SYSTEMATIC EXPERIMENTAL SURVEY ON PROJECTILE FRAGMENTATION AND FISSION INDUCED IN COLLISIONS OF $^{238}$U AT 1 A GeV WITH LEAD


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Systematic experimental survey on projectile fragmentation and fission induced in collisions of $^{238}\text{U}$ at 1 A GeV with lead

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Abstract

Projectile fragmentation and fission, induced in collisions of $^{238}\text{U}$ at 1 A GeV with lead, have systematically been studied. A complete survey on the isotopic production cross sections of all elements between vanadium ($Z=23$) and rhenium ($Z=75$) down to a cross section of 0.1 mb is given. About 600 isotopes produced in fragmentation and about 600 isotopes produced in fission were identified in the GSI fragment separator FRS from magnetic rigidities, time-of-flight values, and the energy loss in an ionisation chamber. In addition, the velocity distributions of all these reaction products have been mapped, and the products are unambiguously attributed to the different reaction mechanisms due to their kinematical properties. The results are compared with empirical systematics and previous data. The velocity of the fragments obtained in the fission process by the Coulomb repulsion allows to reconstruct the TKE-value of the break-up and to identify the atomic number of the fissioning nucleus in hot fission. The mean velocities of light projectile fragments were found to be higher than the beam velocity.

Key words: Giant resonances; General properties of fission; Projectile fragmentation.

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Peripheral collisions of heavy ions at relativistic energies have acquired a renewed interest during the last years. New experimental facilities offer new possibilities to improve our knowledge on the different reaction mechanisms involved [1–7]. After pioneering work at LBL [8,9], the heavy-ion synchrotron SIS at GSI Darmstadt allowed for the first time comprehensive studies of fragmentation and fission of $^{238}$U projectiles at relativistic energies. The Fragment Separator (FRS) installed at the SIS served as a unique tool to separate and to identify all isotopes produced in the break-up of the relativistic projectiles [10–15]. Recoil separators give access to the reaction kinematics, and this information allows to disentangle the different reaction mechanisms observed in the interaction of the $^{238}$U projectiles. The interaction cross section of the system $^{238}$U + $^{208}$Pb at 750 AMeV which amounts to 13.4 b [16] is distributed among 2000 isotopical cross sections in the range of 100 mb down to 1 nb. Integral cross sections were measured for $^{238}$U projectiles for different targets and energies [8,16,17]. The reaction mechanisms were studied revealing new aspects of electromagnetic dissociation and fragmentation [18–21], as well as of low- and high-energy fission [22–24]. The large luminosities achieved in inverse kinematics and the unambiguous isotopical identification of fission products lead to the discovery of the double-magic nucleus $^{78}$Ni and of more than 120 until now unidentified very neutron-rich fission products at cross sections down to 0.3 nb [25–27]. Secondary beams of radioactive heavy isotopes produced from $^{238}$U projectile fragmentation allowed first radioactive-beam studies of nuclear fission [28–31].

The present work reports on a complete survey on isotopic production cross sections of all elements from vanadium ($Z = 23$) to rhenium ($Z = 75$) formed in collisions of $^{238}$U at 1 A GeV with lead down to 0.1 mb. It completes previous investigations at 750 A MeV [21,23,24] which were kinematically less detailed and restricted to $Z \leq 52$ since the main interest of the previous experiments was to study new neutron-rich isotopes [25–27]. In accordance with previous results, contributions from electromagnetic and nuclear interactions are expected. Electromagnetic interactions predominantly excite the low-energy part of the giant dipole resonance at about 12 MeV, eventually leading to the evaporation of a few neutrons or to low-energy fission [18,22,23]. Since the nuclei near the projectile are not covered in the present experiment, only the fission products and not the neutron-evaporation products from electromagnetic interactions can be observed. In nuclear collisions, depending on the impact parameter, a number of nucleons is removed from the projectile. Due to the excitation energy induced, which on the average amounts to 27 MeV per abraded nucleon [32], evaporation residues and fission products are produced.

