PRODUCTION CROSS SECTIONS OF NEUTRON-DEFICIENT NUCLEI IN $Z = 30$–36 REGION IN ^{78}Kr+Be FRAGMENTATION REACTION*

A. Kubiela[a], H. Suzuki[b], O.B. Tarasov[c], M. Pfützner[a]

[a]Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland
[b]RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[c]Facility for Rare Isotope Beams, Michigan State University
East Lansing, Michigan 48824, USA

Received 30 November 2022, accepted 11 January 2023, published online 22 March 2023

We investigated the production of neutron-deficient nuclei in a fragmentation reaction of ^{78}Kr at 345 MeV/nucleon on a beryllium target in the framework of the abrasion–ablation model. The model parameters were deduced using experimental cross sections in the region. We compiled a dataset of predicted cross-section values for 5–7 most neutron-deficient isotopes of each element from zinc to krypton.

DOI:10.5506/APhysPolBSupp.16.4-A18

1. Introduction

The study of nuclei close to the proton drip-line is one of the most important frontiers of nuclear physics. Nuclear models working well in less exotic regions of the chart of nuclides can be tested at the edge of nuclear stability. Interesting phenomena, such as two-proton radioactivity or beta-delayed particle emission [1, 2], occur only in this region and can be investigated.

Short half-lives (order of 1 ms or less) and difficult production are the two major challenges in studies of extremely neutron-deficient isotopes. The former challenge forces the use of special production techniques, like in-flight fragmentation. The latter comes mainly from the fact that production cross sections for exotic, neutron-deficient nuclei are generally low, which limits production rates and gathered statistics in a given beam time. Reliable estimation of these production rates is a crucial part of planning the experiment at the proton drip-line region, but often the information on the cross sections is also quite limited.

* Presented at the Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 28 August–4 September, 2022.

Recently, we have conducted an experiment at the RI Beam Factory (RIBF) of the RIKEN Nishina Center aimed at studying two-proton radioactivity of ^{54}Zn. Ions of interest were produced by impinging a ^{78}Kr beam at 345 MeV/nucleon on a 10-mm thick beryllium target and separated using the BigRIPS separator [3, 4]. In addition to the decay studies, results of which will be published elsewhere, we have measured the production cross sections of ^{54}Zn, ^{55}Zn, and ^{56}Zn [5]. As the resulting values were significantly smaller than anticipated, we investigated a way to better estimate the production of nuclei in the region using the abrasion–ablation (AA) model [6]. Results of this investigation for even-Z nuclei between zinc and krypton were published in Ref. [5]. Here, we provide the complete dataset including the predicted cross sections for odd-Z nuclei.

2. Abrasion–ablation model

In the geometrical LISE^{++} AA model [6], the fragmentation reaction proceeds in two steps. The first one, abrasion, accounts for the removal of nucleons in the overlap region of the colliding ions [7] and the excitation of the projectile prefragment. The second step, ablation, is based on the fusion–evaporation model LisFus [8]. It employs a fast analytical calculation of fusion residues cross sections. An analytical solution of the evaporation cascade provides fast calculations and allows cross-section determinations for exotic nuclei, not accessible with the Monte Carlo technique.

Six parameters of the AA model were varied in the present work. Four of them are used to characterize the distribution of the excitation energy of the prefragment created in the abrasion phase. The fifth parameter is related to the effective Coulomb barrier and the final one is an overall normalization factor. In addition, the important input to the AA model is the table of masses of all nuclei in the region between the projectile and the fragments of interest. More details on the AA model are given in Ref. [6].

To deduce the parameters of the AA model, we used the measured cross sections. The available data for 17 nuclei in the $Z = 30$–36 region [9–11], including our $^{54-56}$Zn results [5], were used to find the AA model parameters by the least squares fitting. Furthermore, this procedure was conducted for 11 different mass models [5]. The best agreement of the predicted cross sections with experimental data was found for one version of the Hartree–Fock–Bogoliubov model (HFB22) [12].

3. Results and discussion

All results, also for odd-Z elements, are collected in Table 1 and Fig. 1. It can be seen that the AA model with the HFB22 mass table, shown with the red solid lines, describes the measured cross sections very well. In contrast,

Table 1. Production cross section predicted by the AA model with the HFB22 mass table for neutron-deficient isotopes in the range of $Z = 30$–36 in the fragmentation of ^{78}Kr on beryllium.

