Production of high purity $^{52}$g Mn from $^{nat}$V targets with $\alpha$ beams at cyclotrons

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Abstract

**Background:** Radioisotope $^{52}$g Mn is of special interest for multimodal imaging (PET/MRI) applications and the main production route is based on proton/deuteron beams on Chromium (natural/enriched) targets. Using state-of-art nuclear reaction codes (Talys, Empire and Fluka), we perform a comparative study with the alternative $^{52}$g Mn production with the reaction $^{nat}$V($\alpha$,x)$^{52}$g Mn.

**Results:** This production channel, novel in the context of medical applications, provides a good source of $^{52}$g Mn, where very high radionuclidic purity can be maintained up to 3 weeks. Since $^{nat}$V consists already of 99.75% $^{51}$V, there is no need of enriched target material and the corresponding high-cost implications. The production of the main long-lived contaminants, i.e. $^{53}$Mn and $^{54}$Mn, is considered with care and the integral yields of the reactions are compared with the alternative production routes. Specifically, the production of the $^{54}$Mn contaminant, which could be the most dangerous for clinical applications, turns out to be lower when compared with the natural Chromium target.

**Conclusions:** This channel turns out competitive with respect to the other considered production routes. The study also reveals poor accuracy of the relevant cross-section data set and indicates that better data and theoretical descriptions are needed for a precise evaluation of $^{nat}$V($\alpha$,x)$^{52}$g Mn.

**Keywords:** Cyclotron radionuclide production; $^{52}$g Mn; $^{53}$Mn; $^{54}$Mn; multi-modal imaging; $\alpha$-induced reactions; nuclear reactions modeling.

1 Background

The search and production of innovative radioisotopes for medical applications is a topic of great interest nowadays, particularly for advancements in theranostics and multimodal imaging. In this work, we are interested in the latter case, which boosts up the diagnostic image information by simultaneously using two different physical processes. For example, to obtain a combined PET/MRI scan with just one single radio-pharmaceutical, one must consider a $\beta^+$ emitting radionuclide which could be bound to a paramagnetic compound. Radionuclides that fits these characteristics are $^{52}$g Mn, $^{52m}$Mn, and $^{51}$Mn[1]. We are interested here in the production of $^{52}$g Mn: its decay properties, and those of contaminants typically involved in the production methods, are reported in Tab. 1.

$^{52}$g Mn appears particularly interesting because it has a relatively long half-life (5.6 d) suitable for the radiolabeling of pharmacokinetics of antibodies and other slow biological compounds. Its $\beta^+$ emission is characterized by a very low maximum
energy, about 0.6 MeV, thus leading to a very good resolution of PET scans. On the other hand, $^{52}\text{g}{\text{Mn}}$ decay to $^{52}\text{g}{\text{Cr}}$ occurs with the emission of three prompt $\gamma$ rays which contribute negatively to the patient’s dose in clinical applications and could interfere with erroneous signals in PET’s $\gamma$-based image reconstruction.

The effective dose burden implied by the use of $^{52}\text{g}{\text{Mn}}$ as brain tracer in Mn-Cl$_2$ compound has been carefully investigated with computational dosimetry codes in Ref. [2]. It was found that the radiation dose released with $^{52}\text{g}{\text{Mn}}$ is 130 times higher than $^{51}\text{Mn}$. Since the manganese-chloride compound is retained in the body for a long time, the longer physical half-life of the $^{52}\text{g}{\text{Mn}}$ radionuclide affects negatively the effective dose to the patient.

The standard production routes of $^{52}\text{g}{\text{Mn}}$ at cyclotrons are based on the following reactions: $^{52}\text{Cr}(p,n)^{52}\text{g}{/m}\text{Mn}$, $^{53}\text{Cr}(p,2n)^{52}\text{g}{/m}\text{Mn}$, and $^{54}\text{Cr}(p,3n)^{52}\text{g}{/m}\text{Mn}$, which can be exploited at energies lower than 20 MeV or, even, with 16 MeV cyclotrons [1]. The use of natural Chromium targets has been extensively investigated: $^{52}\text{Cr}$ constitutes 84% of $^{\text{nat}}\text{Cr}$, while $^{53}\text{Cr}$ is 10% and $^{54}\text{Cr}$ is 2%; the remaining 4%, made of $^{50}\text{Cr}$, contributes only to contaminants production but not to the production of the radionuclide of interest. The cross section for the reaction with protons on $^{\text{nat}}\text{Cr}$ is large enough to provide sufficient yield for preclinical applications [3]. Production with natural Chromium targets is favourable also because the radionuclidic purity is very high for long periods (up to a few months), thanks also to the long half-life of $^{52}\text{g}{\text{Mn}}$.

The main drawback of the approach with a natural target is the production of impurities during the irradiation, in particular the long-lived $^{53}\text{Mn}$ and $^{54}\text{Mn}$, mainly via the reactions: $^{53}\text{Cr}(p,n)^{53}\text{Mn}$, $^{54}\text{Cr}(p,2n)^{53}\text{Mn}$, and $^{54}\text{Cr}(p,n)^{54}\text{Mn}$. The formation of both long-lived contaminants can be avoided by irradiation of highly enriched $^{52}\text{Cr}$ targets and should therefore not impose stringent limitations for potential clinical uses of $^{52}\text{g}{\text{Mn}}$. However the use of enriched material significantly increases the production costs and implies the development of a target-recovery protocol.

The main purpose of this study is the search of an alternative and competitive route to produce $^{52}\text{g}{\text{Mn}}$ with high radionuclidic purity and high production yield. The work is done in support to the activities of the project METRICS (Multimodal PET/mRi Imaging with Cyclotron produced $^{51}/^{52}\text{Mn}$ and stable paramagnetic Mn iSotopes) in the framework of the SPES/LARAMED project at INFN-LNL.

As promising route, we have investigated the production reaction $^{\text{nat}}\text{V}(\alpha,x)^{52}\text{g}{/m}\text{Mn}$ which is dominated by the channel $^{51}\text{V}(\alpha,3n)^{52}\text{g}{/m}\text{Mn}$. Generally, this production route is not mentioned in the medical radioisotope literature.

