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Calculations of ^{86}Y production *via* various nuclear reactions

SADEGHI Mahdi[1,*] ZALI Akram[2] MOKHTARI Leila[3]

[1] *Agricultural, Medical & Industrial Research School, P.O. Box: 31485-498, Gohardast, Karaj, Iran,*

[2] *Faculty of Engineering, Research and Science Campus, Islamic Azad University, Tehran, Iran*

[3] *Physics Faculty, University of Zanjan, P.O. Box: 45195/313, Zanjan, Iran*

Abstract This study obtains a suitable reaction to produce ^{86}Y. The ^{86}Y excitation functions *via* ^{86}Sr(p,n)^{86}Y, ^{86}Sr(d,2n)^{86}Y, ^{85}Rb(^{3}He,2n)^{86}Y and ^{85}Rb(α,3n)^{86}Y reactions were calculated by TALYS-1.0 code and compared with the reported measurement. Requisite thickness of targets was obtained by SRIM code for each reaction. The ^{86}Y production yield was evaluated with attention to excitation function and stopping power. The ^{86}Sr(p,n)^{86}Y reaction was determined as most interesting one due to its highest production yield and advantages to get high radionuclide and radiochemical purity.

Key words Yttrium-86, Excitation function, Target thickness, Production yield

1 Introduction

Yttrium-86 can be used as a PET imaging surrogate for ^{90}Y. It has a half-life of 14.74 h and decays by 66% electron capture and 34% positron emission to ^{86}Sr emitting simultaneously γ-rays of 1076.6 (82%), 1153.2 (30.5%) and 627.8 (32.6%)[1-4]. Production of ^{86}Y has been studied *via* the ^{86}Sr(p,*x*n)[5,6], ^{85}Rb(^{3}He,*x*n)[6] and ^{85}Rb(α,*x*n)[7,8] reactions. The excitation function measured in 1991[5] *via* the ^{86}Sr(p,*x*n) process in 7.7–29.5 MeV showed the maximum cross section of 810 mb at 14.8 MeV. Rosch F, *et al*[6] found that the (p,n)-reaction leading to the formation of ^{86}Y at a threshold energy of about 6 MeV. And also in Ref.[6] they reported the nuclear data relevant to the ^{86}Y production *via* the ^{85}Rb(^{3}He,2n) reaction, which starts contributing at 8 MeV, with a maximum in cross section at about 18 MeV. They reported values of 270 mb for the natural isotopic composition, corresponding to 370 mb for extrapolation of ^{85}Rb enrichment to 100%. The experimental nuclear data related to the ^{85}Rb(α,3n)^{86}Y was reported by Iwata S[8], Levkovskij V N[5] and Guin R, *et al*[7]. Their works show the maximum cross sections of about 640 mb at 36 MeV, 1020 mb at 41 MeV and 654 mb at 41 MeV, respectively.

In this work, adequate reactions for ^{86}Y production in a cyclotron were investigated using TALYS-1.0 code and compared with the experimental data. The essential thickness of target material and the ^{86}Y production yield were evaluated. Finally, the suitable reaction was determined to take full benefit of excitation function and to avoid the formation of radionuclidic impurities.

2 Methods

2.1 Calculation of excitation function

Excitation functions of ^{86}Sr+p, ^{86}Sr+d, ^{85}Rb+^{3}He and ^{85}Rb+α reactions were calculated by using TALYS-1.0 code[9,10]. To take full benefit of the related excitation functions and to minimize the undesired radionuclide impurities formation, incident proton energy should be achieved using TALYS-1.0 code. The physical thickness of the target layer is chosen, for a given beam/target angle geometry, to provide a light-particle exit energy. According to SRIM code[11], the required thickness of target layer was calculated. It is advisable to minimize thickness of the target layer to perform irradiations on 6° target geometry. The calculated thicknesses are shown for ideal reactions in Table 1.

