

Recent highlights on fragmentation reactions

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Abstract. Fragmentation reactions constitute an optimum tool for exploring the nuclear landscape by producing nuclei far from stability at in-flight radioactive nuclear beam facilities. Moreover, they are routinely used in modern cancer therapy treatments. Nevertheless, the large dynamical and isospin range covered by this reaction mechanism are unique features for many fundamental studies. In this work we review some of the most salient recent results in fundamental nuclear physics studies based on fragmentation reactions.

1. Introduction

Fragmentation are peripheral or mid-peripheral reactions induced by heavy ions at energies above the Fermi energy and up to few GeVs per nucleon that we can describe using the participant spectator picture. As a result of the collision three remnants are produced, a participant at mid-rapidity with high temperature and density, and two spectator pre-fragments of the target and projectile nuclei having lost some nucleons and gained excitation energy [1]. Theoretical models explain this reaction mechanism as a two-stage process [2] where the first stage (abrasion) corresponds to the formation of the participant-spectators, and the second stage (ablation) is the de-excitation of the hot spectator nuclei by nucleon or cluster evaporation, fission or even multi-fragmentation.

The general characteristics of fragmentation reactions are relatively well known since the 80s [3]. However, the large dynamical and isospin range covered by this reaction mechanism together with the used of advanced detection setups are key features that justify the present importance of fragmentation reactions in nuclear physics research. For example, fragmentation is a unique mechanism for producing bound nuclear matter at extreme conditions of density, temperature and isospin. This is the reason why fragmentation plays a decisive role in the characterisation of the equation of state for asymmetric nuclear matter. This reaction mechanism is also broadly used for producing nuclei far from stability. In fact, many of the next generation radioactive beam facilities that are being design, built or commissioned are based on this reaction mechanism [4, 5, 6]. Applications are another field of use of fragmentation reactions. The impact of cosmic radiation in space missions and cancer therapy are just two examples.

In this paper we will discuss the most salient features of fragmentation reactions, the historical evolution of fragmentation based research, some recent highlights and the role of fragmentation in the production of nuclei far from stability.

2. Key features of fragmentation

The present and future role of fragmentation reactions in nuclear physics is based in some salient features that make so relevant this reaction mechanism. The first one is the large isospin range

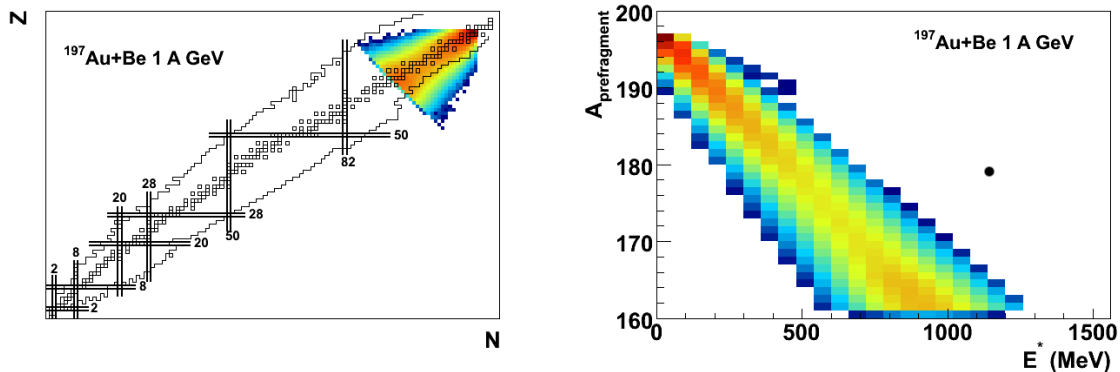


Figure 1. Left panel: Calculated isotopic composition of the projectile pre-fragments produced during the abrasion stage in the fragmentation reaction ^{197}Au on Be at 1 A GeV on top of a chart of nuclides. Right panel: Correlation between the mass of the projectile pre-fragments and the excitation energy they gain for the same reaction.

