Superasymmetric fission of heavy nuclei induced by intermediate energy protons

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The investigation of intermediate-mass fragments (IMF) production with the proton-induced reaction at 660 MeV, on 238U and 237Np target, is present. The data were obtained with the LNR Phasotron U-400M Cyclotron at Joint Institute for Nuclear Research (JINR), Dubna, Russia. A total of 93 isotopes, in the range 30 < A < 200, were unambiguously identified with high precision. The fragment production cross sections were obtained by the means of the induced-activation method in an off-line analysis. Mass-yield distributions were derived from the data and compared with the results of the simulation code CRISP for multimodal fission. A discussion on the superasymmetric fragment production mechanism is also present.

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1 Introduction

The nuclear dynamics is a complex problem joining all the puzzling aspects of quantum mechanics to the difficulties of many-body systems. Besides these factors, the strong interaction, which is up to date not completely understood, adds new challenges for calculations in the nonperturbative regime. Collective nuclear phenomena, as fission, particle
or cluster evaporation and nuclear fragmentation, offer the possibility of studying those complex features of the nuclear dynamics. Aside the interest from the fundamental Nuclear Physics, there are many applications where the knowledge of fragment formation would be helpful. For instance, information on intermediate mass fragments (IMF) cross section is relevant for the design of accelerator-driven systems (ADS) and radioactive ion-beam (RIB) facilities and also in the study of resistance of materials to radiation. IMF are particles with $A > 4$ but lighter than fission fragments, i.e., $A < 100$.

Fragments in high energy nuclear collisions are produced by spallation, fission, and multifragmentation. J. Hufner [1] using as classification parameters the mass number of the fragments, $A$, and their multiplicity, $M$, defined the processes in the following way:

- spallation is the process in which only one heavy fragment with mass close to the target mass $A_T$ is formed (a special case of spallation is the so-called deep spallation where $M = 1$ but $A \sim 2A_T/3$);
- fission is the process in which $M = 2$ and $A$ is around $A_T/2$;
- multifragmentation is the process where $M > 2$ and $A < 50$.

Emission of light particles, with atomic number $Z \leq 2$, usually dominates the yield of reaction products for light target nuclei, while for heavy targets also spallation and fission residua give significant contribution. In this scenario the formation of IMF can happen through one of the following processes:

- Fission of nuclei mass number in the range 120-130 [2].
- Spallation including the emission of IMF, the so-called associated spallation [3].
- Multifragmentation of heavy nuclei [4].

Following this reasoning, as discussed below, for heavy targets the multifragmentation would be the only mechanism for the formation of IMF. Indeed in Ref. [4] it was found that in the reaction of 3.65$A$ $^{208}$Pb with $^1$H the formation of $^{12}$C nuclei presents the characteristics of multifragmentation, with a possible small contribution of binary process. However the formation of IMF was observed even at lower energies [5,7] and in this case the dynamics was characteristic of a binary process with no evidences for multifragmentation. Hence the study of production of IMF from heavy target nuclei at intermediate energies can give new information on the nuclear dynamics. In the present work our objective is the measurement of the cross sections of residual nuclei in the IMF region for reactions on heavy nuclei induced by 660 MeV protons. The experimental data will be analysed by comparison with Monte Carlo calculations with the CRISP code [8,9], as described below.

## 2 Theoretical aspects of IMF formation

It is generally assumed that at intermediate energies the nuclear reaction proceeds in two stages: 1) The incoming fast projectile collides with a single nucleon or with several nucleons transferring momentum and energy to the nucleus and leaves the nucleus accompanied by several light particles; 2) The residual nucleus achieves statistical equilibrium and some nucleons or clusters are emitted from the excited nucleus. At higher energies, when the excitation energy of the residual nucleus per nucleon is $E_x/A \geq 3.5$ MeV/A, the multifragmentation of the nucleus can take place. This reaction mechanism differs from evaporation since it describes a sudden breakup of the nucleus instead of the successive emission of particles.

