, *A*, and *Z* eliminates the influence of the TOF resolution and provides the $\beta\cdot\gamma$ value with a relative uncertainty of $5\cdot10^{-4}$. The correlation of the final fragment mass and the impact parameter of the initial collision is generally known and has been demonstrated in several experiments, e.g. [48]. Therefore, the magnitude of the fragment re-acceleration as the function of the residue mass is a measure of the strength of the MD effects as a function of impact parameter, or in other words as a function of the energy deposited in the participant region.

Another aspect, which comes into play, is the composition of the participant zone. The density build-up and the compression-expansion dynamics are determined by the in-medium properties of the nucleons (which are generally different for protons and neutrons [23]) “donated” by the colliding nuclei. Therefore, the choice of the colliding system determines the proton-to-neutron composition of the participant region, and thus directly addresses the isospin dependence of the nuclear mean field and the EOS. Studies of nuclear multifragmentation at lower incident energies have found a significant change of isotopic yields of emitted fragments with increasing isospin asymmetry of the colliding system [49,50]. This observation led to the term “isospin fractionation” for the isotopic composition of the residual nucleus.

In view of the arguments given above, we are convinced that a systematic exploration of the longitudinal re-acceleration phenomenon can directly lead to the determination of fundamental properties of the nuclear mean field. The unprecedented precision of the measured residue momenta will also serve as reliability test of the used transport codes based on different approaches or using different potentials and parameterizations. By complementing the results obtained by different methods, such as measurements of the particle production or collective observables, the proposed experiment on re-acceleration of the reaction residues can help to improve our knowledge on the equation of state significantly.

III. Proposed experiment

The data obtained by our group, which were presented in the motivation, showed a new way to investigate the nuclear mean field in terms of heavy-ion collisions, but, unfortunately, these data alone cannot be used to extract any finer details on the characteristics of the MFs momentum dependence. Mainly it is the complexity of the heavy-ion collision itself that prevents the detailed analyses.

The re-acceleration magnitude is surely ruled not only by the strength of the MD effects, but also by the time the spectator spends in the reaction zone. This time is on the other hand ruled by the incident velocity of the projectile and the size of the reaction zone and cannot be properly accounted for from measurements performed at the same beam energy. It is related to emission times derived from shadowing effects of secondary particles by the spectator fragments [34,35]

Another complicating feature is the asymmetry of the system. Especially for the case of the U+Ti system, the participant matter is formed by different proportional contributions of projectile and target for different impact parameters. This means an unequal distribution of the isospin in the participant zone, creating hardly evaluable potential gradients. Comparing the U+Ti system with the U+Pb system also implies assumptions on the not-well known isospin dependence of the MF.

Finally it is also the high fission cross section of uranium, which pollutes the desired observables. Since the fission occurs only in the collisions with very high impact parameter, its products do not carry any information on the compression and expansion dynamics that occurs for lower impact parameters. Moreover the masses of fission products are similar to the fragmentation products, which are the direct witnesses of the participants’ explosion. Due to different kinematical properties of the fission and fragmentation products it is possible to separate both reaction mechanisms, but nevertheless the cost to be paid is the precision of the mean momenta for individual isotopes.

Therefore, we propose to perform a dedicated experiment, where two fundamental features of the re-acceleration phenomenon will be studied; the dependence of the re-acceleration on the incident beam energy and the isospin composition of the participant zone.

1) **We propose to study momentum distributions of reaction residues in the reaction of ^{197}Au+^{197}Au at different beam energies E_{beam}= 250, 500, 750, 1000 *A* MeV.** The advantages of this reaction system are manifold. Both, the experimental data (see Fig.2) and theoretical calculations (Fig.1), suggest stronger MD MF effects for rather heavy systems. Gold is a very good candidate, taking into account the very low fission cross section in comparison to other heavier nuclei, such as Pb or U. Neglecting the effects of the neutron skin for very peripheral collisions, the symmetry of the system assures a constant N/Z of the participant zone, given by the isospin of gold, for all possible impact parameters. Since the system is symmetric, the measurement of projectile residues also determines the target residues and their kinematical properties, what allows for an easier relativistic correction on relative projectile-participant-target motion, in contrast to strongly asymmetric systems. Scanning a wide range of incident beam energies offers the possibility to investigate the dynamics of the participants' decompression evolution and its strength. According to the abrasion model [51], different incident energies of a projectile do not have a crucial influence on the fragmentation production in the proposed energy range. Therefore, the proposed incident beam energies would reveal pronounced effects of the compression/expansion dynamics as, on one hand, the spectator spends different time close to the participant zone and, on the other hand, there is a difference in the energy deposited by the projectile, in the rate and in the magnitude of the density build-up. Worth to mention is also the available amount of data on Au on Au collisions, which has been taken almost as "a standard" in heavy-ion collisions. The rich database of experimental [Aladin, FOPI, KaoS, etc.] as well as theoretical studies of this isotope using many different approaches or aiming at various quantities will offer a unique possibility for comparisons and validity crosschecks.

