Future Prospects for Secondary-Beam Production

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Abstract: This contribution discusses the characteristics of different types of nuclear reactions and the influence of the beam energy in view of future prospects for secondary-beam production. First, electronic interactions in the target are considered because they define the usable target thickness. Rather high beam energies are advantageous. Secondly, the nuclear-reaction aspects are discussed. Three reaction mechanisms provide the most promising prospects for the production of secondary beams. Fusion is best suited for the production of nuclei near the proton drip line and of the heaviest elements. Fission specifically populates mid-mass neutron-rich isotopes. Fragmentation and spallation reactions represent rather universal production mechanisms for both neutron-deficient and neutron-rich exotic nuclei, since the fluctuations in the N-over-Z ratio are very important. Due to these large fluctuations, this is the most promising reaction mechanism to reach extremely exotic nuclei over the whole mass range, if sufficiently high primary-beam intensities are available. In particular, it seems to be a unique process for the production of extremely neutron-rich isotopes of elements above the region of fission fragments. These considerations are verified with experimental data. In particular, a systematic overview on the production of residual nuclei in reactions at relativistic energies has been obtained in several experiments recently performed at GSI in inverse kinematics. They allow to give a rather realistic estimate on the prospects for secondary-beam production in next-generation facilities.

Introduction

The exploration of the properties of exotic nuclei has acquired considerably improved conditions since secondary beams of radioactive nuclei became available. The remarkable progress in this field stimulated plans for new-generation radioactive-beam facilities with optimised experimental conditions. The present contribution is intended to investigate possibilities and limitations for the production of secondary beams in a general way, without restricting to a specific technical realisation. Considerations specific to ISOL-type [1] and fragmentation-recoil techniques [2] have been published previously.

It is a rather complex task to find optimum conditions for the production of secondary beams. Important arguments for this search arise from the general features of electronic and nuclear interactions in the target. Characteristics of electronic interactions of the primary projectiles with the target material define the usable target thickness and the heat load of the target. These impose all-important physical and technical limitations on the secondary-beam intensities to be reached.

Another important subject is a discussion of the characteristics of the different reaction mechanisms which can be used for the production of secondary beams of radioactive nuclei. The choice of the reaction mechanism used for the production of secondary beams has decisive consequences for the regions of the chart of the nuclides which can be explored. This choice is closely related to the energy of the primary beam.

As a counterpart of the requirements imposed by the production mechanism, many experiments demand beams of radioactive ions in a specific energy range. Therefore, besides the variation of the nuclear species, the energy is an important experimental parameter, too. This is another argument to emphasise the importance of the beam energy. It ranges from a few hundred keV, needed for mass separation, over energies near the Coulomb barrier, best suited e.g. for fusion reactions, up to relativistic energies, well adapted e.g. to break-up reactions and electromagnetic excitations. Secondary-beam facilities using in-flight production and separation methods provide best conditions for experiments in that specific energy range, the secondary beams are produced. Decoupling the production and the application of the secondary beam requires additional effort, e.g. the use of the ISOL technique with post acceleration. The advantage of independent energies for secondary-beam production and experiment is paid with considerable losses in the procedure of extraction and ionisation as well as with a limitation in life time of the nuclei to be studied [1].

In the first section we will try to find an "optimum" beam energy for the production of secondary beams without entering into the details of the reaction mechanism. Criteria like total reaction rates, ranges and heat load will be discussed. The second section is devoted to a detailed description of the reaction mechanism with special emphasis on recent systematic measurements of isotopic production cross sections that were performed at the GSI accelerator and in-flight identification facilities. The considerations are completed by model calculations which provide a systematic overview on the regions of the chart of the nuclides which can be explored.

