

OPEN ACCESS

Studies of the $^{136}\text{Xe}+p$ and $^{136}\text{Xe}+^{12}\text{C}$ reactions at 1 GeV per nucléon with the SPALADIN setup

To cite this article: O Yordanov *et al* 2012 *J. Phys.: Conf. Ser.* **366** 012051

View the [article online](#) for updates and enhancements.

You may also like

- [A next-generation liquid xenon observatory for dark matter and neutrino physics](#)
J Aalbers, S S AbdusSalam, K Abe et al.
- [Physics potential of searching for 0 decays in JUNO](#)
Jie Zhao, , Liang-Jian Wen et al.
- [Partial cross section of neutron-induced reactions on \$^{136}\text{Xe}\$ at \$E_n = 5\$ MeV for 0 background studies](#)
M Bhike, J H Esterline, B Fallin et al.



The
Electrochemical
Society

Advancing solid state &
electrochemical science & technology



DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research



Studies of the $^{136}\text{Xe}+p$ and $^{136}\text{Xe}+^{12}\text{C}$ reactions at 1 GeV per nucleon with the SPALADIN setup

O Yordanov¹, J É Ducret², T Gorbinet³, S Leray³, A Boudard³ and M D Salsac³

¹ Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

² CEA/IRFU/Service d'Astrophysique CELIA, Université de Bordeaux 1, F-33405 Talence

³ IRFU/Service de Physique Nucléaire, CEA, Centre de Saclay, F-91191 Gif-sur-Yvette

E-mail: orliny@inrne.bas.bg

Abstract. Obtaining a correct description of spallation, in which a proton of energy in the GeV-range interacts with an atomic nucleus, is essential for different research domains in basic nuclear physics, advanced nuclear technologies, space- and medical research. Such a description is based on models developed within the larger framework of nuclear reactions at relativistic beam energies, where a complex interplay of different nuclear excitation and de-excitation mechanisms occurs. At the initial intranuclear cascade stage of the interaction of the target- and projectile nuclei a highly excited prefragment-nucleus is formed, whose decay towards stability could proceed via different mechanisms such as sequential particle evaporation, asymmetric binary decay, fission in the case of fissile nuclei but also the so-called multifragmentation. Employing the inverse kinematics technique by impinging a heavy relativistic beam of ^{136}Xe on light targets of liquid hydrogen and ^{12}C , the SPALADIN experimental setup detects in coincidence neutrons and charged residues with $Z \geq 2$, which include the heavy residual nucleus and the light mass fragments emitted in the course of its formation.

1. Introduction

Based on the high-resolution FRS-spectrometer and the large ALADIN dipole magnet, an extensive experimental program for nuclear reaction studies in inverse kinematics has been pursued at GSI Darmstadt for more than a decade. The outgoing channels of proton-induced reactions with a non-fissile relativistic beam consist in their majority of one heavy residual nucleus, whose formation proceeds via the emission of protons, neutrons and light-mass charged fragments from a highly excited prefragment formed at the initial stages of the reaction. Experiments with the SPALADIN setup are aiming at the reconstruction of the reaction kinematics at relativistic beam energies by detecting the heavy reaction residues in coincidence with the emitted light- to intermediate mass charged fragments and neutrons. This experimental approach was already successfully implemented in the study of spallation of ^{56}Fe at 1 GeV per nucleon [1]. The formation of the heavy residue, depends on the excitation energy of the prefragment-nucleus, formed during the initial intranuclear cascade- or abrasion stage of the reaction. Although the excitation energy of the prefragment is not directly measurable, it can be estimated by detecting the particles emitted during evaporation. The coincident detection of the majority of reaction products is reducing the uncertainties in the input experimental data, which serve for the development of codes simulating the nuclear reactions at relativistic beam

energies starting from their initial nucleon-nucleon collision stage till the formation of the final residue.

