Medical radiaosotopes production: Activation cross-sections of ^{52}Mn by the alpha-induced reaction on natural vanadium (V)

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Excitation functions for α-induced reactions on natural vanadium were calculated in the energy range up to 50 MeV. The production cross sections of ^{52}Mn will be compared to some previously published results and the TALYS (TENDL 2019) code calculations. The integral yield of ^{52}Mn is derived from the calculated cross-sections and compared with those from other production routes.

Keywords: α-particles; ^{nat}V; induced nuclear reaction cross-section; excitation function; integral yield

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I. Introduction

Nowadays, many different stables and radioactive isotopes, each with unique physical and chemical properties, play significant roles in technological applications of importance to our modern society and are substantial to scientific research. One of the most common applications is the use of radioisotopes in medicine. Medical radioisotopes are used to label some special chemical compounds to form radiopharmaceuticals [1].

The radioisotope and radioactive materials have many essential applications in the medical sector, e.g., diagnostic, therapy, and sterilization. The main processes to produce the medical radioisotope and radioactive materials are neutron activation, nuclear fission, charged particles induced reactions, and radionuclide generators [2].

Charged particle (p, d, ^{3}He, α, etc.) induced nuclear reactions to having advantages that can be performed using cyclotrons in hospitals and get high-specific activities. The cross-sections of the charged particle induced reactions are of interest for many applications [3].

The radioisotope ^{52}Mn is an important medical radioisotope for diagnostic tests. The longer-lived ^{52}Mn ground state ($T_{1/2}$ = 5.591 d) has the potential for a PET tracer for preclinical in vivo neuroimaging, cell tracking, immuno-PET, and functional β-cell mass quantification. The long half-life with extremely high radiation that arises from the resulting gamma-ray emissions has limited ^{52}Mn clinical applications [4].

In this study, production cross-sections data of ^{52}Mn will be calculated for the α-particle-induced nuclear reactions on natural vanadium up to 50 MeV. The production cross sections of ^{52}Mn will be compared to some previously published results and the TALYS code calculations. Besides, production yields of ^{52}Mn using the α-particle-induced reactions will be compared with those of proton- and deuteron-induced nuclear reactions.

II. Methods and Calculations

During the past thirty years, several laboratories have reported a large body of experimental data, and the charged particle data centers have compiled many of those data in the Experimental Nuclear Reaction Data (EXFOR) form [5]. The use of nuclear theory for reliable prediction of cross-section data was and is even today limited. The whole evaluation methodology for charged particle data is still at an early stage of development.

Detailed searches for published experimental cross-sections were made, including the following sources: primary publications in journals, EXFOR database of International Atomic Energy Agency (IAEA) Nuclear Data Services (NDS), International Nuclear Information System (INIS) database, Evaluated Nuclear Data File (ENDF), reports and series of the IAEA, other relevant evaluations, private communications, etc.

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The excitation function of α-induced reactions on natural vanadium calculated using the TENDL 2019 (TALYS 1.95). TALYS Evaluated Nuclear Data Library (TENDL) is a nuclear data library, which provides the output of the TALYS nuclear model code system for direct use in both basic physics and applications. The TENDL contains evaluations for seven types (n, p, d, t, ^{3}He, α, γ) of incident particles, for all isotopes living longer than 1 second (about 2800 isotopes), in the 1 keV - 200 MeV energy range, with covariances [6]. It should be mentioned that this study represents a part of (a supplement) systematical study of charged particles-induced nuclear reactions.

Table 1. Possible reactions in this work with their Q-values and threshold energies.

Reaction	Q-value (MeV)	Threshold energy (MeV)
$^{50}V(\alpha,x)^{54}Mn$	8.7585	-
$^{50}V(\alpha,n)^{53}Mn$	-0.1803	0.1947
$^{50}V(\alpha,2n)^{52m}Mn$	-12.6122	13.6229
$^{50}V(\alpha,2n)^{52}Mn$	-12.2344	13.2148
$^{50}V(\alpha,3n)^{51}Mn$	-22.7691	24.5938
$^{50}V(\alpha,4n)^{50m}Mn$	-36.6820	39.6216
$^{50}V(\alpha,4n)^{50}Mn$	-36.4567	39.3783
$^{51}V(\alpha,x)^{55}Mn$	7.9334	Stable
$^{51}V(\alpha,n)^{54}Mn$	-2.2926	2.4727
$^{51}V(\alpha,2n)^{53}Mn$	-11.2314	12.1138
$^{51}V(\alpha,3n)^{52m}Mn$	-23.6633	25.5225
$^{51}V(\alpha,3n)^{52}Mn$	-23.2856	25.1151
$^{51}V(\alpha,4n)^{51}Mn$	-33.8203	36.4775

Table 2. Produced manganese (Mn) radionuclides and their nuclear data [8].