Arguments for an optimum primary-beam energy

The production of secondary beams relies on nuclear reactions of a primary beam in a production target. The optimum use of the primary-beam intensity would require all primary projectiles to be transformed into secondary products. (We neglect here multi-step reactions which are important in rather specific scenarios only, e.g. in a nearly critical enriched uranium target due to fission by secondary neutrons.) However, several limitations make it difficult to reach this aim. Firstly, the beam energy might be consumed in electronic interactions, before the projectiles come into contact with a target nucleus. Secondly, the need to get the secondary products out of the production target, either due to its recoil velocity or due to thermal diffusion, sets constraints to the target thickness.

Figure 1 (left part) summarises the probability for nuclear reactions as a function of the beam energy. The three cases, $^{1}H+^{238}U$, $^{238}U+^{1}H$ and $^{238}U+^{238}U$ represent extremely light and heavy projectiles and targets for illustrating the general characteristics. The influence of electronic interactions in the target is important for the production rates to be reached, because it is decisive for the slowing-down of the projectile during the passage of the target and therefore defines the usable target thickness. Two scenarios are considered: In the first case the target is thick enough to cover the whole range of the projectiles, and in the second case the target thickness is limited to 10% of the projectile range. Nuclear-interaction cross sections are calculated with the analytic description of Benesh, Cook and Vary [3], and the ranges are estimated from the energy-loss relations as cited in [4]. The first scenario may only be realised when extraction by thermal diffusion is used. The second scenario represents a typical case for in-flight production of secondary beams. Besides the reaction probability, the heat load in the target is another important criterion. It puts a constraint on the technical realisation. Optimum conditions are realised if the reaction probability per energy deposit in the target is large. The nuclear reaction probability per heat load is highest for target fragmentation by high-energy protons. However, this advantage is most likely more than compensated for most elements by the intensity losses in the extraction and ionisation process of the ISOL procedure.

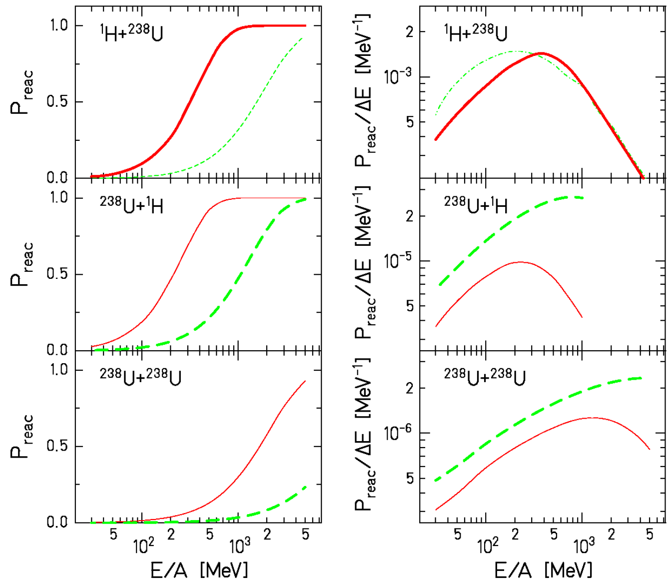

Fig. 1: Overview on nuclear reaction probability and heat load in the production target. Left part: Nuclear reaction probability. Right part: Nuclear reaction probability per energy deposit related to one incoming projectile. In both parts, the target thickness is varied to correspond to 10 % of the range (dashed lines), typical for projectile fragmentation ($^{238}U+^{1}H$ and $^{238}U+^{238}U$), and to the full range of the projectiles (full lines), typical for target fragmentation ($^{1}H+^{238}U$), respectively. The typical cases are marked by thick lines. In projectile fragmentation, the electronic energy loss is considered, in the case of $^{1}H+^{238}U$, also the energy eventually induced in the nuclear reaction (projectile energy and fission energy) is included.

High-quality in-flight separation of secondary beams requires a high probability for fully stripped ions in order to avoid ambiguities in the interpretation of the magnetic deflection due to different ionic charge states. Figure 2 demonstrates that also this gives a strong argument for beam energies of at least 1 A GeV, if secondary beams up to uranium are considered.

