Yield estimation of neutron-rich rare isotopes induced by 200 MeV/u $^{132}$Sn beams by using GEANT4

Jae Won Shin

Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea

Abstract

A so-called “two-step reaction scheme”, in which neutron-rich rare isotopes obtained from ISOL are post-accelerated and bombarded on a second target, is employed to estimate the production yields of exotic rare isotopes. The production yields of neutron-rich rare isotope fragments induced by 200 MeV/u $^{132}$Sn beams bombarded on the $^9$Be target are estimated with Monte Carlo code, GEANT4. To substantiate the use of GEANT4 for this study, benchmark calculations are done for 80 MeV/u $^{59}$Co + $^9$Be, 95 MeV/u $^{72}$Zn + $^9$Be, 500 MeV/u $^{92}$Mo + $^9$Be, and 950 MeV/u $^{132}$Sn + $^9$Be reactions. It is found that $^{132}$Sn beams can produce more effectively neutron-rich rare isotopes with $45 \leq Z \leq 50$ than $^{238}$U beams at the same energy per nucleon.

Keywords: two-step reaction scheme, neutron-rich rare isotope, ISOL, $^{132}$Sn beams, GEANT4

PACS: 25.60.-t, 25.70.Mn, 83.10.Rs, 24.10.Lx

1. Introduction

The rare isotope beams (RIBs) provide us with immense opportunities in wide areas that are not covered by stable ion beams, which include studies of super-heavy nuclei, neutron skins, explosive nucleosynthesis and nuclear

Email address: shine8199@skku.edu (Jae Won Shin)

Preprint submitted to Elsevier 30 September 2014
structure for neutron-rich RIs. These studies are also closely related to ques-
tions such as the origin of elements and the fundamental symmetries. By
producing more exotic isotopes, we may approach new regions of nuclear
structure and can have a chance to reach the limits of nuclear stability and
previously unexplored state of matter. Productions of exotic RIBs are being
carried in facilities such as ISOLDE at CERN, ISAC at TRIUMF, RIBF
at RIKEN, HRIBF at ORNL and IGISOL at JYFL, and are being planned
in FRIB at MSU, SPIRAL2 at GANIL, FAIR at GSI, and SPES at INFN.
The science goals to be explored with RIBs are well discussed in many re-
ports such as U.S. Long Range Plans [1], OECD Global Science Forum [2],
NuPECC Long Range Plan 2010 [3] and reviews such as Ref. [4].

Some of the facilities mentioned above use Isotope Separation On Line
(ISOL) method [5, 6] to produce RIBs, while others use In-Flight Fragmen-
tation (IFF) method [2, 8]. However, as an attempt for producing extremely
neutron-rich isotopes, the so-called “two-step reaction scheme” (TSRS) has
been suggested in Ref. [9]. By post-accelerating some of the fission fragments
from ISOL and fragmenting them one step further, one could produce even
more neutron-rich nuclei covering a wider region of elements which would be
poorly populated by using only either ISOL or IFF method. It was suggested
that a long-lived neutron-rich rare isotope such as $^{132}$Sn produced by fission
of $^{238}$U induced by proton beams could be a good candidate as primary RIBs.

Recently, TSRS has been experimentally validated at the FRagment Sep-
arator (FRS) in GSI [10], where they have first produced $\sim 10^3$ $^{132}$Sn s$^{-1}$ by
using 950 MeV/u $^{238}$U beams on the Pb target and bombarded them on a $^9$Be
target. Their results indicate that TSRS can be indeed effective in producing
more exotic medium-mass neutron-rich isotopes. According to the summary
of the design of RAON in Korea [11, 12, 13], the expected intensity of $^{132}$Sn
can be as large as about $10^8$ particles per second (pps). It is the unique feature of RAON that the isotopes generated by ISOL are post-accelerated and injected to the IFF facility for producing more exotic RIBs.

In this work, we have performed the GEANT4 (GEometry ANd Tracking) [14, 15] simulations for estimating the production yields of exotic rare isotopes by using TSRS. We have calculated the yields of rare isotopes by bombarding 200 MeV/u $^{132}$Sn and $^{238}$U beams on the $^9$Be target and compared the results. By comparing the yields from the two different beams, we may quantify the efficiency of TSRS in producing neutron-rich rare isotopes. The GEANT4 has been used for a number of simulations, but has not been used much for nucleus-nucleus (AA) collisions. For checking the validity of the use of the GEANT4 for this purpose, we have first calculated the isotopic production cross sections for AA collisions and compared them with experimental data as well as with those obtained from another Monte Carlo code, PHITS [16]. We have also compared the results with the predictions from other popular empirical models, EPAX2 [17] and EPAX3 [18].

