Exclusive measurements on ^{56}Fe + p at 1 A GeV with the SPALADIN setup at GSI

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Abstract

A new type of spallation experiments has been carried out at GSI, Darmstadt (Germany) in order to understand the spallation mechanism in greater details. These experiments use the inverse-kinematics technique where the ion beam is directed onto a liquid Hydrogen target, allowing the detection of heavy spallation residues in coincidence with low center-of-mass energy light particles. The setup is based on A Large Acceptance DIpole magNet (ALADIN) coupled with a multitrack Time Projection Chamber (TPC), a hodoscope and a neutron detector. First data on ^{56}Fe+p at 1 A GeV were taken in February, 04. In the on-going analysis, isotopic cross sections have been determined and compared to data taken at the FRagment Separator in GSI. Mean values and width of residue velocity distributions have also been obtained as well as Helium production cross section. First coincidence data are being analyzed.

Key words: Spallation, Fe beam, inverse kinematics, isotopic cross sections, Heavy residue recoil velocity, Helium production
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1. Introduction

Experimental studies on spallation reactions are necessary in order to build reliable models describing this mechanism which can be used for

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many applications from astrophysics to Accelerator Driven Systems (ADS). Many efforts have been done to study the residual nuclei production in inverse kinematics using the SIS heavy-ion beam directed onto a liquid hydrogen target at GSI, Darmstadt (Germany). This enables the detection and identification of all Heavy Residues (HR) thanks to the use of the high quality spectrometer FRragment Separator (FRS). Extensive data and detailed information have been obtained in three regions of the periodic table around Iron, Lead and Uranium [1]. But these data also raised new questions which could not be answered with inclusive experiments alone. In particular, they do not permit to separate the Intra-Nuclear Cascade (INC) phase from the de-excitation phase of the spallation reaction [2]. Such a separation would be necessary for a better understanding of the spallation process. Therefore, spallation experiments of a new type have been carried out at GSI, aiming at more exclusive measurements of residues in coincidence with low Center of Mass (CoM) energy ($\lesssim$ 20 MeV) particles (n, p, d...) [3]. This is made possible through the use of the inverse kinematics as in this case, low CoM kinetic-energy fragments are focused in the very forward angles with respect to the beam direction in the laboratory frame. It is thus possible to assure a large angle and energy coverage in the CoM of the spallation reaction with a detection system of reasonable size in the laboratory.

First data on ^{56}Fe+p at 1 A GeV were taken in February, 04. The choice of Iron is twofold. First, data for light systems present large discrepancies with standard spallation codes for HR far from the projectile that could be understood with coincidence experiments. Second, Iron is important for material damage studies as it is the main component of the window separating the accelerator from the sub-critical reactor in most ADS designs. It becomes then crucial to have a good knowledge of the HR recoil velocity but also of the Helium production which both cause damages in the window.

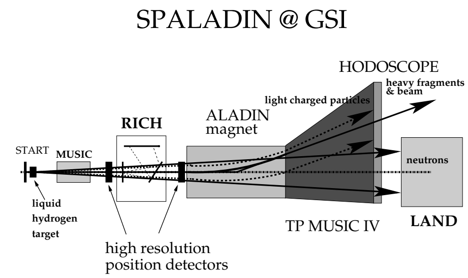

Fig. 1. Schematic SPALADIN experimental set-up. Distance between lH_2 target and hodoscope is 8 m roughly.

