Evaluation the reactions of production the radioactive Iodine-124

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Abstract. Nowadays, the field of radionuclide treatment is enjoying an exciting stage and preparing for further growth and progress in the future. For instance, in Asia, the large spread of liver and thyroid diseases has resulted in several new developments /clinical trials using molecular radiotherapy (i.e. targeted radionuclide therapy). Iodine-124 has unique physical properties including long half-life that adding an advantage for pharmacokinetics and radiopharmaceutical analysis. One of its applications in nuclear medicine is in Positron Emission Tomography (PET). The aim of the present work is to evaluate the production yield of ¹²⁴I via calculated the excitation functions /stopping power for the reactions ²⁵₂Er(P,X)¹²⁴I, ¹²¹Sb(A,N)¹²⁴I, ¹²¹Sb(A,X)¹²⁴I and ¹²³Sb(A,3N)¹²⁴I in the energy range (3.87-62.95)MeV by using Mat-lab and SRIM programs.

Keyword: Cross section, Excitation function, Iodine-124, Integral yield.

1. Introduction
Generally, Radioisotopes are formed in reactors /cyclotrons to be utilized for diagnostic or treatment purposes in healthcare. The reaction is produced via the energy of the projectile particles to be utilized in the production of the target core and the radioisotopes. For situations where perform an experiment is expensive and hard, simulation studies are preferred to carry out owing to it is save both economy and time [1]. In nuclear medicine, iodine radionuclides are exceedingly utilized for labelling monoclonal antibodies, receptors, and other radiopharmaceuticals, specifically in the applications of diagnostic and therapeutic as quantitative imaging over an interval of a number of days is needful [2].

Unluckily, the nuclides most utilized are ¹³¹I, ¹²⁵I and ¹²³I, and all have restrictions. ¹³¹I is considered the most commonly used among the three, and it has very high photon energy for optimal imaging. Moreover, rigorous attenuation correction does not allowed via Single-Photon Emission Computed Tomography imaging (SPECT), though a satisfactory empirical correction may sometimes be realized. ¹²³I has a photon energy which is very low for optimal imaging, particularly quantitative imaging, also it has an extremely long half-life (i.e. half-life is undesirably long). ¹²³I has a half-life which is very short. On the other hand, a positron-emitting nuclide is Iodine-124 with a half-life of 4.176 days, and this allows quantitative imaging over several days by Positron Emission Tomography PET (a powerful non-invasive technique for molecular imaging [2–4].

Among its clinical applications are Na, ¹²⁴I has been used to diagnose/dosimetry in the disease of thyroid and to estimate the springing up of metastatic thyroid carcinoma. Furthermore, [¹²⁴I]-iododeoxyuridine ([¹²⁴I]-I UdR) has been used in measuring the activity of proliferation of tumors in...
patients suffer from tumors of brain, including gliomas and meningiomas. Besides, $^{124}$I-Miodobenzyguanidine ($^{124}$I-MIBG) has got massive potential for utilizing in cardiovascular imaging, diagnosis, and therapy of malignant diseases like carcinoids, neuroblastoma, pheochromocytoma and paraganglioma [3,5–8]. R. Lambrecht et al in (2010) produced Iodine-124 in great yield through >99.5% radionuclidic purity at (48 h) post irradiation and the $^{124}$Te (d,2n)$^{124}$I reaction. Targetry methodology has been explained. The production yield was (0.55±0.06 mCi/µA.h) [9]. R. Weinreich and E. Knust in (1996) was produced $^{124}$I ($T = 4.15$ d) using a compact cyclotron by the nuclear reaction $^{124}$Te (d,2n)$^{124}$I via irradiation of $^{124}$TeO$_2$ with deuterons of energies ($14$ MeV). And then, dry distillation of the radioactive iodine isotopes generated from irradiated target materials. By-products including (8.02d)$^{131}$I, (12.4h)$^{130}$I, (13.0d)$^{126}$I, (60d)$^{125}$I and (13.2d)$^{123}$I have been measured and collected in each charge. After (45 h) decay time, the data demonstration that the total of the activities of these nuclides is below 5% of the $^{124}$I activity [10]. S. S. Salodkinand V. M. Golovkov in (2020) have been investigated the methods of production of Iodine-124 radionuclide in nuclear medicine. The effect of target material, the selected nuclear reactions, the irradiation conditions, and the ways of manufacturing / cooling of the irradiated targets on the Iodine-124 yield is considered [11]. In present work, the yield of $^{124}$I has been calculated via weighted average cross sections and stopping power of $^{nat}$Te(P,X)$^{124}$I, $^{121}$Sb(A,N)$^{124}$I , $^{nat}$Sb(A,X)$^{124}$I and $^{123}$Sb(A,3N)$^{124}$I reactions by using sets of programs like Mat-lab and SRIM.

