Comprehensive analysis of fission-reaction properties in the nuclear spallation of $^{238}\text{U}(1\text{A GeV})$ on deuterium

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(Dated: October 27, 2006)

Fission fragments of 1 GeV $^{238}\text{U}$ nuclei interacting with a deuterium target have been investigated with the FRagment Separator (FRS) at GSI (Darmstadt) by measuring the isotopic production cross-sections and fragment velocities. The combination of these two observables enabled to disentangle the high- and low-energy fission modes. Specific properties of these two modes were analyzed; in particular, the charge distribution of the fissioning projectile-like pre-fragments could be determined for the first time.

PACS numbers: 21.10.Ft; 21.10.Gv; 25.40.Sc; 25.45.-z; 25.75.-q; 25.85.-w; 29.25.Rm

I. INTRODUCTION

Spallation reactions have recently raised an intense research activity, justified by their many practical uses in different fields [1–8]. Beyond that, this type of reactions turned out to be an optimum tool for investigating different de-excitation channels over a wide range of temperatures and fissilities [8–13]. According to the two-step formalism of Serber [14], spallation reactions are assumed to occur in two sequential steps: in the first stage, a thermalized compound nucleus, referred to as pre-fragment, with a rather small deformation and low angular momentum [15], is created as the result of the collision between a light projectile and a heavy target nucleus. During the thermalization process, the nucleus can eject some particles that leave vacancies in the nuclear Fermi distribution, thereby leading to a subsequent increase of the total excitation energy. Depending on the violence of the initial collision—related to the impact parameter of the incoming projectile—the pre-fragments end up with an excitation energy spread over a rather wide range. After thermalization, the excited pre-fragments decay in a second slower stage. Two are the dominant channels through which this de-excitation occurs: fission and evaporation. Depending on the particular decay channel, the process will end up with the formation of a spallation-evaporation or spallation-fission fragment. The well established initial conditions of the thermalized pre-fragments make it possible to relate the measured fragment-productions with the de-excitation process associated with each decay channel.

In two recent publications, the analysis of spallation-evaporation and spallation-fission fragments in the FRagment Separator (FRS) at GSI for the reaction $^{238}\text{U}(1\text{A GeV})+d$ was presented in detail [16, 17]. As pointed out in reference [17], the complexity of this reaction demands an extensive analysis of the physical aspects underlying this reaction. In particular, the most salient characteristics of the spallation of uranium are the high fissilities of the pre-fragments produced in the region of the actinides and the wide range of excitation energies covered by these pre-fragments. Therefore, this system provides a scenario where fission of different heavy nuclei can be investigated at different excitation energies.

Collisions at large impact parameters lead to low-energy nuclear fission, characterized by the presence of structural effects that are responsible for the characteristic asymmetric mass distribution of the final fission fragments. Less peripheral collisions lead to less-fissile lighter highly excited nuclei that cool down by evaporation and/or fission; structural effects are washed out, and the final fission mass distribution becomes systematically more symmetric. These two different regimes of the fission mass distribution were primarily investigated by Turkevich and Niday [18], who proposed two distinct fission modes: an asymmetric and a symmetric mode. Later, Wilkins et al. [19] described the mass partition of the fission fragments by applying the Strutinsky method to the fissioning nuclei at the scission configuration. According to their semi-statistical model, the total potential energy of the system at the scission point is calculated as the sum of the liquid-drop potential, plus the shell-correction terms for each nascent fragment. At low energies, the asymmetric mass distribution stem from two different asymmetric channels: the Standard I (SNI) channel of high kinetic energy, with a spherical heavy partner around $Z \approx 50$, $N \approx 82$, and the Standard II (SNII) channel of lower kinetic energy, with a deformed heavy partner around $N \approx 88$. At increasing energies, the shell structure of the nuclear potential is washed out, and the fission mass distribution is mainly determined by the liquid-drop potential at scission, which favors the symmetric mass partition channel. Further studies of these three fission channels were performed by Brosa et al. [20].

The present paper focuses on the analysis and discussion of the experimental data reported in reference [17] of the fission fragments produced in the reaction $^{238}\text{U} (1\text{A GeV})+d$. In spite of the limited number of experimental observables measured in this experiment for...
each nucleus, the high precision attained made it possible to investigate the fission process in detail: First, by analyzing the recoil velocities of the fission fragments we could separate the different fission modes according to the kinetic energies associated with the configuration of the fissioning nuclei at scission. Second, for each element the measured isotopic cross-sections enabled to separate the low- and high-energy fission components, since they both lead to different mass partitions of the fission fragments. These and other issues regarding the fission process occurring in the reaction $^{238}$U(1A GeV)+d will be discussed.