2. Experimental setup

The SPALADIN experiment was set up in the Cave-C experimental hall of GSI-Darmstadt. The ^{136}Xe -beam of 1 GeV per nucleon was provided by the UNILAC/SIS-18 accelerator facility. A set of plastic detectors generated the trigger signal for the data acquisition system and provided the monitoring of the correct entrance of the primary beam in the setup. The cryogenic target device was located downstream following the set of plastic detectors. Inside of the vacuum module of the target device two vessels filled with liquid hydrogen, a ^{12}C sample and an empty vessel were mounted. Placing a certain target sample in the beamline was done automatically via remote control. Following the target device a four-anode-, P10-operated gas ionization chamber was placed. This so-called forward ionization chamber was aimed primarily at the measurement of the charge of the heavy reaction residue, thus providing direct experimental information on element production yields and the corresponding element production cross sections. The forward ionization chamber was placed in front of the entrance window of the ALADIN dipole magnet. A Time-of-Flight wall was placed behind the exit aperture of the dipole magnet. The ToF-wall served as a detector for light- to intermediate-mass charged fragments. The simultaneous operation of the ToF-wall and the Forward ionization chamber made the setup sensitive for all residues with charges $Z \geq 2$. Neutrons produced in the reaction were detected using the Large Area Neutron Detector (LAND). LAND was positioned along the initial beam direction, at a distance of 10 meters measured from the exit aperture of the ALADIN magnet. In addition to the forward ionization chamber, behind the ToF-wall a second TWIN-ionization chamber was mounted. Having an active volume of nearly 0.5 cubic meters, the TWIN-MUSIC detector offers high charge resolution, combined with horizontal position sensitivity, which is achieved by its specially shaped anodes. By requesting the coincident detection of the same charge in both ionization chambers, events of secondary reactions of the heavy residue with parts of the setup were efficiently suppressed.

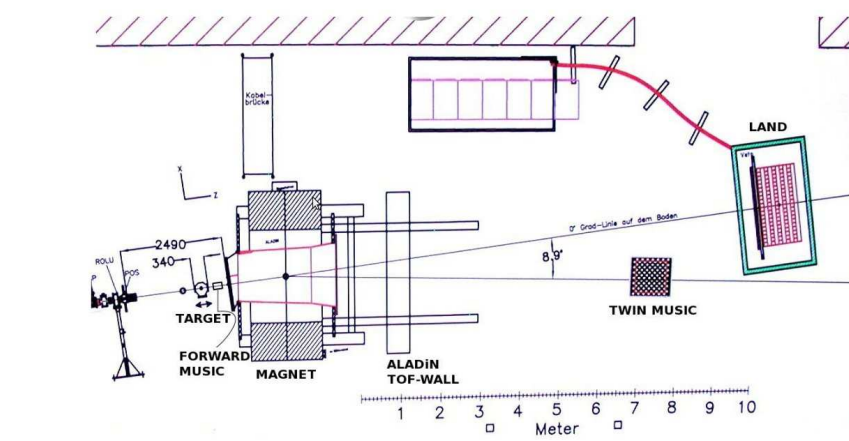


Figure 1. The SPALADIN experimental setup

3. Experimental data

3.1. $^{136}\text{Xe}+p$

The experimental data on proton induced reactions were collected by impinging the primary ^{136}Xe beam on liquid hydrogen, contained in the cryogenic module of target device. Being placed in the primary beam, the titanium target vessel has a non-negligible contribution to the total reaction rate. Therefore dedicated empty-target runs e.g. without liquid hydrogen content, were performed. After combining the two datasets collected with a filled- and an empty target vessel, histograms containing only the statistics from reactions of the primary beam with the liquid hydrogen content were obtained. The preliminary element production cross-sections measured by the forward ionization chamber show agreement with those, measured in a previous experiment with the FRS-spectrometer [2] .

The formation of a certain heavy fragment results from the amount of mass lost within the initial intranuclear cascade stage and evaporation stages of the reaction. The experimental data show, that the production of light charged residues rises if the charge of the heavy fragment is decreasing. This observation is consistent with the expectation that decreasing the mass of the heavy residues requires an increase of the excitation energies of the prefragments. This increase is manifested in the measured intensified emission of light charged residues.

The correlation between the charges of light particles and charged particle multiplicities, measured in coincidence with preselected heavy fragments, are examined too. The analysis has shown, that events of highest multiplicities obtained by the ToF-wall, involve the detection of alpha-particles only. The heaviest intermediate mass fragments, detected by the ToF-wall, are attributed mainly to events with charged particle multiplicities in the ToF-wall of one. It was found, that the charge of the intermediate mass fragment observed with the ToF-wall in an event of unit multiplicity, is comparable to the summary charge obtained in the event of highest multiplicity built up by alpha particles only. It is questionable whether the emission of an intermediate mass fragment in coincidence with a heavy residue can be described by means of evaporation. This hypothesis may be supported by the fact, that the charge of the intermediate mass fragment is related to the summary charge of the alpha particles, emitted in the event of highest multiplicity. On the other hand obtaining two heavy fragments without other charged particles being detected is an experimental sign of fission. This specific point concerning the nuclear reaction dynamics has to be addressed in further experiments.

