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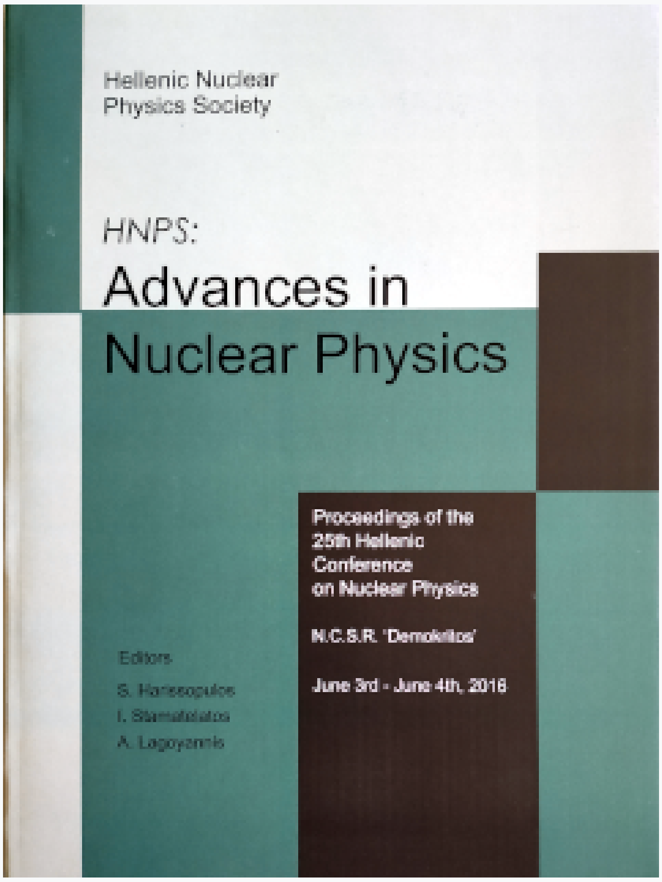

Rare Isotope Production in peripheral heavy-ion collisions in the energy range 15-25 MeV/nucleon

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Rare Isotope Production in peripheral heavy-ion collisions in the energy range 15-25 MeV/nucleon

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Abstract

In this contribution we summarize recent efforts to describe the production of rare isotopes with beams of 15–25 MeV/nucleon expected from low-energy facilities. We first present calculated production cross sections of proton-rich nuclides from collisions of stable beams of mass A$\sim$60–80. Our calculations are performed with the phenomenological deep-inelastic transfer (DIT) model and the microscopic constrained molecular dynamics model (CoMD). De-excitation of the excited quasiprojectiles from the dynamical stage of the reaction is performed with the statistical multifragmentation model (SMM). In addition to the efforts on proton-rich nuclides, we investigated the possibility of producing neutron-rich rare isotopes in the mass range A$\sim$180–200, i.e. near the third r-process peak of A=195. We performed calculations for a ^{208}Pb (15MeV/nucleon) beam and find that the multinucleon transfer mechanism leads to very neutron-rich nuclides in this mass range. We believe that our continued progress on the study of multinucleon transfer reactions using heavy-ion beams of 15–25 MeV/nucleon, can provide new opportunities in rare isotope research in the near future, as planned at the KOBRA facility of RISP in Korea.

1 Introduction

We have recently presented our efforts to study the production of neutron-rich rare isotopes employing the mechanism of multinucleon transfer with stable or radioactive beams in the energy range 15–25 MeV/nucleon expected from the RISP accelerator facility [1–3]. We showed that this approach – termed QP (quasiprojectile) fragmentation – offers the possibility of essentially adding neutrons (along with the usual stripping of protons) to a given stable (or radioactive) projectile by its interaction with a neutron-rich target. Our recent article [4] elaborates on our understanding of the reaction mechanism and our description with the phenomenological DIT (deep-inelastic transfer), as well as the microscopic CoMD (Constrained Molecular Dynamics) models.