In the framework described above the formation of IMF from heavy targets at intermediate energies could only be attributed to fission inside a long evaporation chain (both pre- and post-fission), which is very unlikely. In fact the fission probability of heavy nuclei drops very fast as mass number decreases [10,12], so long evaporation chains would lead to lower fissility nuclei. Another possibility would be a very long evaporation chain leading to light spallation products. This mechanism is limited by the maximum excitation energy allowed before multifragmentation becomes dominant, because the evaporation would cool down the nucleus before the IMF region is reached. Increasing the excitation energy above the 3.5 MeV/A threshold would only increase the contribution from multifragmentation and in this way IMF formed in reactions with heavy targets should be dominated by fragmentation products. Hence, for excitation energies below the multifragmentation threshold the formation of IMF from heavy nuclei would be very unlikely.

A comprehensive set of data on the proton-induced reaction of $^{238}$U at 1 AGeV [5] presents the cross sections of a 254 light nuclides in the element range $7 \leq Z \leq 37$ measured in inverse kinematics. On the base of a detailed study the experimental kinematical information the authors qualified such nuclides as binary decay products of a
fully equilibrated compound nucleus, whereas clear indications for fast breakup processes was absent. These result are corroborated by those from Ref. [6] and [7] and are in contradiction with the scenario described in Ref. [1].

One way to overcome the problem posed by binary production of IMF from heavy targets is by including the possibility of highly asymmetric fission with fragments which can still undergo evaporation to form at the end a nuclide in the region of IMF. This process corresponds to a modification in the classification given by Hufner for fission by using a less restrictive definition for fission, since in this case the fragment would have mass number quite different from $A_T/2$. This supersymmetric mechanism would corroborate the conjecture that evaporation and fission are manifestation of a single mechanism, called binary decay [13]. A complete study of this possibility involves the description of the entire process from the primary interaction of the incident proton up to the evaporation of nucleons from the fission fragments. A task like this can only be performed through the Monte Carlo method.

In this work we use the CRISP code to calculate all the features of the nuclear dynamics during the reaction. CRISP is a Monte Carlo code for simulating nuclear reactions [15] that assumes that nuclear reactions can be separated in the two stages mentioned above: the intranuclear cascade and the evaporation/fission process. This code has been developed during the last 25 years, while it has successfully described many different reactions. The main characteristic of the intranuclear cascade calculation with CRISP is the multi-collisional approach [16, 17], where the full nuclear dynamics is considered in each step of the cascade. In this process the nucleus is modeled by an infinite square-potential which determines the level structure for protons and neutrons. The effects of the nuclear potential are present in the transmission of the particles through the nuclear surface or through an effective mass according to Wallecka mean field approximation [18].

This multicolisional calculation is accomplished by constantly updating all the kinematical variables of all particles inside the nucleus, what opens the possibility of treating more realistically many nuclear phenomena. For instance, the antisymmetrization criteria, which determines a strict observation of the Pauli Principle is performed through a strict observance of the Pauli Principle, allowing the use of physical criteria for separating the intranuclear cascade from the thermalization process [19]. The effectiveness of such approach can be verified in processes which are predominantly dependent on the intranuclear cascade step, as kaon production and hypernuclei decay, which have been studied with CRISP leading to results compatible with experiments [20, 21]. Also the fission of several nuclei has been studied in the quasi-deuteron region [19], where Pauli blocking mechanism is very important in the determination of the residual nucleus.

The evaporation/fission competition was first studied in Ref. [22–24], giving for the first time an explanation to the saturation of the fissility of heavy nuclei below the unit observed in photofission experiments at intermediate energies [25, 26], and afterward it was extended to energies up to 3.5 GeV [27], showing also in this case good agreement with experimental data from Ref. [28]. After the nuclear thermalization, the competition between fission and evaporation processes, which includes neutrons, protons and alpha-particles, is determined through the ratios between their respective widths according to the Weisskopf model for evaporation and to the Bohr-Wheeler model for fission, resulting in

$$\frac{\Gamma_p}{\Gamma_n} = \frac{E_p}{E_n} \exp \left\{ 2 \left[ (a_p E_p)^{1/2} - (a_n E_n)^{1/2} \right] \right\},$$

(1)

and

$$\frac{\Gamma_\alpha}{\Gamma_n} = \frac{2E_\alpha}{E_n} \exp \left\{ 2 \left[ (a_\alpha E_\alpha)^{1/2} - (a_n E_n)^{1/2} \right] \right\},$$