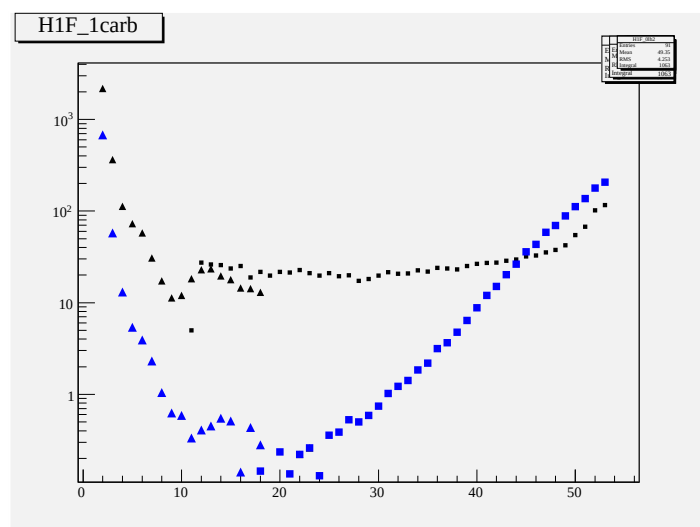


Figure 2. Preliminary element production cross sections (mbarn) for the reactions $^{136}\text{Xe}+p$ (blue) and $^{136}\text{Xe} + ^{12}\text{C}$ (black)

3.2. $^{136}\text{Xe} + ^{12}\text{C}$

At relativistic energies, the initial stages of the reactions of ^{136}Xe with proton and ^{12}C are described by two different approaches. The spallation process i.e. the reaction with protons is modeled by quasi-free nucleon-nucleon scattering at relativistic energies. The reactions with ^{12}C are more complex due to the higher number of nucleons involved in the interaction of the projectile- and target nucleus. Following the projectile-spectator picture, the initial abrasion stage of the fragmentation process proceeds via nucleon-nucleon scatterings in the zone of intersection of both nuclei. Expressed in geometrical terms, the size of the overlapping zone depends on the impact parameter. Due to the possible high number of nucleon-nucleon interactions, in the abrasion process the achievement of higher excitation energies of the prefragment becomes possible, compared to those obtained in single-proton-induced reactions. This is manifested in the measured increased production cross sections of light elements in the reaction $^{136}\text{Xe} + ^{12}\text{C}$. An analysis of the coincident detection of a certain heavy residue in the forward ionization chamber and light charged particles in the ToF-wall, is performed also for the $^{136}\text{Xe} + ^{12}\text{C}$ reaction. The comparison of the distributions shows, that for a selected heavy residue, the mean value of the charge of particles detected in the ToF-wall is higher for the LH2-target than for the ^{12}C one. Considering a liquid hydrogen target, the production of a certain heavy reaction residue relies on the mass loss in the intranuclear- cascade- and the evaporation stage. In the case of impinging the ^{136}Xe on the ^{12}C target, the relevant mass loss occurs in the abrasion stage and the following evaporation. Concerning the possible amount of mass loss in the initial stages of the reaction, the processes of intranuclear cascade and abrasion are essentially different. The intranuclear cascade process in ^{136}Xe nucleus is triggered by one proton, while the abrasion process involves the nucleons from the overlapping zone of the projectile nucleus ^{136}Xe and the target nucleus ^{12}C . Consequently if compared to the intranuclear cascade, the abrasion process is capable to cause far bigger loss of mass, due to the larger number of possible nucleon-nucleon interactions. If ^{136}Xe is impinged on liquid hydrogen i.e. $^{136}\text{Xe} + p$, the relevant mass loss for the production of a certain heavy residue is expected to occur in the evaporation stage of the reaction. If ^{136}Xe is impinged on ^{12}C , the production of the same heavy residue will be achieved by mass losses within the two processes of abrasion and evaporation. Thus, the contribution of evaporation into the required total mass loss will be lower in the case of the $^{136}\text{Xe} + ^{12}\text{C}$ reaction than in the $^{136}\text{Xe} + p$ one. The mass loss achieved in evaporation is proportional to the excitation energy of the prefragment. The decrease of the mass to be lost in evaporation equates to a reduction of the excitation energy of the prefragment. A decreased prefragment excitation energy will reduce the probability for the emission of heavier charged residues, thus making the emission of light charged particles favorable. This effect is manifested in the different mean charges detected in the ToF-wall- the value $\langle Z \rangle_{\text{ToFWall}} = 2.398$ obtained in coincidence with a heavy residue of charge $Z = 35$ from the ^{12}C -target data are lower if compared to the value $\langle Z \rangle_{\text{ToFWall}} = 2.731$ obtained from data, collected with the liquid hydrogen target in coincidence with the same heavy residue of $Z = 35$. Experimental results of the measured element production cross sections in the liquid hydrogen- and ^{12}C -target are shown on fig. 2.

