Addressing the two-step scenario of high-energy ion collisions with $^{136}\text{Xe} + \text{p}$ and $^{136}\text{Xe} + ^{12}\text{C}$ at 1 $\text{A.GeV}$ in inverse kinematics, at the SPALADiN setup of GSI.

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Abstract. We have measured at GSI-Darmstadt (Germany) the reactions $^{136}\text{Xe} + \text{p}$ and $^{136}\text{Xe} + ^{12}\text{C}$, using the inverse-kinematics technique at 1 $\text{A.GeV}$ and the large acceptance SPALADiN setup. The combination of both provides a very good coverage of the phase-space of the excited system decay channels, allowing the study of the relative importance of those decay channels, as well as a very efficient filter to reject from the detection the particles and nuclear fragments of high energy in the projectile centre-of-mass frame, essentially produced in the first-instant nucleon-nucleon collisions, prior to the decay of the excited nuclear system. Our analysis in the two-step scenario permits one to estimate on an event basis $E^*/A$, the excitation energy per nucleon of the decaying nuclear system, and to study the $E^*/A$ dependence of the different decay channels. The $E^*/A$ range of overlap of the $^{136}\text{Xe} + \text{p}$ and $^{136}\text{Xe} + ^{12}\text{C}$ reactions is large and allows for an extensive comparison between both reactions, and therefore provides a strong test bench of the entrance-channel-independence hypothesis of the excited-system decay.

We address the two-step-scenario assumption in the light of our data and their comparison with different up-to-date models.

1. Introduction
Understanding the physical mechanisms, in particular those related to the production of particles and nuclear fragments, occurring in ”high-energy” heavy-ion reactions (typically a few hundreds of MeV) has been a long-range effort since the first GeV-per-nucleon beams started operations, e.g. at LBNL in the 70s. Describing quantitatively these reactions and their numerous channels is of interest for different fields of science, such as astrophysics, the study of hot nucleonic matter, hadron therapy and applications of high-intensity GeV proton beams for energy production or nuclear-waste transmutation or the design of new neutron-source facilities.

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Our basic understanding of these ion collisions can be traced back to a seminal paper of R. Serber in 1947 [1]. In this article, two arguments are claimed to be considered to found the description of these collisions. The first is linked to the wavelength $\lambda$ of the incoming projectile. At energies of the order or above $100 \text{ A.MeV}$, we have $\lambda = \hbar/p < 1 - 2 \text{ fm}$, where $p$ is the projectile momentum. $\lambda$ is of the order or smaller than the nucleons’ radii inside the target nucleus ($r_0 \simeq 1.5 \text{ fm}$). Therefore the projectile “sees” individual nucleons inside the target, not the target nucleus as a quantum single system, and the projectile-target interaction is the incoherent summation of nucleon-nucleon scattering, nucleons coming from both nuclei, the projectile and the target.

Modern theoretical models used in heavy-ion reactions in this energy range rely on the two-step scenario. In the first instants (several $10 \text{ fm/c}$), a series of incoherent nucleon-nucleon collisions can lead to the dispersion of a large fraction of the initial-state kinetic energy, part of which is evacuated from the system by the emission of energetic particles and, to a lesser extent fragments. The rest of the dispersed energy is shared among the remaining degrees of freedom of the excited system, with a distribution which is uniform asymptotically, i.e. for long times. The basic assumption of the two-step scenario is that the decay the excited nuclear system that is produced, which leads to the production of the essential part of the emitted particles and fragments, is driven only by its global properties (mass, charge etc…), i.e. independently of the entrance channel. The first instants of the collision are described by intranuclear cascade models, such as INCL [2] or ISABEL [3] for example. These models, following different Monte-Carlo methods, compute series of nucleon-nucleon scattering up to the point where the energy distribution does not vary statistically under individual scattering. In the models, this happens after a few $100 \text{ fm/c}$. The excited nuclear systems produced at the end of the cascade, one for the target nucleus and one for the projectile, going apart in the centre-of-mass system under momentum conservation, are called remnants, in particular throughout this paper. At the end of the cascade calculation, the main features of the remnants are estimated, namely mass, charge, total excitation energy and total angular momentum. The decay of the remnants is calculated via deexcitation mechanisms working at the scale of the nuclei: particle/fragment emission such as evaporation or asymmetric fission, and fission. The models used to that end are essentially statistical and must cover the entire phase space of the final states accessible with the remnants’ characteristics.

