Calcium targets for production of the medical Sc radioisotopes in reactions with p, d or α projectiles

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1 Introduction

Majority of medically interested radioisotopes are produced in reactions induced by neutrons i.e. in reactors. Nevertheless, the alternative methods of their production are being extensively developed. The advantages and drawbacks of each production route are well presented by M. A. Synowiecki et al in [1].

The studies on the alternative methods were triggered by unplanned shut-downs of reactors several years ago which caused the shortage of isotopes (i.e. 99Tc) widely used in medical applications. These studies are also stimulated by development of the diagnostic techniques and by search for replacements having longer half-life than isotopes recently used in PET scanning. One of the alternative method of these radioisotopes production is use of the reactions induced by accelerated projectiles such as protons, deuterons or alpha particles.

These studies cover search for replacements of PET isotopes such like 18F (T1/2≈110 min), 68Ga (T1/2≈68 min, 60Cu (T1/2≈24 min), 61Cu (T1/2≈20 min) and 15O (T1/2≈122 s). The scandium isotopes are among potential replacements. The scandium radioisotopes which are β+ emitters (44Sc and 48Sc, T1/2=3.97 h and 3.89 h, respectively) can replace currently used PET scanning isotopes mainly due to their longer half-life. Another interesting scandium isotope, 45Sc (T1/2=3.35 d) with its low energy β+ emission, is a good candidate for targeted radiotherapy. This isotope coupled with one of the Sc β+ emitters may represent an ideal theranostic pair. The 44Sc as is well considered a good candidate to be applied in the new β+-γ coincidence PET method [2].

Majority of the studies on the scandium isotopes production via reactions induced by p, d or α projectiles are performed using calcium as a target nucleus. The alternative nucleus is Ti as the source of Sc isotopes but comparison of the cross sections for reactions of both nuclei (Table 1) shows that reaction with Ca nucleus promises much higher production efficiency. As can be found from these data production of 43Sc with very high efficiency can be achieved even applying target composed of the natural calcium employing reaction of 40Ca (96.94 % of nat. abundance) with α particles [3].

Table 1. Example of cross sections for production of 43Sc and 44Sc on reactions of Ca or Ti with p, d or α [4].

| isotope produced | Calcium isotope cross section [mb] (beam energy [MeV]) | Titanium isotope cross section [mb] (beam energy [MeV]) |
|------------------|------------------------------------------------------|--------------------------------------------------------|
|                  | p d α                                               | p d                                                    |
| 43Sc             | 43Ca 400/(9) 44Ca 200/(24)                           | 40Ti 60/(15) 80/(60) 47Ti 70/(25)                      |
|                  | 42Ca 270/(7) 45Ca 700/(15)                           |                                                        |
| 44Sc             | 44Ca 700/(10)                                        | 46Ti 240/(35) 47Ti 70/(15) 48Ti 80/(25)                |
|                  | 43Ca 380/(5) 45Ca 750/(25)                           |                                                        |
|                  | 42Ca 600/(35)                                        |                                                        |

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Table 2. Advantages (+) and drawbacks (-) of use of various chemical form of calcium targets.

| Chemical form | CaCO₃ | CaO | Ca |
|---------------|-------|-----|----|
| (+) The form of the enriched materials easily available commercially; (+) Ready to be used for target preparation by encapsulation, pellets formation, etc. | (+) Achievable by thermal decomposition of CaCO₃; (-) Unstable in air, quick manipulation is required or best to be handled in the inert atmosphere. | (-) Have to be prepared by CaCO₃ conversion; it is a two steps procedure; (-) unstable in the air, it requires handling in the inert atmosphere. |

under the beam
(-) Thermal insulator; Decomposes producing CaO+CO₂. The target cracks when exposed to intensive beams due to this process (see Fig. 1); (-) Production of large amount of ¹³N (decaying in ~10 min via β⁺ to ¹³C).

(+) Dissolves easily in a weak acids; only slightly more difficult than carbonate.

(-) If not sufficient cooling can melt in the beam.

Treatment after irradiation
(+) Dissolves very easily in weak acids.

(-) Thermal insulator; Decomposes producing CaO+CO₂. The target cracks when exposed to intensive beams due to this process (see Fig. 1); (-) Production of large amount of ¹³N (decaying in ~10 min via β⁺ to ¹³C).

(++) Dissolves even in water.

Efficiency
see next table

2 Chemical form of the target

Production of the Sc medical radioisotopes in reaction of Ca nucleus can be done working with unprocessed enriched material i.e. with calcium carbonate (CaCO₃, the chemical form of the enriched Ca isotopes mostly available commercially) or with material converted into either calcium oxide (CaO) or metal (Ca). Work with each target form is advantageous and drawbacks (Table 2). The thermal damages mentioned in Table 2 for calcium carbonate can be eliminated by mixing the target material with a good heat conductor e.g. graphite or aluminium as discussed in [5].

Fig. 1. CaCO₃ target after 2 h irradiation with 15 µA proton beam of 16 MeV.

