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Residue production in ^{136}Xe + p spallation reaction

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Abstract. A research program on spallation reactions in inverse kinematics has been performed at GSI, Darmstadt, taking advantage of the relativistic heavy-ions beams available from GSI accelerators and the high-resolution magnetic spectrometer, used to identify the reactions products in-flight and to determine their kinematical properties. In this paper, we report the results obtained up to now on the spallation reaction ^{136}Xe on protons, focusing on 500 and 200 *A*MeV energies.

1 Introduction

During last years, a vast experimental campaign has been developed at the Fragment Separator [1] (GSI, Darmstadt) to study spallation reactions induced by high relativistic protons. Proton spallation reactions are mandatory for developing intense neutron sources needed for accelerator-driven systems for nuclear waste incineration. They have also interest in astrophysics to understand the cosmic ray reactions with interstellar medium mainly composed by hydrogen nuclei.

The use of the inverse- kinematics method allows the detection of the primary products before β-decay and provides also information about their kinematical properties.

After performing the following systems: ^{197}Au, ^{208}Pb, ^{238}U, ^{56}Fe+p [2], the study of ^{136}Xe on hydrogen at 1000, 500 and 200 *A*MeV is conceived as an extension of that experimental data in order to provide decisive information on the energy dependence of the spallation process, achieving the lowest primary beam energy ever studied at FRS for a projectile that present a behaviour close to the heaviest elements. In particular for such heavy nuclei the N/Z ratio is still sensitive to the deposited excitation energy, contrary to light systems. In addition, the very broad mass range available for products, with almost no symmetric fission, allows to put in evidence decay mechanisms beyond standard evaporation, as asymmetric fission or multifragmentation.

2 Experimental setup

The experimental method has been extensively described elsewhere [3], so we will explain it here very summarily. The primary beam delivered by the SIS synchrotron and continuously monitored by the SEETRAM detector hits a liquid hydrogen target of 87 mg/cm^2 thickness enclosed by a titanium container. In order to subtract the contribution to the measured reaction rate due to the target windows and also from other layers in the beam line, measurements were repeated with the empty target container. The reaction residues that enter with the suitable characteristics the Fragment Separator (FRS) are transmitted through the spectrometer till the ionization chambers (MUSICs) placed after it. They are used to identify in charge each residue by calibrating the energy loss which is related to the square of the residue atomic number.

In addition, two scintillators placed at the dispersive (S2) and the achromatic (S4) focal planes provide the horizontal position where the residue trajectory intersects the focal planes, and the time-of-flight between both planes. The horizontal position gives us the measurement of the radius ρ of the residue trajectory so, knowing the magnetic configuration of

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the spectrometer, we obtain the magnetic rigidity $B\rho$. Along with the measured velocity in the second part of the FRS, deduced from the time-of-flight, the A/Z ratio is determined from the equation:

$$\frac{A}{Z} = \frac{e}{m_0 c} \cdot \frac{B\rho}{\beta\gamma}, \quad (1)$$

where e is the electron charge, m_0 is the nuclear mass and $\beta\gamma$ is obtained from the fragment velocity.

In the case of ^{136}Xe at 200 AMeV, some additional features were needed in the analysis because of the low energy beam. First, as the residues are not longer fully stripped when crossing the MUSIC at such energy, the idea was to reach the charge state equilibrium for the fragment. This means that the changes in the residue atomic charge during the MUSIC crossing are large enough that its average is well defined. In order to assure this charge state equilibrium, an additional ionization chamber was included in the setup. Then, the resolution obtained for the A/Z ratio by using the second part of the FRS information was degraded by the multiple scattering observed in the horizontal position measured at S4, resulting in a poor accuracy on the magnetic rigidity. The problem was solved by applying equation (1) to the first part of the FRS, the corresponding velocity being obtained from its measurement in the second part, corrected for the energy loss in the scintillator at the intermediate focal plane. The improvement in the resolution can be seen in figure 1.

