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DISTRIBUTION OF NUCLIDES PRODUCED IN THE COLLISION OF 1 AGeV ^{238}U -IONS ON p

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Abstract. Production cross sections and kinematical properties of the complete set of fission fragment residues from the reaction ^{238}U (1 A.GeV) + p have been obtained. Isotopic distributions are measured for all elements from O ($Z = 8$) to W ($Z = 74$). Fission velocities and production cross sections are shown as a function of Z , the charge and N , the number of neutrons of the fragments. The very asymmetric pairs of fragments can be attributed to excited fissioning parent nuclei of charge Z , $88 < Z < 92$.

Keywords: NUCLEAR REACTION p(^{238}U ,x), $E = 1$ GeV/nucleon; Measured fission cross sections of 283 isotopes from Gd to Re; Measured fission fragments velocities; Inverse-kinematics method; In-flight separation by high resolution magnetic spectrometer; Identification in Z and A by ToF and energy-loss measurements; Relevance for accelerator-driven subcritical reactors and for production of radioactive beams

PACS: PACS 24.75.+i;25.40.Sc;25.85.Ge;28.50.Dr;29.25.Rm

INTRODUCTION

Proton-induced spallation in the 1 GeV range is important for many future technological applications. ISOL-separators world-wide use the proton on ^{238}U reaction since 35 years, and future radioactive-beam facilities producing neutron-rich isotopes count on it, but a solid base for the primary isotope production is missing. With 1 GeV protons on ^{238}U two main channels are opened; either fission of a more or less excited spallation residue or evaporation of nucleons [1]. The total cross section of 1.97 b divides in $(1.53 \pm 0.15)\text{b}$ for fission leading to all elements between nitrogen and rhenium [2] and $(0.44 \pm 0.06)\text{b}$ for evaporation residues [3].

Evaporation of nucleons is the main source of fragments close to U and down to $Z = 74$. After a rapid fall, within the 10 mass units close to U covering 0.24 b of cross-section, the main part of the evaporation-cross section, the mass distribution stays at 5 mb to 4 mb down to mass losses of 50 mass units. Finally a break-down by a factor of 10 to the level of 0.4 mb is observed for mass loss of 65, where the evaporation meets the fission cross sections.

Fission leads mainly to fragments which cover the domain of $Z = 30$ to 60 . The distribution of velocities and of isotopic yields of fission fragments have been reported [2]. In this region of the chart, fragment velocities in the emitting-source frame and isotopic yields were shown to be consistent with a binary break-up of a parent nucleus with charge number $88 < Z_0 < 92$. Even for the lightest fragments, $Z < 25$, the shape of the measured velocity distribution revealed that they arise from a binary break-up [4]. The element distribution of the fission fragments drops down from $Z = 45$ to $Z = 17$ ($N = 20$), forms a plateau until $Z = 14$ and increases again for smaller values of Z and N [4]. The fission partners of these very light elements are expected in the range of $Z > 74$.

In this presentation we concentrate on the region intermediate between fission fragments (FF) and evaporation residues (EVR).

EXPERIMENT

The experimental study of ^{238}U fragments induced by 1 GeV protons has been performed by using inverse kinematics. The 1 A GeV U beam produced by the GSI accelerator facility collides the nuclei from a H_2 liquid target contained in a Ti cell. Forward emitted fragments, fully stripped, are momentum analysed with the high resolution FFragment Separator, FRS [5], and identified in Z with an ionisation chamber at the end of their trajectory in the FRS. The mass number A is deduced from the time of flight in the second half of the FRS-system.