covered by these reactions due to the fact that the abrasion process is isospin independent. Then, the relative probability for the projectile/target nucleus to lose a given number of neutrons and protons is governed by a hyper-geometrical distribution. This distribution has as mean value the initial N/Z of the projectile/target nucleus but with a large fluctuation as indicated in the left panel of Fig. 1 where the isotopic distribution of pre-fragments for the reaction ^{197}Au on Be at 1 A GeV is shown down to a mass loss limit (25% of the initial projectile/target mass) for which the fragmentation picture is still valid. As can be seen, the abrasion process largely explore the isospin degree of freedom, even beyond the presently known limits of the chart of nuclides. Unfortunately, the subsequent evaporation process is not only governed by temperature but also by the relative binding energies for protons and neutrons favouring the production of slightly neutron-deficient isotopes for which the binding energies for protons and neutrons are similar. This process reduces then, the isospin fluctuations.

The second key feature of fragmentation reactions is the large dynamical range covered at different impact parameters. The most peripheral reactions are governed by few nucleon-nucleon collisions at low density. Under those conditions projectile and target lose few nucleons and gain little excitation energy. At low temperatures the statistical decay times will be relatively long. In peripheral collisions projectile and target lose a larger number of nucleons reaching also higher temperatures, typically 2 to 4 MeV. At this impact parameter the density at which the nucleon-nucleon collisions take place are close to the saturation density and the statistical decay times are shorter because of the higher temperatures but the de-excitation chain will be longer since a larger number of nucleons or clusters will be emitted by the hot nuclei. In mid-peripheral collisions the number of nucleons involved is considerably larger and also the excitation energy gained by the system. Under these conditions the thermal expansion of projectile and target spectators produces nuclear matter at low density and high temperature (5-10 MeV) that eventually ends up in a clustering or multi-fragmentation process.

These features of fragmentation reactions justify the important role of this reaction mechanism to explore nuclear matter at the extreme of density, temperature and isospin, but also for producing nuclei far from stability.

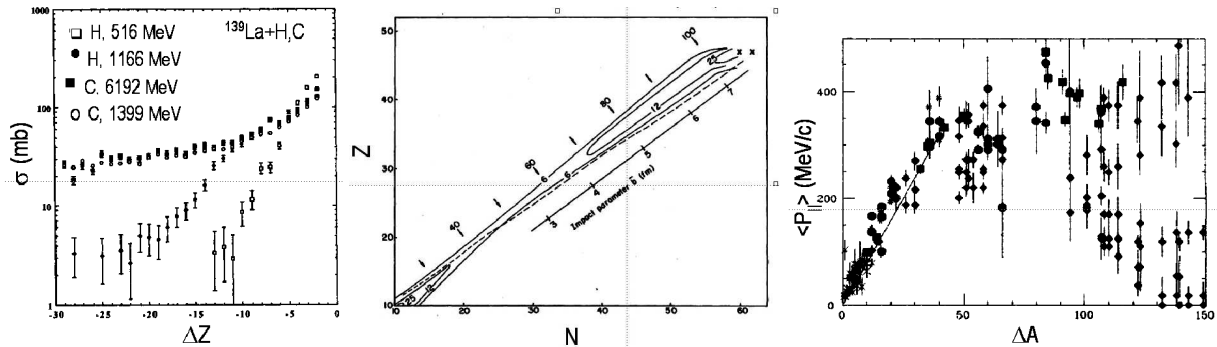


Figure 2. Main global features of fragmentation reactions obtained at the Bevalac. Universality of the fragment yields above the limiting fragmentation regime (left panel). Universality of the isotopic composition of the final residues along the evaporation corridor (central panel). Universality of the energy loss per number of nucleons lost in the collision (right panel).

