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Estimation of the Annual Absorbed Dose of Protons Produced from 12C (Alpha, P) 15N Reaction

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ABSTRACT

1. This study focuses on the theoretical and computational determination of the activity of N-15 produced through the 12C(α, p)15N nuclear reaction. The investigation involves the use of alpha particles (α) bombarding carbon-12 nuclei, resulting in the formation of nitrogen-15 (15N) through proton (p) emission.
2. The calculation methodology encompasses quantum mechanical models and nuclear reaction theory to predict the cross-sections governing the 12C(α, p)N15 reaction at various incident alpha particle energies. Utilizing these cross-sections, the reaction rates are computed, and subsequently, the activity of the produced N-15 is estimated.
3. The impact of reaction parameters such as energy, angular momentum, and nuclear structure on the reaction dynamics is explored. In this research, SRIM and MATLAB programs were used to calculate the Cross section for alpha and carbon-12 interaction, simulate the account yield of 15N, and predict the distribution of N-15 activity.

The results of this study provide valuable insights into the fundamental processes governing the 12C(α, p)15N reaction, aiding in the understanding of nucleosynthesis pathways in astrophysical environments and contributing to the development of nuclear models. The calculated N-15 activity serves as a crucial parameter for applications in fields such as nuclear astrophysics, nuclear medicine, and isotope production for various scientific and industrial purposes.

Keywords: Annual effective dose, cross-section, MATLAB.

INTRODUCTION

Humans are continuously exposed to nuclear radiation, sourced from various origins including cosmic rays originating in space. Solar particles penetrate the Earth's atmosphere, initiating a series of secondary interactions and decays. The ionizing component of cosmic rays produces, on average, an absorbed dose rate in the air of 32 n Gy.h^{-1} at sea level in the mind – latitudes corresponding to an effective dose rate of 32 n Sv.h^{-1} [1]. Taking into account shielding by building for the ionizing component and distribution of world population with altitude, the population _ weighted average annual effective dose from cosmic rays is 380 $\mu\, Sv$[1] Cosmic rays consist of high energy particles with a mean energy 10^4 MeV, such as proton, high energy electrons, alpha particles, and light atomic nuclei[2,3], The atmosphere acts as a shield and reduces very considerably the amount of cosmic ray reaching the earth's surface.
Man-made sources of Radiation

The soil's chemical composition, a blend of solids reflecting the region's geological profile, plays a crucial role. Radioactive elements and heavy metals in soil behave according to geological formations and mineralization within the troposphere. Radionuclides in soil pose significant challenges due to their geochemical mobility, facilitating widespread pollution across environmental components[4]. Natural processes like weathering, sedimentation, and chemical reactions in the Earth's crust lead to variable concentrations of primitive radionuclides in soil[5]. The uranium, actinium, and thorium series of naturally occurring radionuclides contribute substantially to the background external radiation[6]. Gamma radiation emitted by these materials, present ubiquitously in soils, constitutes the primary source of both internal and external radiation exposure to humans, accounting for approximately 85 % of the received radiation dose. Certain human activities exacerbate these radiation levels. With an increasing emphasis on population safety and radiation exposure prevention, the field of health physics is gaining importance. Research on radionuclide distribution in the environment and associated doses serves as vital baseline data for developing radiation protection guidelines and regulations[7-10].