II. KINEMATICS OF FISSION FRAGMENTS

In order to understand the general trend of the kinematics of fission fragments arising from uranium-like excited pre-fragments, we show in Fig. 1 the velocity distributions of the reaction products (in the frame of the projectile) measured in the reaction $^{238}$U(1A GeV)+d for elements above Z=28. Due to the particular characteristics of the cryogenic deuterium target—discussed in detail in a previous publication [17]—the fragment productions were contaminated by the presence of titanium windows surrounding the deuterium target. The kinematics of fragments generated in the whole system is compared in Fig. 1 with that measured with a titanium dummy target of thickness 36.32 mg/cm$^2$, equivalent to the titanium windows replacing the production target (left and right panels, respectively). The distributions of each system shown in the figure were obtained for each element by integrating the contributions of the whole isotopic chain. It is worth mentioning that the contribution of the Ti dummy to the velocities measured with the production target was subtracted in the following in order to obtain the kinematics associated specifically to the reaction $^{238}$U(1A GeV)+d.

In Fig. 1, the evaporation fragments lay in a region of velocities close to that of the primary beam, while the forward- and backward-emitted fission fragments—produced by the cuts in angular acceptance of the FRS on the phase-space of the fission fragments [21, 22]—correspond to the upper and lower wings. The increase of the fission velocities as the atomic number of the fragments decreases is a natural consequence of the momentum conservation between the light and heavy fission fragments in the frame of the fissioning system. Of particular interest is the increase of velocities of evaporation fragments observed at low atomic numbers observed for the reaction induced with the titanium dummy target (right panel). This finding is in clear contradiction with the expected reduction of evaporation velocities for decreasing projectile masses [23], and was interpreted as being due to the blast of compressed nuclear matter during the first stage of the reaction [24, 25].

The fission velocities $v_{fiss}$ of fragments ranging from vanadium (Z=23) to dysprosium (Z=69), in the reference frame of the fissioning systems, were determined with the method described in Ref. [17] (see Figs. 10-12 in Ref. [17]). Figure 2 shows the fission velocities for some selected isotopic chains. These velocities are slightly larger than those one would directly deduce from the two components in Fig. 1 due to the influence of the limited angular acceptance of the FRS. The empty dots seen for the lightest isotopes correspond to nuclei that were significantly produced by secondary reaction in the target, as described by P. Napolitani et al. [26].

The measured fission velocities reflect the total kinetic energy released in the fission process itself. According to the semi-statistical scission-point model of Wilkins et al. [19] the main contribution to this energy comes from the Coulomb repulsion of the two nascent fragments at the scission point and depends only weakly on the dynamics of the process from saddle to scission. In a “hard” statistical version of this model, the latter contribution can be neglected compared to the dominant Coulomb term and thus the total kinetic energy (TKE) is given by:

$$ TKE = \frac{Z_1 \cdot Z_2 \cdot e^2}{D} \quad (1) $$

where $e$ is the electron charge, and $Z_1$ and $Z_2$ refer to the charge of the two fission fragments. The distance $D$ between the two uniformly charged spheroids which constitute the fission fragments is given by:

$$ D = r_0 A_1^{1/3} \left(1 + \frac{2\beta_1}{3}\right) + r_0 A_2^{1/3} \left(1 + \frac{2\beta_2}{3}\right) + d \quad (2) $$