3. Selected historical achievements

The first records we have on nuclear fragmentation are from the 50s were photographic plates mounted in balloons registered the first fragmentation reactions induced by cosmic rays [7]. This plates showed, for the first time, the splitting of an atomic nuclei into many pieces as a consequence of the collision of two heavy ions at relativistic energies.

The first accelerator where controlled fragmentation reactions were investigated was the Bevalac. Systematic studies performed during the 70s and 80s made it possible to establish the main characteristics of these reactions. The main conclusion of these studies was that the production of residual nuclei in fragmentation reactions could be described in terms of global features. These studies clearly showed that above a certain threshold in the kinetic energy of the projectiles (limiting fragmentation regime) the mass and nuclear charge yields of fragmentation residues presented a universal pattern [8], as shown in the left panel of Fig. 2. It was also shown that the isotopic composition of these residues followed a universal pattern on the chart of nuclides, called evaporation corridor [9] (Fig. 2 central panel). Finally, it was observed that the kinetic properties of the residual nuclei also presented a universal behaviour according to the mass loss of the final residues up to a certain limit [10] (Fig. 2 right panel). It is then not surprising that these systematic behaviours brought Hüfner to conclude about the dominant role of phase space considerations in fragmentation [3].

However, the second generation of heavy ion facilities (NSCL in the USA, GANIL and GSI in Europe and RIKEN in Japan) together with advanced detection set-ups made it possible to enter the era of the precision and multi-parametric measurements. In particular, high-resolving power spectrometers and full-acceptance detection set-ups provided a new insight into these reactions. These accurate measurements showed during the 90s and the first decade of the new century that the universal behaviour of fragmentation reactions was in many cases a first order effect and that second order effects could bring new physics. Some examples were the following:

- Deviations of the kinematic properties of the fragmentation residues at large mass losses or smaller impact parameters were observed [11]. These effects were proposed as signatures of the spectator response to the participant blast evidencing the momentum dependence of the nuclear interaction [12].
- Isospin memory effects in the position of the evaporation corridor in the chart of nuclides were interpreted as a signature of the limiting temperature reached by hot nuclei entering the multi-fragmentation regime [13].

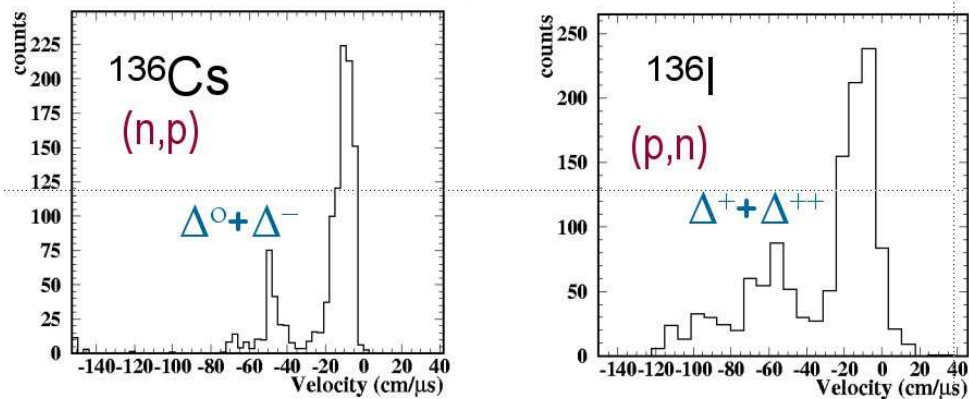


Figure 3. Momentum distributions of the ^{136}Cs and ^{136}I nuclei produced in isobar charge exchange reactions, (n,p) and (p,n) respectively, in collisions induced by ^{136}Xe projectiles on beryllium at 1 A GeV.

On the other hand, multi-parametric measurements were extremely useful in the characterisation of the nuclear multi-fragmentation and their interpretation in terms of the liquid-gas phase transition probing EOS at low density. The experiments INDRA at GANIL [14], Miniball at NSCL [15] and Aladin at GSI [16] contributed to the characterisation of the multi-fragmentation process in symmetric nuclear matter [17, 18, 19]. One of the most salient results in this field was the caloric curve representing the liquid-gas phase transition of nuclear matter [20].