### Table 1

| Radionuclide | Half-life       | Decay mode | Branching ratio | Daughter   |
|--------------|-----------------|------------|-----------------|------------|
| $^{51}\text{Mn}$ | 46.2 m         | $\beta^+$ | 100%            | $^{51}\text{Cr}$ |
| $^{52}\text{g}{\text{Mn}}$ | 5.6 d          | $\beta^+$ | 100%            | $^{52}\text{Cr}$ |
| $^{52}\text{m}{\text{Mn}}$ | 21.1 m         | $\beta^+$ | 98.25%          | $^{50}\text{Cr}$ |
| $^{52}\text{m}{\text{Mn}}$ | 21.1 m         | IT        | 1.75%           | $^{52}\text{g}{\text{Mn}}$ |
| $^{53}\text{Mn}$ | $3.6 \times 10^6$ y | EC       | 100%            | $^{53}\text{Cr}$ |
| $^{54}\text{Mn}$ | 312 d          | EC        | 100%            | $^{54}\text{Cr}$ |
(see for a recent review [4]), nor in the IAEA Livechart website [5], an internationally recognized reference for the production of medical radioisotopes. The IAEA Livechart website mentions helium beams only for $^3$He particles in the generator-like sequence: $^{52}$Cr($^3$He,3n)$^{52}$Fe to $^{52}$Fe(EC $\beta^+$)$^{52}$Mn.

The reaction nat$^5$V($\alpha$,x)$^{52}$Mn has been studied by various authors in the last 50 years, both for the ground and for the metastable state. The experimental data for this reaction are collected in the EXFOR database [6].

Different routes to produce the $^{52}$Mn isotope have been measured in [7] using natural targets with Cr, V and Fe and with proton, deuteron or alpha beams. Both cross-sections and integral yields are given with an estimated error of 13%. A first attempt to compare theory models and experiments with $\alpha$-particles on a variety of targets, including $^{51}$V is given in Ref.[8].

Subsequently, several measurements have been performed with important advancements in experimental techniques and with comparisons with reaction models (statistical and pre-equilibrium mechanisms) that have been gradually refined and improved over the years: [9], [10], [11], [12], [13], [14], [15], [16], [17]. Finally, new results on alpha particles on Vanadium targets have been published recently, in [18].

Overall, the measured excitation functions show a similar structure with an initial peak followed by a decrease: the peak corresponds to alpha emission mainly by evaporation of the compound nucleus, while the tail is dominated by the pre-equilibrium decay. The data spread is significant and can be attributed to the long period over which the data were taken and to the different experimental techniques used over the years. The large number of published measurements and the large spread in the data demands for an accurate nuclear data evaluation of the cross section, given its importance for medical applications. In addition, it is important to assess also the theoretical uncertainty arising from the different models employed and this will be taken into account in the present paper.

We use nuclear reactions codes to identify the energy intervals and irradiation conditions most suited for the production. After performing the cross sections analysis, we calculate the thick target yield for an hypothetical irradiation with $\alpha$ particles on a nat$^5$V target of a given thickness, and from there we compute the time-evolution of the isotopic and radionuclidic purities, assuming a sufficiently long cooling time.

Finally we compare the results obtained using nat$^5$V targets and $\alpha$ beams with those derived from natural Chromium, with proton beams. In addition we make a comparison with enriched Chromium targets, considering both proton and deuteron beams.

## 2 Methods

### 2.1 Nuclear reaction codes

The study of the reaction implies the adoption of different models to describe compound nucleus formation/decay and pre-equilibrium dynamics. We have made use of three of the most up-to-date nuclear reaction codes: Talys [19], Empire [20] and Fluka [21]. The nuclear reaction mechanisms relevant for radionuclide production at cyclotrons are dominated by compound nucleus formation and by pre-equilibrium emission and all the three codes are based on nuclear reaction models developed to describe these processes. A quick review of all the models used can be found in [22] and in the codes references.
Talys (version 1.9) is a software for the simulation of nuclear reactions that includes many state-of-the-art nuclear models to cover most of the reaction mechanisms encountered in light particle-induced nuclear reactions [19]. The nuclear reaction rates evaluated by the code are based on the Hauser-Fesbach model [23] for the equilibrium mechanisms and on four different theoretical frameworks for the pre-equilibrium process. The level density is another important quantity to take into account to describe the reaction and Talys has six possible options for its description, ranging from the simplest Fermi gas model to more complex microscopic approaches.

Empire (version 3.2.3) is a nuclear reaction code based on various nuclear models and designed for calculations over a broad range of energies (from few keV up to hundred MeV) and incident particles (nucleons, photons, deuterons and light ions). The code accounts for the major current nuclear reaction models, such as Optical Models, Coupled Channels and DWBA (Distorted Wave Born Approximation) models for elastic and inelastic scattering; Exciton model and Hybrid Monte Carlo Simulations for pre-equilibrium emission; and finally the Hauser-Feshbach model for compound nucleus [20].

Fluka (development version 2018.2) is a general purpose code for modelling particle transport and interaction with matter; it covers an extended range of applications, spanning from proton and electron accelerator shielding to calorimetry, dosimetry, detector design, radiotherapy and more [21, 24, 25]. The code, based on the PEANUT (PreEquilibrium Approach to Nuclear Thermalisation) module, can be used to calculate the production of residual nuclei and in many cases the results are already validated with experimental data. Residual nuclei (and, thus, radionuclides) emerge directly from the inelastic hadronic interaction models and can be calculated for arbitrary projectile-target configurations (including nucleus-nucleus interactions) and energies. Regarding the production of isomers, the Fluka version used in this work does not have a built-in routine to predict the correct branching for the production of different states of the same radionuclide, but it distributes the cross section equally over the different states: for this reason, we only consider the results of Fluka in the cases where the separation between ground and metastable nuclides is not explicitly involved.

2.2 Uncertainty evaluation with Talys

With Talys, a total of 24 different model combinations results from the possible level density and pre-equilibrium options. Many calculations found in literature refer to a default option, but this is not always the best choice and therefore alternative option configurations have been introduced and evaluated. For example the so-called "Talys adjusted" configuration of Ref. [26] has been often used. However, both cases rely on the selection of a single model for level density and pre-equilibrium, disregarding all the others, and not exploiting the full potentiality and versatility of the code. In the next, we introduce a novel way to deal with the theoretical variability provided by the different models. Instead of plotting all the 24 curves, we compare the different models introducing a statistical band along similar ideas explored in Ref [27]. Starting from the 24 different model calculations, a band is constructed from the interquartile range, given by the difference between the third
(Q_3) and the first (Q_1) quartile. In addition we introduce for each energy a “Best Theoretical Evaluation” (BTE) of the cross section by taking the average of the first and third quartile, and associate to it the uncertainty given by the half-width of the interquartile band:

$$\sigma_{BTE} = \frac{Q_1 + Q_3}{2}, \quad \Delta\sigma_{BTE} = \frac{Q_3 - Q_1}{2}. \quad (1)$$

Some models of the ensemble may show a too large variability, over- or under-estimating by large the data. If we consider the interquartile band, spanning quartiles Q_1 and Q_3, only the central 50% calculations are retained, and this leads to a more reasonable description.