(2)

for evaporation and by

$$\frac{\Gamma_f}{\Gamma_n} = K_f \exp \left\{ 2 \left[ (a_f E_f)^{1/2} - (a_n E_n)^{1/2} \right] \right\},$$

(3)

where

$$K_f = K_0 a_n \frac{2(a_f E_f)^{1/2} - 1}{4A^{2/3}a_f E_n},$$

(4)

for fission. The parameters $a_i$ stand for the density levels calculated by the Dostrovsky’s parametrization [29] and $E_i$ is given by

$$E_n = E - B_n,$$

$$E_p = E - B_p - V_p,$$

$$E_\alpha = E - B_\alpha - V_\alpha,$$

$$E_f = E - B_f,$$

(5)
where \( B_n, B_p \) and \( B_\alpha \) are the separation energies for neutrons, protons and alphas, respectively and \( B_f \) is the fission barrier. \( V_c \) stands for the Coulomb potential.

At each step \( n \) of the evaporation the excitation energy of the compound nucleus left is modified by

\[
E^n = E^{n-1} - B - V - \varepsilon .
\]

where \( \varepsilon \) is the kinetic energy of the emitted particle.

If the nucleus undergoes fission, the the fragments are determined according to the Multimodal - Random Neck Rupture Model (MM-NRM) \[30\], which takes into account the collective effects of nuclear deformation during fission through a liquid-drop model and single-particle effects through microscopic shell-model corrections. The microscopic corrections create valleys in the space of elongation and mass number, each valley corresponding to one different fission mode \[30\].

According to the MM-NRM the fragment mass distributions are determined by the uncorrelated sum of the different fission modes. At present it is supposed that there are three distinct fission modes for the heavy nuclei: symmetric Standard I (S1), Standard II (S2). In the Superlong mode the fissioning system with mass \( A_f \) presents itself at the saddle-point in an extremely deformed shape with a long neck connecting the two forming fragments, which will have masses around \( A_f/2 \). The Standard I mode is characterized by influence of the spherical neutron shell \( N_H \approx 82 \) and of the proton shell \( Z_H \approx 50 \) in the heavy fragments with masses \( M_H \approx 132 - 134 \). The Standard II mode is characterized by influence the deformed neutron shell closure \( N = 86 - 88 \) and proton shell \( Z_H \approx 52 \) in the heavy fragments with masses \( M_H \approx 138 - 140 \).

The fission cross section as a function of mass number is then obtained by the sum of three Gaussian functions, corresponding to the three modes mentioned above \[31\]:

\[
\sigma(A) = \frac{1}{\sqrt{2\pi}} \left[ \frac{K_{1AS}}{\sigma_{1AS}} \exp \left( -\frac{(A - A_S - D_{1AS})^2}{2\sigma_{1AS}^2} \right) + \frac{K_{1AS}}{\sigma_{1AS}} \exp \left( -\frac{(A - A_S + D_{1AS})^2}{2\sigma_{1AS}^2} \right) + \frac{K_{2AS}}{\sigma_{2AS}} \exp \left( -\frac{(A - A_S - D_{2AS})^2}{2\sigma_{2AS}^2} \right) + \frac{K_{2AS}}{\sigma_{2AS}} \exp \left( -\frac{(A - A_S + D_{2AS})^2}{2\sigma_{2AS}^2} \right) + \frac{K_S}{\sigma_S} \exp \left( -\frac{(A - A_S)^2}{2\sigma_S^2} \right) \right].
\]

where \( A_S \) is the mean mass number determining the center of Gaussian functions; and \( K_i, \sigma_i, \) and \( D_i \) are the intensity, dispersion and position parameters of the \( i^{th} \) Gaussian functions. The indexes \( AS, S \) designate the asymmetric and symmetric components.

The CRISP code works on an event-by-event basis, and therefore the parameter \( A_S \) in Eq.3 is completely determined by the mass of the fissioning nucleus \( A_f \), that is, \( A_S = A_f/2 \). The quantities \( A_S + D_{1AS} = A_H \) and \( A_S - D_{1AS} = A_L \), where \( A_H \) and \( A_L \) are the masses of the heavy and light fragment, respectively, determine the positions of the heavy and light peaks of the asymmetric components on the mass scale. The values of \( A_H = 2A_S \) is treated as the masses of nuclei that undergo fission in the respective channel.