Nucleus	σ [b]	Nucleus	σ [b]	Nucleus	σ [b]
^{54}Zn	4.10×10^{-15}	^{59}Ge	3.91×10^{-14}	^{65}Se	2.01×10^{-11}
^{55}Zn	3.76×10^{-13}	^{60}Ge	7.06×10^{-13}	^{66}Se	9.57×10^{-10}
^{56}Zn	1.60×10^{-11}	^{61}Ge	1.48×10^{-10}	^{67}Se	7.87×10^{-8}
^{57}Zn	1.93×10^{-10}	^{62}Ge	5.30×10^{-9}	^{68}Se	2.19×10^{-6}
^{58}Zn	2.52×10^{-8}	^{63}Ge	4.57×10^{-7}	^{66}Br	2.99×10^{-14}
^{59}Zn	1.24×10^{-6}	^{64}Ge	1.32×10^{-5}	^{67}Br	4.45×10^{-13}
^{56}Ga	1.42×10^{-15}	^{61}As	1.29×10^{-15}	^{68}Br	1.07×10^{-10}
^{57}Ga	1.31×10^{-14}	^{62}As	5.69×10^{-13}	^{69}Br	4.97×10^{-9}
^{58}Ga	2.51×10^{-12}	^{63}As	5.32×10^{-12}	^{70}Br	2.21×10^{-7}
^{59}Ga	4.44×10^{-11}	^{64}As	1.17×10^{-9}	^{67}Kr	2.40×10^{-15}
^{60}Ga	9.07×10^{-9}	^{65}As	2.89×10^{-8}	^{68}Kr	2.45×10^{-14}
^{61}Ga	1.25×10^{-7}	^{66}As	4.79×10^{-6}	^{69}Kr	4.65×10^{-12}
^{62}Ga	1.24×10^{-5}	^{63}Se	1.59×10^{-14}	^{70}Kr	1.73×10^{-10}
^{58}Ge	7.56×10^{-16}	^{64}Se	4.02×10^{-13}	^{71}Kr	1.19×10^{-8}

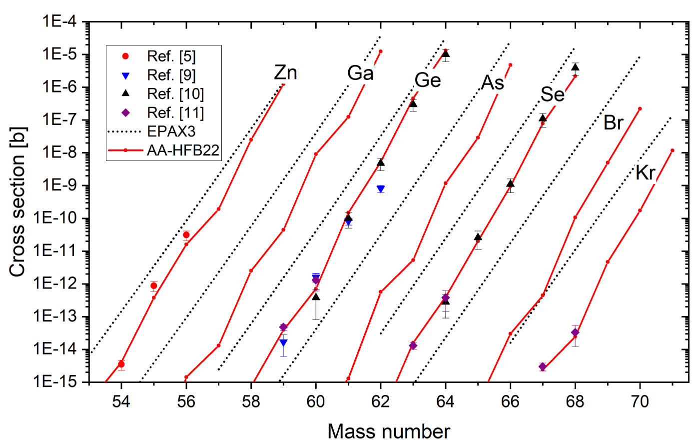

Fig. 1. (Color online) Production cross sections predicted by the AA model with the HFB22 mass table [12] for neutron-deficient isotopes in the range of $Z = 30$–36 in the fragmentation of ^{78}Kr on beryllium (red, solid line), compared with predictions of the EPAX3 parameterizations [13] (dotted line) and with the measured values for isotopes of zinc, germanium, selenium, and krypton.

the dotted lines in Fig. 1 represent predictions of the EPAX3 [13] universal empirical formula. As was hinted already before [5, 11], EPAX3 largely overestimates production cross sections in this region (up to 2 orders of magnitude). The AA model further shows that the more neutron-deficient the isotope is, the larger is the discrepancy between the EPAX3 and AA–HFB22 results. The values predicted by the AA–HFB22 model for the isotopes of odd-Z elements drop with the decreasing neutron number faster than for the even-Z ones. This is observed for the isotopes which are proton unbound.

4. Summary

Using the abrasion–ablation (AA) model with the HFB22 mass model, we have predicted the production cross sections for the most neutron-deficient nuclei in the region from zinc to krypton in the fragmentation reaction of ^{78}Kr at 345 MeV/nucleon on a beryllium target. The predicted results are in agreement with literature data available for the most neutron-deficient isotopes of Zn, Ge, Se, and Kr, while the EPAX3 parameterization largely overestimates cross sections in this region. We have compiled the table with cross section values predicted by the AA model for 5–7 most neutron-deficient isotopes of each element between zinc and krypton. We believe that they represent the best estimate for those nuclei for which experimental values are not known.

This work was supported by the U.S. National Science Foundation under grant No. PHY-2012040 and the National Science Center, Poland (NCN), under contract No. 2019/33/B/ST2/02908.

REFERENCES

[1] M. Pfützner *et al.*, *Rev. Mod. Phys.* **84**, 567 (2012).
[2] B. Blank, M.J.G. Borge, *Prog. Part. Nucl. Phys.* **60**, 403 (2008).
[3] T. Kubo, *Nucl. Instrum. Methods Phys. Res. B* **204**, 97 (2003).
[4] T. Kubo *et al.*, *Prog. Theor. Exp. Phys.* **2012**, 03C003 (2012).
[5] A. Kubiela *et al.*, *Phys. Rev. C* **104**, 064610 (2021).
[6] O.B. Tarasov, `https://lise.nscl.msu.edu/AA`, online, accessed 11.2022.
[7] J. Wilson, L.W. Towsend, F.F. Badavi, *Nucl. Instrum. Methods Phys. Res. B* **18**, 225 (1986).
[8] O.B. Tarasov *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **204**, 174 (2003).
[9] A.A. Ciemny *et al.*, *Phys. Rev. C* **92**, 014622 (2015).
[10] A. Stolz *et al.*, *Phys. Lett. B* **627**, 32 (2005).
[11] B. Blank *et al.*, *Phys. Rev. C* **93**, 061301 (2016).
[12] S. Goriely *et al.*, *Phys. Rev. C* **88**, 024308 (2013).
[13] K. Sümmerer, *Phys. Rev. C* **86**, 014601 (2012).