In the present work, we used the intranuclear cascade code of Li`ege, in its version developed for the GEANT4 package: INCL++ [4]. This code was acknowledged as one of the best performing nuclear cascade models in a workshop organized by IAEA in 2008 to benchmark models to be used in the extensive simulations needed for the design of accelerator-driven systems (ADS) [5]. The decay of the remnants was computed with three codes: ABLA07 [6], GEMINI++ [7] and SMM [8]. These are described in the literature, to which we refer the reader for further details. In our experiment, the choice was made to compare two reactions: proton on $^{136}\text{Xe}$ and $^{12}\text{C}$ on $^{136}\text{Xe}$. The first reaction favours, in principle, lower excitation energies and larger remnants from $^{136}\text{Xe}$ (in mass and charge), whereas the second one occurs with potentially larger energy transfers to the target nucleus $^{136}\text{Xe}$, leading to higher excitation energy per nucleon $E^{**}/A$ and smaller remnants in average. In principle, if selection via observables could be made on remnant characteristics, a comparison of the decay channels of both reactions for sets of similar remnants could be performed, which could provide a strong test bench of the two-step scenario and models used within.

2. Detection setup
Our detection setup is displayed in fig. 1. SPALADiN was installed in the former Cave C of GSI, now the R3B hall. We used the inverse kinematics, with a $^{136}\text{Xe}$ beam at $1 \text{ A.GeV}$ directed onto: 1) a liquid hydrogen target for the $^{136}\text{Xe} + p$ reaction; 2) a carbon foil for $^{136}\text{Xe} + ^{12}\text{C}$. 


Figure 1. Our SPALADiN experimental setup. The beam comes from the left. The target and an ionization chamber for the identification of the residue of the projectile (Forward MUSIC) are located upstream of the ALADiN magnet. The other detectors for charged fragments (ALADiN ToF-Wall and Twin MUSIC) and neutrons (LAND) are positioned downstream of the magnet.

Figure 2. $^{136}Xe + ^{12}C$: Correlation between excitation energy per nucleon of the prefragment $E^*/A$ and the detected charge of the events $Z_{\text{bound}}$, mean, $\langle E^*/A \rangle$ and rms, $\sigma(E^*/A)$. The numbers shown on the left figure correspond to the $\langle E^*/A \rangle$ bins, where the data are integrated. The line at $E^*/A = 4.2 \text{ MeV}$ is a threshold value in ABLA07 for the excitation energy of the prefragment above which the decay can be computed with a dedicated multifragmentation module.

Details concerning our detection may be found in [9, 10]. The combination of the inverse kinematics, of the beam energy and of the large-aperture setup with its magnetic analysis provided an efficient filter to select out fast particles and fragments produced during the first instants of the reactions and focus, therefore, on the decay of the $^{136}Xe$ remnants. Detection efficiencies and acceptances were determined in a range from 80 % for the neutrons to almost 100 % for the projectile residues [9, 10].
3. Excitation-energy determination

As a first attempt to determine on an event-basis some of the characteristics of the remnant (in the two-step model), we consider $E^*/A$. In the literature two observables have been used for this variable: $M_{\text{tot}}$, the total detected-fragment multiplicity and $Z_{\text{bound}} = \sum z_i \geq 2 Z_i$, the sum of the charge of the detected fragments heavier than the hydrogen isotopes. Using GEANT4 [11] for the simulation of our experiment, we were able to demonstrate that $Z_{\text{bound}}$ is well adapted to that purpose [9, 10]. As shown in fig. 2 (left), we have defined bins in $Z_{\text{bound}}$ to study the $E^*/A$ dependence, six for $^{136}Xe + ^{12}C$ (red symbols) and four for $^{136}Xe + p$.

