PRODUCTION PATHWAYS FOR MEDICALLY INTERESTING ISOTOPES*

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Abstract

Radioisotopes are commonly used in nuclear medicine for treating cancer and new, more effective treatment options are always desired. As a result, there is a national need for new radioisotopes and ways to produce them. A computer program was created that evaluates the daughters for all known reactions of projectiles (gamma rays, protons or neutrons) with every stable target isotope by comparing the cross-sections for each reaction at a desired energy. It then outputs a list of the potential daughter isotopes that are most likely to be generated. The program then evaluates the decay chains of these daughters to provide a list of the possible decay chains that contain a radioisotope of interest. By knowing the daughter production and decay chain for each isotope, it is possible to go from the desired radioisotope to the stable isotope that can be used as a target for its production. This project facilitates the search for new pathways to creating useful theranostic isotopes.

INTRODUCTION

Radioisotopes are used in nuclear medicine for diagnostic, therapeutic, and preventive purposes. However, certain research radioisotopes still do not have a reliable production source, leading to a need for new isotope production pathways. Radioisotopes are produced by the irradiation of a target isotope with a projectile. The irradiated mother isotope may produce several daughters, some of which can decay further (granddaughters). There are many different decay chains for each daughter isotope; therefore, an efficient process is required to identify suitable target isotopes. Additionally, many other radioisotopes are co-produced during irradiation, some of which are potentially harmful. The initial focus was to examine new pathways for medically interesting radioisotopes identified by the Department of Energy Isotope Program (DOE IP) [1].

To carry out an overview of all known reactions of projectiles with stable isotopes, their decay chains, and the co-produced isotopes, the computer program SNIPP (Search for New Isotope Production Pathways) was developed. SNIPP evaluates possible target isotopes by analyzing direct and cascade reactions by irradiation production for all stable or long-lived isotopes with different projectiles and selecting reactions that produce medically useful radioisotopes to find new production pathways. Using the output from the cascade reactions of the irradiation section, the program goes on to evaluate the isotope decay data and search for medically interesting radioisotopes that are produced. Lastly, it analyses the isotopes that are co-produced during the initial irradiation.

In evaluating the results, reactions that led to isotopes of the same element as the target were rejected. These would require isotopic purification of the radioactive target, a difficult, if not impossible task.

METHODS

The SNIPP program is divided into three sections: irradiation production, decay reactions, and post-processing.

Irradiation Production

The irradiation section analyzes reactions according to input parameters entered by the user. These include whether the target consists of the naturally occurring mix of isotopes (mixed) or has been isotopically purified (pure); the start and end isotope for the search list; the production method (direct or cascade); the projectile (gammas, fast or thermal neutrons, low or high energy protons); a minimum cross section and half-life window for the daughters; and the projectile energy. For purified isotopes, the isotopic purification percentage may be entered. The projectile parameters used for the data presented in this paper are those used for previous papers [2] and were selected considering the most likely production method. The cross-sections were obtained from the TENDL database [3] and the half-lives were obtained from National Nuclear Data Center Wallet Cards (NWC) [4]. Using these parameters, the program identifies reactions with cross sections and half-lives within the entered parameters.

Decay Reactions

The decay section tracks the decay paths of the radioisotopes produced by cascade reactions in the irradiation section. The data of the current existing isotopes, which includes the list of isotopes, their decay modes, and the branch percentages, was obtained from the Berkeley spreadsheet based on data from the NWC [4]. The program goes through the list of isotopes and follows each isotope's decay branch to find isotopes of interest according to the user entered list of isotopes.

Post-Processing

The post-processing section analyzes the results from the irradiation and decay sections. For both direct and cascade results from the irradiation section, it finds reactions that

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produce medically interesting isotopes according to the input list, and the isotopes that are co-produced in these reactions. The final output of SNIPP is a list of medically interesting daughter and granddaughter isotopes, the targets and reactions that produce them, and information on the produced isotopes and the reactions that produce them. The flow chart of the program is shown in Fig. 1.