where $A_1$ and $A_2$ are the mass numbers of the two nuclei, $d$ is the distance between the tips of the spheroids and $\beta_1$ and $\beta_2$ refer to their quadrupole deformations at scission. According to the scission model, at low excitation energies these two latter parameters are affected by the shell structure of the two nascent fragments, while at higher energies they can be determined on the basis of the liquid-drop model. In the present discussion, we use the parameters proposed by Wilkins et al. for the macroscopic version of their model, corresponding to high-energy fission: $r_0=1.16$ fm, $d=2$ fm and $\beta_1 = \beta_2 = 0.625$. These values were later confirmed by Böckstiegel et al. [27] by analyzing the TKE measured in nuclear-induced fission of several actinides and pre-actinides. From these equations it was possible to determine the velocities of the fission fragments $v_{fiss}$ as a function of the charge of the fissioning nucleus ($Z_{fiss}=Z_1 + Z_2$) considering momentum conservation between the two fragments in the frame of the fissioning system. Furthermore, the mass of the second fission partner $A_2$ was imposed by following the Unchanged-Charge-Density (UCD) criteria which preserves the mass-to-charge ratio of the fissioning nucleus ($A_{fiss}/Z_{fiss} = A_1/Z_1 = A_2/Z_2$) in the fission process (i.e. we explicitly neglect post-scission neutron evaporation). This approximation did not noticeably modify the final result since the dominant dependence of $v_{fiss}$...
is the charge of the fissioning nucleus. From Eqs. 1 and 2, the velocity of a fission fragment with atomic and mass numbers $Z$ and $A$, in the reference frame of the fissioning system, can be determined by:

$$v_{\text{fiss}} = \left\{ \frac{2Z(Z_{\text{fiss}} - Z)^2e^2}{m_0AZ_{\text{fiss}}r_0A^{1/3}[1 + 2/3\beta_1 + (Z_{\text{fiss}}/Z - 1)^{1/3}(1 + 2/3\beta_2)] + d} \right\}^{1/2}$$

where $Z$ and $A$ are the atomic and mass numbers of the fission fragment considered, and $m_0$ is the nuclear mass unit. In this equation we used the values of the parameters $r_0$, $d$, $\beta_1$, and $\beta_2$ described above.

Fig. 2 compares the measured velocities with the values calculated with Eq. 3 for different $Z_{\text{fiss}}$. Five elemental sequences are shown, ranging from the lightest and the heaviest elements measured, around the light and heavy peak of the asymmetric fission mode, and around symmetry. The different isotopes of a given element can be produced by different parent nuclei: the most neutron-rich isotopes are produced by the heaviest fissioning elements including uranium ($Z=92$), protactinium ($Z=91$) and thorium ($Z=90$), while the neutron-deficient ones are populated by lighter fissioning systems (see also Figs. 10-12 in Ref. [17]). This trend is in agreement with the $Z_{\text{fiss}}^2/A_{\text{fiss}}$-dependence of the fission: As a consequence of the low fissionabilities of light parent nuclei (low $Z_{\text{fiss}}$), only the most neutron-deficient isotopes (low $A_{\text{fiss}}$) have a chance for undergoing fission due to their smaller fission barriers; the fragments produced by these parent nuclei populate thus the neutron-deficient side. On the contrary, the high fissionabilities of heavy fissioning systems extend the productions to more neutron-rich fragments.

This argument establishes a link between excitation energy of the parent nuclei and velocity of the fission fragments: fissioning nuclei with a low value of $Z_{\text{fiss}}$ were created with a significantly high number of removed protons from the uranium projectile during the first stage of the reaction. Since the number of vacancies left in the Fermi-sea of the pre-fragment is directly related with the excitation energy deposited in the system, the more neutron-deficient fission fragments—coming from light fissioning nuclei—were produced by high-energy fission. On the contrary, the low-energy fission component contributes to the production of the most neutron-rich fragments.

It is remarkable that for charges in the regions $50 \leq Z \leq 52$ and $40 \leq Z \leq 42$, the velocities of these neutron-rich nuclei cross the line of maximum possible velocities calculated from Eq. 3 for uranium fissioning nuclei. A similar trend was previously observed by Enqvist et al. [28] in electromagnetic-induced fission of $^{238}$U on lead at 1A GeV. Figure 3 compares the measured velocities in that work for tellurium and zirconium (squares) with the present data (dots). As can be seen, both reactions show a similar trend for the velocities of these neutron-rich isotopes (empty symbols). According to the scission model of Wilkins et al. [19], the increase of fission velocities—or TKE—with respect to the values predicted by Eq. 3 might be interpreted as a signature of low-energy asymmetric fission modes, for which the shell structure of the nascent fragments leads to more compact shapes—or equiva-
FIG. 2: Isotopic distribution of velocities of some selected fission fragments, in the reference frame of the fissioning systems, produced in $^{238}$U(1A GeV)+d [17] (dots) compared to the values calculated from Eq. 3 (see text for details). The calculations were obtained for different fissioning systems: uranium Z=92 (solid line), radium Z=88 (dashed line), mercury Z=80 (dotted line) and rhenium Z=75 (dash-dotted line). Empty dots correspond to nuclei with a secondary-reaction contamination greater than 50%.
FIG. 3: Fission velocities of tellurium and zirconium isotopes measured in the reference frame of the fissioning system in the reactions $^{238}\text{U}(1\text{A GeV})+\text{d}$ (dots) and $^{238}\text{U}(1\text{A GeV})+\text{Pb}$ [28] (squares). The open symbols represent the isotopes that were mainly produced by low-energy asymmetric modes (see text for more details). The solid line correspond to the velocities calculated from Eq. 3 for uranium fissioning nuclei.