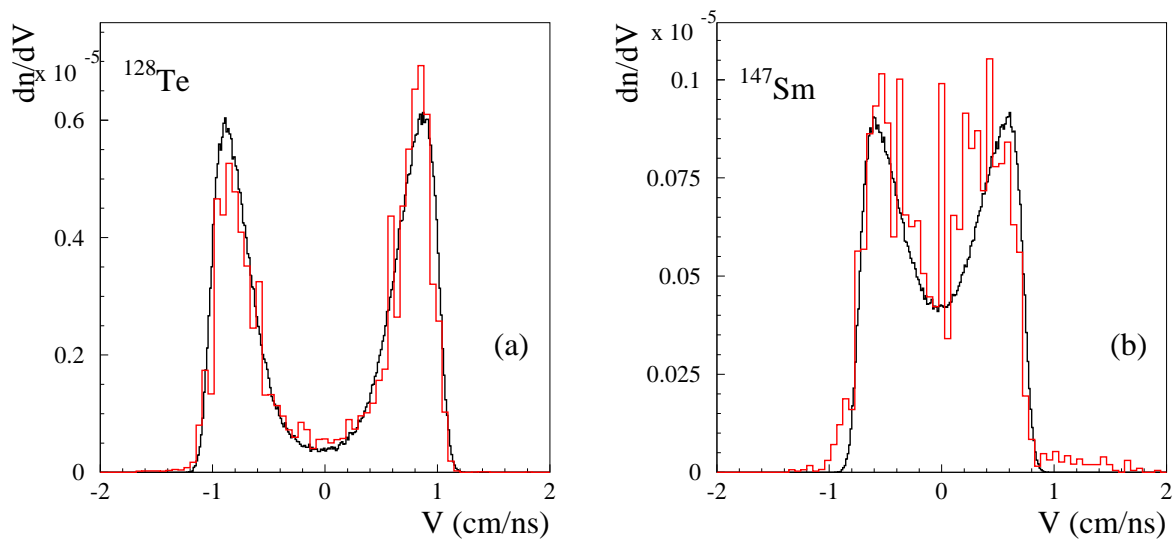


FIGURE 1. Examples of fission fragments velocity distributions in the rest frame measured for ^{128}Te and ^{147}Sm . The fission velocity is deduced from the distance between the external sides of the distributions. It decreases with the mass of the fragment. The simulations reproduce the spectra.

The velocity for each fragment is precisely determined by its magnetic rigidity, once they are identified. The FRS identification-method is precisely explained in the contribution of M.-V. Ricciardi to this conference.

Within a momentum window of 3 % , fragments separated in the FRS, are detected and identified in Z and A. The successive scanings of the FRS magnetic rigidity allow to reconstruct the velocity spectra of each fragment however truncated by the FRS angular acceptance of ± 15 mr. The rest frame velocity spectra of fission fragments is obtained by applying the Lorenz transformation to the lab. spectra.

A bunch of 3 to 4 isotopes of the 36 elements populated by fission are simultaneously measured. This coherence minimizes the relative uncertainties. The transmission through the FRS increases towards 100% for fragments with masses $A > 150$. The production cross sections are obtained by integrating the velocity distributions and accounting for the transmission in the FRS.