One important observable of fission is the charge distribution of a given isobaric chain with mass number \( A \). It is assumed that the change distribution of the fission fragments is well described by a Gaussian function characterized by the most probable charge, \( Z_p \), of an isobaric chains \( A \) (centroid of the Gaussian function) and the associate width parameter, \( \Gamma_z \) of the distribution as following \[32 \[33\]:

\[
\sigma_{A,Z} = \frac{\sigma_A}{\Gamma_z \pi^{1/2}} \exp \left( -\frac{(Z - Z_p)^2}{\Gamma_z^2} \right),
\]

where \( \sigma_{A,Z} \) is the independent cross section of the nuclide, \( Z, A \).

\( Z_p \) stands for the most probable charge for the charge distribution of an isobaric chain with mass number \( A \) and \( \Gamma_z \) is the corresponding width parameter. The values \( Z_p \) and \( \Gamma_z \) can be represented as a linear functions of the mass numbers of fission fragments,

\[
Z_p = \mu_1 + \mu_2 A,
\]

and

\[
\Gamma_z = \gamma_1 + \gamma_2 A.
\]

Here, \( \mu_i \) and \( \gamma_i \) are parameters fixed through a systematic analysis of atomic number distributions of fission fragments. The values for all parameters used in the present work are reported in Table II.
With the code described above, many spallation and fission calculations were performed, showing good agreement with the available experimental data. We emphasize that the CRISP code is able to simulate nuclear reactions of several kinds, as those initiated by protons [34-37], photons [19,28,38-40], electrons [11,13] or hypernuclei [21,41,45], with energies from 50 MeV up to 3.5 GeV, and on nuclei with masses going from $A = 12$ up to $A = 240$ and with several observables: spallation products, strange particles, fission products, hyperon-decay particles, fragment mass and atomic number distributions. The code has been applied in the study for development of nuclear reactors [46-50]. Thus the CRISP code is a reliable tool to investigate properties of nuclear reactions.

3 Experimental Procedure

A natural uranium target of 0.164 g and 0.0487 mm thick and neptunium target of 0.742 g and 0.193 mm thick were exposed to an accelerated proton beam of 660 MeV in energy from the LNR Phasotron, Joint Institute for Nuclear Research (JINR), Dubna, Russia [51]. The proton flux was determined by the use of an Al monitor [52]. The monitor was irradiated with targets and had the same size as the targets. The cross section for the $^{27}$Al(p,3pn)$^{24}$Na reaction equals 10.8±0.7 mb at 600 MeV of proton energy was used. The irradiation time was 27 min at an proton beam intensity of about $3 \times 10^{14}$ protons per min.

The induced activity of the targets was measured by two detectors, an HPGe detector with the 20% efficiency and an energy resolution of 1.8 keV ($^{133}$2 keV for the $^{238}$U target and a Ge(Li) detector with the 4.8% efficiency and a resolution of 2.6 keV ($^{133}$2 keV for the $^{237}$Np target. Recording of the g spectrum was carried out with a high-rate 4-input multichannel buffer MASTER 919, which automatically determined the dead time. The identification of the reaction products, and the determination of their production cross section, were performed using data from [53] by means of half-lives, energies and intensities of $\gamma$-transition of radioactive fragments.

In the absence of a parent isotope, the cross section of fragment production for each fragment is determined using the following equation:

$$\sigma = \frac{\Delta N \lambda}{N_p N_n k \epsilon \eta \left(1 - \exp(-\lambda t_1)\right) \exp(-\lambda t_2) \left(1 - \exp(-\lambda t_3)\right)},$$

(11)

where $\sigma$ denotes the cross section of the reaction fragment production (mb); $\Delta N$ is the area under the photopeak; $N_p$ is the projectile beam intensity (min$^{-1}$); $N_n$ is the number of target nuclei (in 1/cm$^2$ units); $t_1$ is the irradiation time; $t_2$ is the time of exposure between the end of the irradiation and the beginning of the measurement; $t_3$ is the time measurement; $\lambda$ is the decay constant (min$^{-1}$); $\eta$ is the intensity of $\gamma$-transitions; $k$ is the total coefficient of $\gamma$-ray absorption in target and detector materials, and $\epsilon$ is the $\gamma$-ray-detection efficiency.