4. Results and discussion

In the discussion here, we restrict ourselves to the total multiplicity observable $M_{\text{tot}}$. Our data are shown in fig. 3 for both reactions and for the different $E^*/A$ intervals. Note that the proton data were scaled to $^{12}C$ ones according to:

$$\sigma_p^e(M_{\text{tot}}, \langle i \rangle) = \sigma_{\text{exp}}^e(M_{\text{tot}}, \langle i \rangle) \times \frac{\int \sigma_{\text{exp}}^{12C}(M_{\text{tot}}, \langle i \rangle) dM_{\text{tot}}}{\int \sigma_{\text{exp}}(M_{\text{tot}}, \langle i \rangle) dM_{\text{tot}}}$$

(1)

where $\sigma_p^e$ and $\sigma_{\text{exp}}^{12C}$ are the measured cross sections for $^{136}Xe + p$ and $^{136}Xe + ^{12}C$ respectively, integrated over bin $\langle i \rangle$ in $E^*/A$. We observe in fig. 3 that the $M_{\text{tot}}$ distributions of the two reactions almost overlap in the four common intervals, after the scaling. This is a strong argument in favour of the two-step scenario: A selection in $E^*/A$ is sufficient to characterize the remnant and produce the same $M_{\text{tot}}$ distributions in the decay phase of the reactions.

In figs. 4 and 5 the comparison of our data with three models (INCL++ with ABLA07, GEMINI++ and SMM) is shown. We note a reasonable description of our data for both reactions of the high-multiplicity tails of these distributions. This means essentially that the detection efficiencies and the setup acceptance have been correctly estimated in the data analysis and the simulation.

For the $^{136}Xe + p$ reaction (fig. 4) we observe a strong overlap of the three model predictions, a least for the first three $E^*/A$ bins. Differences show-up for the highest $E^*/A$. This may be interpreted as a dependence of the $M_{\text{tot}}$ distribution on the sole cascade phase of the reaction, in a similar way as $Z_{\text{bound}}$. Hence, the discrepancy observed on the low-$M_{\text{tot}}$ side of the distributions,
except for the first $E^*/A$ bin, side of the distribution where possible errors in the data analysis and simulation are the smallest, is meaningful of a problem which may be tracked in the cascade model to describe this reaction at increasing $E^*/A$. To investigate this further, looking to $M_{\text{tot}}$ for $^{136}\text{Xe} + ^{12}\text{C}$ is helpful. We note indeed in fig. 5 that the low-$M_{\text{tot}}$ tails of the distributions for this reaction are much better predicted by at least two models, ABLA07 and GEMINI++ than the corresponding ones of $^{136}\text{Xe} + p$. We must anyway note that SMM, even though it doesn’t reproduce the data of both reactions, when combined with INCL++, has the same behaviour as the data for the $M_{\text{tot}}$ distributions (both sets of distributions scale). On the contrary, ABLA07 and GEMINI++ behave differently from one reaction to the other through $E^*/A$ selection.

![Figure 4](image1.png)  

**Figure 4.** Evolution of the $M_{\text{tot}}$ distributions with $\langle E^*/A \rangle$ for $^{136}\text{Xe} + p$ (blue squares) compared with the deexcitation models: ABLA07 (solid green), GEMINI++ (dotted blue) and SMM (dashed red) coupled with INCL.

