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# Experimental investigation and theoretical calculation for $^{3}$He induced nuclear reactions on vanadium

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ABSTRACT

Using stacked-foil activation technique and gamma-ray spectrometry, excitation functions for $^{3}$He induced nuclear reactions on $^{nat}$V were measured. Cross-sections for $^{nat}$V($^{3}$He,xn)$^{52m,g}$Mn and $^{nat}$V($^{3}$He,pxn)$^{51}$Cr nuclear reactions were measured up to 27 MeV utilizing the MGC-20E cyclotron of ATOMKI. The measurements establish for the first time consistent excitation curves. Comparisons with results for values derived from different theoretical codes were included. Integral yield were calculated.



## 1. Introduction

The excitation functions of charged particles induced nuclear reactions are important for many practical and medical applications: thin layer activation (TLA), accelerator technology and optimization of large scale production of medical radioisotopes etc. It is also required for testing nuclear reaction codes predictions. The long-lived radioactive nuclide $^{51}$Cr ($T_{1/2}$ = 27.7 d) is a commonly used marker for medical diagnostics. It is produced commercially in many forms as $^{51}$Cr-HSA (Human Serum Albumin), chromium chloride, sodium chromate and the widely used $^{51}$Cr-EDTA (Ethylenediaminetetraacetic acid) [1–3]. Vanadium is one of the coating metals of the High-Speed Steel (HSS) alloys that are used in many applications in various mechanical and cutting tools. Therefore, the activation of vanadium can be used in determination of the activity-depth distribution through TLA. Induced nuclear reactions of protons, deuterons and alpha-particles on natural vanadium were found in the literature [4–7]. In this work excitation functions for $^{3}$He induced reactions on natural vanadium measured by using the stacked-foil technique are being presented up to 27 MeV for the first time. Excitation functions of the nuclear reactions producing the long-lived radioisotopes $^{52g}$Mn and $^{51}$Cr were evaluated from their respective thresholds up to 27 MeV. Excitation functions of the nuclear reactions producing the short-lived isotopes $^{52m}$Mn and $^{51}$Mn were evaluated in an energy window near the end of our energy range. The natural occurrence of vanadium consists of two isotopes: the first one is the stable $^{51}$V with abundance of 99.75% and the second one is the very long-lived $^{50}$V with only 0.25% abundance. Therefore, cross-section data of $^{nat}$V can be considered as isotopic cross-section data in most cases.

## 2. Experimental

Cross-sections were measured by the activation method utilizing the stacked-foil technique at MGC-20E cyclotron of Institute for Nuclear Research (ATOMKI), Debrecen, Hungary. The experimental set-up and data processing were similar to that described in our earlier publications [8,9]. High purity natural vanadium foils (>99.98% supplied by Goodfellow, England) with a thickness of 8.41 μm were assembled together with natural titanium foils with a thickness of 12 μm in one stack. The stack consisted of 17 high purity natural V foils and 7 high purity natural Ti monitor foils. It was irradiated in a Faraday-cup like target holder with collimator

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and secondary electron suppresser. Irradiation took place for one hour using 27 MeV incident $^{3}$He-particle beam with a constant current of 100 nA. The energy and flux of the extracted beam were derived from the accelerator setting and the charge integrated on the Faraday-cup. The monitors were used as projectile energy degradation, recoil catchers and for exact determination of the beam intensity and energy by re-measuring the excitation function for the $^{nat}$Ti($^{3}$He,x)$^{48}$V reaction over the entire energy domain. For energy degradation along the stack, the stopping power of $^{3}$He-particles in vanadium was calculated using the SRIM-2013 code [11]. The incident energy was estimated at 26.7 ± 0.3 MeV at the middle of the first foil in the stack. The uncertainty of energy increases along the stack due to cumulative effects, it reaches its maximum of ±1.4 MeV at the last foil.

The activity of the produced radionuclides was measured with standard high resolution γ-ray spectrometer consists of HPGe detectors coupled to multi-channel analyzers. The spectra were measured at different and large distances to avoid coincidence losses. Detectors efficiencies for different measuring distances were carefully determined using different standard sources. There was no chemical separation after irradiation. Spectra analysis were done using γ-analysis program FGM [11]. Measurements of the induced activity started shortly after EOB (End of Bombardment) and repeated four times later.

The cross-sections were calculated from the well-known activation formula taking into account the measured activity, the particle flux and the number of target nuclei. The contributing reactions of each product and their *Q*-values are given in Table 1. The decay data and *Q*-values were taken from NuDat 2.6 data base [12]. Direct and cumulative processes were taken into account. The beam energy and intensity parameters were adapted by comparing the excitation function of the monitor reaction $^{nat}$Ti($^{3}$He,x)$^{48}$V with the recommended values of the IAEA-TECDOC 1211 see (Fig. 1) [13].

The uncertainty on each cross-section was estimated in the standard way [14] by taking the square root of the sum in quadrature of all individual contributions. The following individual uncertainties are included in the error calculations: incident particle intensity (7%), determination of the peak areas including statistical errors (3%), decay data (3%), the number of target nuclei including non-uniformity (5%) and detector efficiency (7%). The total uncertainty of the cross-sections was evaluated to be approximately 12% and, in some cases it was higher.