4. Recent highlights

According the impact parameter in fragmentation reactions, one can produce bound nuclear matter under different conditions of temperature and density. Moreover, one can also explore the isospin degree of freedom by using non stable projectiles. In this section we will discuss few selected examples of recent investigations based on the use of fragmentation reactions to produce nuclear matter under different conditions of temperature, density and isospin asymmetry.

4.1. Charge-exchange reactions in extremely peripheral collisions.

Extremely peripheral fragmentation reactions can be used to investigate bound nuclear matter at low density and temperature. The high-resolving-power magnetic spectrometer Fragment Separator at GSI has been used to investigate single nucleon-nucleon collisions in relativistic heavy-ion collisions leading to isobar charge-exchange reactions. This reaction channel corresponds with a high probability to a single nucleon-nucleon collision at low density [21]. Fig. 3 shows how the magnetic analysis of the residual nuclei produced in collisions induced by ^{136}Xe projectiles on a beryllium target at 1 A GeV provided a sufficient resolution to disentangle the quasi-elastic and Δ -resonant channels for both isobar charge exchange reactions corresponding to the production of ^{136}Cs (n,p) and ^{136}I (p,n).

These data give an excellent opportunity to characterise in medium elastic and inelastic nucleon-nucleon collisions at low density. The use of different targets such as hydrogen or deuterium also can give access to different excitation modes of the Δ -resonance. Moreover, applying this technique in fragmentation reactions induced by nuclei far from stability will provide extremely interesting information on the isospin asymmetry dependence of nucleon-nucleon collisions helping to constrain the isovector component of the nuclear potential. All

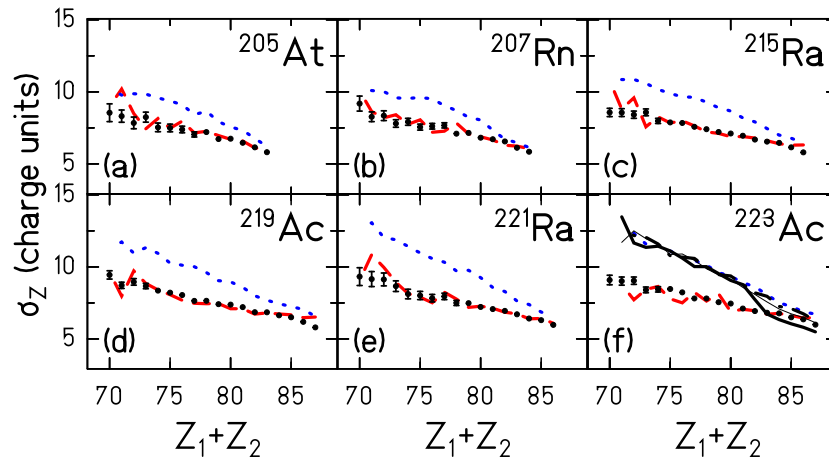


Figure 4. Width of the charge distribution of fission residues as a function of the total nuclear charge of both fragments obtained in the fission of different spherical fissile nuclei. The data are compared to predictions obtained with the Kramers model (dotted line) and the full time-dependent description of transient effects for a reduced viscosity parameter $\beta=4.5 \cdot 10^{21} \text{ s}^{-1}$ (dashed line).

these results are extremely relevant for the characterisation of the symmetry energy using heavy ion collisions interpreted with transport codes.