![Figure 5](image2.png)  

**Figure 5.** Evolution of the $M_{\text{tot}}$ distributions with $\langle E^*/A \rangle$ for $^{136}\text{Xe} + ^{12}\text{C}$ (red crosses) compared with the deexcitation models: ABLA07 (solid green), GEMINI++ (dotted blue) and SMM (dashed red) coupled with INCL.

The different behaviour of ABLA07 and GEMINI++ in the two reactions means that these calculations for the $M_{\text{tot}}$ distributions are sensitive not only to $E^*/A$ but also to other characteristics of the remnant, such as its mass $A_R$, its charge $Z_R$ or its total angular momentum $J_R$. Even if the $J_R$ distributions are very different from one reaction to the other, we could show that the predictions for $M_{\text{tot}}$ depend weakly on $J_R$ by forcing the $J_R$ distribution for $^{136}\text{Xe} + p$ to resemble that of $^{136}\text{Xe} + ^{12}\text{C}$ at the end of the intranuclear cascade in the calculation. The sensitivity of the calculations on $A_R$ and $Z_R$ for $M_{\text{tot}}$ is much stronger. Let us first note that in INCL++, $E^*/A$, $A_R$ and $Z_R$ are correlated: Smaller remnants are produced by multiple hard nucleon-nucleon scattering, which are leading on average to higher $E^*/A$. Anyway it should be underlined that these correlations are different in the two reactions: For a given $E^*/A$ bin, the remnants are on average smaller for $^{136}\text{Xe} + ^{12}\text{C}$ than for $^{136}\text{Xe} + p$. Hence the determination of $E^*/A$ characterizes different remnant statistics in the two reaction. Moreover, the dependence of $M_{\text{tot}}$ on $A_R$ and $Z_R$ may be understood by considering that for a given excitation energy per nucleon, the remnant will decay in fewer fragments and nucleons, whatever the decay mechanism, if $A_R$ and $Z_R$ are smaller. In this framework, the disagreement between the models and our data for $^{136}\text{Xe} + p$ on the left part of the $M_{\text{tot}}$ distributions with increasing $E^*/A$ may be interpreted,
in the framework of the two-step model, as unsufficient nucleon removal during the cascade for a given $E^*/A$.

5. Conclusion
We studied in the present work two reactions, $^{136}\text{Xe} + p$ and $^{136}\text{Xe} + ^{12}\text{C}$, at 1 $A\cdot\text{GeV}$. We used the inverse kinematics technique, whose combination with both the beam energy and our large acceptance setup SPALADiN, permitted us to detect in coincidence the decay products of $^{136}\text{Xe}$: neutrons, light-charged fragments and beam residues. The high detection efficiency as well as the acceptance allowed to reach a good sensitivity to the reaction mechanisms.

We analyzed our data in the two-step scenario of the description of the ion collisions: a fast intranuclear cascade followed by the slow decay, with many open channels, of the so-created excited nuclear system (the remnant). In this modelling, we made use of the observable $Z_{\text{bound}}$ on an event basis, to estimate the excitation energy per nucleon, $E^*/A$ of the remnant. We investigated the dependence of the total detected-particle multiplicity $M_{\text{tot}}$ on $E^*/A$ for both reactions. The comparison of our data with models drove to the conclusion that the remnant mass and charge as computed in our cascade model should be more alike in both reactions than they are presently.

The analysis of our results is still going on, with more detailed work on additional observables. In the short term, the perspectives of this work are essentially on the modelling, with the aim of a more quantitative description of our data by the model. In the longer term, a program similar to what has been done at GSI within the SPALADiN collaboration would take a large advantage of the well-improved performances of the detection as being designed and built for the FAIR/R3B facility. As an example, we can quote the aimed 95 % efficiency of neuLAND as compared to the 80 % we had in our experiment with the LAND neutron detector. Another example is the increased bending power and angular aperture of the new R3B-GLAD magnet as compared to ALADiN, which will provide, if combined with a dedicated detection, sensitivity on the kinematics of the light fragments emitted in the decay of the remnant.

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