In the present article, we first summarize our initial efforts regarding the production of proton-rich isotopes in the range Z=10–40. Our approach, involving peripheral nucleon exchange and then binary deexcitation (or multifragmentation), constitutes an efficient way to access extremely proton-rich rare isotopes for a broad variety of studies. Careful review of the current literature indicates that there is a lot of activity in the nuclear physics community concerning the production of proton-rich nuclei at and beyond the proton drip line. Interest has aroused in prompt or sequential two-proton emission [5–9], as well as for nuclides with astrophysical importance in nucleosynthesis cycles involving proton-rich nuclei [10,11].

We performed calculations of proton-rich isotope production cross sections based on our usual hybrid approach: the dynamical stage of the projectile-target interaction is described with either the phenomenological deep-inelastic transfer (DIT) model [12], or with the microscopic constrained molecular dynamics (CoMD) model [14,15]. Subsequently, for the de-excitation of the projectile-like fragments (quasi-projectiles), our version [16] of the statistical multifragmentation model (SMM) [17,18] is employed. In this microcanonical SMM version, careful adjustment of the excitation-energy dependence of the symmetry energy is performed according to our previous findings [16,18]. We shoewed that our approach constitutes an efficient way to access extremely proton-rich rare isotopes for spectroscopy or reaction studies.

In parallel to the efforts of proton-rich nuclide production, we investigated the possibility of producing neutron-rich nuclides in the mass range A∼180–200, i.e. near the isotones of N=126, that constitute the third r-process peak of A=195. This region of n-rich nuclides is of primary importance at present, as indicated by a number of recent references (e.g. [19,20] and references therein). We initiated our study by performing DIT/SMM and CoMD/SMM calculations for a ^{208}Pb (15 MeV/nucleon) beam interacting with neutron-rich targets and found that the multinucleon transfer mechanism leads to very neutron-rich nuclides in this mass range.

We conclude that we are at the stage of using the present theoretical framework of DIT/SMM or CoMD/SMM for the prediction of exotic proton-rich nuclei or neutron-rich nuclei employing appropriate intense stable beams at the KOBRA/RISP facility.

