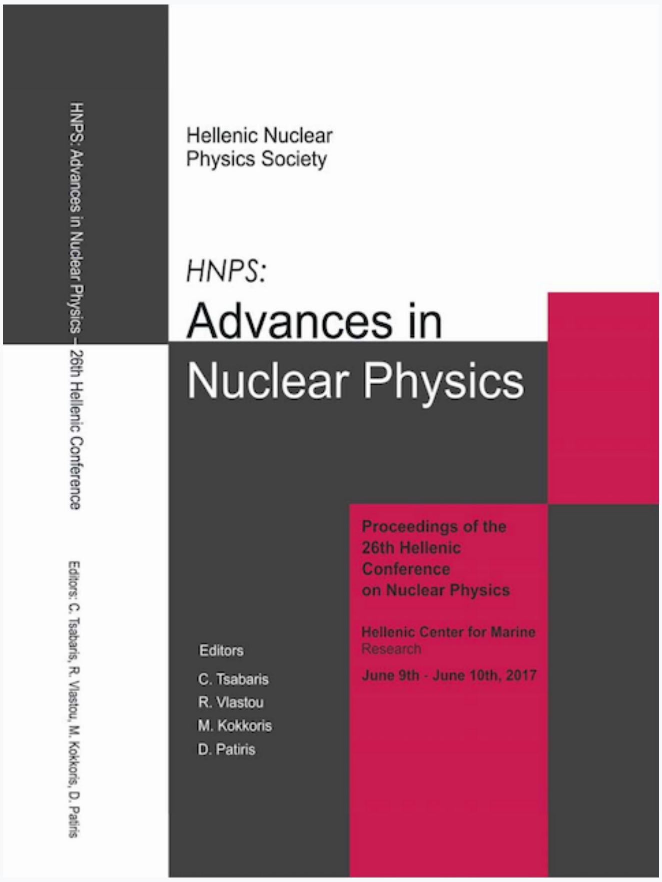
HNPS Advances in Nuclear Physics

Vol 25 (2017)

HNPS2017



Neutron-rich rare isotope production with stable and radioactive beams in the mass range A~40-60 at 15 MeV/u

A. Papageorgiou, G. A. Souliotis, Y. K. Kwon, K. Tshoo, A. Bonasera, M. Veselsky

doi: [10.12681/hnps.1970](https://doi.org/10.12681/hnps.1970)

Neutron-rich rare isotope production with stable and radioactive beams in the mass range A ~ 40-60 at 15 MeV/nucleon

A. Papageorgiou[1,*], G.A. Souliotis [1], Y.K. Kwon[2], K. Tshoo[2], A. Bonasera[3,4], M. Veselsky[5]

[1]*Laboratory of Physical Chemistry, Department of Chemistry, University of Athens, Athens 15771, Greece.*
[2]*The Rare Isotope Science Project (RISP), Institute for Basic Science, Daejeon 305-811, Korea. 3*
[3]*Cyclotron Institute, Texas A&M University, College Station, Texas, USA.*
[4]*Laboratori Nazionali del Sud, INFN, via Santa Sofia 62, I95123 Catania, Italy.*
[5]*Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia.*

Abstract This work reports on our continued efforts to study the production of rare isotopes with heavy-ion beams at energy 15 MeV/nucleon. Our calculations are based on a two-step approach: the dynamical stage of the collision is described with either the phenomenological Deep-Inelastic Transfer model (DIT) [1], or with the microscopic Constrained Molecular Dynamics model (CoMD) [2,3,4]. The de-excitation of the hot heavy projectile fragments is performed with the Statistical Multifragmentation Model (SMM) [4]. We first present experimentally acquired production cross sections of neutron-rich nuclides from collisions of a ^{40}Ar stable beam with targets of ^{58}Ni, ^{64}Ni and ^{27}Al [5] and we compare them with our calculations. Then we performed calculations for the same beam (15 MeV/nucleon) with other neutron rich targets such as ^{48}Ca and ^{238}U and find that the multinucleon transfer mechanism leads to very neutron-rich nuclides in mass range A ~ 40-60. Motivated by the high production cross section of target ^{238}U, we performed calculation with beam of ^{48}Ca (15 MeV/nucleon). We found that we can produce radioactive beams of ^{46}Ar and ^{54}Ca which can be separated and hit another target of ^{238}U, participating in reactions of multinucleon transfer which can produce extremely neutron-rich and even new isotopes.