In this way we have a reference value for cross-section depending on all models provided by the code, and a statistical indeterminacy depending on the variability of the models themselves. The same procedure has been applied to evaluate not only cross sections, but also yields, activities, isotopic, and radionuclidic purities, both for the radionuclide of interest and its contaminants. The BTE approach derives from descriptive statistics and connects to the concept of trimmed average: it provides a robust estimator of the theoretical cross section and allows to discard in a consistent way the outlier values provided by a subset of the models. These outliers can be seen, for example, in Fig. 1 with the two dashed lines, corresponding to the maximum and minimum values of the 24 model calculations. This approach is alternative to other more sophisticated techniques developed to introduce a theoretical uncertainty band, like for example the multistep method [28], in which a rescaling of the models to experimental data is performed, or total Monte Carlo techniques [29], in which the parameters of the models are sampled randomly to assess the variability of the calculation outcomes. Our description appears more practical, since it trims the calculations at the edge of the set and provides quickly the final result in a single deterministic step.

## 3 Results

### 3.1 Cross sections analysis

The cross section of the reaction natV(α,x)52gMn is reported in Fig. 1. The experimental data taken from the literature are compared with the calculated results obtained with the reaction codes Talys, Empire, and, when relevant, Fluka (see SubSect. 2.1). A dispersion of data, accumulated over a period of few decades, is evident, complicating the precise evaluation of the production yield. Talys results are exhibited following the scheme presented in Ch.2 to take into account the variability of the models: a ”best theoretical evaluation” (solid line), an interquartile range (gray band), and the min and max values of all the models considered (dashed lines). Unfortunately, even taking into account the variety of Talys models, in the energy region below 45 MeV, the calculations overestimate significantly the trend of the data, but the data spread prevents a precise determination of the overestimation factor. Similarly, the Empire calculation are slightly lower than the measured cross section, but the extension of the underestimation is difficult to assess.

The ratio between 52gMn and the sum of all Mn cross sections is shown in Fig. 2, in order to identify the energy region where this quantity is higher. The maximum
of the ratio occurs in correspondence of the maximum of the cross section at 40 MeV for the production of $^{52g}$Mn. Performing an irradiation in this energy region would thus lead to the maximum production of $^{52g}$Mn with the minimum level of contamination. This residual contamination, however, would not be negligible, since the cross section ratio has a maximum value of about 0.6.

Nevertheless, it is important to observe that the majority of the produced isotopes are characterized either by a very short or by a very long half-life. In particular, $^{48}$Mn, $^{49}$Mn, $^{50}$Mn, $^{51}$Mn and $^{52}$Mn have half-lives smaller than one hour and their contamination, both in terms of isotopic and radionuclidic purity, would be thus negligible after few hours. On the other hand $^{53}$Mn, whose half-life is of about $3.6 \times 10^6$ years, would not affect the radionuclidic purity in a significant way and would not release significant dose in the patient. $^{54}$Mn, with an intermediate half-life of about 312 days, could represent a problem for the patient health. For this reason, in Fig. 3 the cross section of the reaction $^{nat}$V(α,X)$^{54}$Mn is shown. The agreement between the experimental data ([12], [14], [15], [16], [17], [18], [30], [31], [32]) and the three nuclear codes is very good, showing a maximum around 13 MeV. On the contrary, at the maximum production of $^{52g}$Mn, around 40 MeV, the cross section for $^{54}$Mn is very low. This fact appears evident if we take into account only $^{54}$Mn as contaminant and we plot the quantity

$$r = \frac{\sigma_{52g} \text{Mn}}{\sigma_{52g} \text{Mn} + \sigma_{54} \text{Mn}},$$

as shown in Fig. 4. Above the energy of about 30 MeV, the production of $^{52g}$Mn is almost pure, with respect to its most dangerous contaminant. In the next Section we will focus on the region around 40 MeV, to evaluate the $^{52g}$Mn production yields and purities.

### 3.2 Yields and purities

Once the most promising energy window for the production of $^{52g}$Mn is identified, it is possible to design the irradiation conditions. The production rate of a nuclide for a beam impinging on a target of a given material and thickness can be calculated with the formula [33, 34]

$$R = \frac{I_0}{z_{\text{proj}}|e|} \frac{N_a}{A} \int_{E_{\text{out}}}^{E_{\text{in}}} \sigma(E) \left( \frac{dE}{\rho dx} \right)^{-1} dE,$$

where $I_0$ is the charge beam current, $z_{\text{proj}}$ the atomic number of the incident particle (2 in this case), $e$ the electron charge, $N_a$ the Avogadro number, $A$ the target atomic mass, $E_{\text{in}}$ and $E_{\text{out}}$ the energy of the projectile impinging on the target and after exiting from the target, respectively, $\sigma(E)$ the production cross section for the nuclide, $\rho$ the target density and $dE/dx$ the stopping power of the projectile in the target, calculated with the Bethe-Bloch formula [35]. In this case the irradiation parameters are: beam current of 1 $\mu$A, incident energy of 48 MeV, target thickness of 200 $\mu$m (corresponding to $E_{\text{out}} = 33.9$ MeV), and irradiation time of 1 h. Radionuclides from $^{50}$Mn to $^{55}$Mn are produced in this energy window.
The rate of production for all the Mn isotopes of interest are calculated, and for $^{52}_g$Mn it was found to be between $5.6\times10^8$ and $1.45\times10^9$ nuclei/s, depending on the different codes and models. From the rate, the time evolution of the number of nuclei of a specific isotope can be obtained, during and after the irradiation, by means of standard Bateman equations. Every manganese radionuclide of interest decays in different chemical elements, with the only exception of $^{52m}_n$Mn, which decays in $^{52}_g$Mn with a branching ratio of 1.75% and with a half-life of about 21.1 minutes.