lently, lower values of $D$ in Eq. 2— with the subsequent increase of the Coulomb repulsion. Attending to the particular structure of the potential as a function of nuclear deformation, the low-energy asymmetric fission mode consists of two channels: the Standard I (SI) channel (with higher kinetic energy) corresponding to a spherical heavy fission partner (N≈82) and the Standard II (SII) channel (with lower kinetic energy) that corresponds to a deformed heavy fission partner (N≈88) [19, 20].

The contribution of these two low-energy asymmetric modes to the fragment production in uranium fission was investigated by Donzaud et al. [29] from electromagnetic-induced fission on lead. According to this work, SI is placed around $^{134}\text{Te}/^{164}\text{Zr}$ and SII around $^{142}\text{Xe}/^{96}\text{Sr}$. Thus, the large velocities observed in Fig. 2 for neutron-rich isotopes in the region $50 \leq Z \leq 52$ and $40 \leq Z \leq 42$ can be interpreted as being due to the most compact shapes of the SI channel. By contrast, the higher deformations of the SII channel lead to lower velocities that can not be separated from those calculated for the high-energy symmetric fission mode.

The dependence of the velocities of the fission fragments on their charge can also be illustrated by the mean fission velocities $\bar{v}_{\text{fiss}}$, averaged over the isotopic chains of each fission element. These velocities are shown in Fig. 4, together with the results obtained by M. Bernas et al. [30] and M.V. Ricciardi et al. [31] for $^{238}\text{U} (1\text{A GeV})+\text{p}$. Here, we have limited the discussion to the high-energy fission component, by excluding the velocities of the most neutron-rich isotopes and the velocities of nuclei produced by multiple reactions in the target.

Figure 4 compares the elemental distribution of $\bar{v}_{\text{fiss}}$, for both reactions, with the results determined from Eq. 3 using the values of the parameters obtained in the nuclear-induced fission measurements of Böckstiegel et al. [27]. The different lines correspond to the velocities of the fission fragments arising from fissioning nuclei with different atomic numbers. When the calculated lines are compared with the data measured in the two reactions, several conclusions can be reached: First, since none of the lines coincides exactly with the data, fissioning systems with a total charge between 75 and 93 are necessary to reproduce the data. Moreover, the lighter fission elements tend to cross the lines corresponding to lighter fissioning parent nuclei, indicating that those fragments were mainly produced by rather high-energy fission. Second, although the two reactions investigated show very similar trends, one observes lower velocity values for the reactions induced on deuterium, indicating also the stronger contribution from lighter fissioning systems. This becomes more evident in the region of light fission fragments where the deviation of the data toward lighter fissioning elements is more pronounced in the deuterium case. Similar trends were already observed for the reactions $^{208}\text{Pb}(1\text{A GeV})+\text{p,d}$ [32, 33] and for the high- and low-energy fission components in $^{238}\text{U}(750\text{A MeV})+\text{p,d}$ [29, 34].