Radionuclide	Decay mode, %	Half-life	Eγ (keV)	Iγ (%)
^{55}Mn	Stable			
^{54}Mn	EC 99.99	312d	834.8	99.9
^{53}Mn	EC	3.7×10^{6}y	X-rays only	
^{52m}Mn	β^{+} 98.2	21.1min	1434.0	98.2
^{52}Mn	β^{+} 29	5.591 d	1434.0 935.5 744.2	100 94.5 90.0
^{51}Mn	β^{+} 97	46.2min	963.72	96.8
^{50m}Mn	β^{+} 100	1.75min	783.3	100
^{50}Mn	β^{+} 100	283ms	3628	0.03

We studied the excitation function of $^{50}V(\alpha,2n)^{52}Mn$, and $^{51}V(\alpha,3n)^{52}Mn$ reactions. Naturally occurring vanadium (V) is composed of one stable isotope ^{51}V (99.75%) and one radioactive isotope ^{50}V (0.25%) with a half-life of 1.5×10^{17} years [7]. Each radionuclide was identified by its characteristic γ-rays shown in Table 1-2.

III. Results and Discussion

A comparison between our calculated cross-sections and the previously reported data together with the theoretical calculations using the TALYS code is presented. The present calculation cross-section data are shown in figures 1-7 together with the experimental results in the literature and the theoretical calculations.

a. $^{52}Cr(p,n)^{52}Mn$ and $^{52}Cr(d,2n)^{52}Mn$ reactions

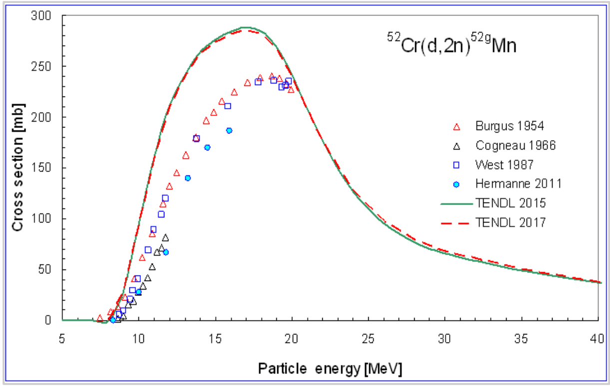

Figure 1. Recommended cross sections for $^{52}Cr(d,2n)^{52}Mn$ reaction [4].

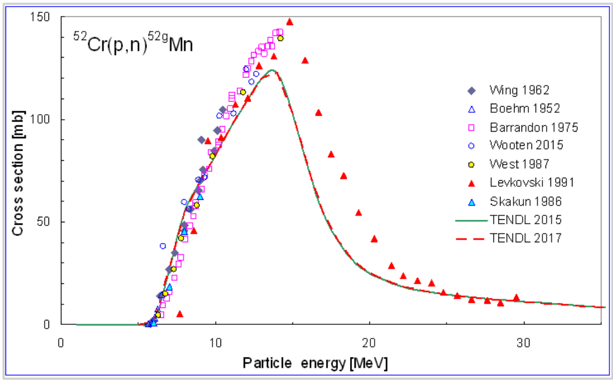

Figure 2. Recommended cross-sections for $^{52}Cr(p,n)^{52}Mn$ reaction [4].

The production of ^{52g}Mn utilizing accelerators compared to some previously published results and the TALYS code calculations on proton- or deuteron-induced nuclear reactions.

b. $^{50}V(a,2n)^{52}Mn$ and $^{51}V(a,3n)^{52}Mn$ reactions

The excitation functions for $^{50}V(\alpha,2n)^{52}Mn$- and $^{51}V(\alpha,3n)^{52}Mn$-induced nuclear reactions were calculated from their respective threshold energy up to 50 MeV. The present calculation cross-section data are shown in figures together with the previous experimental results in the literature and the theoretical calculations [9].