Finally, we calculate the isotopic purity (IP) of $^{52}_g$Mn, defined as

$$IP = \frac{n_{^{52}_g\text{Mn}}}{n_{^{50}\text{Mn}} + n_{^{51}_g\text{Mn}} + n_{^{52}_g\text{Mn}} + n_{^{53}_g\text{Mn}} + n_{^{54}_g\text{Mn}}}$$

where $n$ is the number of nuclei, and the corresponding radionuclidic purity (RNP),

$$RNP = \frac{A_{^{52}_g\text{Mn}}}{A_{^{50}\text{Mn}} + A_{^{51}_g\text{Mn}} + A_{^{52}_g\text{Mn}} + A_{^{53}_g\text{Mn}} + A_{^{54}_g\text{Mn}}}$$

where $A$ represents the activity of the specific isotope ($^{55}$Mn does not contribute because it is stable). In Figs. 5-6 the time evolution of IP and RNP are shown, both for a short and a long time scale.

At the End of Bombardment (EoB), the IP reaches values of about 0.45-0.75 (Fig. 5), and the disagreement between the two codes reflects the different results for the cross sections already shown in Fig. 1. The value is not so high due to the production of $^{53}_g$Mn which can be considered stable at the timescale shown, and therefore does not affect significantly the RNP. Indeed, the RNP reaches a value close to 1 after few hours, due to the very short half-lives of $^{50}_g$Mn, $^{51}_g$Mn and $^{52m}_n$Mn, as well as to the small production of $^{54}_g$Mn and the negligible activity for $^{53}_g$Mn.

The Talys BTE value (with the corresponding uncertainty) of the activity of $^{52}_g$Mn at EoB is about $6.23\pm0.80\text{ MBq}$, while Empire gives $3.20\text{ MBq}$. Despite this discrepancy, the RNP remains close to one for about 20 days for both calculations, as shown in Fig. 6. For this reason we consider the reaction $^{nat}\text{V} (\alpha,x)^{52}_g\text{Mn}$ of particular interest as an alternative route for $^{52}_g$Mn production.

4 Discussion

4.1 Comparison with other production routes

The standard route for the cyclotron production of $^{52}_g$Mn is $^{nat}\text{Cr} (p,x)^{52}_g\text{Mn}$ and has been recently reviewed in Refs. [3, 4]. The first reference presents new data for the cross section and confirms the peak between 12 and 16 MeV, suited for an hospital cyclotron. The second reference is a comprehensive and historical review on the production of medical radionuclides and refers to the $^{nat}\text{Cr} (p,x)^{52}_g\text{Mn}$ reaction as the main production channel. Also the deuteron-induced reaction $^{52}\text{Cr} (d,2n)^{52}_g\text{Mn}$, with enriched target, has been previously explored as an alternative route and compared with the proton channel [11].

We have evaluated cross sections, rates and purities also for reactions involving chromium targets. In particular, in Fig.7, we compare the cross sections from $^{nat}\text{Cr}$ and $^{nat}\text{V}$ targets. We report in the figure also the experimental data from the
literature for the \( ^{nat}\text{Cr}(p,x)^{52g}\text{Mn} \) reaction (see Refs. [36], [37], [38], [39], [40]). Instead, we omit the experimental data for \( ^{nat}\text{V}(\alpha,x)^{52g}\text{Mn} \) because they have been already given in Fig.1.

The cross sections for the two reactions appear comparable in magnitude, and obviously shifted in the energy range. In case of \( ^{nat}\text{Cr} \) targets, Empire provides good reproduction with a slight overestimation of the peak, while Talys gives an almost excellent description, with a minimum underestimation of the peak. The situation with \( ^{nat}\text{V} \) targets has been extensively described while commenting Fig.1, with the result that Talys probably overestimates significantly the data, the Empire calculations may produce a possible underestimation, but the experimental data are excessively scattered to arrive at a definitive conclusion.

It is interesting to compare also the radionuclidic purities that can be obtained with both reactions, as shown in Fig. 8. The two reaction codes exhibit a different trend which reflects the diverse behaviour with the cross sections. Talys highlights a more favorable time evolution of the RNP for \( \alpha \) impinging on natural V target. On the contrary, Empire shows a similar behaviour for the two RNPs with a very small advantage for the Chromium targets. However, to draw a definitive conclusion, better data for the reaction \( ^{nat}\text{V}(\alpha,x)^{52g}\text{Mn} \) are needed.

For all the production routes considered, we assess from the integral yields the irradiation energy range corresponding to the highest purities. This kind of optimization is crucial because the quantity and quality of the product are essential for subsequent radiochemistry studies, dosimetric evaluations and, eventually, preclinical studies to confirm the feasibility of the production route.

We show in Figs. 9 and 10 the integral yields obtained for the reactions \( ^{nat}\text{V}(\alpha,x)^{52g}\text{Mn} \) and \( ^{nat}\text{Cr}(p,x)^{52g}\text{Mn} \), respectively. For comparison, in the latter figure we have also added the integral yield obtained with the enriched chromium target, \( ^{52}\text{Cr}(p,n)^{52g}\text{Mn} \) and finally, we complete the analysis by considering also the production channel \( ^{52}\text{Cr}(d,2n)^{52g}\text{Mn} \), shown in Fig. 11.

In all cases, the irradiation parameters of the integral yields are: 1h irradiation time; 1 \( \mu A \) for the beam current; and a target thickness large enough to stop completely the beam inside the target. The curves show the variation of the integral yield with the incident beam energy, and from there it is possible to derive the yield for a target of a given thickness. We assume for all the targets a thickness of 200 \( \mu m \) and derive from the stopping power the energy of the beam at the exit of such target, \( E_o \). The yield of a target with 200 \( \mu m \) thickness is then given by the difference of the integral yield evaluated at \( E_i \) and \( E_o \), where \( E_i \) denotes the incoming-beam energy.

In all considered cases, the irradiation energy window has been optimized taking into account the steepness of the integral yield, the minimization in the contaminant production and the 200 \( \mu m \) constraint of the target thickness. The resulting energy ranges are reported in the left column of Tab. 2, and highlighted as well by a vertical green shaded area in Figs. 9, 10, and 11.

The results with \( ^{nat}\text{V} \) are given in Fig. 9. We report integral yields obtained with Talys and Empire. For Talys the results are given in terms of the BTE value and its associated uncertainty, following Eq. 1, which is highlighted as a gray band on figure. In addition, the data by Dmitriev at al. [7] are reported together with a
linear interpolation obtained from these data. It seems that Talys overestimates the yield by a factor of about 2, in line with our findings with the cross sections (see Fig. 1). On the other hand, the experimental data (and/or its linear interpolation) and Empire calculations appear fairly consistent.