III. FISSION PRODUCTION CROSS-SECTIONS

The isotopic production cross-sections of fission fragments were shown in Figs. 14-16 in our previous publication [17] for elements ranging from vanadium Z=23 to thulium Z=69. In Fig. 5 we plot again these cross-sections for some selected isotopic chains, and compare them with the results presented in Ref. [30]. The shape of the different isotopic chains is well described by a wide Gaussian curve, with maximum productions.
found around palladium (Z=46), corresponding to symmetric charge partitions of the fissioning nuclei. For some particular elements above Z=50 — in particular tellurium (52Te), xenon (54Xe) and barium (56Ba) —, one can clearly see the development of a secondary “shoulder” in the neutron-rich tail of the main Gaussian distribution. As discussed in Ref. [17], this enhancement in the production of neutron-rich isotopes for elements above tin, arises from the low-energy asymmetric fission mode, which favor the production of fission fragments around N=82 (from SI channel) and N=88-90 (from SII channel). These two channels are overlapped with the dominant high-energy symmetric channel [19, 20]. The polarization of the heavy asymmetric fission fragments towards the neutron-rich side makes it possible to distinguish the asymmetric channels from the dominant symmetric channel. On the other hand, the same polarization makes the lighter asymmetric partners move towards the neutron-deficient side, where the symmetric channel has maximum production. Consequently, the “shoulder” observed for the heavy asymmetric fragments can not be clearly seen for the lighter asymmetric partners (ranging from 33As to 42Mo). Furthermore, the discussed traces of low-energy fission channels are not observed for elements above 50Pr and below 30Zn. These nuclei are thus produced by high-energy fission; indeed, it is well known that high-energy fission leads to very broad charge distributions centered around the symmetric charge partition with smooth tails that extend in the region of light and heavy elements [29, 33, 34]. In the following, we discuss the information extracted from the measured fission fragments in more detail.

A. Isotopic production cross-sections of fission fragments

A better understanding of the fission process in uranium-induced reactions on deuterium can be achieved by comparing the isotopic chains of fission elements measured in this work with those obtained by M. Bernas et al. [30] for the reaction $^{238}$U$(1A \text{ GeV})+p$ (see Fig. 5).

For those elements which were partially produced by low-energy fission, the smooth hump observed in the neutron-rich side is comparable in both reactions; those isotopes come from the most peripheral, or equivalently less energetic, collisions. Due to the wide spatial distribution of the deuterium, many of these collisions were induced by a single nucleon, leading to results equivalent to those obtained with protons. Apart from this, the reaction induced with deuterium shows higher neutron-deficient fission-fragment productions than the proton case. According to the $Z^2/A$-dependence of the fission barriers, this trend reveals an increasing light-fissioning nuclei contribution, which was already observed when analyzing the velocities of the fission fragments (Fig. 2 and Figs. 10-12 of Ref. [17]). As the charge of the fissioning parent nuclei decreases, so does their neutron number, and thereby the production of fission fragments moves toward the neutron-deficient side.

Other observables characterizing the distribution of final fission fragments are the mean $N/Z$-ratio and the widths of the isotopic distributions of fission fragments. Figure 6 shows the results obtained in the present work, together with those analyzed by M. Bernas for the reaction induced with protons at $1A \text{ GeV}$ [30].

The lower average values of $N/Z$ and the broader widths of the isotopic chains $\sigma_N$ observed for the deuterium system with respect to protons are the direct result of the lighter fissioning systems that contribute to the productions of these fragments. Moreover, the larger excitation energies of the fissioning nuclei produced with deuterium also contribute to the broadening of the fission-fragment distributions [35]. Apart from this, the large values of $N/Z$ and $\sigma_N$ found around 53Cs are partly due to the polarization induced by shell effects in the low-energy fission channels.

B. High- and low-energy fission processes

The two groups of fission fragments already mentioned, from 50Sn to 60Nd and from 42Mo to 30Zn, show a symmetric high-energy and an asymmetric low-energy fission component in the neutron-rich side. The contribution of these two channels to the isotopic chains was obtained by fitting two Gaussian functions to the data, as shown

![FIG. 4: Measured fission-fragment mean velocities $v_{fiss}$ as a function of proton number for the reactions $^{238}$U$(1A \text{ GeV})+d$ (full dots) measured in Ref. [17], and $^{238}$U$(1A \text{ GeV})+p$ (open circles) obtained from Refs. [30, 31]. The lines indicate the velocities calculated from Eq. 3 for different fissioning elements: uranium Z=92 (full line), radium Z=88 (dashed line), mercury Z=80 (dotted line) and rhenium Z=75 (dash-dotted line).]
Post-scission neutron emission at low energies

The mean values and widths of the neutron-rich Gaussian functions were used to estimate the mean mass numbers and mass dispersions of the low-energy fission elements. The results are shown in table I together with the values obtained for asymmetric fission of $^{238}$U(750A MeV) on lead [29].