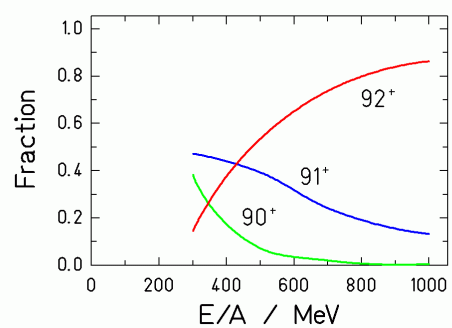

Fig. 2: Probabilities of the different ionic charge states, calculated for uranium ions behind a niobium foil.

We conclude that energies in the range of 500 MeV to 1 GeV are optimum for the considered case of target fragmentation. They combine nuclear-reaction probabilities close to one with large values of $P_{reac}/\Delta E$. For projectile fragmentation, optimum reaction rates in the range of 20% combined with relatively high values of $P_{reac}/\Delta E$ are found at energies around 1 A GeV. Also other criteria, most of which already outlined in ref. [4], e.g. the high probability for fully stripped ions up to ^{238}U and strong forward focussing of the reaction products, strongly favour this energy range.

Characteristics of the reaction mechanisms

Neutrons offer very specific possibilities for inducing nuclear reactions. They combine low nuclear-reaction thresholds with the lack of electronic energy loss. Most interesting is fission of actinides by neutrons, available with high intensities in fission reactors or produced by conversion of charged-particle beams in a thick target. The intensities of low-energy fission, however, are concentrated to a number of mid-mass neutron-rich isotopes. Very large neutron fluxes corresponding to the conditions of the r process which produced most of the heavy nuclei in nature would be optimum to produce extremely neutron-rich nuclei. But it is completely out of reach to apply these conditions in a laboratory in a controlled way.

Radioactive nuclei with proton-to-neutron ratios considerably different from those in the valley of beta stability, eventually even reaching up to the driplines, can be produced in heavy-ion reactions or in bombardments of suitable target nuclei with high-energetic protons. The minimum primary-beam energy is given by the Coulomb barrier which corresponds to beam energies per nucleon around 5 MeV. In this energy regime, the nuclear and the Coulomb potential play an important role. With the exception of very peripheral collisions which lead to transfer of a few nucleons, the tendency to minimise the surface energy leads to fusion in most cases, if relatively light nuclei are considered. With increasing Coulomb force between the reaction partners, however, deep-inelastic collisions and finally fast fission become important. Fusion is a mechanism which leads to a very much controlled production of specific nuclei, given by the sum of nucleons in projectile and target. Due to the curvature of the beta-stability line, which bends more and more to the neutron-rich side with increasing mass, fusion is well suited for the production of neutron-deficient nuclei up to the proton drip line. Massive transfer or deep-inelastic reactions populate nuclei in the vicinity of projectile or target, respectively. Fast fission and fusion-fission lead to the production of more or less neutron-rich nuclei in the mid-mass region.

Going up in energy, the Fermi energy marks the transition to reaction mechanisms governed by individual nucleon-nucleon interactions. The nuclear potential and even more the Coulomb repulsion tend to become negligible. At energies well above the Fermi energy, the bombardment of heavy nuclei with nucleons, e.g. protons, or with other nuclei can be considered as a sequence of collisions of individual quasi-free nucleons. The role of the nuclear potential is reduced to that of a container. The influence of the potential on the collision dynamics is negligible. These reactions can well be represented by the intra-nuclear cascade model or, in the case of heavy-ion collisions, also by the abrasion model. The reaction partner of interest will partly survive as a spectator with approximately unchanged velocity with a number of nucleons being ejected. Unlike the reaction mechanisms which are characteristic for the sub-Fermi energies, the variation of binding energies of protons and neutrons as a function of neutron excess has almost no influence on the reaction process. Therefore, the products arising from high-energy collisions show a very important fluctuation in the N/Z degree of freedom corresponding directly to the statistics of the nucleon-nucleon collisions.