Usually, the cross section of an isotope production in the reaction under investigation is direct and independent (I) of the parent nuclei decay, and the cross section is determined by Eq. (11). If the yield of a given isotope receives a contribution from the $\beta^-$-decay of neighboring unstable isobars, the cross section calculation becomes more complicated [54].

If the formation probability for the parent isotope is known from experimental data or if it can be estimated on the basis of other sources, then the independent cross sections of daughter nuclei can be calculated by the relation:

$$\sigma_B = \frac{\lambda_B}{\left(1 - \exp(-\lambda_B t_1)\right) \exp(-\lambda_B t_2) \left(1 - \exp(-\lambda_B t_3)\right)} \times$$

$$\left[ \frac{\Delta N}{N_p N_n k \epsilon \eta} - \sigma_A f_{AB} \frac{\lambda_A}{\lambda_B - \lambda_A} \lambda_B \exp(-\lambda_A t_1) \exp(-\lambda_B t_2) \left(1 - \exp(-\lambda_A t_3)\right) \right] \left[ \frac{\lambda_B}{\lambda_B^2} - \left(1 - \exp(-\lambda_B t_1)\right) \exp(-\lambda_B t_2) \left(1 - \exp(-\lambda_B t_3)\right) \right],$$

(12)

where the subscripts $A$ and $B$ label variables referring to, respectively, the parent and the daughter nucleus; the coefficient $f_{AB}$ specifies the fraction of nuclei $A$ decaying to nuclei $B$ (this coefficient provides the idea of how much the $\beta$-decay affects our data; and $f_{AB} = 1$, when the contribution from the $\beta$-decay corresponds 100%); and $\Delta N$ is the total photo peak area associated with the decays of the daughter and parent isotopes. The effect of the forerunner can be negligible in some limit cases — for example, in the case where the half-life of the parent nucleus is very long, or in the case where the fraction of its contribution is very small. In the case when parent and daughter isotopes could not be separated experimentally, the calculated cross sections are classified as cumulative ones (C).
4 Results and Discussion

The cross sections for fragment production from reactions induced by 660 MeV protons on uranium and neptunium are shown in Fig. 1. In both cases a prominent peak is observed around the symmetric fragment mass, which is indeed composed by fragments from the symmetric fission mode, but also presents a contribution from two asymmetric modes \[\text{S1 and S2} \].

Some analysis on the mass distribution for the p+237Np and p+238U systems have been performed for the mass range \(70 < A < 150\) \[9\]. In this work we have added data in the region of intermediate mass fragments corresponding to \(30 < A < 70\) and in the region \(150 < A < 200\). The measured cross sections for the nuclei in this mass range are listed in Table I, where the quoted errors include contributions from those associated with the statistical significance of experimental results (2-3\%), those in measuring the target thickness (3\%), and those in determining the detector efficiency (10\%). Usually, studies on the production of fission fragments do not extends to light nuclei \[5\] and the inclusion of this region in our analysis can bring up interesting features of the dynamics for fission fragments production.

In fact, theoretical calculations, based on the mass asymmetry parameter and fission barrier height \[5\] have shown that for heavy targets, and at intermediate or low energies, the cross sections for IMF are very small. As a consequence most of the experimental observations available in the literature for fission seems to die out for atomic numbers below \(Z=28\). In Fig. 1 we observe that for both 238U and 237Np the presence of IMF in reactions at a relatively low energy as in the case of the present study can hardly be attributed to multi-fragmentation. The observation of another shoulder at the region of \(170 < A < 200\), for both distributions, reinforces the idea of a binary process as the origin of the IMF. These observations, therefore, are in agreement with the results obtained by Ricciard et al. \[5\]. In this work we present the results of a study, performed with the simulation code CRISP, for the possibility of describing the new experimental data on the light mass region as a result from fission or spallation. To this end a super-asymmetric fission mode, as described in the next section, was included in the code.