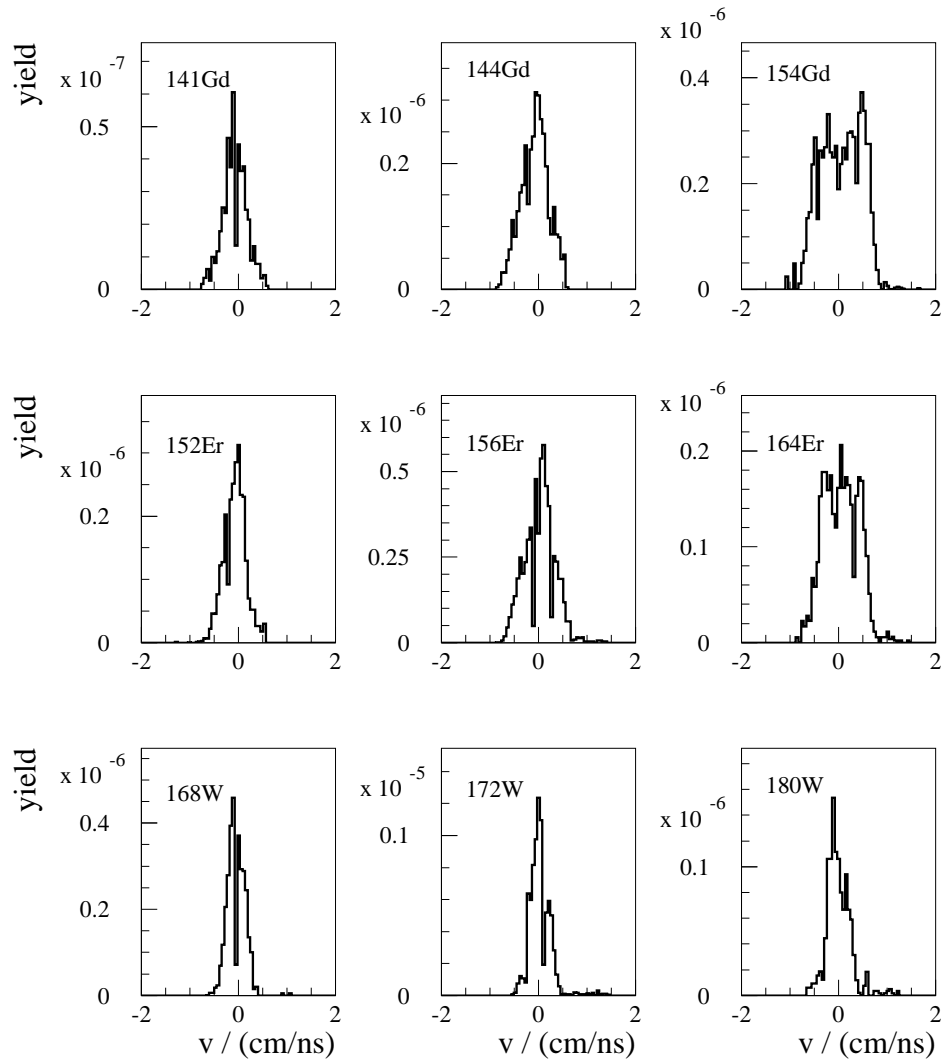


FIGURE 2. Fission fragment velocity spectra in the rest frame for selected isotopes of element $Z = 64, 68, 74$.

The velocity distribution of a fragment reveals the process from where it comes; either fission or evaporation from the excited spallation residue.

Two examples of FF spectrum are shown in Fig. 1. This basic experimental results are simulated using Monte-Carlo calculations including kinematics and FRS opening angle [2]. The fission velocity decreases with increasing mass A (or Z), as expected from momentum conservation in fission.

For heavier FF both wings tend to come close together and finally join in a somewhat rectangular plot as seen in Fig. 2 for ^{154}Gd , where velocity-distributions of isotopes of three elements of Z = 64, 68 and 74 are shown; The three lightest isotopes, in the left column, are EVR produced either in the Ti-windows of the H_2 target or to a smaller amount in secondary reactions of primary abundant heavier EVR [8, 9]. The heaviest isotopes in the right column are fission fragments. The isotopes shown in the central column are mixtures of EVR and FF with changing weights of both processes. The very different mass and charge dependencies of the velocity distributions for both types of fragment allow for a separation and unfolding of the two production mechanisms [3, 10].