* Corresponding author. *E-mail address:* msadeghi@nrcam.org

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Table 1 Required thickness for ^{86}Y production

Reaction	$^{86}Sr(p,n)^{86}Y$	$^{86}Sr(d,2n)^{86}Y$	$^{85}Rb(^{3}He,2n)^{86}Y$
Energy range / MeV	15→4	13→5	15→27
Target thickness / μm	42.95	30.20	100.54

2.2 Calculation of theoretical yield

The production yield Y (in Bq) can be calculated by Eq.(1).

$$Y = \frac{N_L H}{M} I(1-e^{-\lambda t}) \int_{E_1}^{E_2} \left(\frac{dE}{d(\rho x)} \right)^{-1} \sigma(E) dE \quad (1)$$

where N_L is Avogadro number, H is isotope abundance of the target nuclide, M is the mass number of the target element, $\sigma(E)$ is the cross section at energy E, I is the projectile current, $dE/d(\rho x)$ is the stopping power, λ is the decay constant of the product and t is the time of irradiation. The production yield of ^{86}Sr *via* several reactions was calculated using the Simpson numerical integral as Eq.(1) (Table 2).

Table 2 ^{86}Y production yield for various reactions

Reaction	$^{86}Sr(p,n)^{86}Y$	$^{86}Sr(d,2n)^{86}Y$	$^{85}Rb(^{3}He,2n)^{86}Y$
Energy range /MeV	6–15	15–19	10–15
Theoretical yield, TALYS code /MBq·μA^{-1}·h^{-1}	215.49	91.68	1.76

3 Results

3.1 Excitation function of $^{86}Sr(p,n)^{86}Y$ reaction

Strontium carbonate targets have been used for producing ^{86}Y[1-4]. Excitation functions calculated by TALYS-1.0 code are shown in Fig.1 at different decay channels after proton bombardment of enriched strontium (isotopic abundance of ^{86}Sr is 9.86%). The reactions lead to the formation of ^{85}Y, $^{84/85/86}Sr$, and ^{83}Rb impurities. Although the separation of isotopic contaminations is not impossible by virtue of chemical methods, non-isotopic impurities can be separated in this way. As seen in Fig.1, the optimum bombarding energy range is 6–30 MeV, with the maximum cross section of 873 mb at 15 MeV. However, the threshold energy of ^{85}Y is also 15 MeV. Despite of the shorter half-life of ^{85}Y than ^{86}Y, it has high cross section. The ^{85}Y production has to be avoided, and the incident proton energy must be about 15 MeV. ^{86}Sr, the only impurity produced in this energy range, can be separated by chemical methods.

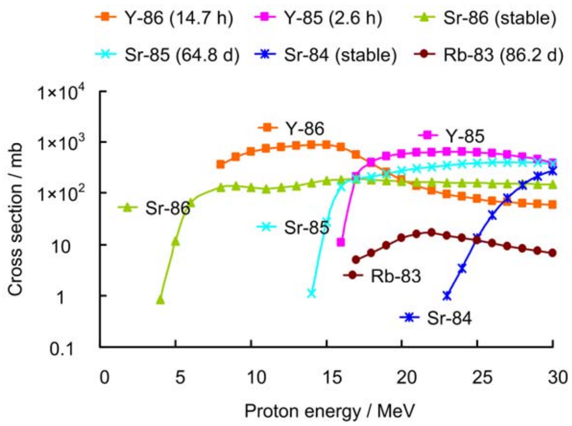

Fig.1 Excitation function of $^{86}Sr(p,n)^{86}Y$ reaction.

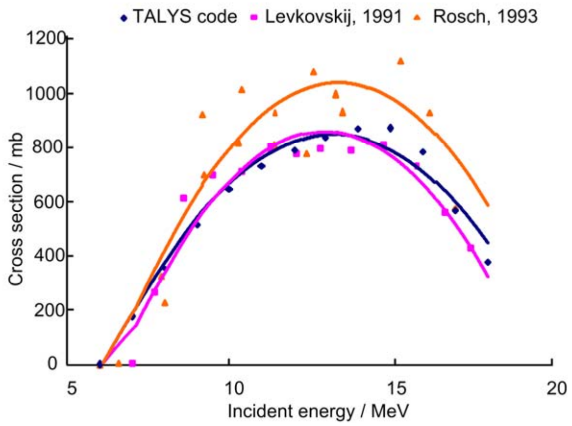

Fig.2 Comparison of experimental data and TALYS-1.0 code for excitation function of $^{86}Sr(p,n)^{86}Y$ reaction.

Fig.2 shows a comparison between the calculated cross section from TALYS code and the experimental data in Refs.[5,6]. The calculated data are in agreement with the experimental data. By virtue of SRIM code, the required target thickness should be 80 μm. According to cross section data of TALYS-1.0 code and stopping power, the ^{86}Y production yield would be 215.49 MBq·μA^{-1}·h^{-1}.