2. Experimental setup

The SPALADIN setup (Fig. 1) is based on A Large Acceptance DIpole magNet (ALADIN) coupled with a multitrack and MUlti-Sampling Time Projection Chamber (TPC MUSIC IV) [4]. This TPC is composed of 3 planes of ionization chambers and 4 planes of Proportionnal Counters (PC) which enable a good charge identification for Z respectively larger and lower than 10, down to protons. The use of flash ADC's permits the simultaneous detection of several tracks localized in the three dimensions. The rigidity reconstruction is made possible by the tracking performed with the PC's coupled with the information given by two high resolution drift chambers used upstream of the ALADIN magnet. The heavy-fragment velocity is determined with a Ring Imaging CHerenkov ($\delta\beta/\beta < 10^{-3}$) whereas the Light-Charged-Particle (LCP) velocities are determined by Time Of Flight measurements from a start scintillator to a hodoscope placed at the end of the setup. Masses can then be deduced by the knowledge of the particle rigidity, velocity and charge. They are obtained with a resolution of about $\delta A/A = 1.4\%$ FWHM (Fig. 2). A small MUlti Sampling Ionization Chamber is placed after the target in order to detect charge changes within the setup. Neutrons are detected in multiplicity in a Large Area Neutron Detector (LAND) of high efficiency.

3. Heavy residues (HR) analysis

The HR production cross sections have been determined for isotopes between Z=12 and Z=25 [7].

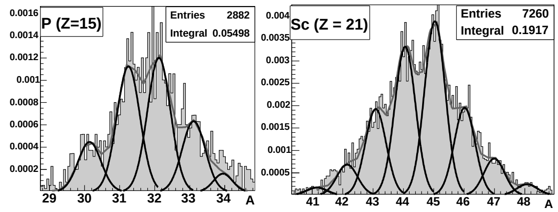

Fig. 2. Reconstructed mass distributions for P and Sc elements, normalized to the number of incident beam particles. The gaussian fits represented are used for cross section determination.

They can be compared with a previous experiment performed at GSI-FRS having a lower angular acceptance [5]. This also allows to verify the good control of particle identification and trigger efficiency. Isotopic cross sections $\sigma(A,Z)$ are obtained from the yield $Y(A,Z)$ of a given isotope per incident beam particle by the formula $\sigma(A,Z) = Y(A,Z)/N_{at}(targ) \times f_{sec}$, where $N_{at}(targ)$ is the number of Hydrogen atoms per unit area in the target and f_{sec} is a factor correcting count rates for secondary reactions. The target thickness can be estimated with the difference between beam velocity in the RICH for full and empty target runs. The value obtained (88.5±0.4 mg/cm^2) is in agreement with a previous measurement of 87.4±2.2 mg/cm^2 [6]. The estimated double reactions in the target remain small and are taken into account ($< 5\%$ contribution to the cross section). Since not only Hydrogen but also all materials in the beam line contribute to $Y(A,Z)$, empty target corrections have been performed. Moreover, almost all reactions between the small MUSIC and MUSIC IV ($\gtrsim 90$ %) can be signed with a change of charge of the HR. These events are rejected and production cross sections are then re-normalized element by element to the production cross section calculated in the small MUSIC. Results and comparisons with previous data are presented for four different elements on Fig. 3. The agreement is good for most isotopes. Larger error bars (lower statistics) for Z=25 are due to the use of a different trigger for residues close to the projectile. We can also point out that the interpolated value for ^{54}Mn, not measured in [5], overestimates the value obtained here.

The HR longitudinal velocity distributions for Z>12 have been determined with the RICH, corrected for the velocity loss from the middle of the target to the middle of the RICH, and transformed into the projectile rest frame. Preliminary results are presented on Fig. 4, where error bars are only statistical. The variations of the mean recoil velocities with the mass of the residue are significantly different from [5]. This would correspond to higher momentum transfer from the proton to the nucleus as predicted by the INCL4+Gemini[8,9] code. The widths of the velocity distributions agree well with [5] and with codes for the highest masses. The differences between [5] and the present experiment for both the mean velocities and the widths are under investigation.