INTRODUCTION

The study of the nuclear landscape toward the astrophysical r-process path and the neutron drip-line have received special attention by the nuclear physics community (see, e.g., [1]). To reach a high neutron-excess in the products, apart from proton stripping, capture of neutrons may be necessary from the target. Such a possibility is offered by reactions of nucleon exchange at beam energies from the Coulomb barrier [2,3] to the Fermi energy (20-40 MeV/nucleon) [4,5].

In this section we present the results of the calculation of peripheral heavy ion reactions. We compare our results with experimental data from the reaction ^{40}Ar + ^{64}Ni at beam energy 15 MeV/A, which were acquired as described in [6], as well as from the reactions ^{40}Ar + ^{181}Ta [7] and ^{48}Ca + ^{181}Ta [8] found in the literature. The calculation were performed with the phenomenological model DIT [9] and the microscopic CoMD [10], which describe the dynamical stage of the nucleon exchange, and the statistical de-exitation model SMM [11].

* Corresponding author, email: soulioti@chem.uoa.gr

CALCULATIONS FOR STABLE BEAMS OF ^{40}Ar AND ^{48}Ca AT 15 MeV/A

In Fig 1, we show the calculated mass distributions of projectile-like fragments with Z=12-19 from the reaction ^{40}Ar (15 MeV/A) + ^{64}Ni performed by CoMD/SMM (dashed red line) and DIT/SMM (solid green line) compared with the experimental data (black points). We observe that in the isotopes close to the projectile (Z=16-19), the results of the two models are almost identical, while they are in good agreement with the data. Subsequently, the largest part of the calculations will be performed with the DIT model, as it can conduct results of higher statistics in less time than the CoMD model.

After the presentation of the comparisons between our calculations with the experimental data, we can feel certain that the results of both DIT and CoMD can be considered as valid. Hence, they can be used to predict the results of reactions that have not taken place yet.

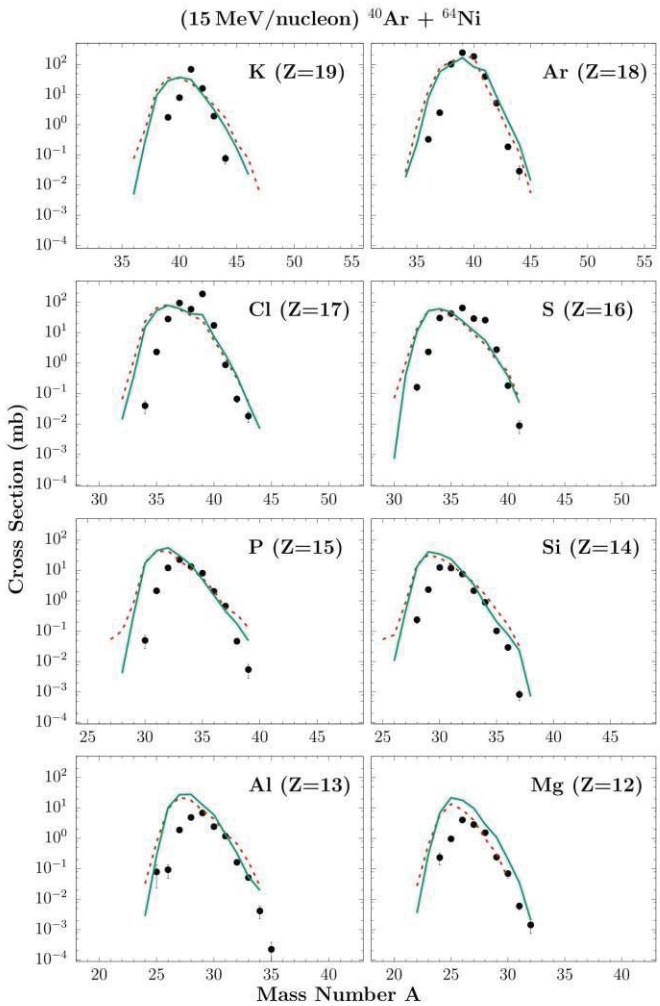


Fig. 1. Calculated mass distributions of projectile-like fragments with Z=12-19 from the reaction ^{40}Ar (15 MeV/A) + ^{64}Ni performed by CoMD/SMM (dashed red line) and DIT/SMM (solid green line) compared with the experimental data (black points) [6].