The outline of the paper is as follows. In Sec. 2, the simulation methods used in our study are summarized. In Sec. 3, we first show benchmark calculation results and present the yields of the isotopes obtained by $^{132}$Sn and $^{238}$U beams at 200 MeV/u, for the comparison of the results. A summary is given in Sec. 4.

2. Simulation method

Before we use the GEANT4 (v10.0) [14, 15] for TSRS, we have first performed some benchmark simulations. The production cross sections of the isotopes fragmented by AA collisions are calculated by using hadronic models such as the G4BinaryLightIonReaction [19, 20] and the G4QMDReaction [21]. We have also performed similar simulations with PHITS (v2.52) [16].
by using JAERI Quantum Molecular Dynamics (JQMD) for comparison with the results from GEANT4.

We distinguish our simulation methods by referring to them as “G4-BIN”, “G4-QMD” and “P-JQMD”:

- G4-BIN: GEANT4 simulation with the G4BinaryLightIonReaction model.
- G4-QMD: GEANT4 simulation with the G4QMDReaction model.
- P-JQMD: PHITS simulation with the JAERI Quantum Molecular Dynamics (JQMD).

To see the effectiveness of TSRS, we calculate the production yields of rare isotopes by bombarding 200 MeV/u $^{132}$Sn and $^{238}$U beams on the $^9$Be target, and compare them. As our simulation engine, the G4-BIN is used for the calculations, and the reasons why we use this model will be discussed in Sec. 3.1. In the production of the isotopes through the fragmentation by AA collisions, ionization processes cause the energy loss of the ions in the target. The G4ionIonisation is used for simulating such energy loss. The above mentioned hadronic and electromagnetic models are described on the web, and the Physics Reference Manual is also available.

3. Results

3.1. Benchmark test of simulation methods for the production cross sections

AA collisions involve extremely complicated processes, and it is not yet well established how accurately various simulation tools can describe them. We thus begin with presenting our benchmarking calculations for the adopted hadronic models.
Recently, several simulations have been performed for AA collisions with stable beams such as $^{12}$C, $^{20}$Ne and $^{24}$Mg, $^{40}$Ar and $^{56}$Fe by using Monte Carlo codes such as GEANT4, PHITS, FLUKA and so on. In these studies, partial and total fragmentation cross sections have been calculated, and reasonable agreements with the experimental data are obtained.

In this work, we extend such studies by considering heavier neutron-rich beams on the $^9$Be target; 80 MeV/u $^{59}$Co + $^9$Be, 95 MeV/u $^{72}$Zn + $^9$Be, 500 MeV/u $^{92}$Mo + $^9$Be, and 950 MeV/u $^{132}$Sn + $^9$Be. Furthermore, in contrast to the above studies, in which the production cross sections are calculated for each element with a sum over isotopes, we analyze the isotopic production cross sections of AA collisions for detailed comparisons.

Our calculated production cross sections for the above reactions are shown in Figs. 1∼4 by the filled symbols; the red circles for the G4-BIN, the blue squares for the G4-QMD and the orange triangles for the P-JQMD. For comparison, we have also plotted the predictions from EPAX2 (the dashed lines) and EPAX3 (the solid lines) together with the experimental data (the open squares in black) taken from the EXFOR database.

Figures 1, 2, 3 show the results for 80 MeV/u $^{59}$Co, 95 MeV/u $^{72}$Zn, and 500 MeV/u $^{92}$Mo beams on the Be target, respectively. The G4-BIN (red circles) is found to be superior to other models in reproducing the experimental data. EPAX2 and EPAX3 also reproduce well the experimental data for most cases, but underestimate in some cases, in particular, for the production of the $^{31}$Ga isotopes for $^{72}$Zn beam. The P-JQMD (orange triangles) and the G4-QMD (blue squares) overestimate the production of neutron-rich isotopes of heavier elements by a factor of $\lesssim 10^4$, while they give results as good as the G4-BIN
Figure 1: (Color online) Production cross sections of various isotopes due to the collision $^{59}\text{Co} + ^{9}\text{Be}$ at 80 MeV/u. The open squares in black denote the experimental data [34], and the dashed (solid) lines represent EPAX2 (EPAX3) results. The simulation results are denoted by the filled symbols; the red circles for G4-BIN, the blue squares for G4-QMD and the orange triangles for P-JQMD.
Figure 2: (Color online) Production cross sections of various isotopes due to the collision $^{72}$Zn + $^9$Be at 95 MeV/u. The open squares in black denote the experimental data [35]. See the caption of Fig. 1 for the meaning of other symbols.
for the production of light elements.