2. Decay Scheme of Iodine-124

Iodine-124 has decay scheme as shown in Fig. (1). At minimum, there are 97 gamma-ray transitions, 25 electron capture transitions and 6 positron transitions. Within the limits, 23% of decays result in emission of positron. Furthermore, there is several high energy gamma rays, some in coincides with the emissions of the positron [2-4].

![Figure 1. Simplified decay scheme of $^{124}$I](image)

3. Theoretical background

For several decades, the possible use of radionuclides in treatment has been recognized. The most important advantage of radionuclide therapy is the ability to deliver a greatly concentrated absorbed dose to the tumor with preserving the surrounding natural tissue. Targeted radionuclide treatment has become one of the most favourite kinds of cancer treatment due to the administration of radionuclides is slightly invasive and the period of therapy is shorter than chemotherapy. A number of radionuclides including Iodine-124 have been successfully utilized for diagnostic and therapeutic [1,12]. There is a large number of reactions that is utilized for producing $^{124}$I, relying on the particles, cyclotron and the
energies that are available in executing the irradiations [5]. In present work, $^{124}\text{I}$ has been produced by utilizing proton induced $^{120}\text{Te}(\text{P},X)^{124}\text{I}$ reaction and $^\alpha$ induced $^{121}\text{Sb}(\text{A},\text{N})^{124}\text{I}$, $^{124}\text{Sb}(\text{A},\text{X})^{124}\text{I}$, $^{123}\text{Sb}(\text{A},3\text{N})^{124}\text{I}$ reactions. The energy data for every reaction are obtained from the database of EXFOR and using Matlab programs language to calculate weighted average cross sections (W) for each reaction individually as the following:

$$W = \frac{\sum w_i y_i}{\sum w_i}$$  

$$w_i = \frac{1}{\mu_i^2}$$

where $\mu_i$ is the standard deviation for sample i and $y_i$ is the cross section value for sample i [13]. The cross section is one of the most significant physical quantity describing nuclear reactions. Experimentally, it can be calculated or measured utilizing varied technique (i.e. models) of nuclear reactions [14].

Furthermore, the integral yield (i.e. the overall number of the formed nuclei through an irradiation time) of these reactions is calculated according to the equation below [15]:

$$Y(t) = t \int_0^L l(x) \sigma(x) \left( \frac{P}{\rho \text{e}} \right) dx$$

$$= t l_0 \int_{E_0}^{E_i} \left( -\frac{1}{\rho \text{d}x} \right)^{-1} \left( \frac{\sigma(E)}{\rho \text{e}} \right) \text{d}E$$

$$= t l_0 y$$

Here, $\rho$ is the target isotope number density of sample material, $t$ is the irradiation time, $L$ is the thickness of sample material, $\sigma(x)$ is the cross section to produce the isotope at depth $x$ in the sample, $Z$ is the charge number, $l_0$ is the number of beam particles irradiating the sample per unit irradiation time, $E_0$ initial beam energy, $E_i$ is the energy of the beam at the exit of the sample, $(-\frac{1}{\rho \text{d}x})^{-1}$ is the stopping power and $y$ is the thick target product yield (i.e. is the number of the formed nuclei per unit induced electric charge). It is used for both stable / radioactive products, however is frequently utilized for stable ones.

On the other hand, the number of the formed nuclei existing in the sample material ($t$) satisfies when the product is radioactive with decay constant($\lambda$) according to the relation below:

$$\frac{dN(t)}{dt} = \frac{dY(t)}{dt} - \lambda N(t) = l_0 y - \lambda N(t)$$

The solution is

$$N(t) = l_0 y \left( \frac{1 - e^{-\lambda t}}{\lambda} \right)$$

Then

$$\frac{\lambda N(t)}{l_0} = y \left( 1 - e^{-\lambda t} \right) = a(t)$$

where $\frac{\lambda N(t)}{l_0}$ represented the activity of the sample material per unit current at $t$ and $a(t)$ is the decay rates of the product per unit current [15].
4. Result and discussion
The values of the cross section for \(^{nat}\)Te(P,X)\(^{124}\)I, \(^{121}\)Sb(A,N)\(^{124}\)I, \(^{nat}\)Sb(A,X)\(^{124}\)I and \(^{123}\)Sb(A,3N)\(^{124}\)I reactions are calculated from previous studies [16-29], in the range of energies (3.87-62.95MeV) with a step of (0.5 MeV).

The weighted average cross sections for the above mentioned reactions have been calculated using equations (1 and 2) and rely on the data of proton and \(\alpha\) induced, energy and cross sections published via the (EXFOR) library affiliated to the International Atomic Energy Agency by using Mat-lab (8.3a 2014) program.