2 Proton-Rich nuclide production at 15–25 MeV/nucleon

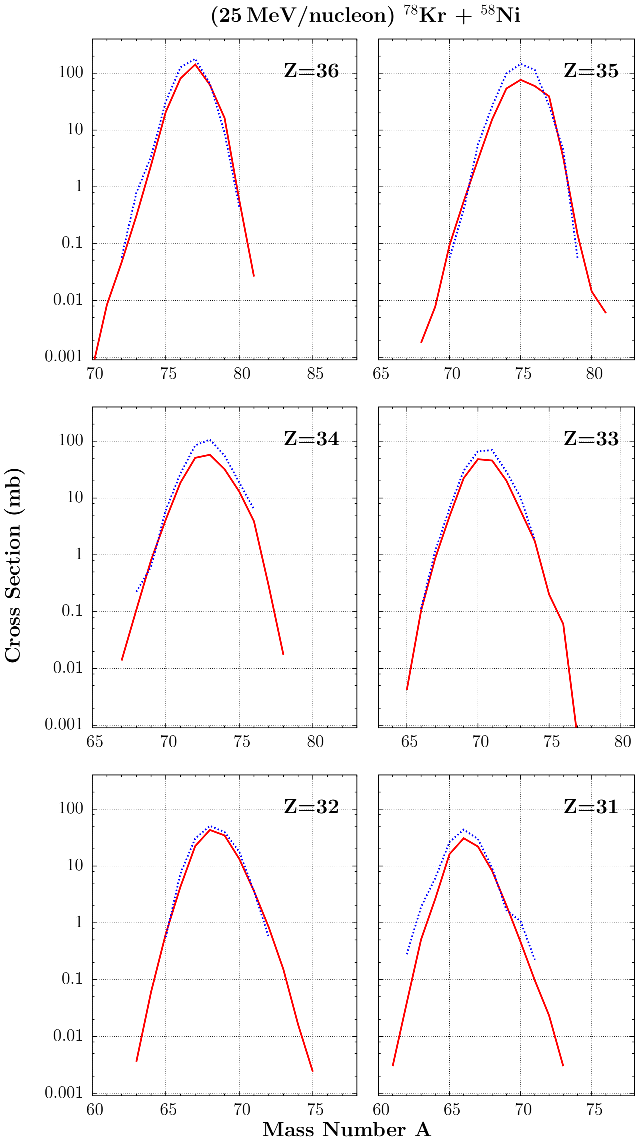

Fig. 1. Calculated mass distributions (lines) of proton-rich nuclides with Z=31–36 from the reaction ^{78}Kr(25 MeV/nucleon)+^{58}Ni The calculations are: DIT/SMM (solid red line) and CoMD/SMM (dotted blue line)

In Fig. 1, we present the calculated mass distributions of elements with Z = 31–36 from the reaction a ^{78}Kr(25 MeV/nucleon)+^{58}Ni. As already mentioned, in the calculations, we employed the standard DIT code (solid red line) and the CoMD code (dotted blue line). Our version of the SMM code [16] was used for the de-excitation stage. From the figure we observe an overall agreement in shape of the two calculations the DIT/SMM and the CoMD/SMM. We note that the CoMD calculations are only preliminary and that higher statistics runs are now underway. However, the present comparison reassures that our reaction approaches are in mutual agreement.

In Figs. 2, 3 we present the calculated mass distributions of elements with Z=25–30, Z=19–24, respectively, from the reactions of 25 MeV/nucleon ^{78}Kr and ^{64}Zn beams with a ^{58}Ni target. The calculations are with DIT/SMM for ^{78}Kr+^{58}Ni (solid red line) and ^{64}Zn+^{58}Ni (dashed green line). Interestingly, we note that for Z=30–25, essentially near the ^{64}Zn projectile, the cross sections of proton-rich nuclides are higher with this projetile compared with the ^{78}Kr projectile. However, for lower mass fragments the cross sections from both beams are nearly similar on the proton-rich side.

In the following we provide, some examples of production rates assuming a primary beam of ^{78}Kr with intensity of 100 pnA (6x10^{11} particles/s) and a 20 mg/cm^2 ^{58}Ni target: ^{65}As (4μb, 4.0x10^2 counts/s), ^{58}Zn (8μb, 8.0x10^2 counts/s), ^{42}Ti (10μb, 1.0x10^3 counts/s), and ^{23}Al (10μb, 1.0x10^3 counts/s).

We mention that we are also studying the reactions of both ^{78}Kr and ^{64}Zn beams with ^{27}Al, ^{48}Ti, as well as ^{112}Sn targets with results comparable to that of the ^{58}Ni target that we present here. As a subsequent step, we plan to explore the dependence of the production cross sections on the beam energy. Apart from our chosen 25 MeV/nucleon energy (on which we have performed extensive experimental work in the past with neutron-rich beams), we will also try detailed calculations at 15 and 35 MeV/nucleon. We also plan to compare the present calculations with data from fragmentation reactions [21,22]. Furthermore, we plan to apply our approach in the use of proton-rich RIBs from the first stage of KOBRA to produce even more proton-rich nuclides that can be studied at the subsequent stages of KOBRA.

Apart from the issue of production cross sections of the proton-rich nuclides from the above reactions, we point out that their angular distributions have to be carefully considered when applied to the KOBRA RIB production scheme. Our event-by-event calculations allow full event tracking of the products through the beam-optics simulation of the KOBRA separator, as it has been studied by the members of the KOBRA team. From a practical standpoint, we remind that the DIT code is a rather fast code (in contrast to the computer-intensive CoMD code) and thus, can be used effectively for the design of experiments with proton-rich radioactive beams at the KOBRA/RISP facility.