Radon is a colorless, odorless, and tasteless radioactive gas that occurs naturally in the environment. It belongs to the group of noble gases and is chemically inert. The main source of radon is the radioactive decay of uranium, found in varying concentrations in soil, rocks, and water. Radon is part of the uranium decay series and is formed when uranium undergoes radioactive decay, producing radium, which in turn decays into radon gas [11].
The most common uranium isotopes that contribute to radon production are uranium-238 and uranium-235. These isotopes decay through a series of intermediate products until radon gas is produced. Once radon gas is released from the ground, it can enter buildings, especially those with basements or foundations in contact with soil, and build up to potentially dangerous levels [12].
Health risks associated with exposure to radon gas Radon is a known carcinogen, and exposure to high levels of radon is a major public health concern. The primary health risk associated with radon exposure is lung cancer. When radon gas is inhaled, it undergoes radioactive decay in the lungs, producing solid radioactive particles known as radon progeny or decay products. These particles can attach to dust and other airborne particles and, when inhaled, can settle in the lungs [13]. Alpha particles released during the decay of radon gas can damage lung tissue and increase the risk of lung cancer. In fact, radon is the second leading cause of lung cancer after smoking. The risk is especially high for individuals who smoke and are exposed to high levels of radon [14]. It is important to note that the risk of lung cancer associated with radon is a long-term effect, and symptoms may not appear until many years after exposure. Mitigating radon levels in homes and workplaces is critical to reducing the risk of lung cancer associated with radon exposure. Regulatory standards and guidelines exist to help manage and reduce radon concentrations in indoor environments, and radon testing is recommended, especially in areas where radon is known to be prevalent [15,16]

There are some studies that study the contamination of soil, air, water, and other products with radon. From the results of these studies [4-7], it was confirmed that the air is polluted with radon gas, which emits alpha particles with high energies, as well as soil contamination with radon daughters, which in turn emits other particles with high energies.

The concentration and abundance of C-12 in the air
Carbon-12, one of carbon's three isotopes, alongside the stable Carbon-13 and the radioactive Carbon-14, maintains a consistent presence in Earth's atmosphere [17]. The atmospheric composition reveals that nearly 99% of carbon atoms are Carbon-12, with a concentration of approximately 98.89%. It is crucial to acknowledge that these figures represent averages and may exhibit slight variations in different environmental settings. Isotope ratios play a significant role in scientific investigations, including applications in carbon dating and isotopic analyses within geochemistry and biology [18, 19].

The isotopes N^{15} and C^{12} have been investigated using several reactions, such as $N^{15}(p,\gamma)O^{16}$ and $N^{15}(p,\alpha)C^{12}$ [20], as well as $C^{12}(\alpha,\alpha)C^{12}$ [21,22]. The primary emphasis of this paper is centered on the alpha capture reaction $C^{12}(\alpha, p)N^{15}$, which presents advantageous characteristics for investigating excited states of N^{15}. Notably, both the target and bombarding nuclei possess zero spin and even parity, restricting the formation of states to those with natural parity, namely J~ = 0^+, 1^-, 2^+, 3^-, 4^+, etc., in the N^{16} compound nucleus. Additionally, for a self-conjugate nucleus like N^{15}, the isobaric spin selection rules for gamma-ray dipole transitions can be applied to glean information about the isobaric spins of the involved states. Previous studies on the alpha capture reaction established an upper limit of 3 x 10^{-29} cm MeV for the target thickness [23,24].

When two charged nuclei surpass their Coulomb repulsion, they have the potential to undergo a rearrangement of nuclear components, akin to the atom rearrangement observed in chemical reactions. This rearrangement can initiate a nuclear reaction, often initiated by the collision of a nuclear projectile, typically a nucleon (neutron or proton), or a light nucleus such as a deuteron or α-particle, with a target nucleus [25]. In cases where excitation energies are low (< 10 MeV), most nuclear reactions lead to the formation of two nuclei, with one possessing charge and mass numbers nearly identical to the target nucleus. These reactions can be represented by equations in the following format.

$$X + a \rightarrow Y + b \qquad \text{Eq. 1}$$

In nuclear reactions where a light projectile nucleus (a) collides with a stationary target nucleus (R) in the laboratory system, the outcome yields a resulting nucleus (Z) along with a light nuclear particle (b), which predominantly carries away the kinetic energy. If nucleus Z remains in an excited state after the emission of particle b, it usually undergoes decay by emitting one or more gamma rays. Conversely, if nucleus Z is beta unstable, it later decays through either electron or positron emission, succeeded by gamma emission [26].
Nuclear reactions at low excitation energies encompass various types, including (p,γ), (n,γ), (n,α), (d,p), (α,n), (p,n), (d,n), (n,p) , …..etc

$$R + a \left| \begin{array}{l} R + a, \\ R^* + a, \\ Z + b, \\ Z^* + b, \end{array} \right. \qquad \text{Eq. 2}$$