RESULTS

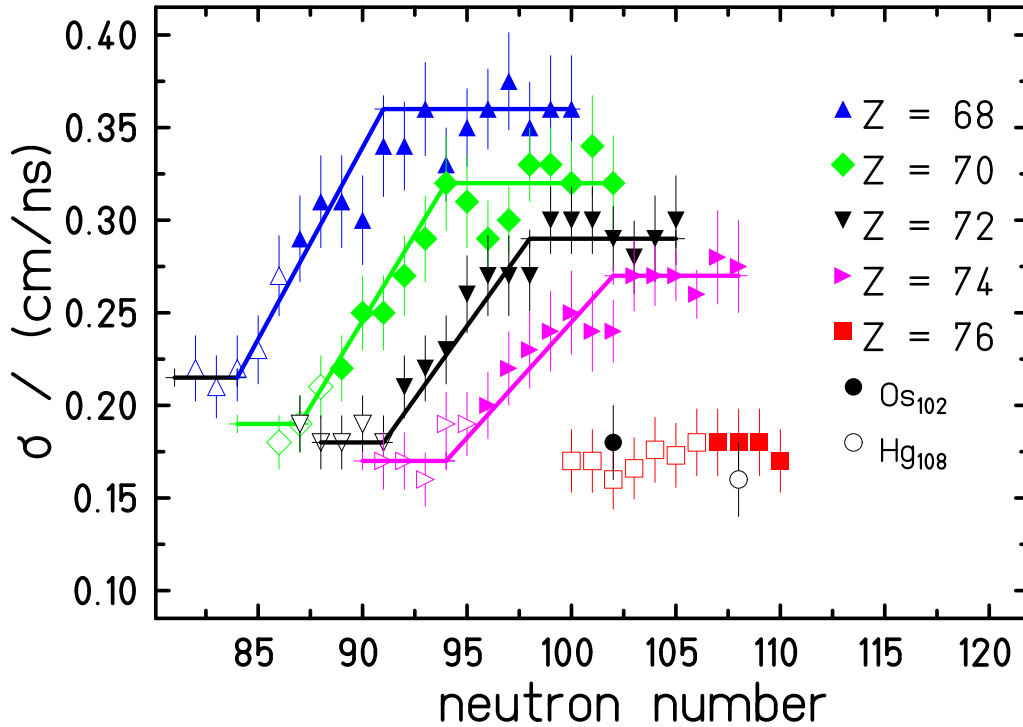


FIGURE 3. Variances of velocity distributions for nuclides produced by fission or as evaporation residues. The horizontal lines indicate the variances for fission products. When the variances drop down, the lines are used to interpolate the relative weight of fission. Empty symbols refer to isotopes where the fission contribution was not extracted. The circles shown on the Z = 76 curve correspond to measured widths from J. Taieb [3] for $\Delta A = 50$ and 60.

The variance of the velocity distributions of the fragments are taken as the ingredients

to evaluate the fission velocities and the share of FF among the transmitted isotopes. Fig. 3 reports the dependence of the variances as a function of the neutron number for the heaviest even elements.

For Z increasing from 68 to 74 all curves show a flat part for heavy isotopes, associated to a pure fission component, followed by a fall when the neutron number decreases. The fall indicates a mixing of fission and evaporation fragments. Towards the end, for the minimum width, a few points from each element correspond to EVR on the Ti windows. This last values increase with the corresponding mass losses as expected from Morrissey systematics [11].