4.2. Dissipative effects in high-energy fission in peripheral collisions.

Peripheral collisions (70-80% of the maximum value of the impact parameter) of heavy projectiles where fissile projectile spectators are produced at relatively high excitation energy (200-400 MeV) can be used to investigate transient effects in fission [22]. Transient effects are a general problem in physics and represent the time a metastable system needs to reach quasi-equilibrium by relaxing its degrees of freedom under the effect of the viscosity of the medium (fluctuation-dissipation theorem). Since transient effects are only perceptible when the lifetime of the metastable system is comparable to the relaxation time of the degree of freedom in question, deformation, we can then understand that those effects can only be investigated in fission at high excitation energies where the statistical fission times are much shorter [23].

The time-evolution of these systems can be described by using transport models with a diffusion and a friction term. In the particular case of fission the degree of freedom the system explores for reaching equilibrium is deformation. Moreover, in this case one needs to include in the corresponding transport/Langevin equation a third term representing the drift force due to deformation dependence of the nuclear potential [24, 25]. The reduced viscosity parameter in these equations represents the coupling between intrinsic (heat bath) and collective (deformation) degrees of freedom.

Dissipative effects have two clear consequences on the fission process. First, the fission probability is reduced since not all the systems reaching the saddle point will fission. Second, the time needed for the relaxation of the deformation degree of freedom favours other competing channels for the nucleus de-excitation such as neutron emission. Therefore, transient effects not only reduces the fission probability but also the temperature of the fissioning system when it reaches the saddle deformation.

Although transient effects in fission are known since long ago [26], the novelty of the recent investigations performed at GSI is that they are based on the use of fragmentation reactions induced by heavy exotic nuclei. These reactions make possible to induce fission under well defined conditions such as low initial deformation and high excitation energy [27, 28]. In this work the observables used to determine transient effects and most particularly the influence of the initial conditions in transient effects were the total fission cross section and the temperature of the fissioning system at saddle, determined from the width of the charge distribution of the final fission fragments.

Since the fragmentation process induces little deformation in the projectile spectator, a first fragmentation of ^{238}U was used to produce fissile spherical nuclei. Then, a second fragmentation reaction was used to induce the fission at high excitation energy of those nuclei. As can be seen in Fig. 4, a given number of spherical fissile nuclei were investigated. In particular, in this figure we show the sensitivity of the width of the charge distribution of the fission fragments (temperature at saddle) displayed as a function of the sum of the nuclear charge of both fission fragments representing the excitation energy gained by the system. As can be seen, a purely statistical description of the process (dotted lines) clearly overestimates the width of the charge distributions except at low excitation energies where the fission lifetime is so long that transient effects are not perceptible. However, a calculation including a transient time of $3.3 \cdot 10^{-21}$ s (dashed lines) perfectly describes the measurements. The observed difference in transient times between spherical and deformed fissioning systems such as ^{238}U [29] was understood as a first evidence for the role of the initial conditions in transient effects.

4.3. Density dependence of asymmetric EOS in mid-peripheral collisions.

The third highlight concerns the study of asymmetric nuclear matter at finite temperature and, in particular, the density dependence of the corresponding equation of state. This topic is extremely relevant not only for the understanding of the dynamics of heavy-ion collisions but also for the description of stellar scenarios at abnormal density such as super-novae and neutron stars.

Theoretical studies have established the parabolic dependence of the nuclear energy per nucleon with the isospin asymmetry. Heavy ion collisions and nuclear resonances have constrained the EOS for symmetric matter but very little is known about the density dependence of the symmetry energy except its value at saturation density which has been established to be around 30 MeV. Unfortunately theoretical predictions describe the EOS around saturation energy but diverge at low densities being the situation at supra-saturation density even worse.

In this discussion fragmentation reactions play a crucial role since we can use the spectator physics to constrain the EOS at low density, in particular projectile multi-fragmentation, and the participant blast physics to constrain the EOS at high density. In these studies one needs clear observables sensitive to nuclear density an isospin asymmetry and theoretical models relating those observables to different equations of state. As it happens with the quark-gluon plasma physics, the present impression is that it does not exist an universal observable providing conclusive constraints to the EOS but one rather needs to combine few of them. Something similar happens with the models describing heavy ion collisions since one can also find models where the sensitivity to the EOS appears in different variables. For example, one can talk about transport models where the EOS appears in the nuclear mean field and the nucleon-nucleon collisions and, statistical multi-fragmentation models where the EOS appears in the properties of the generated fragments through their masses or level densities. The activity in this field during the last few years has been enormous in the low density regime and the reader can find a comprehensive description in Ref. [30]. Here we will just briefly describe three examples.