The initial pair of reactions in this set involve the outgoing particle matching the incident particle, constituting what is termed as scattering. The initial reaction denotes elastic scattering, while the subsequent one signifies inelastic scattering, wherein the target nucleus R transitions to an excited state (R*). The remaining reactions in the set encompass various potential nuclear transmutations, leading to product nuclei that may exist in either their ground states or more frequently in excited states. Typically, the excited product nucleus rapidly decays to its ground state, emitting γ-rays in the process [26].

Cross sections

Cross sections in nuclear reactions play a crucial role in understanding the likelihood of specific reactions occurring. To quantify this likelihood, nuclear physicists often define a parameter known as the cross-section, denoted by σ. This parameter represents the effective size of the nucleus for a particular reaction. The data on reaction cross-sections is vital for gaining fundamental insights into nuclear systems. Mathematically, the cross-section (σ) is defined as the ratio of the reaction rate (R) to the incident particle flux (I), expressed as σ = R / I [27].
where σ: is the cross-section, and is of the order of the square of the nuclear radius. A commonly used unit is the barn: 1 barn = 10^{24} cm^2, R represents the rate of reactions per nucleus per unit time, while I denotes the rate of incident particles per unit time per unit area. The cross-section, measured in units of area, reflects the likelihood of a reaction occurring when a bombarding particle interacts with a target nucleus.
In a broader context, when a particular bombarding particle collides with a target nucleus, various reaction pathways may occur, resulting in the production of different light reaction products over time[28,29]. The total cross-section is therefore defined as the cross-section of a specific reaction, such as ^{12}C (α,b)Y, which represents a binary reaction.

$${}^{4}_{2}\alpha + {}^{12}_{6}C \rightarrow {}^{16}_{8}O + \gamma \qquad \text{Eq. 3}$$
$${}^{4}_{2}\alpha + {}^{12}_{6}C \rightarrow {}^{12}_{6}C + \alpha \qquad \text{Eq. 4}$$
$${}^{4}_{2}\alpha + {}^{12}_{6}C \rightarrow {}^{15}_{7}N + P \qquad \text{Eq. 5}$$
$${}^{4}_{2}\alpha + {}^{12}_{6}C \rightarrow {}^{15}_{8}O^{*} + n \qquad \text{Eq. 6}$$

In this paper cross sections are measured from the website TENDEL 21[30] in the reaction of alpha, and carbon There are many reaction channels, and any single reaction has its cross-section so in this work two reactions have high cross-sections (4 and 5 reactions) were studied.

Experimental Work

1. **Calculate the range of heavy charge particles**

Fig. 1 shows the simulation of the transmission experiment, contemplating a scenario in which a parallel stream of energetically charged particles, all possessing identical energy levels, is directed toward a designated material. The thickness of this material can be adjusted as desired. Located on the opposing side of the material, a detector is poised to register the particles that pass through it. The assumption is that the direction of the particles remains constant, and the detector is capable of capturing all particles that successfully traverse the material, regardless of their energy levels being minimal.