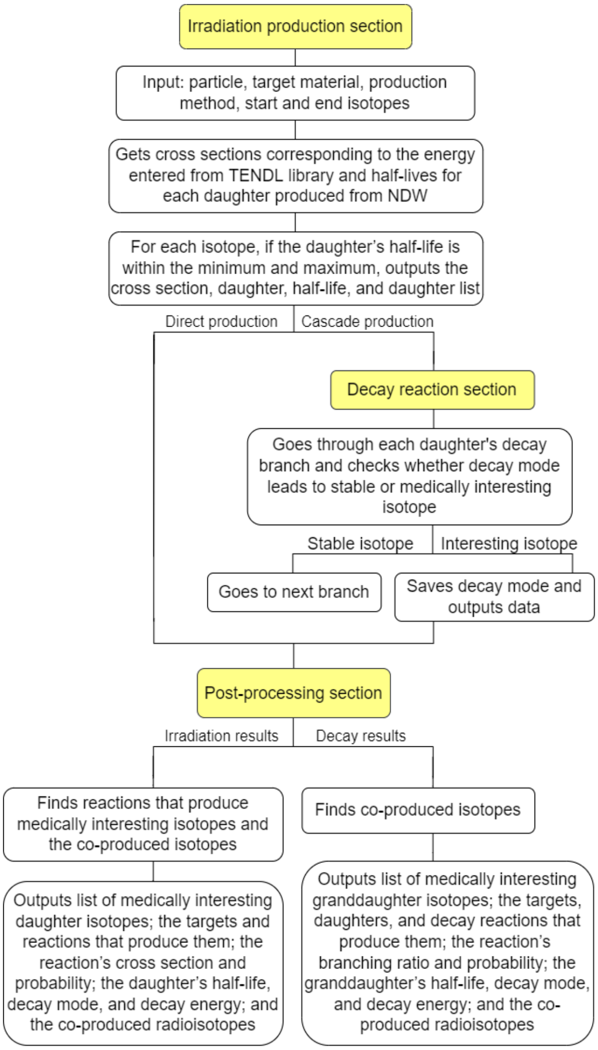

Figure 1: Program flowchart.

RESULTS

For this paper, SNIPP was run for irradiation and decay production gamma and proton reactions using naturally occurring target isotopes. A total of 71,084 gamma reactions and 74,316 proton reactions were examined. Of these, 9 gamma reactions and 36 proton reactions produced isotopes of medical interest via irradiation production. From these reactions, examples with large cross sections and small co-production of undesirable isotopes were selected.

Gamma Irradiation

Two pathways were found for the production of ^{47}Sc, (see Table 1). The first reaction is ^{48}Ti (γ,p) ^{47}Sc, with a cross section of 13.3 barn and a reaction probability of 9.8 barn (the reaction probability is the product of the cross-section and the fraction of the relevant isotope in the target). This reaction co-produces ^{48}Sc; which could be significantly reduced by using an isotopically purified target. The second reaction is ^{51}V (γ,α) ^{47}Sc, which has a cross section of 0.6 barn and a reaction probability of 0.6 barn, and no co-produced isotopes.

Table 1: Results for 20 MeV Gamma Pathway for ^{47}Sc

	Irradiation Production								
	Target	**% of Isotope in Target**	**Reaction**	**Cross section (barns)**	**Daughter**	**Half-life (days)**	**Decay mode**	**Energy (MeV)**	**Reaction probability (barns)**
	^{51}V	99.8%	^{51}V (γ,α) ^{47}Sc	0.6	^{47}Sc	3.3	β-	0.6	0.6
	^{48}Ti	73.7%	^{48}Ti (γ,p) ^{47}Sc	13.3	^{47}Sc	3.3	β-	0.6	9.8
Co-Produced	^{49}Ti	5.4%	^{49}Ti (γ,p) ^{48}Sc	4.6	^{48}Sc	1.8	β-	4.0	0.2

Two production pathways for ^{67}Cu were found (see Table 2). The reaction ^{68}Zn (γ,p) ^{67}Cu has a cross section of 2.0 barn and a reaction probability of 0.4 barn, and no co-produced isotopes. The reaction ^{71}Ga (γ,α) ^{67}Cu has a cross section of 0.7 barn and a reaction probability of 0.3 barn. This reaction co-produces ^{67}Ga with a reaction probability of 12.1 barns. This pathway would be improved by using an isotopically purified target.