2) **We propose to study momentum distributions of reaction residues in the reaction of ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn at the incident beam energy E_{beam}= 1 *A* GeV.** The choice of ^{112}Sn and ^{124}Sn isotopes offers the opportunity to study the influence of the participants' isospin composition on the strength of the participant blast. Strong effects of the momentum dependence of the symmetry MF have been predicted in this energy regime [52]. Different combinations of isovector fields at large densities reached in the collisions, lead to very different predictions for the participant flow [52]. As counterpart of the difference for the participant flow, we expect strong differences [4] for the momentum transfer to the spectators that would be detectable using systems with different isospin content. Since the proposed systems are again symmetric, the relevant advantages as stated for the case of ^{197}Au+^{197}Au will prevail. The N/Z ratio of ^{112}Sn is 1.24, and the one of ^{124}Sn is 1.48. Moreover, even though these Sn systems differ slightly by the mass of the nuclei, we are convinced that such effects can be accounted for. Since the N/Z ratio of the ^{124}Sn is very similar to that of ^{197}Au (N/Z=1.49), the conclusions on the effects of different masses, i.e. the sizes of the fireball, can help to disentangle even a minor influence of the same effect in comparison of the two tin systems. The choice of the incident energy respects the best conditions for the transmission of the reaction products through the FRS. The dependence of the participant isospin effects on the beam energy might be the subject of future experiments. We expect that our results on the spectator response to the

participants' blast with respect to the isospin of the participant zone can yield very precise information complementing recent efforts to constrain the asymmetry dependence of the EOS. Systematic studies done for the same reaction systems at 50 *A* MeV will help to disentangle effects of isospin asymmetrization due to dynamical freeze-out effects [50].

IV. Additional interest

Although not in the center of attention of the present proposal, the fission data arising from the reaction ^{197}Au+^{197}Au are also very interesting. Compared to the reaction ^{197}Au + p studied in reference [53] the abrasion process should lead to a larger production of highly excited projectile residues. Thus, in principal, higher fission cross-sections than in the proton-induced fission of ^{197}Au should be expected. However, at high excitation energies fission is hindered by dissipation [53,54] (which is expected to increase with the excitation energy) and by the thermal instabilities that arise at temperatures larger than 5 MeV [55]. Therefore, the determination of the isotopic cross sections of the reaction ^{197}Au+^{197}Au would give valuable information on fission dynamics and on the suppression of fission caused by thermal instabilities.

V. Beam time request

For the measurements of the final residue momenta the standard configuration of the FRS will be used: this set-up allows for a data acquisition rate of $\approx 2\cdot 10^3$ events/s. Based on the previous experience to reach a mean velocity uncertainty of +/- 0.01 cm·ns^{-1} approximately $1\cdot 10^4$ events/nucleus are needed. In the case of simultaneous transmission of several fragments in the same separator setting, we expect a ratio between the highest and the lowest cross section of about 10. Therefore $1\cdot 10^5$ events/nucleus are needed on the average to obtain the desired uncertainty for the given nuclei with the lowest cross section. Since in one setting the number of transmitted isotopes is app. 40, we need $4\cdot 10^6$ events/setting. A counting time of 30 minutes appears sufficient for one setting. In order to reconstruct the full velocity distribution for each fragment, the $B\rho$ scanning should be made in steps of 1.5%. For each beam we consider two series of $B\rho$ setting, one for lighter and one for the heavier nuclei. Since $B\rho$ is app. proportional to the A/Z of the detected fragments, the difference of this quantity for the most neutron-rich and most neutron-deficient nuclei in one class of settings determines the interval of the $B\rho$ to be scanned and thus the total number of settings needed. The number of settings for each beam and setting class is given in **Tab.1**. To conclude, we estimate the total beam time needed for the complete realization of our experimental program, including 1 calibration shift for each beam and beam energy, to **34** shifts.

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Tab.1: Beam time request for different beams and beam energies. Note: additional 15 minutes for the beam time request are accounted for the scaling of the FRS magnets for each individual setting.

Projectile	Beam energy	Type of measurement	# of settings	Beam time requested
197-Au	250 *A* MeV	low Z fragments	30	30x(30+15)min = **22,5 h**
		high Z fragments	20	20x(30+15)min = **15,0 h**
197-Au	500 *A* MeV	low Z fragments	30	**22,5 h**
		high Z fragments	20	**15,0 h**
197-Au	750 *A* MeV	low Z fragments	30	**22,5 h**
		high Z fragments	20	**15,0 h**
197-Au	1000 *A* MeV	low Z fragments	30	**22,5 h**
		high Z fragments	20	**15,0 h**
112-Sn	1000 *A* MeV	low Z fragments	30	**22,5 h**
		high Z fragments	20	**15,0 h**
124-Sn	1000 *A* MeV	low Z fragments	30	**22,5 h**
		high Z fragments	20	**15,0 h**
Total				**225 h ≈ 28 shifts**