The values measured in the present work differ from the so-called primary mass numbers $A^H_H$, $A^L_L$ of the heavy and light nascent fission fragments by the number of neu-
trons emitted after scission. By assuming that these fragments originate from the low-energy fission of uranium isotopes, the mean total number of post-scission neutrons \( \bar{\nu}_{\text{tot}} \) emitted by a given element pair can be deduced according to equation:

\[
\bar{\nu}_{\text{tot}} = A_0 - \left[ \bar{A}(Z_H) + \bar{A}(Z_L) \right]
\]

(4)

where \( \bar{A}(Z_H) \) and \( \bar{A}(Z_L) \) correspond to the mean mass numbers of the heavy and light fission elements reported in table I. The mean mass of the fissioning uranium isotopes \( A_0 \) depends on the excitation energy at which fission takes place. This quantity was assumed by C. Donzaud et al. [29] to be equal to 237.8 and 237.2 for electromagnetic-induced fission at 12 MeV and 20 MeV, respectively. In the case of nuclear-induced reactions, the fissioning nuclei gain an average of 27 MeV per abraded fragment pairs. Since the structural effects that govern the low-energy fission disappear above 40 MeV, we have assumed \( A_0 = 237 \) for the present analysis. As will be seen later, the systematic error on \( \bar{\nu}_{\text{tot}} \) induced by this assumption does not modify our final conclusions. Apart from this, the use of Eq. 4 implicitly neglects post-scission proton evaporation; an approximation that is justified due to the neutron-excess of these low-energy fission fragments, and consequently to the high energies needed to evaporate protons.

The results of this calculation for the different fission-fragment pairs are shown in Fig. 8. Despite the possible systematic uncertainty of \( \bar{\nu}_{\text{tot}} \) induced by the assumed value \( A_0=237 \), we observe a smooth reduction in the number of post-scission evaporated neutrons for the less asymmetric fission pairs \( (\overline{50}{\text{Sn}}-\overline{42}{\text{Mo}}; \overline{53}{\text{Sb}}-\overline{41}{\text{Nd}}; \overline{52}{\text{Te}}-\overline{40}{\text{Zr}} \) and \( 53{\text{I}}-39{\text{Y}} \). The explanation lies on the excitation energy of the two fission fragments: using the semi-statistical scission-point model of Wilkins et al. [19], the energy available for post-scission neutron emission arises from the deformation energy \( E_{\text{def}} \) of the fission fragments at the scission point and the intrinsic excitation energy \( E_{\text{int}} \). Assuming that this latter contribution remains constant, the reduction of \( \bar{\nu}_{\text{tot}} \) with the decreasing asymmetry reveals more compact scission configurations for these pairs and consequently lower deformation energy \( E_{\text{def}} \) values. By contrast, the larger \( \bar{\nu}_{\text{tot}} \) values for the more asymmetric pairs corresponds to larger deformations. Within this framework, such a finding provides an interesting tool for disentangling the two asymmetric fission channels which contribute to the low-energy fission component: the compact SI channel—with high TKE— which feeds the group of elements around \( 52{\text{Te}} \) (and their light partners around \( 40{\text{Zr}} \)), and the deformed SII channel—with lower TKE values— producing the more asymmetric fission pairs. The neutron shells that define these two channels (SI, \( N=82 \) and SII, \( N=88-90 \) ) are also compatible with the primary masses \( A'_H, A'_L \) of the fission fragments deduced from the values shown in table I, including the calculated post-scission neutrons. Finally, it is noteworthy that the same distribution of fission channels was deduced independently by analyzing the high velocities of the neutron-rich fission fragments, as described above.

The mean mass numbers shown in table I for the present reaction are slightly lower than those obtained by Donzaud et al. [29]. This is easily explained by taking into account the intrinsic excitation energy \( E_{\text{int}} \) of the nascent fission fragments. The higher \( E_{\text{int}} \) values for low-energy nuclear-induced fission, with respect to electromagnetic-induced reactions, lead to larger post-scission neutron multiplicities. Apart from this, an increase of the excitation energy \( E_{\text{int}} \) damps the shell effects and favors the liquid-drop behavior, giving rise to the high-energy symmetric fission channel. In order to characterize the fragment distributions produced by this channel, Fig. 9 shows the separated contributions of the high-energy and low-energy components to the elemental

**FIG. 6:** Mean \( N/Z \)-ratio (left) and neutron widths \( \sigma_N \) (right) distributions of fission fragments produced by uranium on deuterium (full dots) [17] and uranium on proton (empty dots) [30].
dependence of $\bar{N}/Z$ and $\sigma_N$.