Motivated by these results, we performed calculations with a beam of the same mass range, but far more neutron rich, ^{48}Ca (15 MeV/A). In Fig. 2, we show our calculations for the reactions ^{48}Ca (15 MeV/A) + ^{64}Ni (solid red line), ^{48}Ca (15 MeV/A) + ^{238}U (dashed green line) and ^{48}Ca (15 MeV/A) + ^{208}Pb (dashed-dotted yellow line) compared the data we found in the literature from the reaction ^{48}Ca (140 MeV/A) + ^{181}Ta [8] (open blue points). Our calculations for the low energy reactions seem to favor the production of neutron-rich isotopes in contrast with the data of the high energy reaction, where neutron capture is rather unlikely to happen. If we examine the distribution of the calcium isotopes we can see that with the use of ^{238}U as a target, we can produce nuclei that have captured up to 6-7 neutrons, like ^{54}Ca.

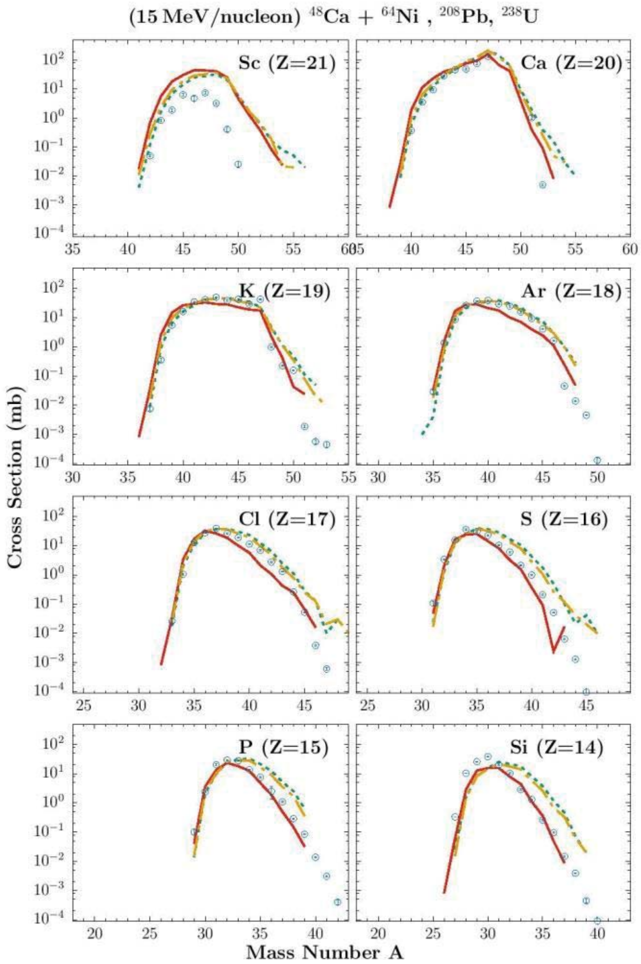


Fig. 2. Calculations for the reactions ^{48}Ca (15 MeV/A) + ^{64}Ni (solid red line), ^{48}Ca (15 MeV/A) + ^{238}U (dashed green line) and ^{48}Ca (15 MeV/A) + ^{208}Pb (dashed-dotted yellow line) compared with the data we found in the literature from the reaction ^{48}Ca (140 MeV/A) + ^{181}Ta [3] (open blue points).