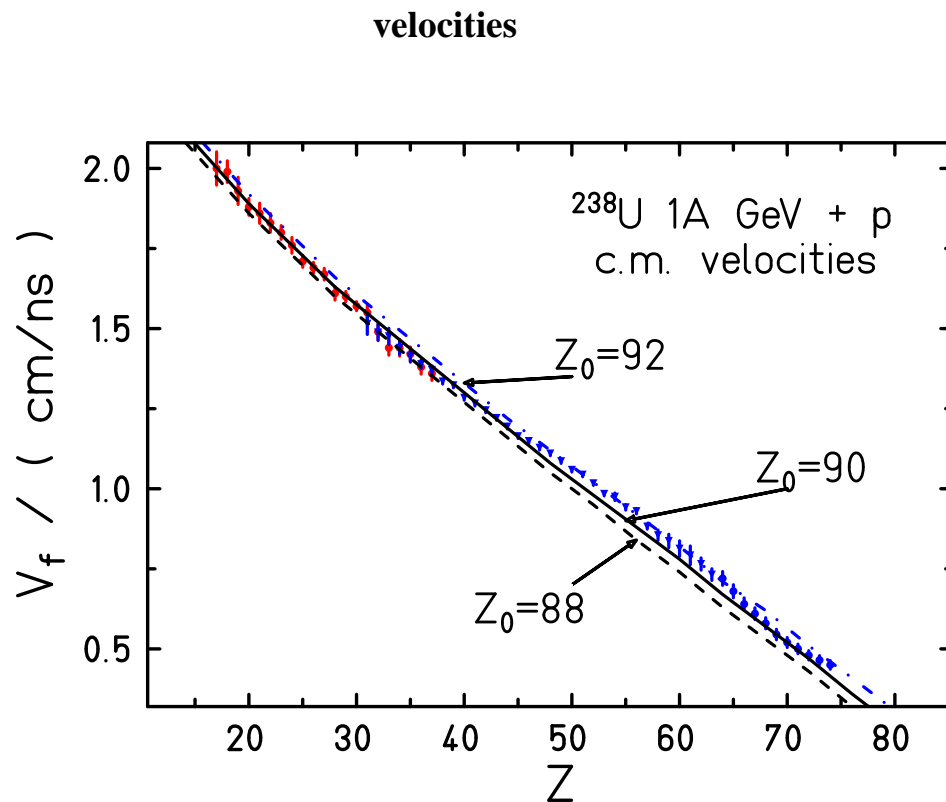


FIGURE 4. The c.m. velocity of fission fragments measured as a function of the atomic number. The three lines: dashed $Z = 88$, full line $Z = 90$, and dashed-dotted line $Z = 92$, are calculated assuming Coulomb repulsion with a radius r_0 being kept constant and fixed by the measured value of the velocity for symmetric fission of ^{220}Th taken as normalisation.

The longitudinal projection of the velocity vectors becomes a rectangle for heavy FF. The measured distribution is the convolution of a rectangle with a normal distribution due to fluctuations of the reduced momenta of the fissioning parent nuclei. These fluctuations are mainly due to a range of recoils by evaporation. In our previous work [2], the related width was evaluated to be $\sigma_r = 0.13$ cm/ns. The width (FWHM) of the rectangle is the sum of forward and backward velocities i.e. twice v_f . The variance of the measured peak σ_{meas}^2 is related to the variance of fission σ_f^2 by $\sigma_{meas}^2 = \sigma_r^2 + \sigma_f^2$. As σ_f

is larger than σ_r , we set $\sigma_f^2 = v_f^2/3$, and it follows $v_f = \sqrt{3}\sigma_f$. The velocities v_f obtained for each Z , are shown in Fig. 4. The 3 lines are calculated assuming a coulomb potential acting between the two emitted fragments of mass \bar{A} . Three parent fissioning elements Z_0 are tested and the measured values are all included in a Z_0 -window of 88 to 92.

Isotopic cross sections

Cross sections are obtained by integrating the c.m. velocity distributions of each isotope. A few other corrections are required [2]

1) For $64 \leq Z \leq 67$, the fission velocity varies between 0.71 to 0.6 cm/ns and the transmission increases from 90% to 100%. For $Z > 67$ the transmission is taken as 100%.