Table 2: Results for 20 MeV Gamma Pathway for ^{67}Cu

	Irradiation Production								
	Target	**% of Isotope in Target**	**Reaction**	**Cross section (barns)**	**Daughter**	**Half-life (days)**	**Decay mode**	**Energy (MeV)**	**Reaction probability (barns)**
	^{68}Zn	18.4%	^{68}Zn (γ,p) ^{67}Cu	2.0	^{67}Cu	2.6	β-	0.6	0.4
	^{71}Ga	39.9%	^{71}Ga (γ,α) ^{67}Cu	0.7	^{67}Cu	2.6	β-	0.6	0.3
Co-Produced	^{69}Ga	60.1%	^{69}Ga (γ,2n) ^{67}Ga	20.1	^{67}Ga	3.3	ϵ	1.0	12.1

Proton Irradiation

Two production pathways were found for producing ^{52}Mn with 20 MeV protons (see Table 3). The first reaction is ^{52}Cr (p,n) ^{52}Mn, with a cross section of 68.8 barn and a reaction probability of 57.7 barn. The second reaction is ^{53}Cr (p,2n) ^{52}Mn, with a cross section of 305.0 barn and a reaction probability of 29.0 barn. In both pathways no other isotopes are co-produced when irradiating naturally occurring chromium, making this an extremely interesting production pathway with a total reaction probability of 86.7 barn from naturally occurring chromium.

The production of ^{55}Co from ^{56}Fe by the reaction ^{56}Fe (p,2n) ^{55}Co was also identified. Three isotopes are co-produced when irradiating iron: ^{55}Co, ^{52}Mn, and ^{56}Mn from three different iron isotopes (see Table 4). However, their reaction probabilities are small (the reaction probability is less than 1% of the reaction probability for producing ^{55}Co) and chemical separation of the desired radioisotope and the unwanted co-produced radioisotopes would be possible.

Therefore, this would also be a viable pathway to produce ^{55}Co.

Table 3: Results for 20 MeV Proton Pathway for ^{52}Mn

	Irradiation Production								
	Target	**% of Isotope in Target**	**Reaction**	**Cross section (barns)**	**Daughter**	**Half-life (days)**	**Decay mode**	**Energy (MeV)**	**Reaction probability (barns)**
	^{52}Cr	83.8%	^{52}Cr (p,n) ^{52}Mn	68.8	^{52}Mn	5.6	EC	3.7	57.7
	^{53}Cr	9.5%	^{53}Cr (p,2n) ^{52}Mn	305.0	^{52}Mn	5.6	EC	3.7	29.0
Co-Produced	^{52}Cr	None							
	^{53}Cr	None							

Table 4: Results for 20 MeV Proton Pathway for ^{55}Co

	Irradiation Production								
	Target	**% of Isotope in Target**	**Reaction**	**Cross section (barns)**	**Daughter**	**Half-life (days)**	**Decay mode**	**Energy (MeV)**	**Reaction probability (barns)**
	^{56}Fe	91.8%	^{56}Fe (p,2n) ^{55}Co	60.5	^{55}Co	0.7	EC	2.4	55.5
Co-Produced	^{54}Fe	5.8%	^{54}Fe (p,γ) ^{55}Co	0.5	^{55}Co	0.7	EC	2.4	0.03
	^{56}Fe	91.6%	^{56}Fe (p,n+α) ^{52}Mn	0.5	^{52}Mn	5.6	EC	3.7	0.5
	^{57}Fe	2.1%	^{57}Fe (p,2p) ^{56}Mn	4.8	^{56}Mn	0.1	β-	3.7	0.1

Two production pathways were found for ^{48}V by irradiation production (see Table 5). The first is ^{48}Ti (p,n) ^{48}V, with a cross section of 74.5 barn and a reaction probability of 54.9 barn. The second is ^{49}Ti (p,2n) ^{48}V, with a cross section of 431.7 barn and a reaction probability of 23.3 barn. These reactions have a significant number of co-produced isotopes; however, most of them have small reaction probabilities. The exception is the reaction ^{46}Ti (p,d) ^{45}Ti with a cross-section of 360.7 barn and a reaction probability of 30.0 barn. However, the lifetime of ^{45}Ti is 3 hours, so it will have decayed to negligeable values after a day. This reaction has been used before, so it is not a new pathway [5]. But is does indicate the power of SNIPP to identify pathways.