In addition, the momentum distributions of all reaction products have care-
Fig. 1. Schematic drawing of the fragment separator with the essential detector equipment. The beam-current monitor SEETRAM registered the primary-beam intensity. Two scintillation detectors measured the horizontal positions at the mid-plane (S₂) and at the exit (S₄) of the separator as well as the time-of-flight. The MUSIC detector was used to determine the nuclear charge.

fully been mapped in order to deduce the kinematics of the reaction process. To obtain absolute production cross section of each isotope, the knowledge of the reaction process is crucial because the transmission through the FRS depends strongly on the reaction mechanism.

2 Experiment

The experiment has been performed at the GSI fragment separator [11]. The primary beam of $^{238}$U with an energy of 1 A GeV impinged on a 50.5 mg/cm² lead target which was mounted at the entrance of the fragment separator. The relatively small target thickness was chosen in order not to disturb the kinematical properties of the reaction products. The total number of $^{238}$U ions on the target was about $2.2 \cdot 10^{10}$.

The fragment separator, a two-stage magnetic spectrometer, is dispersive at the intermediate image plane (S₂) and achromatic at the exit (S₄). It was equipped with essentially two 5 mm thick scintillation detectors [12] which measured the horizontal positions at the center and at the exit of the spectrometer as well as the time-of-flight in the second half of the separator (see fig. 1). In addition, a MUSIC (MUltiple-Sampling Ionisation Chamber) [13] was mounted at the exit in order to determine the energy loss of the reaction products. The primary-beam intensity was recorded permanently by measuring the current induced in a secondary-electron transmission monitor [14].
The operation conditions of the spectrometer and of the detectors were chosen to be optimized for the detection of elements produced by fission. Therefore, the experiment was restricted to elements between vanadium and rhenium. Since the momentum acceptance of the fragment separator is limited to about 3%, 17 different magnetic-field settings were used in order to span the range from 12.1 Tm to 15.6 Tm in magnetic rigidity, populated by the reaction products in the element range of interest.

3 Data analysis

The isotopes produced in the target were identified by determining their magnetic rigidities in the first stage of the spectrometer from the horizontal position at the dispersive midplane. This information was combined with the time-of-flight in the second half of the spectrometer in order to determine the \( A/q \) ratio of the reaction products. Since the second scintillator was mounted 2.6 m in front of the final image plane, the horizontal position at the exit served to determine the angular correction to the flight path through the separator. From the energy loss in the MUSIC detector, the nuclear-charge values of the reaction products were deduced.

Figure 2(a) shows the charge response of the MUSIC detector, recorded for one setting of the fragment separator at \( B\rho = 14.4 \) Tm, demonstrating the excellent resolution \( (Z/\Delta Z = 140) \). The characteristic pattern of elemental yields due to electromagnetic-induced fission of \(^{238}\text{U}\) served for an absolute charge calibration (see [22]).

Once the nuclear charge \( Z \) is determined, the mass number \( A \) of any reaction product is obtained from the magnetic rigidity \( B\rho \), determined from the horizontal position at the central image plane, and the velocity \( v = \beta \cdot c \), determined from the time-of-flight between the central image plane and the exit of the spectrometer by using the relation

\[
B\rho = \beta \gamma \cdot \frac{A}{q} \cdot c \cdot \frac{m_0}{e},
\]

(1)

where \( \gamma \) is the Lorentz parameter, \( c \) the velocity of light, \( m_0 \) the nuclear mass unit, and \( e \) the charge of an electron. Figure 2(b) demonstrates the mass resolution \( (A/\Delta A = 320) \) achieved. In the figure, neutron-deficient tin isotopes are produced by projectile fragmentation and neutron-rich isotopes by fission. The calibration in mass number was performed by passing the primary beam through the spectrometer and verified by comparing with cross sections in [21,23], where the mass calibration is based on the increased production of \(^{134}\text{Te}\) in low-energy fission of \(^{238}\text{U}\).
Fig. 2. (a) Charge response of the MUSIC detector, recorded for one setting of the fragment separator at $B_\rho = 14.4$ Tm. (b) Mass spectrum of tin isotopes, accumulated in two settings of the fragment separator at $B_\rho = 12.8$ Tm and $B_\rho = 13.1$ Tm.