Moreover, the integral yield \(^{nat}\)Te(P,X)\(^{124}\)I, \(^{121}\)Sb(A,N)\(^{124}\)I, \(^{nat}\)Sb(A,X)\(^{124}\)I and \(^{123}\)Sb(A,3N)\(^{124}\)I reactions have been evaluated by using equations (3-8) depended on the values of stopping power that was calculated via Zeigler formula through (SRIM-2013) program. The results of the integral yields are given in table (1).

| Nuclear reaction | Energy (MeV) | Thick target yield of \(^{124}\)I(\(\frac{Bq}{\mu A.h}\)) |
|------------------|-------------|--------------------------------------------------|
| \(^{nat}\)Te(P,X)\(^{124}\)I | 10 – 20 | 1400 – 1447 |
| \(^{121}\)Sb(A,N)\(^{124}\)I | 30 – 45 | 184.6 – 200 |
| \(^{nat}\)Sb(A,X)\(^{124}\)I | 26.72 – 47 | 446 – 575 |
| \(^{123}\)Sb(A,3N)\(^{124}\)I | 32 – 45 | 1942 – 2273 |

The calculated results of excitation functions and integral yields are presented in Figures. 2 – 9.

Figure 2. Excitation function of (\(^{nat}\)Te(P,X) (\(^{124}\)I

Figure 3. Integral yield of (\(^{nat}\)Te(P,X) (\(^{124}\)I
Figure 3. Excitation function of $^{121}\text{Sb}(A,N)~^{124}\text{I}$

![Figure 3](image)

Figure 4. Excitation function of $^{\text{nat}}\text{Sb}(A,X)~^{124}\text{I}$

![Figure 4](image)

Figure 5. Excitation function of $^{123}\text{Sb}(A,3N)^{124}\text{I}$

![Figure 5](image)
Figure 6. Production Yield for $^{nat}Te(P,X)^{124}I$ reaction.

Figure 7. Production Yield for $^{121}Sb(A,N)^{124}I$ reaction.

Figure 8. Production Yield for $^{nat}Sb(A,X)^{124}I$ reaction.
Figure 9. Production Yield for $^{123}Sb(A,3N)^{124}I$ reaction.

We observed from figures (2-5) that the cross section of the $^{nat}Te(P,X)^{124}I$, $^{121}Sb(A,N)^{124}I$, $^{nat}Sb(A,X)^{124}I$ and $^{123}Sb(A,3N)^{124}I$ reactions is proportional to the energy of the incident particle.  

$^{nat}Te(P,X)^{124}I$ reaction: It has two maximum cross-section values which are(148.3824mb,164.9666mb) at energies (35 MeV, 59MeV) respectively.

$^{121}Sb(A,N)^{124}I$ reaction: it has one maximum cross-section value which is(461.6968mb) at about18.1 MeV. After that, the cross-section values start decreasing until reaching to (0.7882mb) at energy (58.42 MeV).

$^{nat}Sb(A,X)^{124}I$ reaction : It has two maximum cross-section values which are (1.1107 $\times$ 10$^3$mb, 1.0681 $\times$ 10$^3$mb) at energies (36.5 MeV, 39MeV) respectively.

$^{123}Sb(A,3N)^{124}I$ reaction: It has one maximum cross-section value which is(1.33 $\times$ 10$^3$mb) at energy35.5 MeV. After that, the cross-section values start decreasing until reaching to (0.1579 $\times$ 10$^3$mb) at energy of58 MeV.

On the other hand, we noticed that after each maximum cross-section value, the cross-section values begin to decrease as the energy of the incident particle increases. Furthermore, the integral yield of $^{nat}Te(P,X)^{124}I$, $^{121}Sb(A,N)^{124}I$, $^{nat}Sb(A,X)^{124}I$ and $^{123}Sb(A,3N)^{124}I$ reactions are directly proportional to the energy of the incident particle as shown in figures (6-9).

It is obvious that the values of the yield are different from one reaction to another owing to the difference in reaction cross section and energy of incident projectile. Choosing a suitable energy range for the incident particle improves the production process (i.e. Increases iodine yield and reduces impurities. The yields of reactions $^{121}Sb(A,N)^{124}I$ and $^{123}Sb(A,3N)^{124}I$ were in agreement with [30]. Generally, iodine-124 is formed good yield through the nuclear reaction $^{123}Sb(A,3N)^{124}I$.

5. Conclusions
The main objective of this work is the possibility of producing radioactive Iodine-124 to be used in nuclear medicine (i.e. diagnostic and therapeutic applications including Positron Emission Tomography (PET)), as it has physical and chemical properties that qualify it for that. So, it was produced theoretically from different reactions by utilizing sets of programs like SRIM and Mat-lab. From the results that shown in table (1), we can conclude that the reactions
$^{123}\text{Sb}(A,3N)^{124}\text{I}$ are the best of other reactions to the production of iodine with the least possible energy (i.e. $^{123}\text{Sb}(A,3N)^{124}\text{I}$ reaction is ideally suited to produce Iodine-124.

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