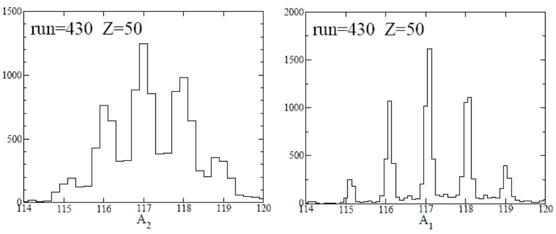

Fig. 1. Mass resolution for tin fragments obtained by using the standard procedure with $B\rho_2$ (on the left) and the one obtained from $B\rho_1$(on the left).

Combining the value obtained for the atomic number and the mass-over-charge ratio, a complete isotopic identification was performed as shown in figure 2 for the case of 200 AMeV.

3 Results

3.1 Energy evolution of the system

One of the aims of the xenon campaign was to study the behaviour of a proton plus heavy element system when the energy of the reaction goes down. This energy dependence of the residue production becomes important for thick targets like in ADS systems where a significant part of the spallation reactions are induced by secondary particles or protons already moderated in a previous spallation reaction.

As expected, the residue production close to the projectile increases when we go down in the reaction energy. This effect

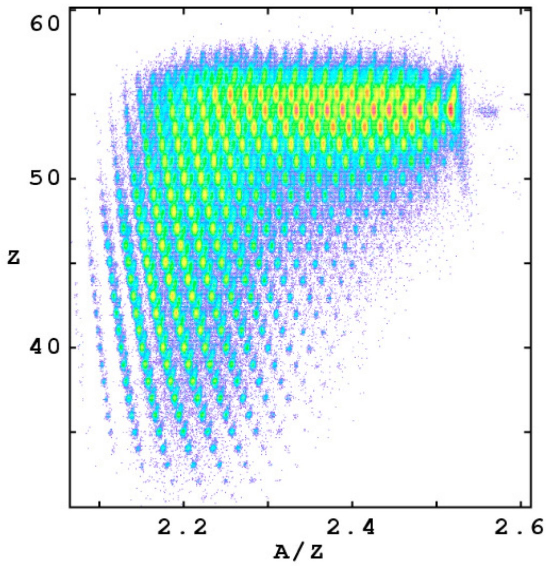

Fig. 2. Identification pattern of the ^{136}Xe + ^{1}H at 200 AMeV data where each spot corresponds to one isotope. The plot collects the counts from the hydrogen target including the contribution of the reactions produced in the titanium layers of the setup.

is explained by the decrease of the mean excitation energy involved, from 140 MeV to 90 MeV at 1 AGeV and 500 AMeV respectively, calculated with the intra-nuclear cascade code BRIC [4]. It must be noted that the total reaction cross section does not vary too much with the energy as follows from Karol's formula [5], so the reduction of the heavy residue production at 1 GeV is compensated by the apparition of lighter residues than those observed at lower energies.

3.2 Comparison to codes

First comparisons with codes dedicated to the description of the spallation process were performed on the mass distribution obtained by summing all the measured isotopic cross sections for the reaction ^{136}Xe + ^{1}H at 500 AMeV. Figure 3 shows the production cross sections as a function of the mass loss with respect to the projectile compared with three different calculations. The dotted curve is a combination of the INCL4 intra-nuclear cascade [6] with the ABLA de-excitation code based of the Weisskopf-Ewing formalism which includes only the evaporation of neutrons, protons, deuterons, tritons, ^{3}He and alphas [7]. The production cross sections close to the projectile are overpredicted whereas the intermediate mass evaporation residues are underpredicted with the INCL4-ABLA combination. This behaviour could be explained because the production of intermediate mass fragments (IMF) is not implemented in the standard ABLA code. Recently, the range of emitted fragments was extended above Z = 2 in the new version ABLA07, presented in this conference by M.V. Ricciardi et al. [7]. As shown on the solid line in figure 3, the cross sections calculated with ABLA07 (and also GEM [9]) are closer to the data. Here, the prefragments arising from the first stage of the spallation reaction were calculated with the BURST model developed at GSI, which is based on