3.2 Excitation function of $^{86}Sr(d,2n)^{86}Y$ reaction

According to the TALYS code calculations, deuteron bombardment on enriched strontium target as carbonate causes to produce $^{85/87}Y$ radionuclidic impurities (Fig.3).

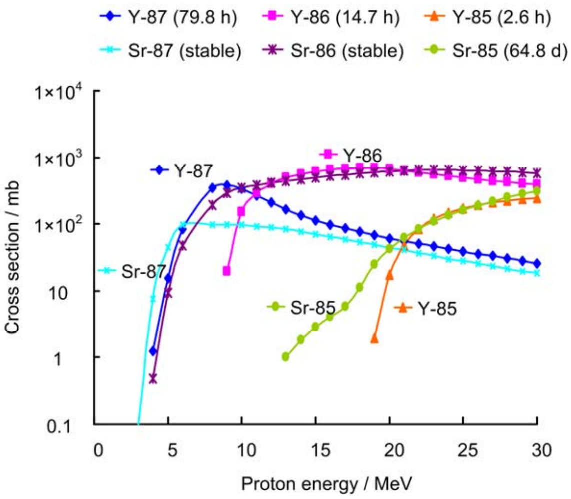

Fig.3 Excitation function of $^{86}Sr(d,2n)^{86}Y$ reaction.

The (d,2n)-reaction leads to the formation of ^{86}Y starts at a threshold energy of 8 MeV and reaches a maximum cross section of 691 mb at 19 MeV. If the incident energy is 19 MeV, the production of ^{85}Y will be avoided, but ^{87}Y ($t_{1/2}$=79.8 d) impurity will be produced in all energy regions. To reduce the production of ^{87}Y, an energy range of 15–19 MeV was chosen and the production yield was calculated. The required target thickness should be 30 μm and ^{86}Y production yield is 91.68 $MBq \cdot \mu A^{-1} \cdot h^{-1}$ for cross section data of TALYS-1.0 code.

3.3 Excitation function of $^{85}Rb(3He,2n)^{86}Y$ reaction

To produce ^{86}Y by $^{85}Rb+^{3}He$ reaction, rubidium has been employed as carbonate (isotopic abundance of ^{85}Rb is 72.16%). As shown in Fig.4, the radionuclidic impurities are ^{87}Y (3.35 d) and ^{85}Y (2.6 h). The maximum cross section of ^{86}Y is 294 mb at 16 MeV. The threshold energy of ^{85}Y production is 15 MeV. In order to prevent ^{85}Y production, the ^{3}He incident energy should be less than 15 MeV. In 10–15 energy range, there is no radionuclide impurity with high cross section. The non-isotopic contaminate is ^{86}Sr (stable) and ^{85}Sr (64.8 d). In Fig.5 the calculated data is compared with experimental data in Ref.[6]. The TALYS prediction shows less values of cross section than the experimental data. According to SRIM code, the thickness has to be 8 μm for 6° geometry and ^{86}Y production yield is 1.76 $MBq \cdot \mu A^{-1} \cdot h^{-1}$.

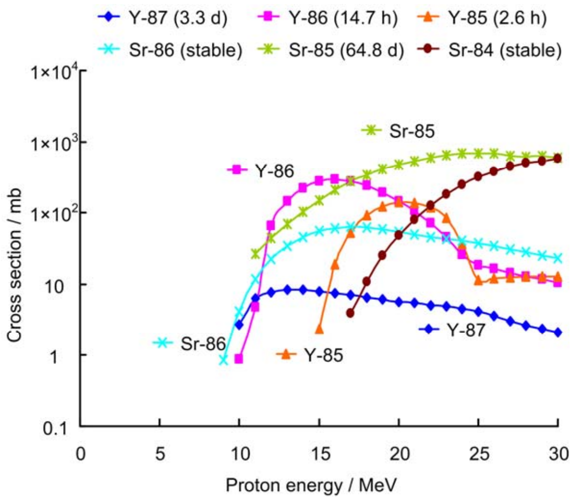

Fig.4 Excitation function of $^{85}Rb(^{3}He,2n)^{86}Y$ reaction.