## 3. Theoretical calculations

The experimental cross-sections were compared to theoretical cross-sections calculated by the nuclear codes TALYS-1.6 [15] and EMPIRE-3.1 "Rivoli" [16]. For TALYS prediction, the data in the TENDL library (2014) [17] based on calculations of the $^{3}$He induced reactions of the TALYS-1.6 code were used. The data in TENDL library (2013) [18] based on TALYS-1.4 code [19] were also calculated but, we found that the data in the two versions of TENDL library (2013, 2014) are the same. So, only the data in TENDL library 2014 were used.

**Table 1**
Contributing nuclear reactions kinematics.

| Product | Contributing reactions | *Q*-value (MeV) | $E_{th}$ (MeV) |
|---|---|---|---|
| $^{52g}$Mn | $^{51}$V($^{3}$He,2n) | −2.71 | 2.87 |
| | $^{50}$V($^{3}$He,n) | 8.34 | 0 |
| $^{52m}$Mn | $^{51}$V($^{3}$He,2n) | −3.06 | 3.25 |
| | $^{50}$V($^{3}$He,n) | 8.71 | 0 |
| $^{51}$Mn | $^{51}$V($^{3}$He,3n) | −13.24 | 14.03 |
| | $^{50}$V($^{3}$He,2n) | −2.19 | 2.32 |
| $^{51}$Cr | $^{51}$V($^{3}$He,p2n) | −9.25 | 9.80 |
| | $^{50}$V($^{3}$He,pn) | 1.80 | 0 |

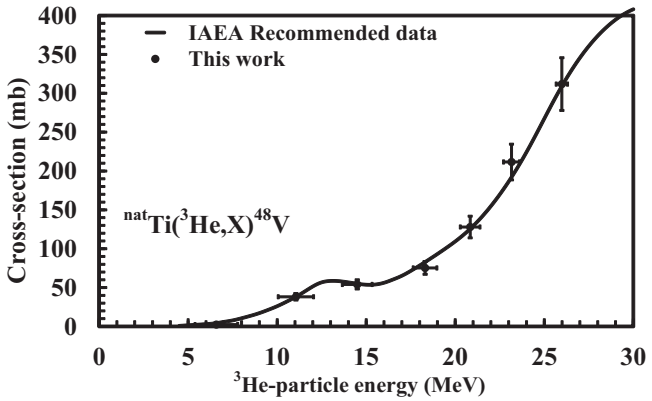


**Fig. 1.** Excitation function of $^{nat}$Ti($^{3}$He,x)$^{48}$V nuclear reaction.

## 4. Results and discussion

Excitation functions of the induced reaction $^{nat}$V($^{3}$He,x)$^{52m,52g,51}$Mn and $^{51}$Cr are shown in (Figs. 2–4); the experimental data as well as the theoretical results. The numerical values of the cross-sections of the investigated reactions and their uncertainties are presented in Table 2.

### 4.1. $^{nat}$V($^{3}$He,xn)$^{52g,m}$Mn

The radionuclide $^{52}$Mn has a ground state with $T_{1/2}$ = 5.6 d decays for 100% EC + β$^{+}$ and short-lived isomeric state with $T_{1/2}$ = 21.2 min that decays for 98.3% EC + β$^{+}$ and 1.7% IT. We measured the cumulative cross-section of the ground state after total decay of the isomeric state because of the small fraction of isomeric transition. The ground state cross-section was evaluated using three intense gamma-lines; ($E_{\gamma}$ = 744.2 keV, $I_{\gamma}$ = 90%), ($E_{\gamma}$ = 935.5 keV, $I_{\gamma}$ = 94.5%) and ($E_{\gamma}$ = 1434.1 keV, $I_{\gamma}$ = 100%). The isomeric state has only one intense gamma-line, ($E_{\gamma}$ = 1434.1 keV, $I_{\gamma}$ = 98.3%), which is unfortunately the same line in the ground state decay scheme. So, the isomeric cross-section was evaluated using its intense gamma-line after subtraction of the activity due to the ground state decay. Two channels are contributing to $^{52}$Mn formation; $^{50}$V($^{3}$He,n) and $^{51}$V($^{3}$He,2n).

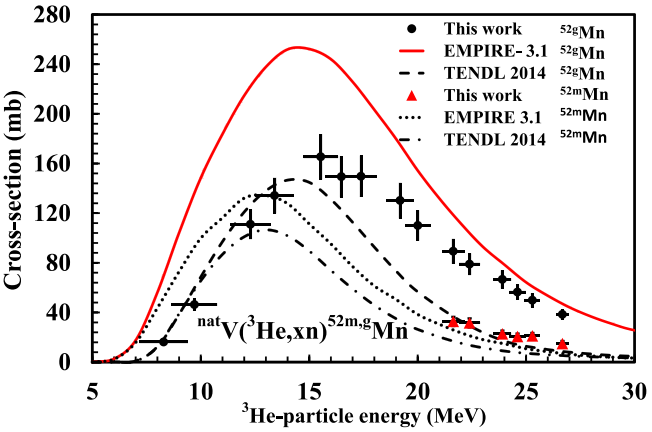


**Fig. 2.** Excitation function of $^{nat}$V($^{3}$He,xn)$^{52m,g}$Mn nuclear reaction.