For an unambiguous isotopic identification of the reaction products, the analysis was restricted to ions which passed both stages of the fragment separator fully stripped. The losses in counting rate due to the fraction of incompletely stripped ions had to be corrected for. While the fully stripped ions dominated behind the lead target with a probability of more than 90% for rhenium – with increasing probability for lighter ions – the scintillation material at the central image plane was a less efficient stripper material. The ionic charge-state distribution behind the production target was calculated with the 3-state model of T. Brohm [33]. The ionic charge-state distribution in the second stage of the spectrometer could be measured by recording the horizontal position at the exit as a function of the energy-loss signal of the MUSIC. This spectrum is shown in Fig. 3. The three bands correspond to three different ionic charge states in the second half of the FRS since the position at the exit depends much more strongly on the ionic charge state than the MUSIC signal. In this way, the relative weights of the fully stripped, the hydrogen-like and the helium-like fraction could be determined. The correction is important for heavy fragmentation products. In the range of fission ($Z = 31-59$), as analyzed in this experiment, the ions are fully stripped.

Another correction to be applied considered the losses due to secondary reactions in the scintillation detector in the midplane of the spectrometer. These losses were estimated by the prescription of Benesh et al. [6] for the total reaction cross section. Most of these secondary-reaction products do not reach the exit of the separator due to the magnetic selection of the second stage. Thus, their contribution to the measured data is negligible.

Finally, the isotopic productions in the titanium window (4.5 mg/cm$^2$) which separates the ultra-high vacuum of the SIS accelerator from the vacuum of the separator and in the aluminium foils of the beam monitor (total thickness 8.9
Fig. 3. Two-dimensional cluster plot of the nuclear charge deduced from the MUSIC versus the horizontal position recorded with the scintillation detector at the exit of the fragment separator. The different areas correspond to contributions with different ionic charge states in the second half of the spectrometer. The largest area represents fully stripped ions, in the middle there are ions with one electron, and the smallest area to the left belongs to the helium-like isotopes. The spectrum is recorded for one setting of the FRS at $B\rho = 12.8$ Tm.

mg/cm$^2$ could not be neglected. They represent about 30% of the reaction products observed. This contribution was subtracted by means of a model calculation as reported in ref. [34].

The measured counting rates, attributed to a specific isotope, were normalized to the number of primary fragments as recorded with the beam-current monitor. A calibration factor of $(2900 \pm 150)$ projectiles per second for a monitor current of $10^{-9}$ A, as deduced from the calibration with an ionisation chamber [15] was applied. In addition, the data were corrected for the dead time of the data-acquisition system.

While the velocity distributions of all isotopes were fully covered due to the series of different $B\rho$ settings, the limited angular acceptance of the FRS had to be corrected for in order to obtain absolute cross sections. This correction was performed in a similar way as described in a previous publication [22]. The angular acceptance was determined with the help of Monte-Carlo calculations with the code MOCADI [35] which simulates the transport of particles through the FRS. The results of these calculations revealed that the transmission losses of the FRS can effectively well be represented by a sharp cut in angle at the entrance of the FRS. The opening angle $\phi$ of the cone corresponding to the angular acceptance was found to vary as a function of the horizontal positions of the beam in the central image plane and at the exit [36].

The velocity distributions of fragmentation and fission products have different
Fig. 4. Two-dimensional cluster plots of the velocity distributions versus neutron number, given for a selected number of elements (Z = 28, 34, 40, 46, 52, 58, and 64). The velocities have been converted into the frame of the projectiles in the middle of the production target. The cluster plots are shown in linear scale.
Results

The main results of the present experiment are shown in figures 4 and 5. Figure 4 demonstrates the different kinematical properties of fission products and fragmentation products. The velocity values have been deduced from the measured magnetic rigidities in the first section of the spectrometer. The reduction in velocity due to the energy loss in the second half of the production target was added. From this velocity value, the calculated primary-beam velocity in the center of the production target has been subtracted using relativistic relations. While the velocities of the fragmentation products, corresponding to the most neutron-deficient isotopes, peak close to the beam velocity, the fission products carry the recoil of the fission process. Due to the limited angular acceptance of the spectrometer, only those fission products which are emitted in forward or backward direction can be measured. This explains that the neutron-rich isotopes show two groups in velocity, one by about 1 cm/ns faster and another by the same amount slower than the projectiles. It is obvious that the isotopic production rates can be decomposed and attributed separately to the two production mechanisms.