All reactions discussed above end up in the formation of a thermalised excited nucleus. This excitation energy amounts to a minimum of 20 to 40 MeV in fusion reactions. It may reach up to a few hundred MeV in the case of reactions near the Coulomb barrier. It is subject to an important fluctuation and may reach to considerably higher values for relativistic heavy-ion collisions. The excited nuclei cool down by emitting nucleons and light clusters. Another possible decay process during the evaporation cascade is given by nuclear fission. Due to the deexcitation phase the products discussed above resulting from the high-energy collision are not directly observable.

During the deexcitation phase, the nucleus cools down, and the nuclear potential, in particular the binding energies, become more and more important. The evaporation process is mainly characterised by the competition of neutron and proton evaporation. If the evaporation chain is long enough, the final residues are situated on a characteristic and rather universal ridge on the chart of the nuclides, situated between the proton drip line and the valley of beta stability. Fission in any stage of the deexcitation process populates more or less neutron-rich fragments in the mid-mass region with rather important fluctuations in mass and quite limited fluctuations in neutron excess.

These considerations are verified with experimental data. In particular, a systematic study of the production of heavy residual nuclei in reactions at relativistic energies has been performed at GSI in several recent experiments in inverse kinematics [5,6,7,8,9,10,11,12,13,14,15,16,17,18,19]. They cover projectiles from ^{129}Xe to ^{238}U in combination with target nuclei ranging from hydrogen to lead. These experiments allow it for the first time to obtain a complete overview on the isotopic production cross sections in relativistic nuclear collisions. Some of the results are presented in other contributions to this conference [20,21]. On the basis of these data, realistic parameters for model calculations can be deduced in order to improve the predictive power of these models.

The results of model calculations [22] which are cross-checked with the available experimental data are presented in figure 3. The isotopic distributions resulting from the different reactions show very specific characteristics. Fragmentation leads to more and more mass loss when the energy deposit due to higher center-of-mass energy is increased until the conditions of limiting fragmentation are reached. The characteristics of fission depend sensitively on both reaction partners. Fission of ^{208}Pb produces mid-mass nuclei near the beta stability, while fission products of ^{238}U reach far to the neutron-rich side. A very specific contribution of low-energy fission, characterised by shell effects in the fragments, is observed in electromagnetic-induced fission from ^{238}U + ^{208}Pb.

Since the exploration of nuclei at the proton drip line is well advanced, most effort will be invested in future secondary-beam facilities to extend our knowledge on neutron-rich nuclei. Fission induced in relativistic heavy-ion collisions has lead to the first production of a great number if mid-mass neutron-rich isotopes [8], including the doubly magic ^{78}Ni [14]. Dedicated experiments to explore to which amount fluctuations in the N-over-Z ratio induced in relativistic nuclear collisions survive the deexcitation phase have given encouraging results (see refs. [5,23]). The removal of up to 5 protons from ^{197}Au without evaporation of any neutron has been observed. Cold fragmentation seems to be most promising tool for approaching the neutron drip line.

The good actual knowledge of the characteristics of the nuclear reactions as outlined above allows for choosing conditions for the secondary-beam production which are optimised to specific needs. These considerations will be of fundamental importance when designing future secondary-beam facilities.