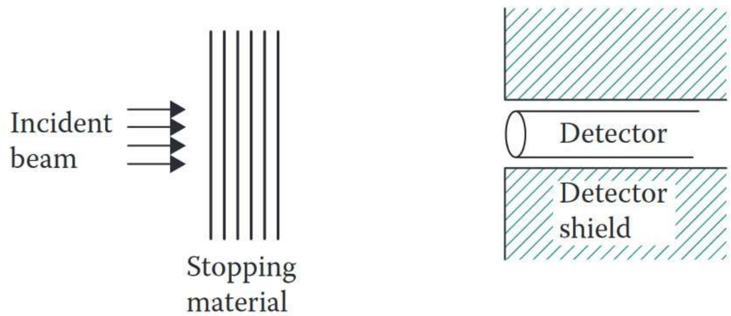

Fig.1: The simulation of transmission experiment

The quantity of particles, denoted as N(t), passing through a thickness t, undergoes variation, as depicted in Fig. (2). Initially, N(t) remains constant despite changes in t. Beyond a particular thickness, N(t) experiences a rapid decrease, eventually reaching zero. The thickness at which N(t) diminishes to half its initial value is termed the mean range, denoted as R. The thickness at which N(t) becomes practically negligible is referred to as the extrapolated range, denoted as R_e. The disparity between R and R_e typically amounts to 5% or less. Unless specified otherwise, the term "range" denotes the mean range R. Empirical formulas have been devised to express the range as a function of particle kinetic energy. Specifically for alpha particles, the range in air at normal temperature and pressure is provided by

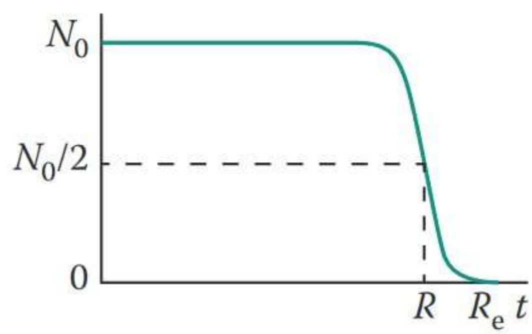

Fig. 2: The quantity of heavy charged particles (such as alpha particles, protons, deuterons, and tritons) passing through a given thickness *t*

R(mm, air) = exp (1.61$\sqrt{T\ (Mev)}$) $\quad 1< T \le 4\ Mev$ Eq. 7

R (mm, air) = exp (0.05 T(MeV)) + 2 .85 T $Mev^{2/3}$ $\quad 4 < T \le 10$ Eq. 8

After many attempts to calculate the range of alpha particles in carbon for a good result we will use a program called (SRIM) [31]is a collection of software packages that calculate many features of the transport of ions in

matter.
The compound-nucleus model adeptly elucidates nuclear reactions induced by relatively low-energy striking particles, specifically projectiles with energies below approximately 50 million electron volts.

2. Interaction of Alpha Particles with Matter

When a charged particle traverses a medium it progressively loses its energy by transferring it to the electrons of the medium atoms or by emission of electromagnetic radiation (bremsstrahlung) [32]. This phenomenon allows for ionization to take place within a given medium (solid, liquid, or gas) through the creation of ion pairs. When an alpha particle traverses through the medium, the Coulombic attraction between the alpha particle and the atomic electrons of the medium increases its effective mass. This augmentation facilitates ionization either through Coulombic interaction or direct collision of the alpha particle with atomic electrons. As the alpha particle moves through the medium, it generates thousands of ion pairs until its kinetic energy is entirely dissipated within the substance it traverses. Alongside ionization, another significant mechanism through which alpha particles transfer their energy to matter is via electron excitation [33].

3. Stopping power

Stopping power, denoted as –dE/dx, represents the average linear rate of energy loss of a heavy charged particle within a medium (typically expressed in units like MeV cm $^{-1}$). This parameter is crucial in radiation physics and dosimetry, serving as a fundamental measure of the medium's ability to slow down the particle.
Stopping power due to ionization–excitation $for\ \alpha$ particale is [14] :

$$\frac{dE}{dx}\left(\frac{mev}{m}\right) = 4\pi r_{\circ}^{2} z^{2} \frac{mc^{2}}{\beta} \text{ N Z } [\ln(\frac{m c^{2}}{I} \beta) - \ln(1-\beta^{2}) - \beta^{2} \qquad \text{Eq. 9}$$