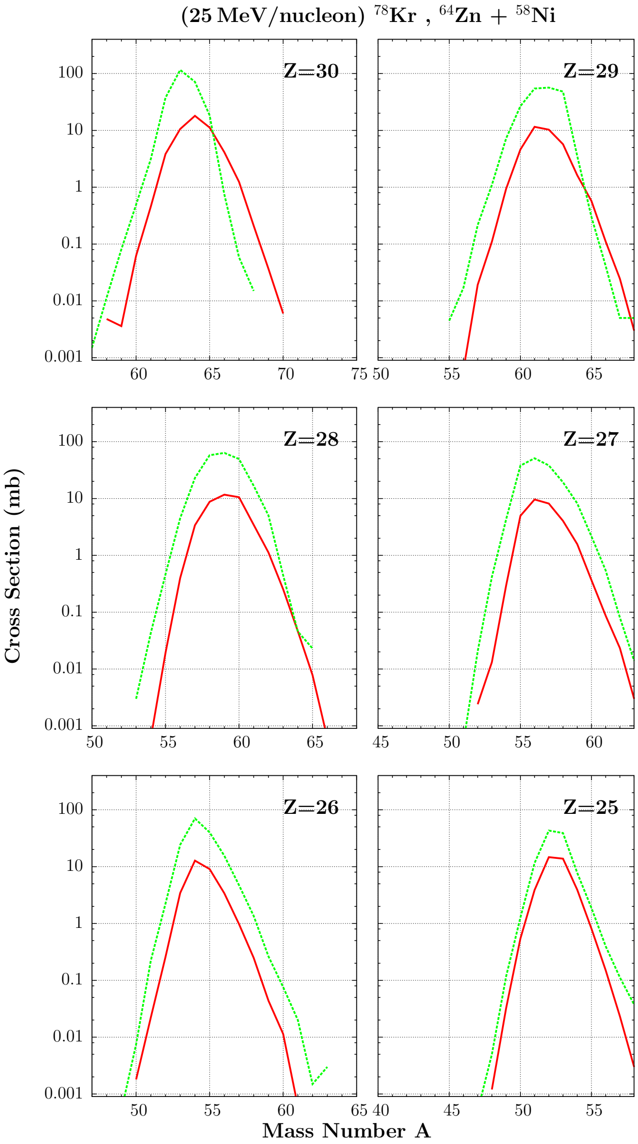

Fig. 2. Calculated (DIT/SMM) mass distributions (lines) of proton-rich nuclides with Z=25–30 from the reactions ^{78}Kr(25 MeV/nucleon)+^{58}Ni (solid red line) and ^{64}Zn (25 MeV/nucleon)+^{58}Ni (dashed green line).

3 Results with mass A∼180–200 beams at 15 MeV/nucleon

In parallel to the proton-rich nuclide studies, we investigated the possibilities of producing neutron-rich rare isotopes in the mass range A=180–200, i.e. well above the typical heavy fission-fragment mass, accessible to the standard ISOL facilities or the projectile-fission facilities (see, e.g. [23]).

We performed calculations for a ^{208}Pb (15MeV/nucleon) beam interacting with a ^{64}Ni and a ^{48}Ti target with our DIT/SMM and CoMD/SMM code framework and we found that the multinucleon transfer mechanism can lead