The values of $\bar{N}/Z$ for fragments produced by the high-energy symmetric fission channel (between $^{43}$Tc and $^{49}$In) show a regular increase with the proton number that reflects a polarization effect $\delta A$ of the fission fragments:

$$\delta A = \left( \bar{A} - Z \cdot \frac{A_0}{Z_0} \right)_{Z=\text{const.}}$$  \hspace{1cm} (5)

where $A_0$ and $Z_0$ are the mass and proton numbers of the average fissioning nucleus, obtained from table III. From this increase, a charge polarization of -0.04 was deduced, in agreement with the value found by M. Bernas et al. [30] for the system U+p. This constant behavior of the charge polarization of -0.04 was predicted by P. Armbruster [35] for the high-energy fission domain.

**Total cross-section for asymmetric and symmetric fission channels**

The elemental low-energy fission component, deduced from the integrated neutron-rich Gaussian functions, was
FIG. 9: Mean $N/Z$-ratio (left) and neutron widths $\sigma_N$ (right) distributions of fission fragments produced by uranium on deuterium (dots) showing the contribution from low-energy asymmetric fission (asterisks).

FIG. 10: Elemental distribution of fission cross-sections (dots) with the contribution from low-energy asymmetric fission (asterisks) in the reaction $^{238}\text{U}(1\text{A GeV})+d$.

In spite of the rather high uncertainties in the separation method, the Z-integrated cross-section of the two asymmetric groups were compatible with each other and equal to $92\pm27$ mb. This cross-section is slightly below the value of $105\pm10$ mb measured for the reaction induced with uranium on proton [30], though still compatible within the error bars. From these measurements we see that the low-energy fission component represents less than 5% of the total fission cross-section ($\sigma_{fiss}=2.00\pm0.42$ b) reported in Ref. [17].

Table II depicts the separated contributions to the total cross-section measured for the systems $^{238}\text{U}(1\text{A GeV})$ on proton and deuterium. The references of these measurements are included in the table.

**Distribution of fissioning nuclei at high excitation energies**

The general properties of the high-energy fissioning nuclei could be determined from the fission-fragment distributions. From Fig. 10 a mean value of $43.7\pm0.2$ and a total width of $7.7\pm0.2$ charge units were deduced from the charge distribution of high-energy symmetric fission fragments. These results are compared to those obtained for the reaction $^{238}\text{U}(1\text{A GeV})$ on proton [30] in table III. The differences between the two systems can be understood as being due to the broader distribution of fissioning systems in the reaction induced on deuterium, and

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**Table II: Total fission cross-section ($\sigma_{fiss}$), asymmetric component of fission cross-section ($\sigma_{fiss}^{\text{asym}}$), evaporation cross-section ($\sigma_{ev}$) and total reaction cross-section ($\sigma_{tot}$) for reactions induced by $^{238}\text{U}(1\text{A GeV})$ on different targets.**

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<th>Reaction</th>
<th>$\sigma_{fiss}$ (mb)</th>
<th>$\sigma_{fiss}^{\text{asym}}$ (mb)</th>
<th>$\sigma_{ev}$ (mb)</th>
<th>$\sigma_{tot}$ (mb)</th>
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<td>$910\pm110$ [16]</td>
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</tbody>
</table>
As can be seen, the elements that contribute to the high-energy fission process cover a rather broad region that extends from $^{93}_{\text{Np}}$ to $^{75}_{\text{Re}}$. The sharp decrease at the upper end of this distribution and in particular the fact that neptunium ($Z=93$) is the heaviest element contributing to the fission events agrees well with the findings in charge-pickup cross-sections found in the $^{208}_{\text{Pb}}$ system [41] and prove that the approximations used for deducing the fissioning elements were not crucial. Moreover, if the velocities of the most neutron-deficient nuclei produced by secondary reactions in the target are omitted in the previous analysis, a mean charge of 86.8±1.0 is found from the $Z_{\text{fiss}}$ distribution. These results show a good agreement with the value 87.4±0.4 obtained by the independent measurement of the isotopic distributions presented in Fig. 10, despite the approximations described in section II. Further improvements of this method, as well as systematic studies of the approximations used will be discussed in a forthcoming paper.