where $r_{\circ} = \frac{e^{2}}{mc^{2}} = 2.818\times 10^{-1}$ m =classical radius of electrons.
$m c^{2} = rest\ mass\ energy\ of\ the\ electron = 0.511\ mev$,
$\beta = \frac{v}{c}$, $c = 3\times 10^{8}\ {}^{m}/_{S}$; $v = velocity\ of\ the\ particle$
N is the number of ${}^{atoms}/_{m^{3}}$ for the material though which the particle moves, Z is the atomic number of the material, z is the charge number of the incident particle (z = 2 for α) , $and\ I$ is the mean excitation potential of the material.
The range of an alpha particle in air at normal temperature and pressure is given by [turner]:

$$R\ (mm) = \exp[\ 1.61\sqrt{E_{K\ (Mev)}}\ ] \qquad 1< E_{K} \leq 4\ Mev \qquad \text{Eq. 10}$$

$$R(mm) = (\ 0.05\ E_{k} + 2.85\ )E_{K}^{3/2}\ (MeV) \qquad 4\leq E_{K} \leq 15\ Mev \qquad \text{Eq. 11}$$

where the E_{K} is the kinetic energy of alpha partical.
If the range of an alpha particle is known in one material, its range in another material can be determined by applying the Bragg – Kleeman rule [34]:

$$\frac{R_{1}}{R_{2}} = \frac{\rho_{2}}{\rho_{1}}\sqrt{\frac{A_{1}}{A_{2}}} \qquad \text{Eq. 12}$$

where ρ and A are the density and atomic weight respectively.

4. Energetics of Threshold Reactions

The reaction occurs when the energy of the photon, denoted by hv, is greater than or equal to the energy required, represented by –Q, for the increase in mass. The condition for the threshold energy in a neutron reaction differs. In this case, the neutron must possess sufficient energy to not only provide the increase in mass, denoted by –Q, but also to sustain the continued motion of the center of mass of the colliding particles after the collision. However, for photons, the latter requirement is typically negligible.

Threshold energy calculations involve considering a head-on collision scenario. A particle with mass M1 collides with another particle of mass M2, initially at rest. As a result of the reaction, the identities of the particles change, leading to generally different masses, represented by M3 and M4, after the encounter.

Theoretical Concepts
Indoor exposures to radon 222 daughters significantly contribute to the overall radiation dose received by the general population. However, the precise nature and extent of indoor exposures remain uncertain. Interest in this

topic has grown recently due to the increased use of measures that might reduce mechanical ventilation or infiltration rates in buildings, potentially leading to higher concentrations of radon daughters [35].

^{15}N Yield

In the context of nuclear reactions occurring as a charged particle beam passes through a target, a certain number of light product particles N are produced per unit time. Referring to Fig. (3), the yield is determined by the equation:

$$y\,(x) = I_{\circ}\, N_d\, \sigma\, x \qquad \text{Eq. 13}$$

For a target that is not infinitesimally thin, the beam experiences energy loss as it traverses the target. In this case, the yield is given by: [36]

$$Y_n = \int_{E_{th}}^{E_b} \frac{\sigma\,(E')\eta(E')f\, dE'}{\frac{dE}{dx}(E')} \qquad \text{Eq. 14}$$

Here, E_{th} = E_b - ΔE, let ΔE denote the energy loss of the beam within the target, where f represents the quantity of target atoms within each target molecule, and $\frac{dE}{dx}$ (E') represents the stopping power per target molecule. If the target is sufficiently thick, with one atom per molecule (i.e., f=1), and assuming $\eta(E') = 1$, then the resulting yield is termed the thick-target yield, given by: [37]

$$Y(E_b) = \int_{E_{th}}^{E_b} \frac{\sigma\,(E)dE}{\frac{dE}{dx}} \qquad \text{Eq. 15}$$

where E_{thr} is the reaction threshold energy

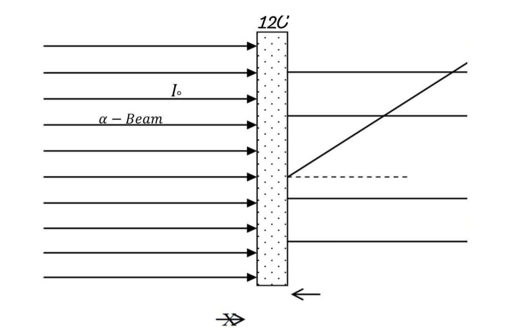

Fig. (3): A visual representation depicting the concept of total cross section by illustrating the decrease in intensity

The quantity *Io* represents the incident particle count per unit area per unit time, while *I* signifies the outgoing particle count per unit area per unit time.