Figure 5 summarizes the totality of isotopic production cross sections measured in the present work on the chart of the nuclides. In addition, the data are given separately for the two production mechanisms, projectile fragmentation and fission.

The fragmentation products populate a corridor, between the valley of stability and the proton drip line, from the projectile down to lowest atomic numbers. The population of the fission products, on the other hand, is limited in the present work to elements between gallium (Z = 31) and praseodymium (Z = 59). Fission produces long isotopic chains, reaching from the fragmentation corridor to the most neutron-rich known nuclei. The most neutron-rich isotopes with an A/Z ratio close to the projectile clearly show the double-humped structure which is characteristic for the low-energy fission of **237,238U**, while in the more neutron-deficient isotopes the dip at symmetric fission is filled. These different features can be traced back to the different excitation energies induced in either electromagnetic or nuclear interactions. These global characteristics have already been discussed in previous publications [20–24] and in a modelisation of fission [34]. However, the data of the present work for the first time fully cover fission products with cross section down to about 100 μb in the range of Z = 31-59 and give a complete survey on fragmentation products between vanadium (Z = 23) and rhenium (Z = 75).
5 Discussion

Projectile fragmentation and fission of $^{238}$U at 750 A MeV induced in collisions with lead were studied in detail in refs. [21,23,24]. In these publications, the low-energy fission induced by electromagnetic interactions was disentangled from the high-energy fission induced by nuclear collisions and also characteristics of different fission channels were derived. This detailed analysis is not repeated in the present work. Besides the production cross sections, the aim of the present work was to obtain full information on the velocity distribution of each isotope.

5.1 Comparison with the EPAX parametrisation

In figure 6, the presently obtained isotopical fragmentation cross sections are compared with the EPAX systematics [7] and experimental data at 750 A MeV [21]. There is an overall fair agreement between the data and the EPAX systematics in position, shape and height of the curves. The agreement is a proof for the universality of the isotopic distribution of fragmentation products. However, the agreement becomes increasingly worse in the heavier elements, where the EPAX prediction is systematically shifted to the neutron-rich side. The noticeable differences of the fragmentation cross sections for neutron-rich nuclei to the former experimental data show, that the experimental uncertainties at the transition between fission and fragmentation are particularly large. In this region the requirements on counting statistics and velocity resolution are especially high to disentangle the contributions from the two reaction mechanisms, see figure 4.

5.2 Velocity distribution of fragmentation products

One of the most interesting aspects of the present data is the fully covered kinematics of both fragmentation and fission products. In fragmentation, the velocity distribution, i.e. the mean value and the width, can be deduced up to a relative mass loss of 70%. The results are presented in figure 7, where average values of velocity and longitudinal momentum are presented as a function of atomic and mass numbers. As can be seen in figure 4, the velocity distributions of the neutron-deficient isotopes of elements below zirconium (Z = 40) are not measured completely: the backward velocities are not fully covered. Therefore, the mean velocities of these light elements are taken only from isotopes that are fully covered, and are marked by open symbols in figure 7.

In order to verify the results shown in figure 7, the same analysis has been
Fig. 5. Two-dimensional cluster plot of the isotopic cross sections on a chart of the nuclides. The production cross sections are given separately for projectile fragments (a) and fission products (b). The lower part (c) shows the sum of both production mechanisms. Full squares correspond to stable isotopes.
performed on the basis of the measured time-of-flight values in the second half of the spectrometer, taking into account the energy loss in the scintillation detector mounted in the central image plane of the FRS. This analysis leads to the same results.

In figure 7, the absolute value of the velocity is calibrated with the known velocity of the primary beam extracted from the measured Bρ-value. The experiment allows for a few checks of this calibration. First, the measured time-of-flight of the primary beam in the second half of the FRS was used, and the same result was obtained. But also the average value of the velocities of the very neutron-rich fission fragments emitted in forward or backward directions and originating from low excitation energies is expected to coincide with the velocity of the primary beam. This analysis, when performed on the basis of the time-of-flight values, was again in good agreement with the other methods. However, the fission-fragment velocities analyzed on the basis of the Bρ values were found to be slightly reduced. This can be seen in figure 4 where the most neutron-rich fission products have slightly higher velocities in backward direction than in forward direction. The reason for this deviation is not clear. By using this last calibration method, the velocities shown in figure 7 would even be higher, that means the acceleration of the light fragmentation products would even be larger. We thus have chosen the velocity calibration from the three methods that give the same results.