The first example corresponds to the results obtained at NSCL/MSU using heavy-ion collisions at Fermi energies. The most salient feature of this work is that it made possible to

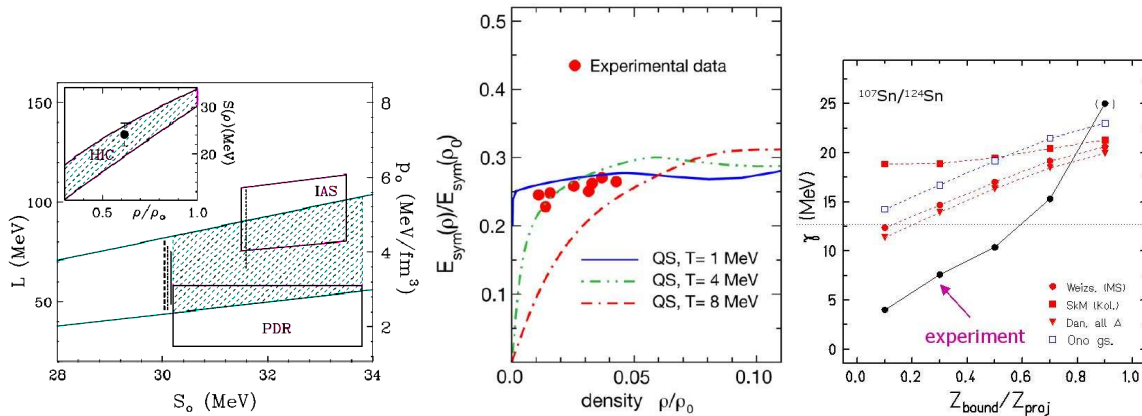


Figure 5. Few selected results constraining isospin asymmetric EOS at low density using fragmentation reactions. The coherent description of several observables allowed to constraint the asymmetric EOS at half saturation density (left panel) and low densities (central panel) using reactions at Fermi energies. Isospin dependent observables obtained in projectile residues in high-energy reactions also contributed to constrain the asymmetric EOS at low density (right panel). See text for details.

constrain the symmetry energy at half the saturation density combining different experimental observables, in particular the neutron and proton diffusion across the neck region between projectile and target and the ratio of the energy spectra of protons and neutrons (left panel in Fig. 5) [31]. Both observables have been investigated for systems having different isospin asymmetry and interpreted with QMD calculations in a consistent way. Moreover the obtained results nicely overlap with constrains obtained from ground and structural properties of nuclei such us giant dipole resonances, pygmy doe resonances or nuclear masses data.

Researchers at Texas A&M have also used reactions at Fermi energies but in order to constrain the asymmetry energy at the lowest possible densities they have used as observables the early emitted light clusters of hydrogen and helium at mid-rapidity. In this case, the information on the asymmetry energy was obtained from isoscaling analysis (ratios of yields of particular nuclear species from two different equilibrated nuclear systems of similar temperature but different isospin asymmetry) that were interpreted using quantum-statistical calculations (central panel in Fig. 5). The main outcome of this work is that in contrast to Hartree-Fock or relativistic mean field calculations the asymmetry energy at low density and low temperatures increases due to clustering effects [32, 33].