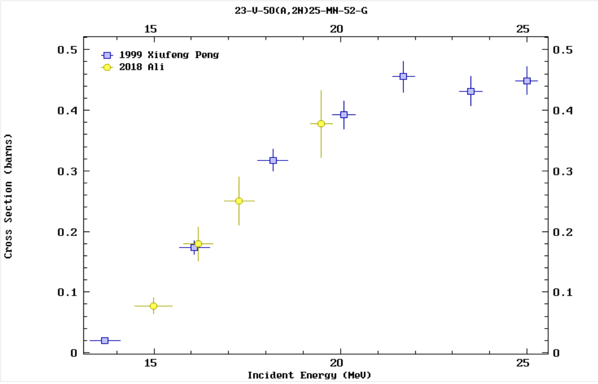

Figure 3. Previous experimental data of $^{50}V(\alpha,2n)^{52}Mn$ nuclear reaction on EXFOR.

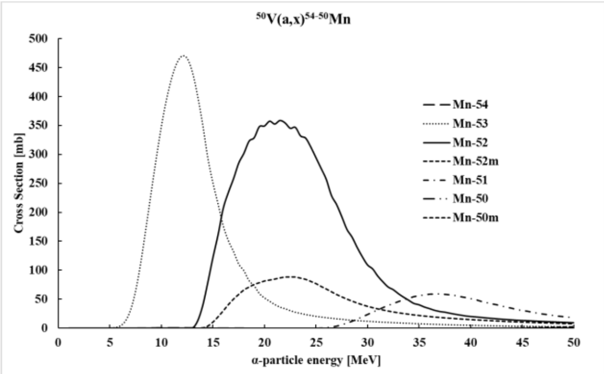

Figure 4. The calculation result of cross-sections $^{50}V(\alpha,x)^{54\text{-}50}Mn$ reactions by TENDL 2019.

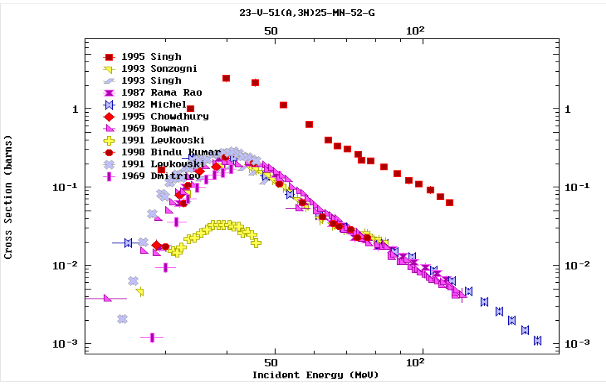

Figure 5. Previous experimental data of $^{51}V(\alpha,3n)^{52}Mn$ nuclear reaction on EXFOR.

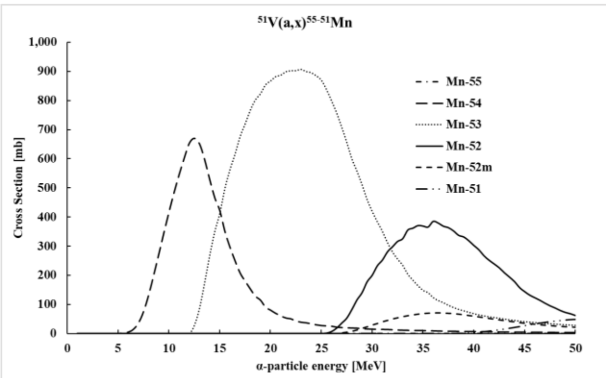

Figure 6. The calculation result of cross-sections $^{51}V(\alpha,x)^{55\text{-}51}Mn$ reactions by TENDL 2019.