IV. CONCLUSIONS

In the present work, the data presented in Ref [17] for the reaction $^{238}_{\text{U}}$(1A GeV)+d on deuterium were analyzed in detail. The comparison of velocities of the fission fragments with predictions of the semi-statistical scission model of Wilkins et al. [19], provided a tool to infer the distribution of fissioning elements contributing to the final fragment productions. Within a given isotopic chain, the most neutron-deficient nuclei were produced by rather light fissioning elements, while the opposite trend was observed for nuclei approaching the neutron-rich side. The distribution of fissioning elements was estimated to range from about charge $Z=75$, for the lightest fission fragments to $Z=93$, for the most neutron-rich isotopes. Moreover, the larger velocities of the most neutron-rich isotopes of Sn, Sb and Te with respect to the theoretical predictions of the model of Wilkins et al. [19] were interpreted as a signature of low-energy fission channels. According to the model of Wilkins et al., the low-energy fission channel SI, associated to the closed shell $N=82$, is characterized by rather compact shapes. Thus, the observed increase of the fission velocity with respect to the model of Wilkins et al. was produced by the increased Coulomb repulsion. This result is in agreement with previous measurements of low-energy induced fission of uranium systems [28, 29].

As far as the production cross-sections are concerned, the comparison of the data measured for the present reaction $^{238}_{\text{U}}$(1A GeV)+d with those obtained for $^{238}_{\text{U}}$(1A GeV)+p [30] revealed an enhanced production of neutron-deficient isotopes arising from the lightest fissioning nuclei in the former case. Furthermore, the equivalent productions of neutron-rich isotopes observed in both reactions, for some particular elements, were interpreted as originated from the low-energy fission component. By fitting each isotopic chain by two Gaussian functions we could determine the contributions of the high- and low-energy components to the total isotopic productions. The $Z$-integrated cross-section of the low-energy component was obtained to be 92±27 mb, which represents a small fraction of the total fission cross-section of 2.00±0.42 b discussed in Ref. [17].

In addition, the mean values and widths of these Gaussian functions also provided the mean mass numbers and mass dis-

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**TABLE III: Mean values of isotopic and isobaric distributions measured for the reactions $^{238}_{\text{U}}$(1A GeV)+d,p [17, 30].** The asymmetric contribution was suppressed in both systems.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\bar{Z}$ (a.ch.u.)</th>
<th>$\bar{A}$ (a.m.u.)</th>
<th>$\sigma_{\bar{Z}}$ (a.ch.u.)</th>
<th>$\sigma_{\bar{A}}$ (a.m.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+d</td>
<td>43.7±0.2</td>
<td>103.0±0.20</td>
<td>7.7±0.2</td>
<td>20.0±0.5</td>
</tr>
<tr>
<td>U+p</td>
<td>44.9±0.1</td>
<td>107.4±0.25</td>
<td>7.0±0.2</td>
<td>17.5±0.5</td>
</tr>
</tbody>
</table>

**FIG. 11: Distribution of fissioning elements contributing to the total production of fission fragments in the reaction $^{238}_{\text{U}}$(1A GeV)+d.**
persions of the high- and low-energy fission component. From these values, the average post-scission neutron multiplicity could be estimated for the different low-energy fission element-pairs. These multiplicities were found to decrease sharply from a rather constant value about 6, for the more asymmetric element pairs, to ~4 for the less asymmetric pairs Te–Zr, Sb–Nb and Sn–Mo. This result indicates a reduction of the deformation energy of these nuclei, which is compatible with the compact shapes expected from the SI asymmetric fission channel, already deduced from the analysis of the fission velocities. Furthermore, by applying this technique we could separate the two asymmetric fission channels (SI and SII). Concerning the high-energy component, the combination of the isotopic production cross-sections and the analysis of the fission velocities with the formula of Wilkins et al. enabled to deduce the distribution of fissioning elements for the first time.

Acknowledgments

This work was partially supported by the Spanish Ministry of Education and Science and Xunta de Galicia under contracts FPA2002-04181-C04-01 and PGIDT01PXI20603PM, respectively, and the European Community under contracts “Access to Research Infrastructure Action of the Improving Human Potential” PRCT-1999-00001, “HINDAS” FIKW-CT-2000-00031 and “Research Infrastructure Action - Structuring the European Research Area” EURISOL DS Project Contract no. 515768 RIDS.

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