In Fig. 4, the results for $^{132}\text{Sn} + ^9\text{Be}$ reactions at 950 MeV/u are shown. All the calculation results do not reproduce well the experimental data. The P-JQMD underestimates the production of $^{48}\text{Cd} \sim ^{51}\text{Sb}$ isotopes, while the G4-QMD overestimates the production of $^{45}\text{Rh} \sim ^{49}\text{In}$ isotopes by a factor of $\lesssim 10^3$. On the other hand, EPAX2 and EPAX3 show rather good overall agreements, though EPAX2 overestimates $^{46}\text{Pd}$ isotopes, EPAX3 underestimates neutron-rich isotopes of $^{49}\text{In}$, and both underestimate $^{51}\text{Sb}$ isotopes. Finally, the G4-BIN, which has shown the best performance for other cases, is also found to overestimate the productions of $^{46}\text{Pd} \sim ^{48}\text{Cd}$ isotopes by $\lesssim 10^2$. Such overestimation of the production cross sections should be ultimately resolved by refining the hadronic models, which is beyond the scope of this work.

These benchmark calculations show that the G4-BIN gives the most reasonable results among the three models. It is expected that the accuracy of the G4-BIN would be better even for the $^{132}\text{Sn}$ beam at energies lower than 950 MeV/u (for instance $\sim 200$ MeV/u) for the following reason. We note that the experimental cross sections are nearly independent of the incident beam energies $^{18, 26, 33, 38, 39, 40, 41, 42}$, where we have plotted experimental production cross sections of $^{48}\text{Pd} \sim ^{50}\text{Sn}$ isotopes due to $^{132}\text{Sn}^{10}$, $^{136}\text{Xe}^{42, 43, 44}$ and $^{238}\text{U}^{45, 46, 47}$ beams. It is clearly seen that the cross sections are mainly characterized by the species of the incident beams, and the energy-dependence is rather weak.

On the other hand, the G4-BIN seems to have some energy-dependence, and the calculated yields at the energy of $\sim 200$ MeV/u agree with the experimental data obtained at 950 MeV/u while G4-BIN overestimates the data at 950 MeV/u for $^{46}\text{Pd} \sim ^{48}\text{Cd}$ isotopes. We plot in Fig. 6 the G4-BIN...
Figure 3: (Color online) Production cross sections of various isotopes due to the collision $^{92}\text{Mo} + ^9\text{Be}$ at 500 MeV/u. The open squares in black denote the experimental data \cite{36}. See the caption of Fig. 1 for the meaning of other symbols.
Figure 4: (Color online) Production cross sections of various isotopes due to the collision $^{132}\text{Sn} + ^{9}\text{Be}$ at 950 MeV/u. The open squares in black denote the experimental data [10]. See the caption of Fig. 1 for the meaning of other symbols.
predictions for the production cross sections of $^{45}$Rh $\sim ^{50}$Sn isotopes due to the $^{132}$Sn beams at 100, 200, 300, 500 and 950 MeV/u on the Be target. The energy-dependence of the G4-BIN is weak for Z= 49$\sim$50, but becomes somewhat stronger as Z decreases below 49. As mentioned, the G4-BIN predictions at the energy of $\sim$ 200 MeV/u agree well with the 950 MeV/u data regardless of the atomic number Z. If the aforementioned experimentally observed energy-independence of the cross section remains down to 200 MeV/u, we expect a good agreement will be obtained between the data and the G4-BIN calculation results at 200 MeV/u, for which the beam energy is being planned for RAON [11, 12, 13].

Similar features can be seen for $^{136}$Xe beam, whose experimental data are available at 500 and 1000 MeV/u. As shown in Fig. 7 the predicted cross sections at 200 MeV/u are close to the data at 500 and 1000 MeV/u, and the energy-dependence of the calculated cross section due to $^{136}$Xe beam is quite similar to that of $^{132}$Sn.