The third example corresponds to the investigation of projectile multi-fragmentation at GSI. This work showed that global observables previously used to characterise the EOS of symmetric matter such as the multiplicities of intermediate mass fragments or the caloric curves are not sensitive to the isospin asymmetry [34]. However, isoscaling analysis of the neutron excess of the fragments showed clear signatures that were linked to the symmetry energy using a statistical multi-fragmentation model. The lower values for the effective symmetry term γ as a function of violence of the collision Z_{bound} when compared to expectations from different model calculations was interpreted as due to the lower density and possible deformation effects in the nascent fragments (right panel in Fig. 5) [35].

With these three examples we can summarise the present efforts for constraining the density dependence of the symmetry energy. Together with the known constraints from nuclear structure data at saturation density we can affirm that during the last few years the study of heavy ion collisions has provided the first constraints at sub-saturation density. However, the energy

dependence at supra-saturation densities remains almost unexplored and therefore a challenge that could be at our reach with the new generation of radioactive beam facilities that are presently under construction.

5. Production of nuclei far from stability with fragmentation reactions.

Fragmentation reactions plays also a decisive role in the production of nuclei far from stability. As previously shown, fragmentation mostly produces neutron-deficient nuclei because of the competition between proton and neutron binding energies in the evaporation process. The in-flight fragmentation of heavy nuclei such as ^{238}U may lead to the fission of the projectile spectator. The corresponding fission residues populates the medium-mass neutron-rich sector of the chart of nuclides. Finally, the large fluctuations in isospin and excitation energy during the abrasion process (see Fig. 1) also allow us to populate cold fragmentation channels where mostly protons are abraded and little excitation energy is induced, populating then the most neutron-rich nuclei.

During the last few years an intense activity have also been carried on for extending the present limits of the chart of nuclides using fragmentation reactions, in particular, in the neutron-rich border. Here we will discuss the most salient results.

In the light region of the chart of nuclides, the most intense activity have been carried on at NSCL/MSU. There the production of light neutron-rich nuclei have been systematically investigated [36]. In particular beams of ^{48}Ca at energies around 140 A MeV were used to produce neutron-rich nuclei. In these investigations, the most salient result was the production of three new isotopes, ^{40}Mg and ^{42}Al , ^{43}Al because two of them, ^{40}Mg and ^{43}Al are located at the neutron drip-line, being the heaviest known drip-line nuclei. Moreover, ^{42}Al was predicted to be unbound and their discovery has implications on the $1p_{3/2}$ orbital filling that would suggest the existence of heavier aluminium isotopes [37].

The production of medium-mass neutron-rich nuclei has also been investigated using fragmentation reactions [38]. An interesting proposal for extending the present limits of the chart of nuclides in this region was a two-step reaction scheme [39]. The idea was to profit the highly produced fission fragments in ISOL facilities for further fragment those fission fragments after their re-acceleration. This scheme would allow to produce extremely neutron-rich nuclei but also to overcome the impossibility of producing refractory elements at ISOL facilities. This idea was investigated at the FRS at GSI where the in-flight fission of ^{238}U was used to produce ^{132}Sn that was then fragmented. The accurate measurement of the production cross sections were used to validate model calculations predicting the expected productions of neutron-rich nuclei in fragmentation reactions. Using this model it was possible to estimate the production of more than 200 medium-mass neutron-rich nuclei at the future EURISOL facility [40]. The production of medium-mass nuclei was also investigated using in-flight fission of ^{238}U at the new "Radioactive Beam Factory" at RIKEN. In this experiment, and thanks to the high intensity reached by this machine, 45 new neutron-rich isotopes were recently discovered in a single experiment [41].