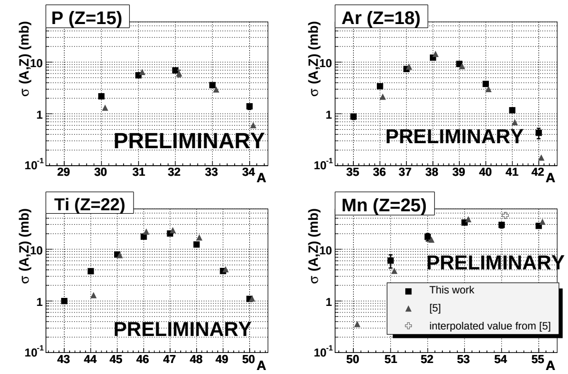

Fig. 3. Examples of isotopic cross sections for phosphorus, argon, titanium and manganese. Shifts on the x-axis are for visibility.

4. He production cross section

The LCP cross section determination is performed with the same method as for HR, but additional correction factors have to be taken into account: A Geant IV simulation [10] shows that the acceptance is limited to 72±2 % for Z = 2 and 22±2 % for Z = 1 due to the 20 cm diameter hole at the entrance of the magnet. Moreover, light fragments with low transverse momentum and having a mass-to-charge ratio similar to that of the accompanying HR cannot be spatially separated from the HR in the TPC, creating a hole in the acceptance leading to 6±3% undetected He particles. Main other uncertainties concern secondary reactions (< 10 %) and MUSIC IV efficiency control for $Z = 2$ ($\varepsilon = 90 \pm 10\%$). This

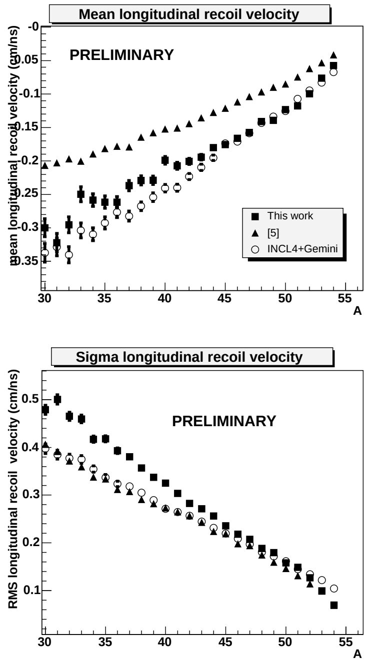

Fig. 4. Mean and RMS of HR longitudinal velocity in the beam frame [7].

leads to a first estimate of He production cross section of 526±85 mb. This value is in agreement with the data from the NESSI collaboration [11]. Further investigations will be done on the acceptance calculation for He produced in the reaction as well as for H particles.

5. Coincidence data

After these inclusive results, the next step will be to use the coincidence data between Heavy Residues and Light Particles in order to study the spallation mechanism. Some indications on the process forming spallation residues far from the projectile are given by the study of intermediate and heavy mass fragments (Z≥3) of multiplicity ≥ 2 detected in coincidence (Fig. 5). These events (≈ 8 %) show that the nucleus de-excitation does not simply consist in light-particle emission. Neutron and LCP multiplicities will also give crucial information on pre-fragment excitation energy.

In a near future, this experiment will be followed by two other ones in order to understand the evolution of the mechanisms with the mass of the system:

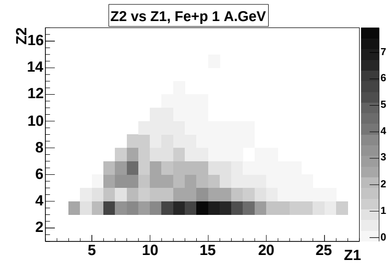

Fig. 5. Second highest fragment charge (Z_2) plotted as a function of highest fragment charge (Z_1) for events with at least two fragments with charge > 2. Units are : number of counts per 10^5 incident ions.

- ^{28}Si+p and ^{136}Xe+p will permit a study of the mechanisms producing intermediate mass fragments as a function of excitation energy
- ^{238}U+p, ^{208}Pb+p and ^{181}Ta+p will allow to understand the dynamics of the fission process in well defined initial conditions and as a function of the excitation energy.

These two proposals have been accepted by the PAC commitee of GSI in March, 2005.

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