Effective Dose Due to Contaminated the air with Protons

The absorbed dose resulting from air contamination with protons can be determined using the formula:

$$D = \frac{Q.N}{m\rho A} \qquad \text{Eq. 16}$$

Where:

D is the absorbed dose in gray (Gy),
Q is the energy imparted by protons in joules (J),
N is the number of protons,

m is the mass of air in kilograms (kg),
ρ is the density of air in kilograms per cubic meter (kg/m³),
A is the mass stopping power of air in square meters per kilogram (m²/kg).
The mass stopping power A can be acquired from tables or databases containing radiation interaction data for various materials, with a value typically around 0.32×10^{-10} J.m^2/kg.
The total energy Q delivered to the medium by the protons is expressed as:

$$Q = N.E \qquad \text{Eq. 17}$$

Where:
N is the number of protons,
E is the energy of each proton in joules

Results and Discussion

A MATLAB program utilizing version 2012b was developed to compute the numerical solutions of Equations (14) and (15). The computations relied on data from the TENDL-2021 website's cross section database, which is a nuclear data repository primarily maintained at PSI and the IAEA Nuclear Data Section. TENDL offers cross section data output from the TALYS nuclear model code system, suitable for direct utilization in both fundamental physics and practical applications. Also the SRIM program was used to provide MATLAB by range of alpha particles. The program considered various alpha energies emitted by radionuclide sources, specifically focusing on discrete mono-energy alpha emissions. Fig. 4 illustrates the program's block diagram.

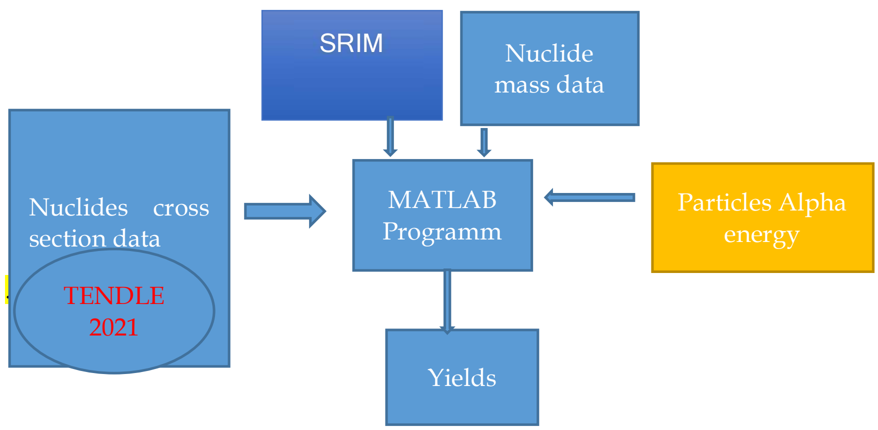

Fig. 4: The block diagram of MATLAB code.

Fig. 4 shows the program was designed for C-12 target nuclide calculations. It was run using alpha particles with different energies emitting from the significant dangerous radioactive waste material. These various energies were affected by the yield of nuclides. The vertical axis represents the normalized residual of 1g target nuclides C-12. The number of N-15 nuclei and protons was effectively increased with alpha energy and the activity of radon increased as presented in Table 1.