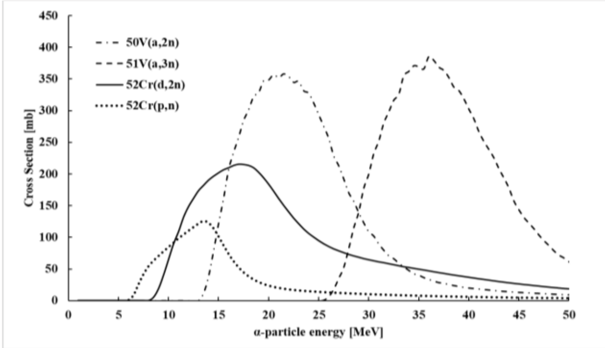

Figure 7. Comparison results of cross-section (^{52}Mn) on the proton-, deuteron-, and alpha-induced nuclear reactions by the TALYS code calculations.

c. Integral yield

The integral yields and activity for the production of the radionuclides ^{52}Mn were calculated in (GBq/mAh) using our calculated recommended excitation function for ^{52}Mn by the proton-, deuteron-, alpha-induced nuclear reactions on Chromium (^{51}Cr) and, Vanadium (^{nat}V). Using external beam energy of 50 MeV, irradiation took place at a constant beam current of 150 nA for about 0-48 hours.

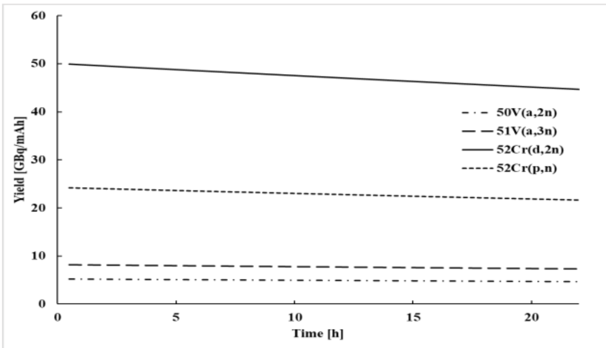

Figure 8. Integral yields of ^{52}Mn production via p, d, α-particle-induced nuclear reactions by the TALYS code calculations.

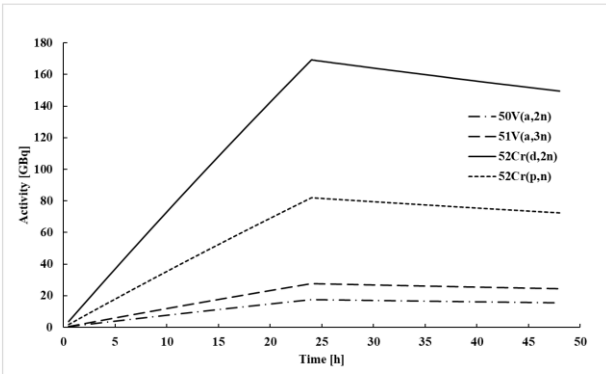

Figure 9. The activity of ^{52}Mn production via p, d, α-particle-induced nuclear reactions by the TALYS code calculations.

IV. Conclusion

^{52}Mn radioisotope is an important medical radioisotope for diagnostic tests. In this work, an alternative root of producing this isotope, either directly or through the ^{52}Mn, namely using accelerators, is introduced and discussed.

Activation cross sections of the alpha-induced reaction on ^{52}Mn were calculated up to 50MeV by the TALYS (TENDL 2019) code. Their excitation functions were compared with earlier experimental data found in the literature as well as theoretical data from the nuclear code TENDL 2019 library.

The excitation functions for the different proton- and deuteron-induced nuclear reactions on the ^{nat}V target are calculated and compared with some previously measured data. This study aims to resolve some contradictions between the existing data and to give a reliable data set for the production of ^{52}Mn and some other isotopes of importance in nuclear medicine besides some impurities.

The present excitation functions confirm some previously measured sets while contradicting others. Theoretical code calculations using TALYS code are performed and show good consistency with the calculated cross-section values. The code calculations can be used for cross-section estimations, when not enough experimental data exist.

The integral yield and activity calculated from the $^{nat}V(\alpha,x)^{52}Mn$ reactions and compared with those of the $^{52}Cr(p,n)^{52}Mn$ and $^{52}Cr(d,2n)^{52}Mn$ reactions. Furthermore, the integral yields are estimated based on the measured excitation functions for all the investigated reactions.

Finally, it is well known that for medical uses, enriched targets have to be used in the production to avoid the secondary produced unwanted impurities. While the studies on natural targets give an idea about the suitable energy range for maximum production of the wanted isotope and minimum of the impurities.

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