First results on the cross-section measurements for the reaction ^{nat}Fe(d,x)$^{52g,m+}$Mn

F. Groppi[1,2], J. Esposito[3] S. Manenti[1,2]

[1] *Physics Department, Università degli Studi di Milano, Milano, Italy.*
[2] *LASA, Physics Department, Università degli Studi di Milano, and INFN, Milano, Italy.*
[3] *INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy.*

INTRODUCTION

Manganese-52 (^{52g}Mn) is a radionuclide that decays by positron emission and electron capture (EC), with a medium-long half-life ($t_{1/2}$ = 5.591 d). It has also a metastable level (^{52m}Mn - $t_{1/2}$ = 21.1 m) that decays by isomeric transition (IT) to the ground level (1.68 % - 377.748 keV). As a positron emitter, ^{52g}Mn can be used in Positron Emission Tomography (PET) imaging to study biological and physiological processes on the same time scale of its decay. The energy of emitted positrons ($<E>_{\beta^+}$ = 244.6 keV; I_{β^+} = 29 %) corresponds to an average range in soft tissue of 0.315 mm: these quantities are comparable with those of fluorine-18 (^{18}F - 252 keV; 97 %; 0.35 mm) and, therefore, it would be possible to obtain diagnostic images of similar intrinsic spatial resolution. Furthermore many studies, more or less recent, suggest different possible areas of application of radioactive manganese in medicine, such as bone scintigraphy, myocardial perfusion imaging, study of diabetes progression, in-vivo tracking of stem cells and immunoPET. As drawbacks, the presence of many concomitant γ-rays may highly increase radiation burden and affect imaging quality.
Thanks to the manganese paramagnetic property, ^{52g}Mn can also be used in Manganese-Enhanced Magnetic Resonance Imaging - MEMRI in combination with PET, opening to the possibility of obtaining multi-modal PET/MEMRI images in order to obtain specific and complementary diagnostic information: this is the aim of the ongoing METRICS project, funded by INFN in the framework of the LARAMED (LAboratory of RAdioisotopes for MEDicine) research program on new/novel radionuclides for nuclear medicine application.

^{52g}Mn can be produced by cyclotron with proton or deuteron beams, mainly exploiting (p,xn) and (d,xn) reactions on natural chromium targets, but also by (p,αn), (p,^{3}He), (d,α2n) and (d,α) reactions on iron targets.

Production with protons has already been extensively studied.
The use of deuteron beams could be a good alternative and may even be more advantageous in terms of higher yield, specific activity and chemical purity. In fact, the deuteron reactions often lead to a broader peak than proton ones that compensates the higher deuteron LET and enhances the thick target yield.

The study of the excitation function of ^{nat}Cr(d,xn)^{52g}Mn reaction was studied in the last years [1].

In this work we present the first results of the production of ^{52g}Mn with a deuteron beam on natural iron (^{54}Fe: 5.8 %; ^{56}Fe: 91.72 %; ^{57}Fe: 2.2 %; ^{58}Fe: 0.28 %): the experiments at higher energy than 20 MeV are limited and report conflicting values for the cross-sections.

In this work, the excitation function for ^{nat}Fe(d,αxn)^{52g}Mn reaction were measured in the 20 – 30 MeV energy range: experimental results are reported and compared with experimental data available in literature [2–5].

EXPERIMENTAL

The excitation functions were determined by using the stacked-foils technique. Two stacks have been prepared, each of them containing three ^{nat}Fe targets.
The irradiations were carried out by accelerating deuterons with the high intensity and high energy cyclotron (AVF IBA-C70XP, K = 70) of ARRONAX research center in Saint-Herblain (FR).
The radioactivity measurements of the targets were performed without any chemical processing at the LASA Laboratory (INFN and Physics Department of University of Milano, Segrate, MI), employing a calibrated high purity germanium (HPGe) detector (EG&G Ortec, 15 % relative efficiency, FWHM = 2.2 keV at 1.33 MeV).
All foils were measured in the same geometrical configuration as that used for the detectors calibration sources in order to avoid corrections for different geometries. The distance from the detector cap was chosen in order to reduce dead time and pile up errors to negligible values (< 0.1 %). The first measurements of the samples were started within few days after end of bombardment (EOB).

The activity values obtained from gamma spectrometry measurements on each target were used for the calculation of the cross-section σ(E) [cm^2·atom^{-1}], through the relation

$$\sigma(E) = \frac{A \cdot M \cdot Z \cdot e}{\rho x \cdot N_A \cdot Q \cdot \lambda} \cdot D(RT) \cdot G(t_{irr}) \cdot e^{\lambda \cdot \Delta t} \qquad (1)$$

where E [MeV] is the beam energy in the target, A [Bq] is

the radioactivity of the nuclide of interest, M [g·mol^{-1}] is the target atomic mass, Z the atomic number of the projectile, e [C] is the electron charge, ρx [g·cm^{-2}] the mass thickness of the target, N_A [atom·mol^{-1}] is Avogadro's number, Q [C] is the integrated deuteron charge, λ [s^{-1}] the decay constant, and Δt [s] the waiting time from the EOB. G(t_{irr}) and D(RT) are respectively the growing factor and the decay factor, which take into account the decay during irradiation and counting time RT.