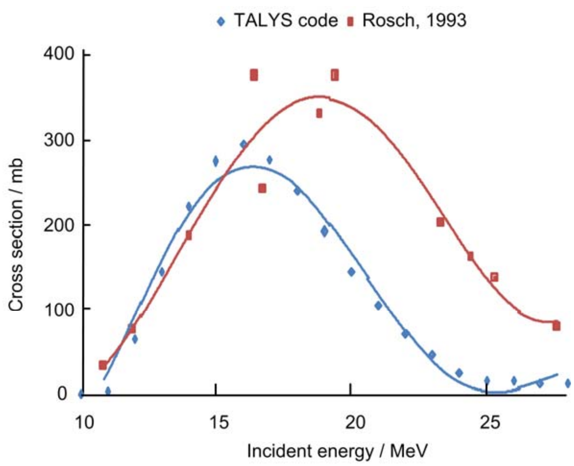

Fig.5 Comparison of experimental data and TALYS-1.0 code for excitation function of $^{85}Rb(^{3}He,2n)^{86}Y$ reaction.

3.4 Excitation function of $^{85}Rb(\alpha,3n)^{86}Y$ reaction

Rubidium can be used as chloride to produce ^{86}Y *via* alpha bombardment. As seen in Fig.6, ^{86}Y production begins at 25 MeV and has a maximum cross section of 956 mb at 40 MeV. In all energy regions, the ^{86}Y production is accompanied with $^{87/88}Y$ impurities, which could not be separated by chemical methods. So there is no energy range at which ^{86}Y can be produced without long-life isotopic impurities. Other contaminations include ^{85}Sr (64.48 d), ^{86}Sr (stable), ^{87}Sr (stable), ^{88}Sr (stable), ^{85}Rb (stable) and ^{84}Rb (32.7 d). In Fig.7, the calculated data is agreement with the cross section value reported in Refs.[5,7,8].

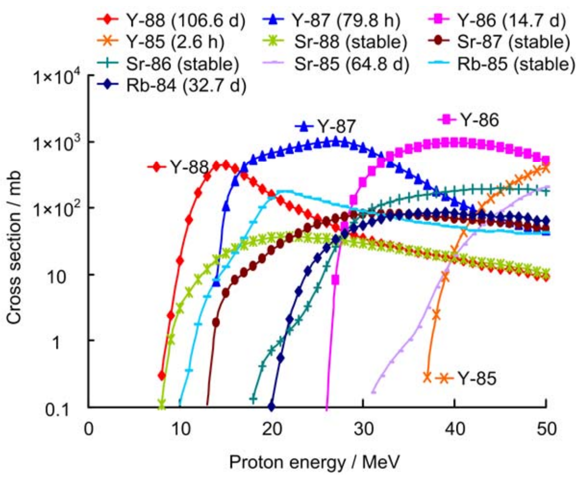

Fig.6 Excitation function of ^{85}Rb(α,3n)^{86}Y reaction.

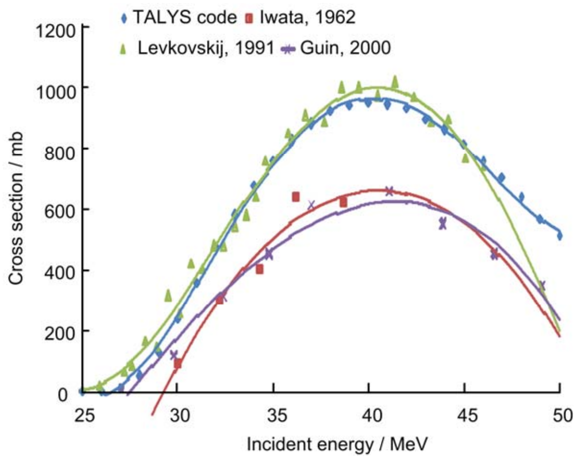

Fig.7 Comparison of experimental data and TALYS-1.0 code for excitation function of ^{85}Rb(α,3n)^{86}Y reaction.

4 Conclusion

The ^{86}Sr(d,2n)^{86}Y and ^{85}Rb(^{3}He,2n)^{86}Y reactions are not desirable to produce no-carrier-added of ^{86}Y because of the production of isotopic impurities. The results of the calculations show that the production yield of ^{86}Y *via* ^{86}Sr(p,n)^{86}Y will be considerably as much than the other reactions. Production of ^{86}Y can be achieve by ^{86}Sr(p,n)^{86}Y ideal reaction for low energy cyclotrons.

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