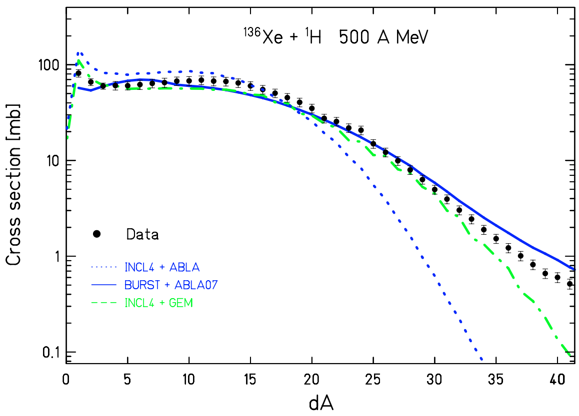

Fig. 3. Production cross section of the evaporation residues in the reaction ^{136}Xe+^{1}H at 500 AMeV shown as a function of the mass loss with respect to the projectile.

the parametrisation of the output results of the intra-nuclear cascade INCL3.

However we can observe a slight underestimation or overestimation for the cross sections of intermediate mass residues depending of the selected calculation. This could be ascribed to, for example, a too low excitation energy given by INCL4 or a weakness in the BURST model.

3.3 Even-odd effect for heavy residues.

Additionally, even-odd staggering was observed in the isotopic distribution of the production cross sections for residues with charge close to the projectile (Z = 53, 54) in the spallation reaction at 500 *A* MeV and 1000 *A* GeV as shown for example in figure 4.

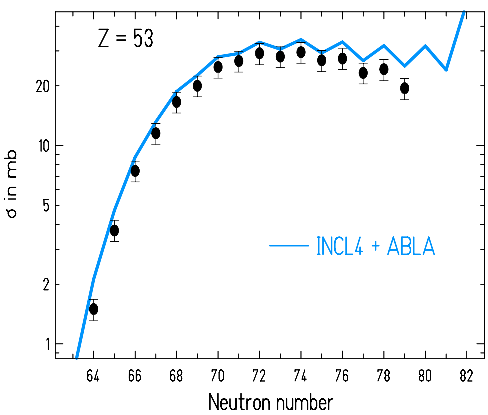

Fig. 4. Isotopic cross sections for Z = 53 measured in the reaction of ^{136}Xe+^{1}H at 500 *A* MeV compared with INCL4+ABLA codes.

A possible explanation to the enhanced production of even-N nuclei with respect to the odd-N ones is that the nuclear structure can manifest in the end products of the decay of highly excited nuclei as suggested by Ricciardi et al. for the light residues in the case of fragmentation reaction ^{238}U + Ti at 1 *A* GeV [10]. Indeed, in the case of the residues close to the projectile, it looks like the excitation energy introduced in the system is low. The hypothesis that the structural effects are restored in the end products when the nucleus cools down and goes from the liquid to the superfluid phase was tested with the ABLA code. Then the staggering was qualitatively reproduced for the isotopic cross sections of Z = 53, 54 measured in the case of ^{136}Xe+^{1}H at 500 *A* MeV (fig. 4). A similar effect observed for the heaviest residues in the fragmentation reaction ^{136}Xe + ^{208}Pb at 1 *A* GeV at GSI was also reproduced under the same assumptions.

4 Conclusions

First of all, it has to be highlighted again that it is the first time at FRS that such a low energy is reached and the good quality of the results proves its viability for these experiments. It has been possible to study a spallation reaction in a wide energy range showing how the residue production is affected and the quality of current codes. Further investigations on the complete set of data obtained at 200 *A* MeV, 500 *A* MeV and 1 *A* GeV will be undertaken to disentangle as far as possible the influences of the intra-nuclear cascade and of the de-excitation stage by testing different intra-nuclear cascades such as INCL4.4, BRIC and EDGAR, presented during this conference, coupled to different evaporation codes, namely ABLA07 or GEM. Some topics such as the odd-even effect need a deeper approach to understand the obtained data in a physical basis.

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