Theoretical study on production of stable and radioactive isotopes from proton irradiated sodium chloride

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Abstract. The search for new radioactive isotopes has been on the rise due to high demands of positron-emitting radionuclides applicable for positron emission tomography (PET) modality in nuclear medicine. In this investigation, proton irradiations of sodium chloride (NaCl) were theoretically highlighted, including discussion on stable and radioactive isotopes produced during proton bombardment of the NaCl target. TALYS 2015-Calculated results indicated that 23Mg, 20Ne, 32S, 35Ar, 37Ar and 34S were expectedly produced following NaCl irradiation with 11 MeV protons. More isotopes such as 22Na, 34mCl, 36Cl and 36Ar were generated when the proton energy was increased to 26.5 MeV. Positron emitting radionuclides were found to dominate.

Keywords: isotopes, positron emission tomography (PET), radionuclides, sodium chloride.

1. Introduction

Production of positron emitting radionuclides has been of great interest due to its application in positron emission tomography (PET) modality for various nuclear medicine-related studies, including cancer studies. Currently the most widely used PET radionuclide in nuclear medicine procedures is fluorine-18 (F-18). The relatively short-lived radionuclide (half life = 109.8 minutes) have been used to detect melanoma metastases [1], breast cancer [2], prostate cancer [3, 4] and pancreatic cancer [5]. While F-18 has been in preference in nuclear medicine diagnosis, the on-going investigation for new radionuclides remains on the rise.

For F-18 production, the target of interest is enriched water (H218O) target [6,7] which is costly and leading to relatively expensive diagnostic procedure. Cheaper materials for producing positron emitting radionuclides are, therefore, of paramount importance and are required to lower the costs of diagnosis. Various materials proposed as material targets for PET radionuclide production have been mostly enriched isotopes that are expensive and possibly unaffordable for most patients in developing countries. Nitrogen-15, Nickel-64, Tellurium-124 are few examples of enriched atoms used as targets for producing PET radionuclides, though their prices are also expensive.

Sodium chloride (NaCl) has been understood to be widely and easily available elsewhere at very affordable prices. This is advantageous and efforts to explore the possible use of NaCl as a target for radionuclide production should, therefore, be taken into account.

In this investigation, NaCl is proposed as a target for producing stable and radioactive isotopes, including positron emitting radionuclides. TALYS-calculated nuclear cross-sections are employed to theoretically study the possibility of producing such radionuclides.
2. Materials and methods

In this theoretical study, nuclear cross-section calculations were performed using the TALYS-2015 codes [8], which has been used elsewhere [9, 10]. The TALYS-based evaluated nuclear data library is also available online [11]. The calculated nuclear cross-sections were evaluated from several nuclear reactions, including (p,n), (p,α), (p,np) and (p,2n) nuclear reaction modes between proton beams and the individual sodium chloride atoms (23Na, 35Cl and 37Cl atoms). These reactions were eventually used to predict possible stable and radioactive isotopes generated as a result of proton bombardment. Moreover isotopes generated at different proton energies are also discussed in this research.

3. Results and discussion

3.1. Nuclear reactions between protons and Na atoms

Sodium atom found in nature is 23Na (100% abundance); thus it is necessary to analyze its reaction following proton irradiation. The TALYS-calculated nuclear cross-sections between proton beams and 23Na atoms indicate that significant radioactivity yields could be obtained for (p,n), (p,α) and (p,np) modes, whereas no significant yield is foreseen for (p,2n) reaction as shown in Figure 1. There are 3 radionuclides potentially be produced by proton bombardment of 23Na target, including 23Mg via 23Na(p,n)23Mg reaction, 20Ne due to 23Na(p,α)20Ne reaction and 22Na from 23Na(p,np)22Na nuclear reaction. It should be noted that proton threshold energies for each nuclear reactions above are different. For 23Na(p,n)23Mg reaction the threshold energy is 5.61 MeV, whereas for 23Na(p,α)20Ne and 23Na(p,np)22Na nuclear reactions are 0 MeV and 13.05 MeV respectively. In addition, the maximum nuclear cross-sections for 23Na(p,n)23Mg, 23Na(p,α)20Ne and 23Na(p,np)22Na nuclear reactions are 947.0 mbarn at 9 MeV-protons, 231.4 mbarn at 8-MeV protons and 250.8 mbarn at 24-MeV protons respectively. It is immediately obvious that 23Na(p,n)23Mg nuclear reaction has the highest nuclear cross-section among the other reactions; thus the most possible observed radionuclide soon after irradiation is 23Mg.