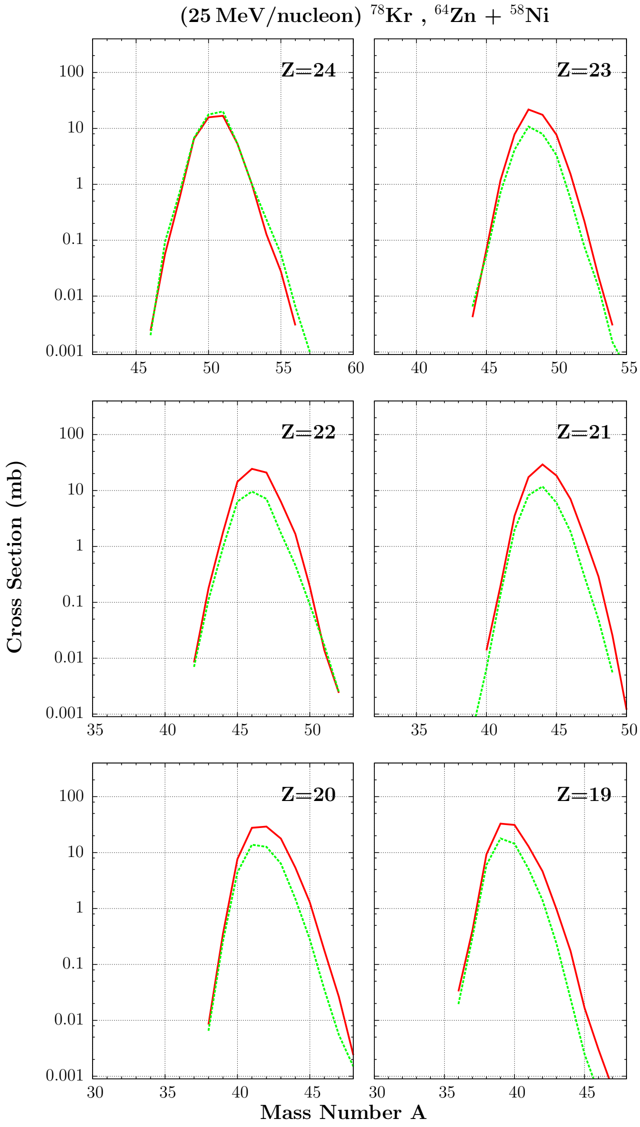

Fig. 3. Calculated (DIT/SMM) mass distributions (lines) of proton-rich nuclides with Z=19–24 from the reactions ^{78}Kr(25 MeV/nucleon)+^{58}Ni (solid red line) and ^{64}Zn (25 MeV/nucleon)+^{58}Ni (dashed green line).

to very neutron-rich nuclides, possibly to new ones in this mass range.

To provide a perspective of the accessible nuclides, we show in Fig. 4 the DIT/SMM calculated production cross sections of projectile fragments from these reactions. We also provide, three examples of production rates assuming a primary beam of ^{208}Pb with intensity of 100 pnA (6x10^{11} particles/s) and a 20 mg/cm^2 ^{64}Ni target: ^{208}Hg (2μb, 2.0x10^2 counts/s), ^{206}Hg (200μb, 2.0x10^4 counts/s), and ^{200}Pt (20μb, 2.0x10^3 counts/s).

So far our comparisons were focused primarily on the use of the ^{64}Ni target (also the Ti tagret) as a good compromise of high N/Z (N/Z=1.29) and moderate size, so that we keep the products as much as possible forward-focused