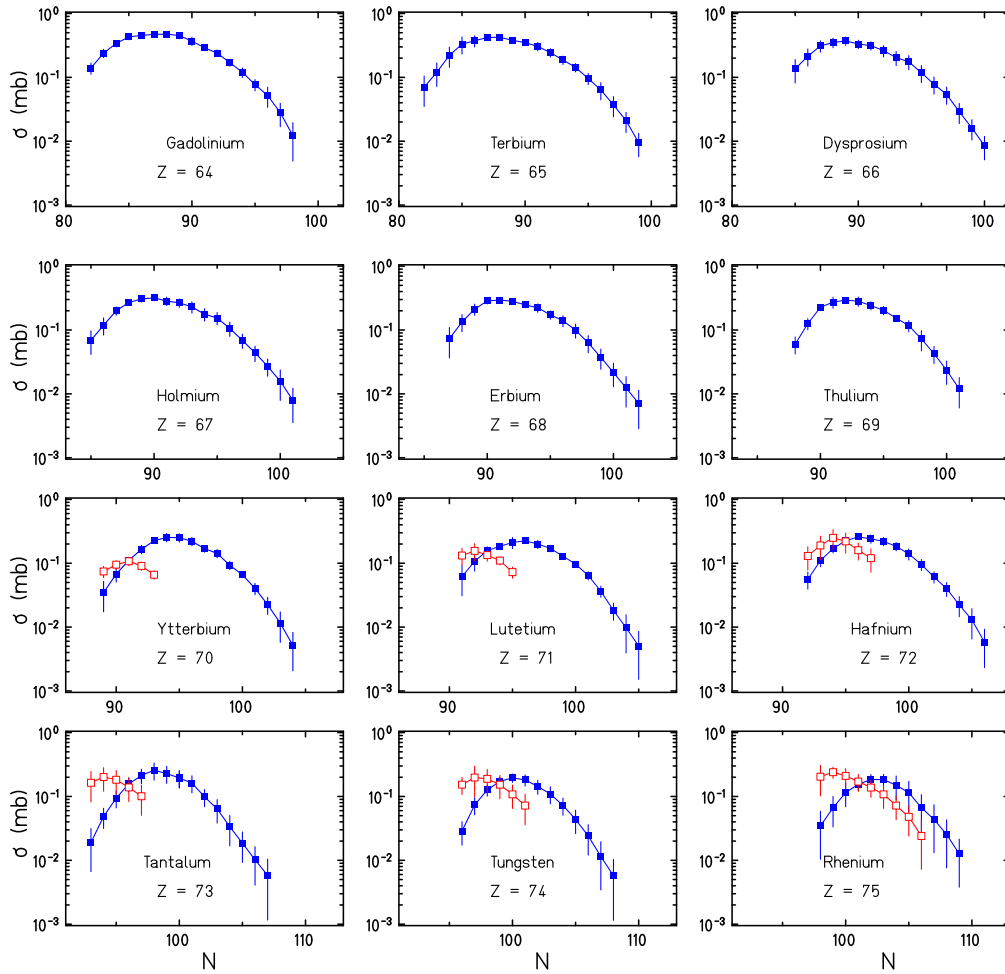


FIGURE 5. Isotopic distributions of cross sections for elements gadolinium to rhenium. fission fragments cross sections are represented by full symbols. The evaporation residue contributions are shown with empty symbols for the three heaviest elements. The large error bars reflect the uncertainties of the separation process.

2) Only fragments totally stripped ($q = Z$) are analyzed here. However, at increasing