Of particular importance is the region of heavy neutron-rich nuclei where the present limits of the chart of nuclide are just few isotopes away from stability while this region is extremely relevant for nuclear structure but also for nuclear astrophysics and in particular for the understanding of the nucleosynthesis r-process. In order to overcome this situation it was proposed to take advantage of the fragmentation of ^{238}U and ^{208}Pb beams to produce heavy neutron-rich nuclei via cold fragmentation channels. The experiment was performed at GSI accelerating these beams around 1 A GeV and using the fragment separator for the identification of the final fragmentation residues. In this case the relativistic energies were of utmost importance for the unambiguous identification of the final nuclei because of the contamination due to charge states. Using this technique, it was possible to produce and identify

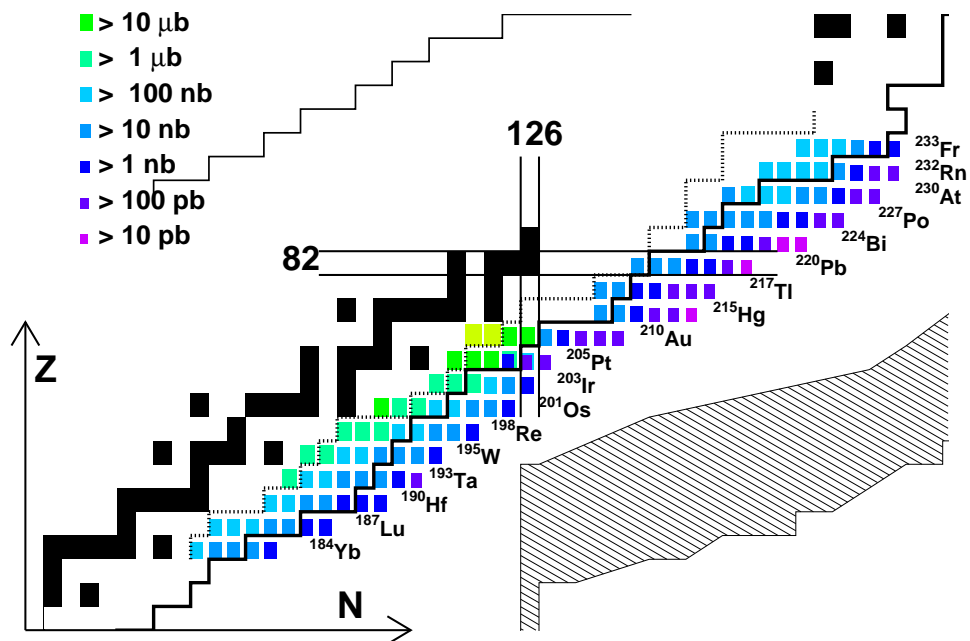


Figure 6. Nuclei produced in the fragmentation of ^{238}U and ^{208}Pb beams at GSI on top of a chart of nuclides, the colour scale represents intervals of production cross section. The dotted line represents the limit of known nuclei as in 1958 and the thick-solid line the limit of known nuclei before these experiments. The hatched area corresponds to an estimation of the path followed by the stellar nucleosynthesis r-process.

for the first time 73 new heavy neutron-rich nuclei shown in Fig. 6 [42, 43]. In this figure, the dotted line represents the limits of the chart of nuclide as in 1958. Therefore, in an experiment with two beams it was possible to produce as many heavy neutron-rich nuclei as in the last 50 years. These outstanding results give us confidence on the major progress that can be obtained exploring the nuclear chart with the next generation of radioactive beam facilities we are presently building.

The access to new regions of isospin will certainly open new opportunities for the fragmentation physics but high quality beams of unstable nuclear species is not the only requirement to face these new challenges. Progress on experimental set-ups is also required. This is why at the moment several experiments providing both high accuracy and full acceptance are being designed for its use at the future fragmentation facilities like the R3B experiment at FAIR [44], the SAMURAI experiment at RIBF [45] or the ATTPC at FRIB [46].

6. Conclusions and outlook.

Fragmentation reactions are used to investigate bound nuclear matter under extreme conditions of density, temperature and isospin since more than 40 years. The large dynamical and isospin range covered by these reactions justify this interest. Moreover, this reaction mechanism plays a key role in the production of nuclei far from stability. Indeed, many of the new radioactive beam facilities under construction are based on this mechanism. High quality beams of unstable

projectiles together with advanced detection setups guarantees the future role of fragmentation for exploring new frontiers in nuclear physics.

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