From the above comparisons of the results by using different models, it is found that the G4-BIN gives more reasonable results for the isotopic productions than other models. The G4-QMD does not reproduce well the experimental data especially for the production of neutron-rich isotopes. The P-JQMD either overestimates or underestimates the experimental data. Thus, we have chosen the G4-BIN as our simulation engine, and the results presented in the next subsection are calculated by the G4-BIN.

3.2. Production yields of neutron rich isotopes by using TSRS

To see the effectiveness of TSRS, one needs to estimate the production yields from TSRS. Production yields are sensitive to the target thickness. As the target thickness increases, the number of the collisions between the incident ions and the target nuclei also increases. But if the target is too
Figure 5: (Color online) Experimental data for the production cross sections of $^{46}$Pd $\sim ^{50}$Sn isotopes. Black boxes are for 950 MeV/u $^{132}$Sn + $^9$Be [10]. Inverted orange triangles are for 1000 MeV/u $^{136}$Xe + $^1$H [43], red circles for 1000 MeV/u $^{136}$Xe + $^9$Be [44] and green triangles for 500 MeV/u $^{136}$Xe + $^2$H [42]. And pink triangles are for 1000 MeV/u $^{238}$U + $^1$H [45], blue stars for 1000 MeV/u $^{238}$U + $^2$H [46], blue triangles for 950 MeV/u $^{238}$U + $^9$Be [47] and and green circles for 950 MeV/u $^{238}$U + $^{208}$Pb [47].
Figure 6: (Color online) Production cross sections of $^{132}\text{Sn} + ^9\text{Be}$. The open squares in black denote the experimental data at 950 MeV/u [10], and the filled symbols with lines represent the G4-BIN results for a few selected incident energies.
Figure 7: (Color online) Production cross sections of $^{136}$Xe beams. Red circles for 1000 MeV/u $^{136}$Xe + $^9$Be [44], inverted orange triangles are for 1000 MeV/u $^{136}$Xe + $^1$H [43] and green triangles for 500 MeV/u $^{136}$Xe + $^2$H [42]. The filled symbols with lines denote the G4-BIN results for a few selected values of incident energy.
Figure 8: (Color online) The total number of ions per incident ion escaping from the Be target. The red squares and the open black circles denote $^{132}\text{Sn}$ and $^{238}\text{U}$ beams of 200 MeV/u, respectively. The lines are to guide the eyes.

Figure 8 shows the dependence of the yields on the target thicknesses. It can be seen that at the energy of 200 MeV per nucleon the optimal thickness is 0.8 cm and 0.5 cm for $^{132}\text{Sn}$ and $^{238}\text{U}$ beams, respectively, and thus these thicknesses are chosen for our simulations of the production yields.

A schematic geometrical setup of our simulation is drawn in Fig. 9. Incident ions are treated as a pencil beam. The $^9\text{Be}$ target is modeled as a cylinder of radius 1 cm, whose thickness is chosen as 0.8 cm and 0.5 cm for $^{132}\text{Sn}$ and $^{238}\text{U}$ beams, respectively. A scoring region of a spherical shell shape is placed surrounding the target. The inner and the outer radius of the scoring region are chosen to be 100 cm and 100.1 cm, respectively. The target area is in vacuum, and the thickness of the scoring region is chosen as 0.1 cm.
cm arbitrarily for convenience and does not affect the results. We score only those isotopes that reach the scoring region. The scoring shell consists of 18 angular bins with an interval of 10 degrees. We find that about $\sim 98\%$ of the yields are concentrated in the forward direction bin with $\theta < 10^\circ$ and thus we show only the scoring results in the forward bin ($\theta < 10^\circ$) for convenience.

Figure 10 shows the yields of the nuclides produced by $^{132}$Sn and $^{238}$U beams. $^{132}$Sn beam produces isotopes mainly with $45 \leq Z \leq 50$, while the products due to $^{238}$U beam are concentrated on the diagonal region of N-Z plane that mainly consists of stable nuclides. We plot the ratios of the yields of the nuclides produced by $^{132}$Sn to those produced by $^{238}$U in Fig. 11, which clearly shows that $^{132}$Sn can produce more neutron-rich isotopes of $45 \leq Z \leq 50$ by nearly two or three orders of magnitudes than $^{238}$U beam.