The result on the mean velocity reduction for small mass losses is in agreement with the expectation that the projectile is slowed down in the nuclear interaction with the target nucleus. For large mass losses, however, the mean velocity of the fragments increases again. The mean velocities of the lightest fragments even exceed that of the beam, as can also be seen directly comparing the velocities in figure 4 for Z = 28 and Z = 64. This is a very surprising feature. In the compilation of Morrissey [5] rather large scattering in the velocities of light fragmentation products has been observed.

The width of the momentum distribution, however, does not show any surprising features. The values are close to the systematics of Morrissey [5]. The deviations to the Goldhaber predictions [1] are to be expected, since this model does not consider the influence of the evaporation stage [38].

The observed features of the velocity distributions may be an important signature of the dynamics of the nuclear collision. In particular the acceleration of light fragmentation products sheds new light on the characteristics of nuclear collisions in mid-peripheral collisions which lead to mass losses from the projectile of more than 50%. Let us stress that in these cases it is not a tail of the velocity distribution which extends to higher velocities than the projectiles as has been observed previously, see e.g. [39]. It is the mean value which tends to increase with increasing mass loss until it finally exceeds the beam velocity.
Fig. 7. Average mean values and standard deviations of the velocity and momentum distributions induced in the fragmentation reactions. (a) Mean velocities as a function of atomic number in the frame of the projectiles. The horizontal solid line gives the velocity of the primary beam as a reference. (b) Average mean values of the longitudinal momentum as a function of mass number. The dashed line gives the expected extrapolated evolution of the velocities for the fragments close to the projectile [5]. See text for details for open symbols in (a) and (b). (c) Average values of standard deviations of the longitudinal momentum distribution as a function of mass number. For comparison, the predictions of the Goldhaber model [1] and of the empirical systematics proposed by Morrissey [5] for the momentum width are given. The fluctuations of the data points are attributed to the statistical uncertainties.

for elements below zirconium. However, the reason for the acceleration of light projectile fragments does not seem to be obvious. The influence of an expansion in the early stage of the reaction due to compression or thermal pressure might be considered as well as the Coulomb repulsion from the fire streak formed from the colliding nucleons of projectile and target. It is interesting to note that these light fragmentation products originate from similar impact parameters than intermediate-mass fragments observed in earlier experiments at ALADIN [40]. The acceleration observed in our experiments is probably intimately related to the understanding of multifragmentation. This problem certainly deserves more detailed considerations on the basis of elaborate theoretical models. This is not our aim in the present work.
5.3 Fission cross section

The data for fission from $^{238}\text{U}$ at 1 A GeV on lead completes the results of a previous experiment [23,24] on the same reaction at 750 A MeV as can be seen in figure 8, where the isotopic production cross sections are shown for a few selected elements. Very long isotopic chains extending over about 20 isotopes from the very neutron-rich to the stable isotopes are observed. In the region of asymmetric fission ($Z = 34$ to 42 and $Z = 50$ to 58) particularly high cross sections of the most neutron-rich isotopes can be attributed to electromagnetic-induced fission. The total fission cross sections, evaluated from the sum of the individual isotopic cross sections of fission products, amounts to $(3.9 \pm 0.6)$ b. The value can be compared to the result of Hesse et al. [16] who obtained a cross section of $(3.54 \pm 0.21)$ b at 750 A MeV beam energy. In ref. [17] the increase in electromagnetic-induced fission cross section for lead is given to be about 0.2 b when the energy of the primary beam of $^{238}\text{U}$ is increased from 750 A MeV to 1 A GeV. Therefore, on the basis of ref. [16] one would expect a value of about 3.7 b for the total fission cross section at 1 A GeV, because the nuclear interactions are supposed to be less sensitive to the beam energy [6,19]. In view of the experimental errors, our data are in good agreement with this expectation.