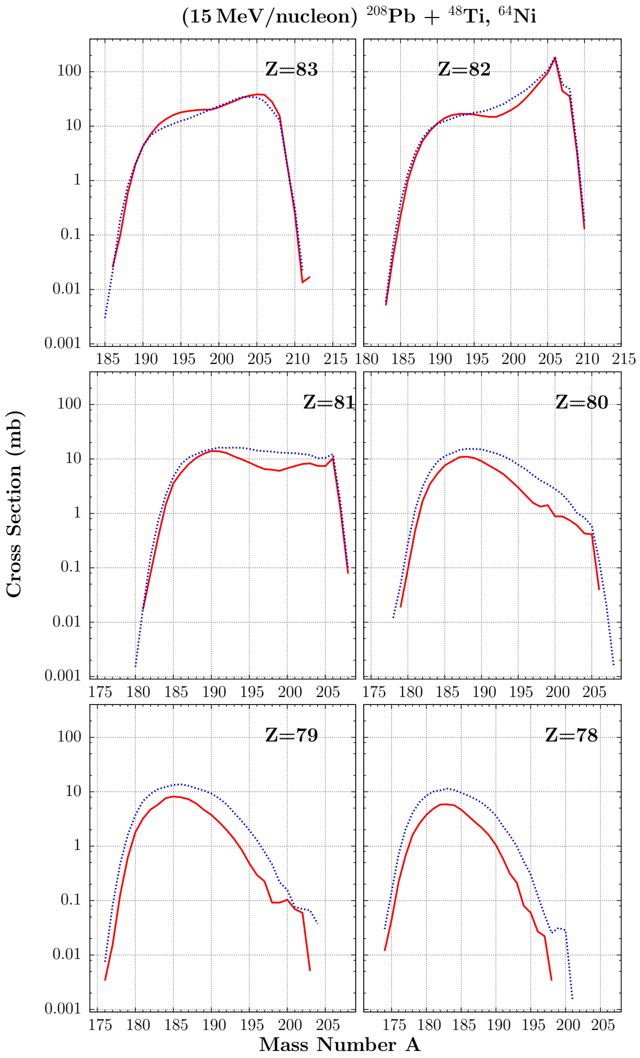

Fig. 4. Calculated (DIT/SMM) mass distributions (lines) of neutron-rich nuclides with Z=78–83 from the reaction of ^{208}Pb (15 MeV/nucleon) with targets of ^{48}Ti (solid red line) and ^{64}Ni (dotted blue line).

(and thus, within the acceptance of the KOBRA separator). As a subsequent step, we plan to explore the reactions of the ^{208}Pb (15MeV/nucleon) beam with heavy targets as ^{124}Sn, ^{208}Pb, ^{232}Th and ^{238}U, in order to appreciate the effect of the N/Z of the target, of course along with the wider angular distibutions resulting from the reactions with these heavier targets. In addition, similar reactions with a ^{198}Pt beam will be explored in detail.

However, from an experimental point of view, we wish to point out that for these heavier projectiles, special attention has to be paid to issues concerning the broad ionic charge-state distribution, as well as the Z and A resolutions of the detection system necessary to perform the particle identification. We mention that in the past, we developed a detailed analysis procedure for heavy beams (i.e. Au, U) in this energy range [24] and succeeded in characterizing the residue distributions from deep-inelastic and incomplete fusion reactions. We even succeeded to identify "new" proton-rich nuclei [25] that have recently been reported in the isotope review article [26]. It is our expectation that we will proceed with our collaborators of the KOBRA group to continue such experimental efforts using appropriate heavy beams from RISP, in order to access new regions of the chart of the nuclides in the near future.

4 Summary and Conclusions

In this contribution, we presented our continued efforts to study the production of rare isotopes with beams of 15–25 MeV/nucleon expected from a low-energy facility, as e.g. the RISP accelerator complex. We first present calculated production cross sections of proton-rich nuclides from collisions of stable beams of mass A$\sim$60–80. Our calculations are performed with the phenomenological deep-inelastic transfer (DIT) model and the microscopic constrained molecular dynamics model (CoMD). De-excitation of the excited quasiprojectiles from the dynamical stage of the reaction is performed with the statistical multifragmentation model (SMM). We find that our approach constitutes an efficient way to access extremely proton-rich rare isotopes for a broad range for spectroscopy studies. In parallel to the efforts on proton-rich nuclides, we investigated the production of neutron-rich rare isopopes in the mass ragne A$\sim$180–200, i.e. near the third r-process peak of A=195. We presented calculations for a ^{208}Pb (15MeV/nucleon) beam and find that the multinucleon transfer mechanism leads to very neutron-rich nuclides in this mass range of interest to spectroscopic and astrophysical studies.

Moreover, since our calculations are complete event-by-event simulations, we are able to systematically study the velocity distributions, the angular distributions and, furthermore, the ionic charge state distributions of the various groups of fragments. This information may help us to perform realistic beam optics simulations of the behavior of the KOBRA spectrometer and the capability to separate and identify the exotic neutron-rich nuclides of interest.

We believe that the present continued progress in the front of peripheral heavy-ion reactions using beams of 15–25 MeV/nucleon, in combination with the unique capabilities of the KOBRA facility are expected to offer new exciting opportunities in rare isotope research in the near future.

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