Detailed production yields of nuclides are shown in Fig. 12 where the
yields of $^{45}$Rh $\sim$ $^{50}$Sn isotopes due to $^{132}$Sn and $^{238}$U beams are plotted with respect to the mass number $A$. We observe that the yield curves due to $^{238}$U beam are more or less parabolic, having the maximum yield value ($\sim 10^{-3}$ per incident ion) at around $A \simeq 2\times Z + 20$ for all the $Z$ values considered here. As $Z$ increases, the curves shift to the region of higher $Z$, but their shapes are almost unchanged for different elements. This behavior is in accordance with the right panel of Fig. 10, where we have observed that the population of the fission fragments of $^{238}$U is concentrated in the diagonal region in the N-Z plane.

The yield curves due to $^{132}$Sn beam also show the tendency to shift as $Z$ increases, and are similar to those of $^{238}$U in the light mass region for most cases of $Z$ values. But the curves deviate from those of $^{238}$U in the heavier mass region. The tails with larger $A$ values are tilted upward for $^{132}$Sn, while those for $^{238}$U drop rapidly. This shows that $^{132}$Sn produces more effectively
Figure 11: (Color online) The ratios of the yields due to $^{132}\text{Sn}$ beam to the yields due to $^{238}\text{U}$ beam. The region where the ratio is greater than $10^3$ is denoted by black.
neutron-rich isotopes than $^{238}\text{U}$ beam. This tendency becomes stronger as $Z$ increases, and the tail for $^{49}\text{In}$ becomes almost flat up to $N=82$. The mass region where the yields due to $^{132}\text{Sn}$ exceed those of $^{238}\text{U}$ keeps increasing in general with higher $Z$: $A \geq 118$ for $^{45}\text{Rh}$, $A \geq 119$ for $^{46}\text{Pd}$, $A \geq 120$ for $^{47}\text{Ag}$, $A \geq 122$ for $^{48}\text{Cd}$, $A \geq 123$ for $^{49}\text{In}$, and $A \geq 114$ for $^{50}\text{Sn}$.

Note that the yield curves due to $^{132}\text{Sn}$ show a shell structure with the cusps developed at the magic number $N=82$. The yield for $N=82$ isotope is about $10^{-8}$ for $^{127}\text{Rh}$, $10^{-6}$ for $^{128}\text{Pd}$, $10^{-5}$ for $^{129}\text{Ag}$, $10^{-4}$ for $^{130}\text{Cd}$ and $2 \times 10^{-3}$ for $^{131}\text{In}$ in the unit of $1/(\text{incident ion})$. For all the cases considered, the yields for the isotopes with $N>82$, which requires more neutrons than the incident $^{132}\text{Sn}$ beam are found to be suppressed by a factor of $\simeq 10$ for each additional neutron.

Our results show that at the energy of 200 MeV/u $^{132}\text{Sn}$ beam is more effective in producing neutron-rich isotopes than $^{238}\text{U}$ beam. In particular, the ratios of the yields increase by factors as big as $10^3$ for $^{131,132}\text{In}$, $^{129,130,131}\text{Cd}$ and $^{127}\text{Ag}$.

4. Summary

We have conducted a simulation study for the isotope production yields due to 200 MeV/u $^{132}\text{Sn}$ and $^{238}\text{U}$ beams on $^9\text{Be}$ target, making use of the G4BinaryLightIonReaction (G4-BIN) hadronic model with GEANT4 as our main engine after comparing simulation methods such as the G4-BIN, the G4-QMD and the P-JQMD. For the production of neutron-rich isotopes with $45 \leq Z \leq 50$, $^{132}\text{Sn}$ is found to be much more efficient than $^{238}\text{U}$ beam, supporting the usefulness of the TSRS mechanism.

In our benchmarking calculations for the production cross sections performed to check the accuracy of various hadronic models, however, we have observed that the adopted the G4-BIN has overestimated the production
Figure 12: (Color online) Yields of $^{45}$Rh $\sim ^{50}$Sn isotopes with respect to mass number. The red squares and the open black circles are for $^{132}$Sn and $^{238}$U beams, respectively.
of neutron-rich isotopes for 950 MeV/u $^{132}$Sn beam on the Be target by a factor of $\lesssim 10^2$. While we have discussed in Sec. 3.1 the reasons why we consider the actual uncertainty of our simulation results with 200 MeV/u beams would be much smaller, the uncertainty is expected to be there and remains to be resolved.

Acknowledgement

This work was supported in part by the Basic Science Research Program through the Korea Research Foundation (NRF-2013R1A1A2063824, NRF-2012R1A1A2007826, NRF-2012M2B2A4030183).

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