3.2. Nuclear reactions between protons and Cl atoms

There are 2 stable chlorine atoms found in nature, namely 35Cl (76% abundance) and 37Cl (24% abundance). Based on the TALYS-calculated nuclear cross-sections between proton beams and 35Cl atoms, the (p,2n) nuclear reaction is, again insignificant compared to the other nuclear modes such as (p,n), (p,α) and (p,2n) as can be seen in Figure 2a. Three possible radionuclides generated during proton bombardment of 35Cl include 35Ar via 35Cl(p,n)35Ar reaction, 32S due to 35Cl(p,α)32S reaction and 34mCl from 35Cl(p,np)34mCl nuclear reaction. The proton threshold energies for 35Cl(p,n)35Ar, 35Cl(p,α)32S and

![Figure 1. TALYS-calculated nuclear cross-sections between protons and Na atoms.](image-url)
\( ^7\text{Na}(\text{p},\text{np})^7\text{Cl} \) nuclear reactions are 8.16 MeV, 0 MeV and 13.01 MeV respectively. Moreover the maximum nuclear cross-section for \( ^7\text{Cl}(\text{p},\text{n})^6\text{Ar} \) is 58.3 mbarn at 14-MeV protons, for \( ^7\text{Na}(\alpha)\text{S} \) is 162.4 mbarn at 11-MeV protons and for \( ^7\text{Na}(\text{p},\text{np})^7\text{Cl} \) is 176.2 mbarn at 24-MeV protons. For 11 MeV protons, since \( ^7\text{Na}(\alpha)\text{S} \) has the highest nuclear cross-section among the other reactions, one would expect to produce more stable sulphur than any other isotopes when the 11-MeV protons are bombarded into \( ^7\text{Na} \) target.

For proton interactions with \( ^7\text{Cl} \) atoms, the TALYS-calculated nuclear cross-sections indicate that significant radioactivity yields could be produced from all investigated nuclear reactions including \( (\text{p},2\text{n}) \) reaction as indicated in figure 2b. There are 4 radionuclides presumably generated in this case, namely \( ^8\text{Ar} \) via \( ^7\text{Cl}(\text{p},\text{n})^6\text{Ar} \) reaction, \( ^7\text{S} \) due to \( ^7\text{Cl}(\alpha)\text{S} \) reaction, \( ^7\text{Cl} \) from \( ^7\text{Cl}(\text{p},\text{n})^7\text{Cl} \) reaction and \( ^7\text{Ar} \) from \( ^7\text{Cl}(\text{p},2\text{n})^7\text{Ar} \) reaction. The threshold energies for \( ^7\text{Cl}(\text{p},\text{n})^6\text{Ar} \), \( ^7\text{Cl}(\alpha)\text{S} \), \( ^7\text{Cl}(\text{p},\text{n})^7\text{Cl} \) and \( ^7\text{Cl}(\text{p},2\text{n})^7\text{Ar} \) reactions are 3.09 MeV, 0 MeV, 10.59 MeV and 10.67 MeV respectively. In addition the nuclear cross-sections for \( ^7\text{Cl}(\alpha)\text{Ar} \), \( ^7\text{Cl}(\alpha)\text{S} \), \( ^7\text{Cl}(\text{p},\text{n})^7\text{Cl} \) and \( ^7\text{Cl}(\text{p},2\text{n})^7\text{Ar} \) reactions are 461.9 mbarn at 10-MeV protons, 172.5 mbarn at 9-MeV protons, 453.1 mbarn at 22-MeV protons, and 148.4 mbarn at 15-MeV protons respectively.