Taking into account only the level of produced activity which is proportional to the nuclei number per cm² as expressed in the formula

\[ A = \Phi n \chi \sigma (1-e^{-\lambda t}) \] (1)

where:

\[ A \] - activity [Bq]
\[ \Phi \] - beam intensity [projectiles/s]
\[ n \] - number of nuclei per mg of the target material
\[ \chi \] - target thickness [mg/cm²]
\[ \sigma \] - reaction cross section [cm²]
\[ \lambda \] - decay constant (=ln2/T¹/₂) [s⁻¹]
\[ t \] - irradiation time [s]

working with metallic form of Ca would be the most favourable. The activity of the Sc radioisotopes produced during the same time of irradiation of Ca metallic target would be nearly tripled comparing to activity produced while using CaCO₃ (or doubled if working with CaO). This is due to the number of nuclei per cm² (N) in targets with thicknesses covering the projectile range in CaCO₃, CaO and Ca. The ratio of nuclei numbers in these targets is ~ 1:2:3, respectively, and thus is the produced activity.

Table 3. 16 MeV proton and 25 MeV alpha ranges and stopping powers in calcium targets

| Chemical form, density | Range* of projectile in material [mg/cm²] | Stopping power* MeV/(mg/cm²) | N [nuclei/cm²] |
|------------------------|------------------------------------------|-------------------------------|----------------|
|                        | 16 MeV p                           | 25 MeV α**                   | 16 MeV p       | 25 MeV α* |
| CaCO₃                  | 2.71 g/cm³                         | 348.59; 56.94                | 0.02576        | 0.2157   | 3.48×Av×10⁻³ | 0.57×Av×10⁻³ |
| CaO                    | 3.35 g/cm³                         | 368.50; 72.025               | 0.02450        | 0.2028   | 6.58×Av×10⁻³ | 1.28×Av×10⁻³ |
| Ca                     | 1.55 g/cm³                         | 389.05; 77.068               | 0.02345        | 0.1922   | 9.72×Av×10⁻³ | 1.92×Av×10⁻³ |

Av – Avogadro constant = 6.022140857×10²³ mol⁻¹;
* calculated using SRIM 2013 code;
** example energy for ⁴³Sc isotope production in ⁴⁰Ca reaction with α;
However, conversion of CaCO₃ into metallic Ca is a time-consuming two steps reduction process [6,7]. The process can be done under vacuum by decomposing carbonate to oxide, followed by the oxide reduction into Ca using metallic (Me) reductants such as e.g. Zr, Ti.

CaCO₃ $\rightarrow$ CaO + CO₂ (heating at temp. > 700 ºC) (2)

2CaO + Me $\rightarrow$ Ca + MeO (reduction) (3)

In addition, process may as well introduce additional contaminants to the target apart from those present in the available starting material. Also the process efficiency (lower than 80%) has to be kept in mind considering metallic target. Therefore, it is better to avoid this conversion if it’s not vital.

Working with metallic Ca would also require a special vacuum containers and/or construction of a transfer vacuum line to the cyclotron to prevent the contact of Ca with air.

Taking these difficulties into account it is much better to work with calcium oxide as target. Although activity produced is only doubled comparing to activity produced with CaCO₃ target of adequate thickness (see Table 3) but conversion to CaO is much easier than conversion to Ca. It can be done either by heating the oxide in flow of the inert gas [8] or in vacuum using the resistant heating. The advantages of the second method are: the instant/online control on the decomposition process via controlling the vacuum and gives the possibility of cooling down the produced CaO in the air free atmosphere. Conversion carried in a special vessel/crucible with the perforated cover (Fig. 2.) and venting-in the vacuum apparatus after completion of the procedure, with inert gas allows the transfer of the produced CaO to the glove box for manipulations needed to produce the final target (e.g. pressing the pellet, encapsulating into container, etc.) without special precautions.

![Fig. 2. Crucible with perforated cover used for calcium carbonate conversion in vacuum by resistant heating.](image)

In addition decrease of the oxygen content in the target results in a significant decrease of the side radioactivity in the irradiation area related to the production of¹⁵N in ¹⁶O(p,x)¹⁵N or ¹⁶O(d,x)¹⁵N reaction.

The oxide targets prepared as inserts into graphite bed as described in [5] survived 45 min irradiation with 15 µA proton beam very well. There were no signs of thermal damage of the target. The irradiation conditions are sufficient to produce ~8 GBq of ⁴⁴Sc irradiating the CaO converted from enriched up to 99.2 % ⁴⁴CaCO₃. Taking into account the activity loses during isotope separation and labelling process, such amount of ⁴⁴Sc should be enough for diagnosing ~ 75 patients (the estimation based on clinical studies for ⁴⁴Sc [9] where 50.5 MBq of ⁴⁴Sc-PSMA-617 were applied for single diagnosis).

3 Conclusions

Production of the research quantities of Sc radioisotopes can easily be performed using targets made directly from calcium carbonate. However, for clinical application when higher activities are required more favourable is to work with targets made from calcium oxide.

Conversion of carbonate into oxide is one step process practically without loses of the often expensive, enriched calcium material.

As it has been shown using the calcium oxide instead of carbonate gives nearly double activity within the same time of irradiation and much less undesirable radioactivity (originating from decay of ¹⁵N formed in the side reaction) is produced in the irradiation area.

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