In Fig. 1 we observe that for both 238U and 237Np there is a shoulder formed by fragments in the region \(30 < A < 70\). The presence of IMF in reactions at a relatively low energy as in the case of the present study can hardly be attributed to multifragmentation. The fact that in both cases we observe also another shoulder at the region \(170 < A < 200\) reinforces the idea of a binary process as the origin of the IMF and therefore our results confirm the findings in Ref. \[5\]. The two known binary processes in nuclear reactions are evaporation and fission. In this work we study the possibility of describing the new experimental data presented here as resulting from fission or from spallation according to the description given in the CRISP code. To this end a superasymmetric fission mode was included, as described below.

5 Superasymmetric fission mode

To take into account the possibility of a super-asymmetric fission we included in the CRISP code another mode, S3, described by the usual gaussian shape from MM-NRM,

\[
\sigma(A)_{3\text{AS}} = \frac{1}{\sqrt{2\pi}} \left[ K_{3\text{AS}} \frac{\sigma_{3\text{AS}}}{\sigma_{3\text{AS}}} \exp \left( -\frac{(A - A_S + D_{3\text{AS}})^2}{2\sigma_{3\text{AS}}^2} \right) \right],
\]

(13)

As in the case of the three modes previously analyzed in Ref. \[9\], \(K_{3\text{AS}}, \sigma_{3\text{AS}}\) and \(D_{3\text{AS}}\) are fitting parameters which allow us to describe the experimental data for fragments produced through the fission channel. In addition to fission we calculated the mass distributions for fragments produced in the deep-spallation process. The results are shown in Figs. 1(a) and 1(b) where we observe that with the inclusion of the superasymmetric mode the experimental data is well described by the fission mechanism according to the CRISP calculations. The deep-spallation mechanism gives only a very small contribution in the heavy fragments region, showing that in fact the superasymmetric fission is the relevant mechanism for the production of fragments in the region \(160 < A < 200\).

The best-fit values for the parameters used in the NN-RNM approach are shown in Table ???. The parameters for the modes S, S1 and S2 were already discussed in Ref. \[9\] therefore we focuss on the parameters for S3. The superasymmetric mode contributes with 0.6\% and 1.2\% of the total fission cross section for 238U and for 237Np, respectively. The total fission cross sections are 1440 mb for 238U and 1360 mb for 237Np. The S3 width is somewhat larger than those for S1 and S2 but smaller than that for S mode. The most striking feature of the superasymmetric mode is the mass number gap around 60 a.m.u. in respect with the symmetric fragment for both cases studied here. Our results confirm that IMF at intermediate energies are formed predominantly through a binary process, and that it is described by a superasymmetric fission mode.
TABLE I: Measured IMFs fission cross sections for the reactions of 660 MeV protons on $^{238}$U, $^{237}$Np.

| Element | Type | Cross section, mb |
|---------|------|------------------|
| $^{28}$Mg | C | 0.003±4.3E-4, 0.186±0.020 |
| $^{34}$mCl | I | 7.7E±4±1.5E-5, 0.08±0.02 |
| $^{48}$S | I | 0.007±1.4E-4, ≤0.08 |
| $^{48}$Cl | I | 0.04±0.008, ≤0.28 |
| $^{59}$Cl | C | 0.053±0.005, 0.023±0.003 |
| $^{41}$Ar | C | 0.0037±7.4E-4, 0.73±0.07 |
| $^{42}$K | C | 0.007±7.0E-4, ≤0.40 |
| $^{43}$K | C | 0.023±0.002, 0.45±0.06 |
| $^{43}$Sc | C | 0.012±0.001, 0.23±0.02 |
| $^{44}$Ar | I | ≤2.5E-4, 0.089±0.02 |
| $^{44}$K | I | 0.031±5.0E-5, 0.22±0.04 |
| $^{44}$mSc | I | ≤0.0025, ≤0.15 |
| $^{44}$mSc | I | 0.065±0.007, 0.12±0.01 |
| $^{45}$K | C | ≤0.0014, 0.024±0.05 |
| $^{46}$mSc | I | 0.036±0.004, 0.94±0.09 |
| $^{47}$Ca | I | 0.024±0.002, ≤0.067 |
| $^{47}$Sc | I | 0.17±0.02, 0.63±0.06 |
| $^{48}$Sc | I | 0.044±0.004, 0.42±0.04 |
| $^{48}$V | I | 0.022±0.002, 0.48±0.05 |
| $^{48}$Cr | I | ≤0.0014, 0.013±0.001 |
| $^{49}$Cr | C | 0.025±0.005, 0.073±0.015 |
| $^{51}$Cr | C | 0.41±0.04, 0.20±0.02 |
| $^{52}$mMn | C | 0.0015±1.5E-4, 0.077±0.008 |
| $^{52}$Mn | I | 0.0085±8.5E-4, 0.205±0.03 |