Table 5: Results for 20 MeV Proton Pathway for ^{48}V

	Irradiation Production								
	Target	**% of Isotope in Target**	**Reaction**	**Cross section (barns)**	**Daughter**	**Half-life (days)**	**Decay mode**	**Energy (MeV)**	**Reaction probability (barns)**
	^{47}Ti	7.4%	^{47}Ti (p,γ) ^{48}V	0.7	^{48}V	16.0	EC	3.0	0.05
	^{48}Ti	73.7%	^{48}Ti (p,n) ^{48}V	74.5	^{48}V	16.0	EC	3.0	54.9
	^{49}Ti	5.4%	^{49}Ti (p,2n) ^{48}V	431.7	^{48}V	16.0	EC	3.0	23.3
Co-Produced	^{46}Ti	8.3%	^{46}Ti (p,α) ^{43}Sc	12.9	^{43}Sc	0.2	EC	1.2	1.1
	^{46}Ti	8.3%	^{46}Ti (p,d) ^{45}Ti	360.7	^{45}Ti	0.1	EC	1.0	30.0
	^{47}Ti	7.4%	^{47}Ti (p,n+α) ^{43}Sc	16.4	^{43}Sc	0.2	EC	1.2	1.2
	^{47}Ti	7.4%	^{47}Ti (p,α) ^{44}Sc	40.5	^{44}Sc	0.2	EC	2.6	3.0
	^{48}Ti	73.7%	^{48}Ti (p,n+α) ^{44}Sc	0.9	^{44}Sc	0.2	EC	2.6	0.7
	^{48}Ti	73.7%	^{48}Ti (p,2p) ^{47}Sc	3.8	^{47}Sc	3.3	β-	0.6	2.8
	^{49}Ti	5.4%	^{49}Ti (p,n+2p) ^{47}Sc	1.5	^{48}Sc	1.8	β-	4.0	0.1
	^{50}Ti	5.2%	^{50}Ti (p,α) ^{47}Sc	16.5	^{47}Sc	3.3	β-	0.6	0.9

The decay reactions returned 7 gamma reactions and 21 proton reactions which produced interesting isotopes. Of these, most contained a large number of co-produced isotopes, and/or produced isotopes that could not be chemically separated from the original target or the co-produced isotopes. Therefore, no acceptable decay reaction pathways were found for the other isotopes listed in the DOE IP list of medically interesting isotopes.

Interestingly, no viable pathways were found for decay reactions for 20 MeV gamma rays, 20 MeV protons or thermal or energetic neutrons.

Additionally, irradiation production pathways for medically interesting isotopes not on the DOE IP list were also found. One example is the production of ^{18}F from ^{18}O by proton irradiation, a pathway which is already widely used in hospital cyclotrons.

CONCLUSION

SNIPP has already been shown to be efficient in finding new possibilities for producing radioisotopes. Up to now, the program has primarily been used to identify production pathways for radioisotopes on the DOE list [1]. However, it is now capable of searching for pathways to produce radioisotopes with desired properties, e.g., alpha emitters with a half-life greater than 3 days. This provides an opportunity to look at a wide set of radioisotopes, including those of industrial interest.

It should be stressed that SNIPP provides guidance on pathways that might be fruitful. Using the cuts that have been assumed, a pathway that is not identified by SNIPP is almost certainly not going to be effective. However, finding a possible pathway with SNIPP does not guarantee that the chemical separation and purification will be easy or cheap. So, identifying a pathway with SNIPP is a necessary, but not sufficient requirement for exploitation.

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