In Fig. 10 we compare the integral yields for a proton beam on $^{nat}$Cr and $^{52}$Cr targets. The results are similar with the enriched target case overperforming with respect to the natural one. The Talys results are very close to the IAEA recommended yields [5] for the enriched chromium target, and similarly, for the natural target, they are close to the data interpolation. In both cases, Empire gives similar results, with a slight overestimation of the yields. The vertical green band refers to a 200 $\mu$m thickness for both targets.

In Fig. 11 the case of deuteron beam on enriched $^{52}$Cr target is illustrated. In the range of interest, [20-15.5] MeV, Talys and the IAEA recommended values are very similar, with the IAEA recommended curve slightly steeper, while Empire results are still close although somewhat lower.

The analysis performed in Figs. 9, 10, and 11 allows to derive the production yields of a target of given thickness, for instance the benchmark 200 $\mu$m assumed in our comparative study. Such quantity is readily calculated as the difference of the plotted integral yields at the bombarding energy $E_i$, and at the target exit energy $E_o$, which takes into account the energy loss in the material. Tab. 2 compares the derived $^{52}$gMn production yield determined from the nuclear reaction codes, and when available, from experimental measures [7] as well as from nuclear data evaluations [5]. We have added in the comparison also the output obtained from the ARRONAX Radionuclide Yield Calculator (RYC) [41], which is based on the TENDL library [29].

It is difficult to recommend a value for the first route reported in Tab. 2 and this reflects the large experimental uncertainty obtained for the cross section, as reported in Fig. 1. Clearly Talys evaluations and the similar RYC value overestimate the yield, while Empire probably underestimates it. One can tentatively extract a significant guess by observing that the Empire curve reproduces the overall trend of the cross section data, if it is rescaled by a factor 1.5/1.7. Under this assumption, we can accordingly rescale the Empire yield in Tab. 2 obtaining approximately 4.3/4.9 MBq/$\mu$Ah. This crude "guesstimate" compares well with the production yield of 4.4 calculated with Talys for protons on $^{nat}$Cr target (see the second line in the Table). As one can see from Fig. 7, for this reaction the Talys results are quite reliable and the corresponding yield provides a good estimate. Therefore, we conjecture that the production yield for the two routes could be very similar, although a definitive conclusion can be drawn only with much better data for the $^{nat}$V($\alpha$,x)$^{52}$gMn cross section. Alternatively, a careful nuclear data evaluation of the existing measurements for this cross section is strongly needed. The comparison in Tab. 2 is completed with two $^{52}$Cr-target reactions, the first with proton and the second with deuteron beams. These two routes are well known and listed in the IAEA medical radioisotopes production database [5] with recommended evaluations for the cross sections. The use of enriched material in the $^{52}$Cr(p,n) route provides an additional 15% production yield in comparison to $^{nat}$Cr, with the advantage of a drastic reduction of contaminants, as will be shown in Tab. 3. The $^{52}$Cr(d,2n) route
produces even more $^{52}\text{gMn}$ (almost a 100% addition), but here the contaminant reduction is not so efficient.

The production of the most relevant contaminants derived under the same irradiation conditions are given in Tab. 3. By far the most critical radionuclide is $^{54}\text{Mn}$. In the case of $\alpha$ particles colliding on $^{nat}\text{V}$ the cross section peaks around 12/14 MeV and rapidly decreases toward very low values at higher energies, in particular in the energy interval of our interest. From the comparison, the production yield of this contaminant is significantly lower for $^{nat}\text{V}$ targets than for $^{nat}\text{Cr}$ ones. This is a clear advantage when comparing natural targets. Obviously, the use of about 100% enriched targets allows to drastically reduce or completely remove the level of contamination, as shown in the third and fourth line of Tab. 3.

Table 2 Comparison of the four production routes analyzed. The irradiation parameters correspond to 1 $\mu$A current and 1 h irradiation time. The optimized energy windows for each route, shown in the left column, correspond to a 200 $\mu$m target thickness. We report Talys calculations with a theoretical error evaluation depending on the variability of the models.

| Reaction $[E_i-E_o]$ (MeV) | Yield (MBq/µAh) |
|-----------------------------|------------------|
| $^{nat}\text{V}(\alpha,x)^{52}\text{gMn}$ [48-33.9] | 6.28 ± 1.27 | 2.88 | 5.57 | 3.17 [7] |
| $^{nat}\text{Cr}(p,x)^{52}\text{gMn}$ [17-14] | 4.41 ± 0.51 | 5.98 | 4.28 | 5.52 [7] |
| $^{52}\text{Cr}(p,n)^{52}\text{gMn}$ [17-14] | 6.64 ± 1.73 | 7.06 | 4.75 | 6.47 [5] |
| $^{52}\text{Cr}(d,2n)^{52}\text{gMn}$ [20-15.5] | 12.00 ± 0.63 | 10.09 | 14.43 | 12.14 [5] |

The effect of the contamination by $^{53}\text{Mn}$ on the total dose released to the patient has not been carefully analyzed yet [1], but it should be of minor importance due to its very long half-life. The very small activities reported in Tab. 3 for this radionuclide strengthen this assumption. Nevertheless the $^{nat}\text{V}$ route produces a slightly larger yield than the $^{nat}\text{Cr}$ one, but still small and very close to each other. For the enriched target cases the route via the reaction $^{52}\text{Cr}(d,n)^{53}\text{Mn}$ gives yield comparable to those with natural targets, while the $^{52}\text{Cr}(p,\gamma)^{53}\text{Mn}$ reaction gives even smaller yield.