5.4 Velocities of fission fragments

Another subject of interest is the velocity distribution of the fission fragments, in particular of the neutron-deficient isotopes produced in hot fission after nuclear interactions. The mean velocity values induced in the fission process are shown in figure 9 as a function of mass number for different selenium, zirconium, palladium, tellurium and cerium isotopes. The values are slightly larger than the average velocities directly deduced from figure 4 because the influence of the finite angular acceptance of the spectrometer has been corrected. This correction takes into account that the length of the velocity vector is larger than its projection on the beam axis if the fragments are emitted in directions which deviate from the beam direction.

Since the two fission fragments of one fission event could not be observed in coincidence in the present experiment due to the limited acceptance of the spectrometer, the mean atomic number of the fissioning nuclei contributing to the yield of the selected fragment cannot be determined directly. However, this information can be deduced from the measured mean velocity of the one fragment observed, if empirical systematics of fission-fragment total kinetic energies are introduced into the analysis.
Fig. 8. Comparison of the isotopic production cross sections for fission from the present work (full circles) in the reaction $^{238}\text{U} + \text{lead}$ at 1 A GeV with data obtained in a previous experiment (open circles [23], open squares [24]) in the same reaction at 750 A MeV for some selected elements. Statistical error bars are shown if they exceed the size of the symbol. Additional systematic errors amount to $\pm 30\%$ (see text).

The total kinetic energy TKE, induced in the fission of sufficiently highly excited nuclei (in order to avoid shell effects) can well be described by the following liquid-drop description [2]:

$$TKE = \frac{Z_1 Z_2 e^2}{D}$$  \hspace{1cm} (3)

with

$$D = r_0 A_1^{1/3}(1 + \frac{2\beta_1}{3}) + r_0 A_2^{1/3}(1 + \frac{2\beta_2}{3}) + d.$$  \hspace{1cm} (4)

$A_1$, $A_2$, $Z_1$, and $Z_2$ denote the mass and charge numbers of a pair of fission fragments prior to neutron evaporation. The parameters ($r_0 = 1.16$ fm, $d = 2.0$ fm, and $\beta_1 = \beta_2 = 0.625$) were adjusted to measured total kinetic energies in a secondary-beam experiment on nuclear-induced fission of several actinides.
and preactinides [29] confirming the values already found in the analysis of ref. [2].

The empirical systematics, formulated by equations (3) and (4), and the equation of momentum conservation are almost sufficient to establish a direct relation between the atomic number $Z_{\text{fis}} = Z_1 + Z_2$ of the fissioning nucleus and the velocity $v$ of a specific fission fragment. Still the mass value of the fissioning nucleus and the pre-neutron mass values of the fission fragments have to be imposed. Due to dissipation effects, one may argue that fission at high excitation energies, in particular above 100 MeV, is hindered (see e.g. [4,19,41]), and only few neutrons are evaporated after fission. Therefore, it is assumed that the fissioning nucleus and the second fission fragment have the same $A/Z$ ratio as the observed fission fragment. That means that any neutron evaporation after fission is neglected. Since the relation between $Z_{\text{fis}}$ and $v$ is influenced only little by the mass values of the fissioning nucleus and of the fission fragments, a more realistic scenario with a few neutrons evaporated from the fragments after fission would not noticeably modify the results given below.

Before applying this relation to the experimental data, one may argue that a specific isotope is not produced by the fission of only one nucleus, but it results from the superposition of several contributions from different fissioning nuclei. Therefore, it was checked that the velocity $v$ of the fission fragment if calculated with the relation described above increases linearly with increasing atomic number $Z_{\text{fis}}$ of the fissioning nucleus. This justifies us to state that $Z_{\text{fis}}$ as calculated from the observed mean velocity value $\bar{v}$ of a specific isotope can be assigned to the mean atomic number $Z_{\text{fis}}$ of the fissioning nuclei contributing to the yield of the selected fragment.