CALCULATIONS FOR RADIOACTIVE BEAM (RIB) OF ^{54}Ca (15 MeV/A)

Radioactive beams are a very useful tool in the investigation of reaction mechanisms and nuclear stability. By using them, we are able to produce very rare isotopes near the neutron drip line. Motivated by the relatively high production cross section of the ^{54}Ca isotope from the reaction ^{48}Ca (15 MeV/A) + ^{238}U, we decided to perform calculations with this RIB. In Fig. 3, we show the DIT/SMM calculations for the reactions ^{54}Ca (15 MeV/A) + ^{64}Ni (solid red line) and ^{54}Ca (15 MeV/A) + ^{238}U (dashed green line). These calculations are, in our opinion, the most interesting result of this work, as it seems that with this RIB and this neutron-rich target we can produce very rare and even new isotopes up to ^{60}Ca, or even beyond.

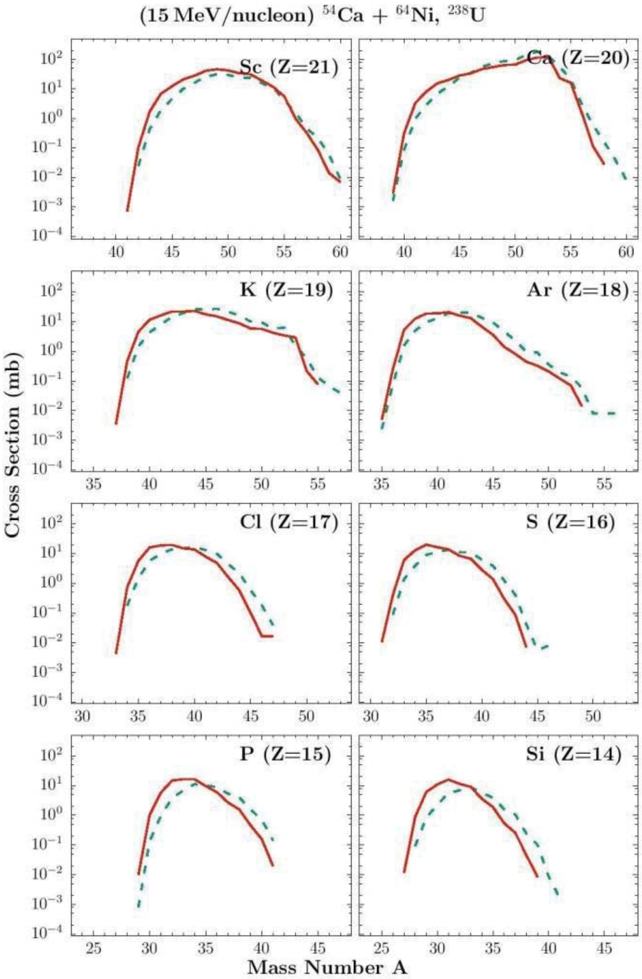


Fig. 3. DIT/SMM calculations for the reactions ^{54}Ca (15 MeV/A) + ^{64}Ni (solid red line) and ^{54}Ca (15 MeV/A) + ^{238}U (dashed green line).

After the presentation of the yields, we proceed to the presentation of the production rates of some important isotopes. In Table 1, we show the predicted cross sections and production rate estimates of some isotopes from the reaction ^{48}Ca (15 MeV/A) + ^{238}U. We have assumed a relatively high beam intensity of 500 pnA (3 x 1012 particles/s) and target thickness 20 mg/cm^2. In this table we report the cross sections and production rates of the radioactive isotopes ^{46}Ar and ^{54}Ca, which were used as RIB. Also, we show the experimentally measured (expt) or theoretically predicted (theo) half life time [12,13] of each isotope.

In Table 2, we show the predicted cross sections and production rate estimates of some isotopes from the reaction ^{54}Ca (15 MeV/A) + ^{238}U. As before, we have assumed that the beam intensity is the production rate of ^{54}Ca from the reaction ^{48}Ca (15 MeV/A) + ^{238}U, which is about 4600 particles/s, and a target thickness of 20 mg/cm^2. We see that production of very rare and even new isotopes , like ^{59}Ca and ^{60}Ca, is predicted in peripheral low energy collisions of the radioactive beam ^{54}Ca.