Table 3 Yields for the main contaminants, $^{54}\text{Mn}$ and $^{53}\text{Mn}$, with the same irradiation conditions discussed in Tab. 2.

| Contaminants | Yield |
|--------------|-------|
|               | Talys | Empire | RYC | Unit |
| $^{nat}\text{V}(\alpha,x)^{54}\text{Mn}$ | 1.94 ± 0.16 | 3.35 | 2.65 | KBq/µAh |
| $^{nat}\text{Cr}(p,x)^{54}\text{Mn}$ | 4.80 ± 0.07 | 5.08 | 3.80 | |
| $^{52}\text{Cr}(p,x)^{54}\text{Mn}$ | - | - | - | |
| $^{52}\text{Cr}(d,\gamma)^{54}\text{Mn}$ | 7.52 ± 0.92 | 41.8 | 6.7 | Bq/µAh |
| $^{nat}\text{V}(\alpha,x)^{53}\text{Mn}$ | 10.6 ± 1.03 | 12.9 | 7.27 | mBq/µAh |
| $^{nat}\text{Cr}(p,x)^{53}\text{Mn}$ | 7.52 ± 0.24 | 7.13 | 6.83 | |
| $^{52}\text{Cr}(p,\gamma)^{53}\text{Mn}$ | 0.23 ± 0.04 | 0.03 | 0.26 | |
| $^{52}\text{Cr}(d,n)^{53}\text{Mn}$ | 9.90 ± 0.24 | 1.44 | 7.15 | |

5 Conclusion
We have investigated the $^{nat}\text{V}(\alpha,x)^{52}\text{gMn}$ production route as a viable alternative for the production of the radionuclide $^{52}\text{gMn}$, which is of significant medical inter-
est for the innovative PET-MRI multi-modal imaging technique. This reaction is not commonly considered for the production of the radionuclide and does not often appear in the relevant literature. We have compared this production method with the well known approach via low-energy protons on natCr targets. We have complemented the comparison considering also enriched 52Cr targets both with proton and deuteron beams.

The experimental data for natV(α,x)52gMn appear very spread and prevent a precise determination for the cross section. The considered nuclear models do not describe the reaction in an optimal way either: Talys calculations do not provide an optimal description of the peak behaviour at 40 MeV, while the Empire results seem to somewhat underestimate the cross section. We have also analyzed all models available in the Talys code, and performed a statistical evaluation of the cross section, based on the model variability itself. We have considered also the cross sections for the Mn contaminants and plotted the ratio between 52gMn and all Mn radionuclides, with the aim to identify a favorable production energy window. In addition, Isotopic and Radionuclidic purities have been investigated.

To compare the four production routes, we have calculated the integral yields and from there, by assuming a standard 200 μm target in all cases, we have tabulated the corresponding production yields, both for 52gMn and its main contaminants.

Our study shows that, likely, natV(α,x)52gMn provides a production yield comparable with the standard natCr(p,x)52gMn approach. However, there is a need of better data for the cross section or a reliable nuclear data evaluation for a more definitive conclusion. Concerning the production of the main contaminant, 54Mn, the reaction with natV appears more promising than with natCr and represents therefore a viable production alternative.

Obviously, one must acknowledge the fact that with natCr the production can be achieved with hospital cyclotrons exploiting low-energy proton beams, while the natV production requires a 50 MeV cyclotron and α particles, which can be currently found only in few research centers. Nevertheless, for infrastructures where this kind of machines are available, it might be convenient to consider the alternative natV(α,x)52gMn reaction.

It is evident that the 52gMn production with enriched 52Cr targets presents significant advantages in production yields and quality due to minor presence of contaminants, but on the other hand it requires the use of more expensive materials and specific technologies for target recovery.

This study indicates that further experimental investigations are needed, given the variability of the theoretical predictions and the spread of experimental data. Future investigations along these lines could be performed at facilities such as Arronax (Nantes, France) or at SPES (Legnaro, Italy).

Appendix
We focus here on how the enrichment of both chromium and vanadium targets affects the production of 52gMn and contaminants. Specifically, we illustrate in Figs. 12 and 13, respectively, the time evolution of RNP with proton and deuteron beams impinging on 52Cr target with hypothetical 100% enrichment.

If we compare these two figures with the corresponding RNP obtained with natural targets, Fig. 8, it is evident that very high purity levels can be maintained over a
much longer period of time in the case of enriched targets. With natural targets, more than 20 days are needed before RNP reduces by 1.5%. Much higher values are needed for protons and deuterons on enriched targets, 150 and 65 days, respectively. However, considering the 5.6 d half-life of $^{52}$Mn, the result with natural targets appears adequate to maintain a sufficiently high RNP, at least for more than three half-lives.

Vanadium has to be considered a monoisotopic element made of $^{51}$V, but the presence in small fraction (0.25%) of the radioactive $^{50}$V, with $1.5 \times 10^{17}$ y half-life, does not make it mononuclidic. It might be odd, but since it is possible to find commercially samples of vanadium with $^{51}$V abundance different from $^{nat}$V, we discuss how this could affect the production. In Figs. 14 and 15 the cross sections for $^{50}$V($\alpha, x$)$^{52}$, $^{54}$Mn and $^{51}$V($\alpha, x$)$^{52}$, $^{54}$Mn provide a clear representation of the reaction dynamics at stake, and exhibit the fine balance between production of the radionuclide of interest and its main contaminant. Following the scheme previously adopted, the calculations have been performed by evaluation of the Talys interquartile range and corresponding BTE.

Radioactive $^{50}$V has the advantage of a minimum production of $^{54}$Mn contaminant, and implies a $^{52}$Mn peak around 20 MeV, at significantly lower energies than the peak with $^{51}$V. These features could be attractive in an ideal and very hypothetical situation of about 100% $^{50}$V target, but become an issue in the case of a $^{51}$V compresence. Indeed, the $^{52}$Mn peak shifts at lower energies with increasing abundance of $^{50}$V, and this interferes with the $^{54}$Mn production from $^{51}$V, which significantly increases at lower energies as well. On the other hand, there is no appreciable advantage when considering enriched $^{51}$V targets, either. A $^{51}$V target with 100% enrichment does not improve the $^{52}$Mn production nor reduce the contaminant production.

**Declarations**

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable.

**Availability of data and material**
All experimental data used for this work have been referenced. Contact the corresponding authors for material and data presented in this work.

**Competing interests**
The authors declare that they have no competing interests.

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**Author’s contributions**
All authors contributed equally to the work presented.