RESULTS

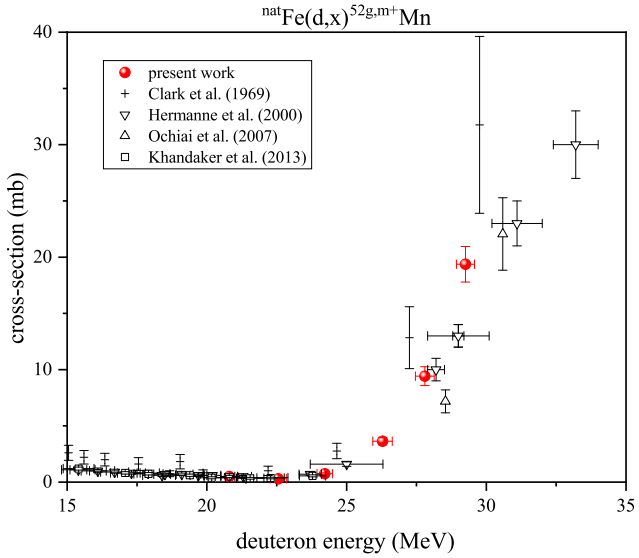

Fig. 1. Excitation function for ^{nat}Fe(d,x)$^{52g,m+}$Mn nuclear reaction.

In our experimental conditions it was not possible to measure the contribution of the metastable level ($t_{1/2}$ = 21.1 m) that decays to the longer lived ground state by IT (1.68 %): the determined cross-section is relative to the cumulative production of $^{52g,m+}$Mn after total decay of its isomer. The experimental excitation function is reported in Fig. 1 compared to past experimental data available in literature [2–5].

With the ^{nat}Fe(d,x) reaction, in addition to the radionuclide of interest ^{52g}Mn, its long-life radioactive isotope ^{54}Mn ($t_{1/2}$ = 312.3 d) is produced (Table 1). The presence of ^{54}Mn decreases the radionuclidic purity of the ^{52g}Mn as it is not possible to separate it chemically.

Fig. 2 shows the results obtained for the cross-section of ^{54}Mn compared with the few data present in literature [2–5].

Due to its long half-life, it was not possible to determine the cross-section for the production of ^{53}Mn ($t_{1/2}$ = 3.74×10^6 a) and we have considered this isotope as stable.

Table 1. The contributing nuclear reactions and the related threshold energies (MeV) for the production of ^{52g}Mn and ^{54}Mn.

Radionuclide	Reaction	E_{th} (MeV)
^{52g}Mn	^{54}Fe(d,α)	0
	^{56}Fe(d,α+2n)	15.88
	^{57}Fe(d,α+3n)	23.79
	^{58}Fe(d,α+4n)	34.17
^{54}Mn	^{54}Fe(d,2p)	2.22
	^{56}Fe(d,α)	0
	^{57}Fe(d,α+n)	2.05
	^{58}Fe(d,α+2n)	12.45

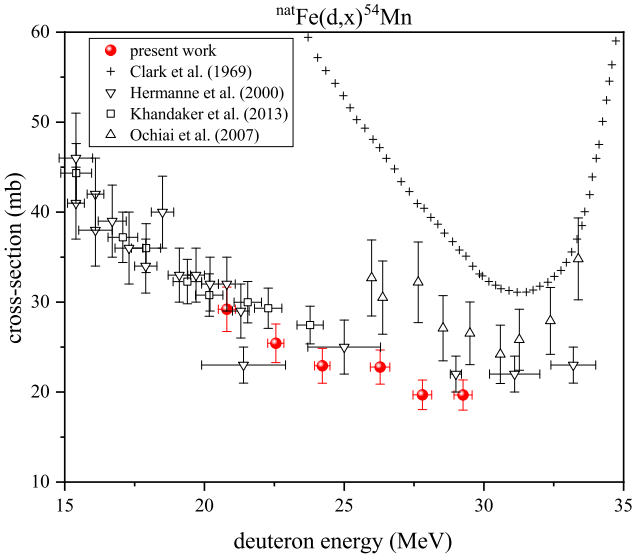

Fig. 2. Excitation function for ^{nat}Fe(d,x)^{54}Mn nuclear reaction.

FINAL NOTES AND REFERENCES

The excitation functions of the nuclear reactions ^{nat}Fe(d,αxn)$^{52g,m+}$Mn and ^{nat}Fe(d,αxn)^{54}Mn were measured covering the deuteron energy range from 20 MeV to 30 MeV. The optimal energy for the production of ^{52}Mn via deuteron route on natural iron is at energies higher than 25 MeV. In fact, the cross-section reaches its maximum values in this energy range. Furthermore, in this range the production of the long-lived radioisotopic impurity due to ^{54}Mn is minimized.

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