Rare isotope	$t_{1/2}$	Reaction Channel	Cross Section (mb)	Rates (s^{-1})
^{54}Ca	0.09 s (expt)	- 0p + 6n	0,03	4.6×10^{3}
^{46}Ar	8.4 s (expt)	- 2p - 0n	2.88	4.4×10^{5}
^{55}Sc	0.09 s (expt)	+1p + 6n	0.051	7.8×10^{3}
^{52}K	105 ms (expt)	- 1p + 5n	0.05	17.6×10^{3}

Table 1. Predicted cross sections and production rate estimates of some isotopes from the reaction ^{48}Ca (15 MeV/A) + ^{238}U.

Rare isotope	$t_{1/2}$	Reaction Channel	Cross Section (mb)	Rates (s^{-1})
^{57}Ca	7 ms (expt)	- 0p + 3n	0.59	1.4×10^{-4} (12 day^{-1})
^{58}Ca	12 ms (theo)	-0p +4n	0..16	3.75×10^{-5} (3 day^{-1})
^{59}Ca	6 ms (theo)	-0p +5n	0.04	9.75×10^{-6} (6 week^{-1})
^{60}Ca	4 ms (theo)	- 0p + 6n	0.008	1.9×10^{-6} (1 week^{-1})
^{54}K	10 ms (expt)	-1p + 1n	0.58	1.4×10^{-4} (12 day^{-1})
^{55}K	4 ms (expt)	- 1p + 4n	0.04	9.4×10^{-6} (6 week^{-1})

Table 2. Predicted cross sections and production rate estimates of some isotopes from the reaction ^{54}Ca (15 MeV/A) + ^{238}U.

SUMMARY AND CONCLUSIONS

In this work we performed a series of calculations of cross sections of projectile fragments from peripheral heavy ion reactions with beam energy 15 MeV/A. More specifically, we presented calculation for the reactions with the stable beams ^{40}Ar (15 MeV/A) and ^{48}Ca (15 MeV/A) + ^{64}Ni, ^{208}Pb, ^{238}U and with the radioactive beam ^{54}Ca (15 MeV/A) + ^{64}Ni, ^{238}U, using the phenomenological model DIT [9], the microscopic model CoMD [10] and the statistical de-excitation model SMM [11]. We saw that our calculations came to a satisfactory agreement with the available experimental data. Then, we predicted the production of very rare and even new isotopes toward the region of ^{60}Ca, which has not been produced yet.

References

[1] J. Erler et al, Nature 486, 509 (2011).
[2] V. V. Volkov, Phys. Rep. 44, 93 (1978).
[3] L. Corradi, G. Pollarolo, S. Szilner, J. Phys. G 36, 113101 (2009).
[4] G. A. Souliotis et al., Phys. Lett. B 543, 163 (2002).
[5] G. A. Souliotis et al., Phys. Rev. Lett. 91, 022701 (2003).
[6] G.A. Souliotis, M. Veselsky, S. Galanopoulos et al., Approaching neutron rich nuclei toward the r-process path in peripheral heavy ion collisions at 15 MeV/nucleon, Phys. Rev. C 84, 064607 (2011).
[7] Mashiro Notani, Projectile Fragmentation reactions and production of nuclei near the neutron drip line, University of Tokyo (Phd thesis).
[8] M. Mocko et al., Projectile fragmentation of 40Ca, 48Ca, 58Ni and 64Ni at 140 MeV/nucleon, Phys. Rev. C 74, 05612 (2006).
[9] L. Tassan-Got and C. Stefan, Deep inelastic transfers. A way to dissipate energy and angular momentum for reactions in the Fermi energy domain, Nucl. Phys. A 524, 121 (1991).
[10] M. Papa et al., Constrained molecular dynamics approach to fermionic systems, Phys. Rev. C 64, 024612 (2001).
[11] J.P Bondorf et al., Statistical multifragmentaition of nuclei, Phys. Rep. 257, 133 (1995).
[12] P. Moller, J.R. Nix et al., Nuclear ground state masses and deformations, Atomic Data Nucl. Data Tables 59, 185-381 (1995).
[13] P. Moller, J.R. Nix et al., Nuclear properties for astrophysical applications, Atomic Data Nucl. Data Tables 66, 131-345 (1997).