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22. Pupillo G, Mou L, Boschi A, Calzaferri S, Canton L, Cisternino S, et al. Production of
21. Battistoni G, Cerutti F, Fassó A, Ferrari A, Muraro S, Ranft J, Roesler S, Sala P. The FLUKA code:
19. Goriely S, Hilaire S, Koning AJ. Improved predictions of nuclear reaction rates with the TALYS reaction code
18. Ali B, Al-Abyad M, Seddik U, El-Kameesy S, Ditró F, Takács S, et al. Activation cross-section data for
17. Peng X, He F, Long X. Excitation functions for
16. Bindu Kumar B, Mukherjee S, Singh NL. Pre-equilibrium model analysis of alpha particle induced reactions up
15. Chowdhury DP, Sujit Pal, Saha SK, Gangadharan S. Determination of cross section of α-induced nuclear

References

1. Brandt M, Cardinale J, Rausch I, Mindt TL. Manganese in PET imaging: Opportunities and challenges. J
2. De Nardo L, Ferro-Flores G, Bolzati C, Esposito J, Melendez-Alafort L. Radiation effective dose assessment of
3. El Sayed R, Massicano AVF, Queen SL, Loveless CS, Lapi SE. Manganese-52 production cross-section measurements via irradiation of natural chromium targets up to 20 MeV. Applied Radiation and Isotopes.
4. Qim SM. Medical Radionuclide Production: Science and Technology. De Gruyter; 2020.
5. International Atomic Energy Agency – Nuclear Data Services. https://www-nds.iaea.org/relnsd/vchart/html/MEDVChart.html; 2007. Accessed 27 Aug 2020.
6. Otuka N et al. Towards a more complete and accurate experimental nuclear reaction data library (EXFOR): international collaboration between Nuclear Reaction Data Centres (NRDC). Nuclear Data Sheet.
7. Dmitriev PP, Konstantinov IO, Krasnov NN. Methods for producing the Mn^{52} isotope. Atomic Energy. 1969;26(5):539–541.
8. Bowman WW, Blann M. Reactions of $^{51}$V and $^{27}$Al with 7–120 MeV α-particles (equilibrium and non-equilibrium statistical analyses). Nuclear Physics A. 1969;131(3):513–531.
9. Michel R, Brinkmann G, Stück R. Measurement and hybrid model analysis of integral excitation functions for α-induced reactions on vanadium and manganese. In: Böckhoff KH, editor. Nuclear Data for Science and Technology. Dordrecht: Springer; 1983. p. 599–600.
10. Rao JR, Rao AM, Mukherjee S, Upadhyay R, Singh N, Agarwal S, et al. Non-equilibrium effects in α-particle-induced reactions in light, medium and heavy nuclei up to 120 MeV. Journal of Physics G: Nuclear Physics. 1987;13(4):535.
11. West HI, Lanier RG, Mustafa MG. $^{52}$Cr(p,n)$^{52}$Cr and $^{52}$Cr(d,2n)$^{52}$Cr excitation functions. Phys Rev C. 1967;35:2067–2076. doi:10.1103/PhysRevC.35.2067.
12. Sonzogni AA, Romo ASMA, Mosca HO, Nassif SJ. Alpha and deuteron induced reactions on vanadium. Journal of radioanalytical and nuclear chemistry. 1993;170(1):143–156.
13. Ismail M. Measurement of excitation functions and mean projected recoil ranges of nuclei in α-induced reactions on F, Al, Co and Re nuclei. Pramana. 1993;40(3):227.
14. Singh NL, Mukherjee S, Mohan Rao AV, Chaturvedi L, Singh PP. Effects of pre-equilibrium nucleon emission on excitation functions of various reactions in vanadium induced by alpha particles. Journal of Physics G: Nuclear and Particle Physics. 1995;21(3):399.
15. Chowdhury DP, Sujit Pal, Saha SK, Gangadharan S. Determination of cross section of α-induced nuclear reaction on natural Cr and Zr by stacked foil activation for thin layer activation analysis. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 1995;103(3):261–266.
16. Bindu Kumar B, Mukherjee S, Singh NL. Pre-equilibrium model analysis of alpha particle induced reactions up to 80 MeV. Physica Scripta. 1998;57(2):201.
17. Peng X, He F, Long X. Excitation functions for α-induced reactions on vanadium. Nuclear Instruments and Methods in Physics Research Section B. 1999;152:432–6.
18. Ali B, Al-Abyad M, Seddik U, El-Kameesy S, Ditrof T, Takács S, et al. Activation cross-section data for α-particle-induced nuclear reactions on natural vanadium for practical applications. Pramana - Journal of Physics. 2018;90(3). doi:10.1007/s12043-018-1527-z.
19. Gorely S, Hilaire S, Koning AJ. Improved predictions of nuclear reaction rates with the TALYS reaction code for astrophysical applications. Astronomy and Astrophysics. 2008;487:767.
20. Herman M, Capote R, Carlson BV, Obložinský P, Sin M, Trkov A, et al. EMPIRE: Nuclear Reaction Model Code System for Data Evaluation. Nuclear Data Sheets. 2007;108:2655–715.
21. Battistoni G, Cerutti F, Fassó A, Ferrari A, Muraro S, Ranft J, Roesler S, Sala P. The FLUKA code: description and benchmarking. AIP Conference Proceedings. 2006;896:31–49.
22. Pupillo G, Mou L, Boschi A, Calzaferri S, Canton L, Cisternino S, et al. Production of $^{52}$Sc with natural vanadium targets: results of the PASTA project. Journal of Radioanalytical and Nuclear Chemistry. 2019;322(3):1711–18.
23. Hanauer W, Feshbach H. The inelastic scattering of neutrons. Physical Review. 1952;87:366.
24. Ferrari A, Sala PR, Fasso A, Ranft J. FLUKA: a multi-particle transport code. CERN Yellow Report. 2005;10. doi:10.2172/87507.
25. Infantino A, Oehike E, Mostacci D, Schaffler P, Trinczek M, Hoehr C. Assessment of the production of medical isotopes using the Monte Carlo code FLUKA: Simulations against experimental measurements. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2016;366:117–123. doi:10.1016/j.nimb.2015.10.067.
26. Duchemin C, Guertin A, Haddad F, Michel N, Mètivier V. Production of medical isotopes from a thorium target irradiated by light charged particles up to 70 MeV. Physics in Medicine and Biology. 2015;60(3):931–946. doi:10.1088/0031-9155/60/3/931.
27. Lamere E, Couder M, Beard M, Simon A, Simonetti A, Skulski M, et al. Proton-induced reactions on molybdenum. Physical Review C. 2019;100(3):034614. doi:10.1103/PhysRevC.100.034614.
28. Hussain M, Sudar S, Aslam MN, Malik AA, Ahmad R, Qaim SM. Evaluation of charged particle induced reaction cross section data for production of the important therapeutic radionuclide $^{186}$Re. Radiochimica Acta. 2010;98(7):385–395. doi:10.1524/ract.2010.1733.
29. Koning AJ, Rochman D. Modern nuclear data evaluation with the TALYS code system. Nuclear data sheets. 2012;113(12):2841–2934. doi:10.1016/j.nds.2012.11.002.
30. Levkovskij VN. Cross-Section of Medium Mass Nuclide Activation (A = 40–100) by Medium Energy Protons and Alpha-Particles (E = 10–50 MeV). Inter-Vesi: Moscow, Russia; 1991.
31. Singh NL, Agarwal S, Rao JR. Excitation function for α-particle-induced reactions in light-mass nuclei. Canadian Journal of Physics. 1993;71(3-4):115. doi:10.1139/p93-017.
32. Hansper YY, Morton AJ, Tims SG, Tingwell CIW, Scott AF, Sargood DG. Cross sections and thermonuclear reaction rates for $^{51}$V($\alpha$,n)$^{54}$Mn and $^{51}$V($\alpha$,p)$^{54}$Cr. Nuclear Physics A. 1993;551(1):158–172. doi:10.1016/0375-9474(93)90309-L.
33. Capote Noy, R et al. Cyclotron Produced Radionuclides: Physical Characteristics and Production Methods. IAEA Technical Reports Series. 2009;468.
34. Iliadis C. Nuclear Physics of Stars. Wiley-VCH, Verlag GmbH & Co. KGaA; 2015.
35. Leo WR. Techniques for Nuclear and Particle Physics Experiments. Springer; 1994.
36. Barrandon JN, Debrun JL, Kohn A, Spear RH. ´Etude du dosage de Ti, V, Cr, Fe, Ni, Cu et Zn par activation avec des protons d’énergie limitée a 20 MeV. Nuclear Instruments and Methods. 1975;127(2):269–278. doi:10.1016/0029-554X(75)90499-1.
37. Klein ATJ, Rösch F, Qaim SM. Investigation of $^{50}$Cr(d,n)$^{51}$Mn and $^{nat}$Cr(p,x)$^{nat}$Mn processes with respect to the production of the positron emitter $^{51}$Mn. Radiochimica Acta. 2000;88(5):253–264. doi:10.1524/ract.2000.88.5.253.
38. Titarenko Yu E et al. Measurement and simulation of the cross sections for nuclide production in $^{56}$Fe and $^{nat}$Cr targets irradiated with 0.04-GeV to 2.6-GeV protons. Phys Atom Nucl. 2011;74:523–536. doi:10.1134/S1063778811040168.
39. Buchholz M et al. Cross-section measurements for the formation of manganese-52 and its isolation with a non-hazardous eluent. Radiochimica Acta. 2013;101(8):491–499. doi:10.1524/ract.2013.2083.
40. Wooten AL, Lewis BC, Lapi SE. Cross-sections for (p,x) reactions on natural chromium for the production of $^{52}$,$^{52m}$,$^{54}$Mn radioisotopes. Applied Radiation and Isotopes. 2015;96:154–161. doi:10.1016/j.apradiso.2014.12.001.
41. Sitarz M, Nigon E, Guertin A, Haddad F, Matulewicz T. New cross-sections for $^{nat}$Mo ($\alpha$,x) reactions and medical $^{97}$Ru production estimations with radionuclide yield calculator. Instruments. 2019;3(1):7.