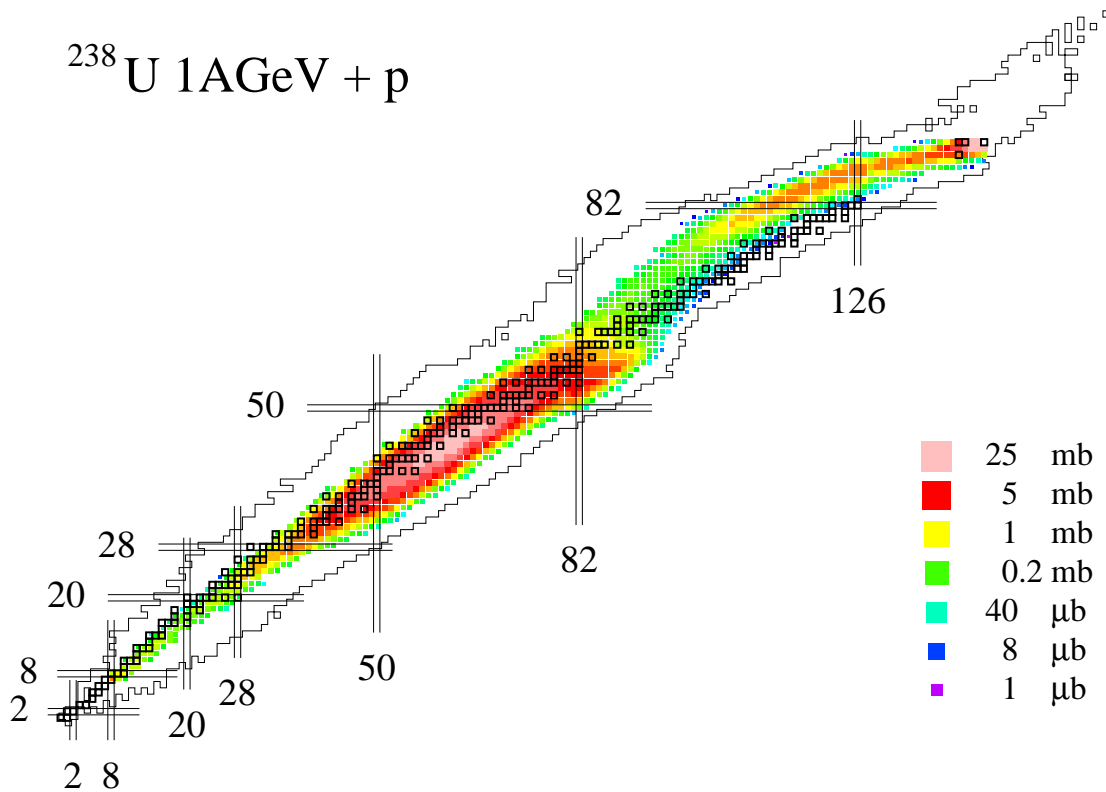


FIGURE 6. The identified isotopes are shown on a chart of nuclei. The logarithm of the experimental cross-sections are indicated by a color scale.

atomic numbers the proportion of the next ionic state ($q = Z - 1$) is no longer negligible and the correction grows from 1.09 for $Z = 64$ to 1.23 for $Z = 73$ [13].

3) Another loss of FF comes from secondary reactions in the scintillator SC2. This loss is calculated using the formulation of Karol [14] for the total cross section. The related correction factor increases from 1.17 for $Z = 64$ to 1.18 for $Z = 73$.

4) Cross sections of neutron-deficient isotopes are excluded when the contamination due to EVR becomes as large as the counting of FF.

The isotopic cross section distributions show similar bell shapes. The contribution of fission extends up to $Z = 75$. It is not possible to conclude about an increment of cross sections for heavy partners of the very light nuclides since the EVR produced on the Ti-windows -or on p- and secondary reaction fragments become predominant at $Z = 74$ and beyond.

On the neutron-rich side, the domain of investigation can be extended much further down to very small cross-sections (0.2 nb). This was demonstrated earlier with the

identification of 117 new neutron-rich FF in U (0.75 GeV) + Be collisions. [6, 7].

The distribution of \bar{N} as a function of Z indicates that many neutrons are emitted together with the formation of a very asymmetric pair of FF. Those rare fission processes are due to highly excited nuclei.

CONCLUSION

Fission fragments are separated and identified up to mass $A = 184$. Velocity measurements allow to deduce velocity distributions of fission fragments and to separate them from evaporation residues. Isotopic production cross sections are obtained for isotopes of the 66 elements produced by U + p fission, down to a threshold value of 0.1 mb covering a range of 0.1 to 14 mb, (Fig. 6), with a systematic uncertainty of 10%. The domain of very heavy FF-partners is investigated for the first time. They are attributed to fission of very excited intermediate parent nuclei in the range $88 < Z < 92$.

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