Although a good description of the fragment production was obtained here with the fission mechanism, it is not possible to exclude that the same description of the experimental data would not be obtained by a mechanism of evaporation which includes the associated spallation, with emissions of fragments heavier than the alpha-particle. In fact it was shown in Ref. [14] that, at least in the ground-state, a global description of fission and cluster emission would be possible in a single theoretical framework. In would be interesting to investigate if such an approach would be valid also for the decay of excited compound nuclei.

FIG. 1: Mass distributions of binary-decay products from the reaction of $^1$H+$^{238}$U (a) and $^1$H+$^{237}$Np (b) at 660 MeV. Circles represent measured isobaric cross sections of the present work and the data taken from [51, 55, 56]; solid line represents fission fragment distributions and dashed line represents the results of deep-spallation, both calculated with the CRISP code.
| Parameter | $^{238}\text{U}$ | $^{237}\text{Np}$ |
|-----------|----------------|----------------|
| $K_{1,AS}$ | $(2.0 \pm 5.0)\%$ | $(1 \pm 1)\%$ |
| $\sigma_{1,AS}$ | $3.5 \pm 0.8$ | $4.5 \pm 0.4$ |
| $D_{1,AS}$ | $18.5 \pm 0.4$ | $21.3 \pm 0.4$ |
| $K_{2,AS}$ | $(19 \pm 5)\%$ | $(7.7 \pm 0.8)\%$ |
| $\sigma_{2,AS}$ | $6.0 \pm 0.5$ | $6.5 \pm 0.6$ |
| $D_{2,AS}$ | $18.0 \pm 0.4$ | $28.3 \pm 0.5$ |
| $K_{3,AS}$ | $(0.5 \pm 0.5)\%$ | $(1.2 \pm 0.3)\%$ |
| $\sigma_{3,AS}$ | $7.0 \pm 0.5$ | $8.0 \pm 0.7$ |
| $D_{3,AS}$ | $57.0 \pm 0.4$ | $62.0 \pm 0.3$ |
| $K_S$ | $(56 \pm 5)\%$ | $(79.0 \pm 7.0)\%$ |
| $\sigma_S$ | $13.0 \pm 0.5$ | $13.7 \pm 1.0$ |
| $\mu_1$ | $4.1 \pm 0.6$ | $5.0 \pm 0.8$ |
| $\mu_2$ | $0.38 \pm 0.01$ | $0.37 \pm 0.01$ |
| $\gamma_1$ | $0.92 \pm 0.08$ | $0.59 \pm 0.02$ |
| $\gamma_2$ | $0.003 \pm 0.001$ | $0.005 \pm 0.0002$ |

6 Conclusion

The cross sections for fragment production in proton-induced fission on $^{238}\text{U}$ and $^{237}\text{Np}$ at 660 MeV were measured at the LNR Phasatron (JINR). The fragment mass distributions covering the region $20 < A < 200$, allowed the study of intermediate mass fragments (IMF) with $20 < A < 70$. It was found that the IMF observed there is a heavier counterpart in the region $170 < A < 200$, indicating that the formation of IMF could be due to a binary process. This hypothesis was tested with the use of the CRISP code by including an addition superasymmetric fission mode described according to the MM-NRM approach.

The results show that it is indeed possible to give an accurate description of the fragment production in the entire region, $20 < A < 200$ by the evaporation/fission mechanism adopted in the CRISP code with the usual fission modes, namely, one symmetric and two asymmetric, and including a forth superasymmetric mode. This last mode produces fragments that are around 60 a.m.u. far from the symmetric fragment mass and contributes with 0.6% and 1.2% of the total fission cross section for $^{238}\text{U}$ and $^{237}\text{Np}$, respectively. Our results are in agreement with previous results evidencing the binary production of IMF at intermediate energy nuclear reaction.

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