**Figures**

**Figure 1** Cross section for $^{nat}$V($\alpha$,x)$^{52}$Mn as predicted by three different codes and compared with the experimental data currently available in the EXFOR database [6]. To take into account the theoretical uncertainty of the all the models available in TALYS, a grey band for the quartiles $Q_1$-$Q_3$ and two dashed line for the minimum and maximum are plotted.

**Figure 2** Total ratios of the calculated cross sections for $^{nat}$V($\alpha$,x)$^{52}$Mn and other Mn isotopes.

**Figure 3** Cross section for $^{nat}$V($\alpha$,x)$^{54}$Mn.

**Figure 4** Partial ratio of the calculated cross sections for $^{nat}$V($\alpha$,x)$^{52}$Mn and the $^{54}$Mn isotope. The energy window with the possibility of high purity production of $^{52}$Mn due to the favorable interplay of the different reactions thresholds is clearly visible.

**Figure 5** Time evolution of the $^{52}$Mn Isotopic Purity for a long time window with an hypothetical one hour irradiation of a $^{nat}$V target with a beam energy of 48 MeV, thickness 200 $\mu$m (corresponding to an exit energy of 33.9 MeV), current of 1 $\mu$A. The inset shows the evolution for the first 24h, including the irradiation time.

**Figure 6** Time evolution of the Radionuclidic Purity for a long and a short (inset) time window.
Figure 7 Comparison of $^{52}\text{g Mn}$ production cross sections from $^{nat}\text{Cr}$ (proton beams) and $^{nat}\text{V}$ ($\alpha$ beams) targets. Data are shown only for $^{nat}\text{Cr}$ targets (refer to Fig. 1 for data on $^{nat}\text{V}$ targets).

Figure 8 Comparison of RNP for $^{nat}\text{V}$ vs $^{nat}\text{Cr}$.

Figure 9 $^{52}\text{g Mn}$ integral yield for a $\alpha$-beam with 1 $\mu$A current and one hour irradiation time. The green shaded area indicates the optimized energy interval used for the 200-µm thick target.

Figure 10 $^{52}\text{g Mn}$ integral yield from $^{nat}\text{Cr}$ and enriched $^{52}\text{Cr}$ targets for a proton-beam with 1 $\mu$A current and one hour irradiation time. The green shaded area indicates the optimized energy interval used for the 200-µm thick target.

Figure 11 $^{52}\text{g Mn}$ integral yield for a deuteron-beam irradiation on enriched $^{52}\text{Cr}$. The irradiation conditions are the same of Figs. 9 and 10.

Figure 12 Time evolution of the radionuclidic purity for the reaction $^{52}\text{Cr}(p,n)^{52}\text{g Mn}$ assuming an 100% target enrichment. The irradiation conditions are those discussed for Tab.2.

Figure 13 The same as Fig. 12 for the reaction $^{52}\text{Cr}(d,2n)^{52}\text{g Mn}$.

Figure 14 Cross sections for the production of $^{52}\text{g Mn}$ and $^{54}\text{Mn}$ with alpha beams on $^{50}\text{V}$.

Figure 15 Cross sections for the production of $^{52}\text{g Mn}$ and $^{54}\text{Mn}$ with alpha beams on $^{51}\text{V}$.