The analysis method is illustrated in figure 9. In addition to the measured velocity values, the lines show the calculated velocities of the fission fragments obtained from the above-mentioned relations when different fissioning elements are assumed. In this way the mean atomic numbers $\bar{Z}_{\text{fis}}$ of the fissioning nuclei can be deduced. They can be used to test any assumptions on isotopic production cross sections of fissile nuclei, their fission probabilities, and the resulting isotopic fission-fragment distributions. Therefore, these data provide a valuable test for the validity of nuclear-reaction models.

Before entering into a detailed discussion of figure 9, we would like to mention that the analysis on the basis of the liquid-drop expressions (3) and (4) is not applicable to the most neutron-rich isotopes which are populated by electromagnetic-induced fission from low excitation energies where shell effects are important. The measured velocities increase strongly for the most neutron-rich isotopes of zirconium and tellurium due to the known influence of shell effects in the asymmetric fission component. These nuclei are strongly
Fig. 9. Mean values of the velocities (full and open dots) induced in the fission process as a function of mass number for selenium, zirconium, palladium, tellurium and cerium isotopes. In addition, the full lines indicate the calculated velocity values corresponding to fission from uranium isotopes to mercury isotopes with the same A/Z ratio as the observed fragment. Neutron evaporation after fission was neglected. Isotopes marked by open symbols were attributed to low-energy fission products, see ref. [23] and figure 8.

produced by the compact standard I fission channel with particularly high kinetic energies [23]. For the most neutron-rich palladium isotopes, on the other hand, fission proceeds by the super-long fission channel with particularly low kinetic energies [23].

However, for the more neutron-deficient isotopes which are produced by nuclear-induced fission, the analysis based on equations (3) and (4) is expected to give realistic results. As a general feature, the more neutron-deficient fission products are produced by the lighter fissioning elements. This finding is in
accordance with the $Z^2/A$ dependence of the fissility: in lighter elements low fission barriers are only found for the neutron-deficient isotopes. In addition, it can be seen from figure 9 that fission fragments with high atomic number are produced by fission of the heaviest elements. The average mother nuclei which end up in cerium isotopes are limited to thorium, protactinium and uranium. For lighter nuclei, the average mother nuclei extend much further down. The most neutron-deficient palladium isotopes around $^{194}\text{Pd}$ are already produced by bismuth mothers on the average. Finally, the most neutron-deficient selenium isotope $^{79}\text{Se}$ originates on the average from the fission of mercury isotopes. This analysis shows that a large variety of different nuclei produced in the nuclear interaction of $^{238}\text{U}$ with lead contributes to the production of fission fragments. This implies that the detailed understanding of the measured fission-fragment distribution relies on the knowledge of the fission properties of a large number of nuclei reaching from uranium down to the mercury region which can be investigated directly in dedicated secondary-beam experiments [28–30]. The understanding of these fission processes is a prerequisite for realistic estimations of the production of secondary beams by projectile fragmentation and fission of relativistic $^{238}\text{U}$ beams.

In a previous experiment [24], the average nucleus contributing to nuclear-induced fission has already been determined to have an atomic number of 85.8. It has also been shown that the fission fragments with the lowest atomic numbers are produced by even lighter fissioning nuclei. The present experiment in addition demonstrates that there is also a strong correlation between the mean atomic number $Z_{\text{fiss}}$ of the fissioning nucleus and the neutron number of the fission fragment: The most neutron-deficient fission fragments are produced by the fissioning nuclei with the lowest atomic number.

6 Summary

The secondary-beam facility of GSI has been used to determine the production cross sections and the momentum distributions of about 1000 secondary projectiles from a $^{238}\text{U}$ beam at 1 A GeV in lead. The data clearly show the characteristics of the different reaction mechanisms. A semiempirical parametrisation of the fragmentation cross sections proved to be quite realistic, with the exception of a slight shift for the heavier elements.

The velocity distributions of the lightest fragmentation products showed a surprising acceleration effect with respect to the primary beam. It is a possible signature of dynamic expansion in mid-peripheral relativistic heavy-ion collisions.

From the velocities of the fission fragments the mean atomic number of the
fissioning nuclei, responsible for their production, could be deduced. A large variety of fissioning elements reaching from uranium down to the lead region is found to contribute to the observed fission products. A strong correlation between the mass number of the fission fragments and the atomic number of the fissioning nucleus has been established.

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