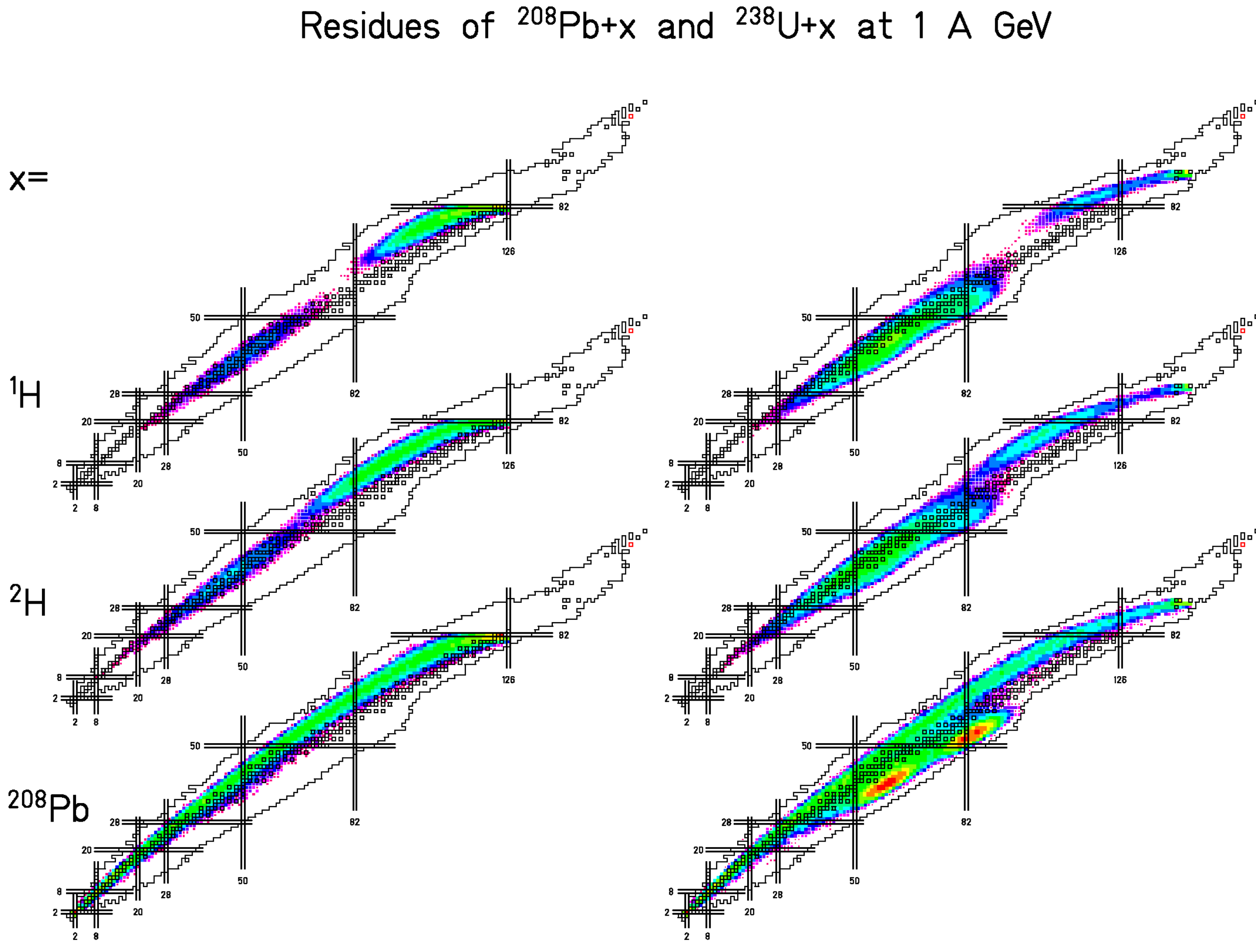

Fig. 3: Systematic overview on calculated isotopic production cross sections in different reactions. For clarity only values above 100 µb are shown.

Summary

In summary, three reaction mechanisms provide the most promising prospects for the production of secondary beams. Fusion is best suited for the production of nuclei near the proton drip line and for nuclei heavier than ^{238}U. Fission, occurring at any stage of the deexcitation phase of heavy nuclei, specifically populates mid-mass neutron-rich isotopes. Fragmentation reactions represents a rather universal production mechanism for both neutron-deficient and neutron-rich exotic nuclei, since the fluctuations in the N-over-Z ratio are very important. Due to these large fluctuations, this is the most promising reaction mechanism to reach extremely exotic nuclei over the whole mass range, if sufficiently high primary-beam intensities are available. In particular, it seems to be a unique process for the production of extremely neutron-rich isotopes of elements above the region of fission fragments. For producing a specific secondary beam with the highest rates, the projectil-target combination should be carefully chosen. Optimum technical conditions are met if the primary-beam energy reaches values around 1 A GeV.

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