### 3.3. Isotopes generated at different proton energies

Based on the results discussed in Subsections 3.1 and 3.2, one can expect to produce stable and/or radioactive isotopes depending on the incoming proton energy. In this subsection, prediction of the produced isotopes is presented based on the available cyclotrons in Indonesia (9.6-MeV cyclotron at Gading Pluit hospital in Jakarta, 11-MeV cyclotron at Dharmas hospital in Jakarta, 18-MeV cyclotron at Siloam hospital in Jakarta and 26.5-MeV cyclotron at BATAN in Serpong). For proton energies between 9.6 and 18 MeV, the expected produced radioactive isotopes include \( ^{\text{Mg}} \), \( ^{\text{Na}} \), \( ^{\text{Ar}} \), \( ^{\text{Ne}} \), \( ^{\text{S}} \), and \( ^{\text{Ar}} \). In this production route, the positron (\( \beta^+ \)) emitting radionuclides are \( ^{\text{Mg}} \), \( ^{\text{Na}} \), \( ^{\text{Ar}} \), and \( ^{\text{Cl}} \), though their half-lives are mostly very short, except for \( ^{\text{Na}} \) whose half-life is very long (2.603 years). For proton energy of 26.5 MeV, two more positron emitting radionuclides are expected to be generated, namely \( ^{\text{Mg}} \) and \( ^{\text{Ar}} \). The properties of each isotope produced from proton-irradiated NaCl target are listed in table 1.

Based on the expected isotopes produced during proton bombardment of NaCl target, the most possible positron-emitting radionuclide used for PET modality is \( ^{\text{Ar}} \) since its half-life is 32 minutes, though further studies on possible chemical compounds to be labelled with \( ^{\text{Ar}} \) are still required. Among the other proton-emitting radionuclide such as \( ^{\text{Mg}} \), \( ^{\text{Na}} \), and \( ^{\text{Cl}} \), \( ^{\text{Ar}} \) is the most possible radionuclide applied for PET since it has the best half life characteristic (between 30 minutes and 2 hours) while the other produced radionuclide has either very short half life such as \( ^{\text{Mg}} \) (11.317 seconds) and \( ^{\text{mCl}} \) (844.5 ms). In addition \( ^{\text{Na}} \) radionuclide has very long half life (2.603 years), which is not appropriate for PET application since it could stay very long time and be harmful in a patient body.
Table 1. Isotopes produced when NaCl target is irradiated with energetic protons

| Target (abundance) | Nuclear reaction | Threshold energy (MeV) | Half life | Emitted particle |
|-------------------|------------------|------------------------|-----------|-----------------|
| Na-23 (100 %)     | •Na(p,n)Mg       | 5.61                   | 11.317 s  | β               |
|                   | •Na(p,2n)Mg      | 18.86                  | 3.876 s   | β               |
|                   | •Na(p,α)Na       | 13.05                  | 2.603 y   | β               |
|                   | •Na(p,α)Ne       | 0                      | stable    | -               |
| Cl-35 (76 %)      | •Cl(p,n)Ar       | 8.16                   | 1.775 s   | β               |
|                   | •Cl(p,2n)Ar      | 20.05                  | 32.00 m   | β               |
|                   | •Cl(p,α)S        | 0                      | stable    | -               |
| Cl-37 (24 %)      | •Cl(p,n)Ar       | 3.09                   | 35.04 d   | ε               |
|                   | •Cl(p,2n)Cl      | 10.59                  | 3.01x10^4 y | β (98.1%) |
|                   | •Cl(p,2n)Cl      |                       |           | ε (1.9%)        |
|                   | •Cl(p,α)S        | 10.67                  | stable    | -               |

4. Conclusions

Theoretical calculations using the TALYS-2015 codes have been performed for proton-irradiated sodium chloride (NaCl) target. According to the calculated nuclear cross-sections of (p,n), (p,np), (p,2n) and (p,α) nuclear reactions, positron emitting radionuclides are mostly produced when energetic protons hit NaCl target. At proton energies between 9.6 and 18 MeV, several radioactive isotopes such as -Mg,-Na,-Ar,-Ar,-Cl and -Cl are expectedly produced, whereas stable isotopes such as -Ne,-S,-S and -Ar are presumably generated. Two more positron-emitting radionuclides (-Mg and -Ar) are predicted to be produced when the proton energy is increased to 26.5 MeV. While most radionuclides produced during proton irradiation of NaCl target emit positrons, further studies on their applications for PET modality are still needed since their half-lives are relatively short. Nevertheless this theoretical study is useful for PET radionuclide production in the future.

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