4. Theory

The performed GEANT4 simulations combined the theoretically predicted residue production in the target with the particle-transport- and detection properties of the setup. The production of residues in the target was calculated by combining of the INCL4 [3] intranuclear-cascade simulation with the codes ABLA [5], SMM [4], GEMINI [6], and ISABEL [7] combined with SMM for simulating the de-excitation of the prefragment. The subsequent particle transport simulation uses the complete description of the setup including detector geometries and detection efficiencies, thus converting the calculated yields in the target into experimentally expected ones. The results of the comparative studies between experimental data and theoretical predictions

on the coincident production of light- to intermediate charged particles and heavy residues are shown on figures 3 and 4. Calculations performed by combining of the INCL4 and ABLA

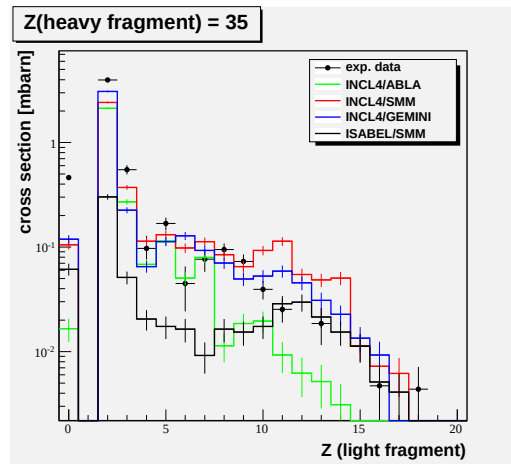


Figure 3. Light- to intermediate residues detected in coincidence with heavy residues of $Z=35$

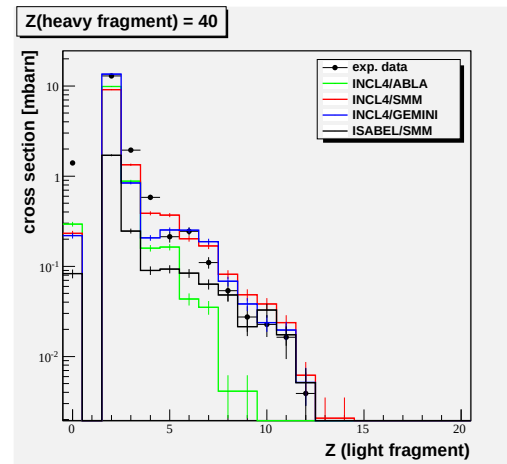


Figure 4. Light- to intermediate residues detected in coincidence with heavy residues of $Z=40$

codes show tendency to underestimate the production of charged particles. Applying the same coincidence conditions, an overestimated production of light charge particles was predicted by calculations combining INCL4 with SMM and GEMINI codes. The production cross sections of the heavy residues are well reproduced by combining ABLA-, SMM- and GEMINI codes with the INCL4. Significant deviation from the experimental elements cross section data were found in simulations performed using a combination of ISABEL and SMM codes.

5. Concluding remarks

Preliminary data on production cross sections and outgoing particle coincidences for $^{136}\text{Xe}+p$ and $^{136}\text{Xe}+^{12}\text{C}$ reactions are presented. A satisfactory description of the experimental data is obtained by means of a GEANT4 simulation of the setup, at which the residue production in proton-induced reactions is calculated by the INCL4 intranuclear cascade simulation, run together with the ABLA, SMM, GEMINI codes. A comparative study of the abrasion and intranuclear cascade mechanisms was performed by comparing the coincident production of heavy residue and light charged particles in the liquid hydrogen and ^{12}C -target. Although the particle removal channels of the nucleon-nucleon collisions occurring in the initial stages of the reactions are not directly observable, the observed differences in the charge distributions of evaporation residues in the $^{136}\text{Xe}+^{12}\text{C}$ - and $^{136}\text{Xe}+p$ -reactions can be explained as a result of an increased mass removal in the abrasion stage of the $^{136}\text{Xe} + ^{12}\text{C}$ reaction.

References

- [1] Le Gentil E *et al.* 2008 *Phys. Rev. Lett.* **100** 022701
- [2] Napolitani P *et al.* 2007 *Phys. Rev. C* **76** 064609
- [3] Boudard A *et al.* 2002 *Phys. Rev. C* **66** 0044615
- [4] Botvina A, Iljinov A S and Mishustin I N 1990 *Nucl. Phys. A* **507** 649
- [5] Junghans A R *et al.* 1998 *Nucl. Phys. A* **629** 635
- [6] Charity R J *et al.* 1988 *Nucl. Phys. A* **483** 371
- [7] Yariv Y and Fraenkel Z 1979 *Phys. Rev. C* **20** 2227