Table 1: Cross-section data and the yields of the reactions $^{12}C(\alpha,\alpha')C^{12}$ and $C^{12}\ (\alpha,p)N^{15}$

E (MeV)	dE/dx Elec	dE/dx $Nuclear$	Range	$^{12}C(\alpha,\alpha')C^{12}$ yield	$C^{12}\ (\alpha,p)N^{15}$ yield
1	408.3	0.4742	0.00270	0	0
2	317.5	0.2619	0.00548	0	0
3	254.5	0.1843	0.00900	0	0
4	112.2	01434	0.01332	0	0
5	182.2	01179	0.01842	0	0
6	159.9	0.1004	0.02428	0	0
7	142.7	0.08762	0.03090	9.9	32.5
8	129.1	0.07786	0.03827	29.4	35.5
9	118.9	0.07014	0.04633	172.0	51.3
10	109.4	0.06388	0.05509	312.0	58.0

The effect of incident alpha particle on the cross section and the result nuclides and its yield are shown in Figures 5, 6 and 7. It's obvious from these results, the reaction of carbon with alpha particles can occur via low energy that equal to alpha particle energy emitting from radon and its daughters. The cross-section is very high for this reaction equal to 650mbarn.

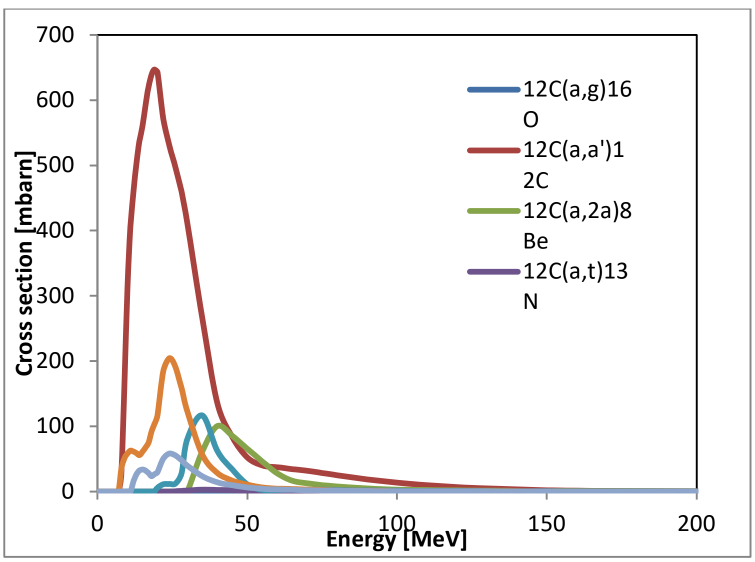

Fig. 5: The cross-section of interaction of C-12 with alpha particles with different energies

Protons are resulting from this reaction with nitrogen-15. The energy of protons can be calculated using q equation.

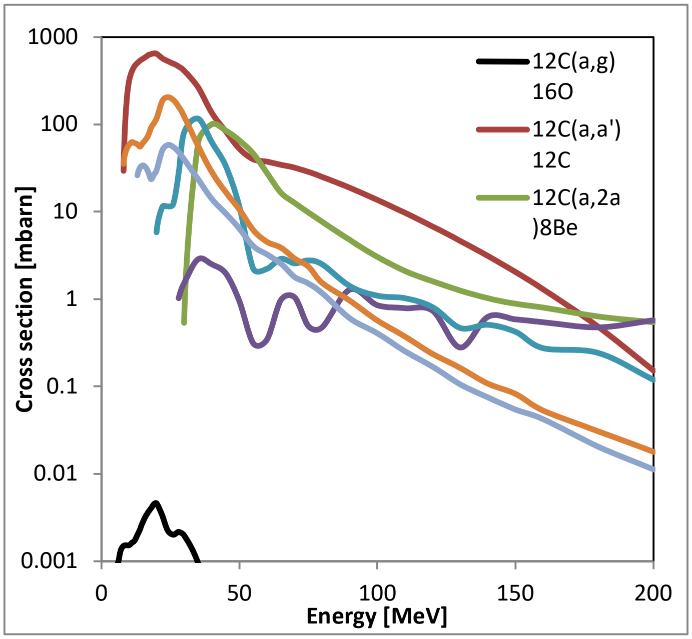

Fig. 6: Part of the relation ship between cross-section and the energy of alpha particles

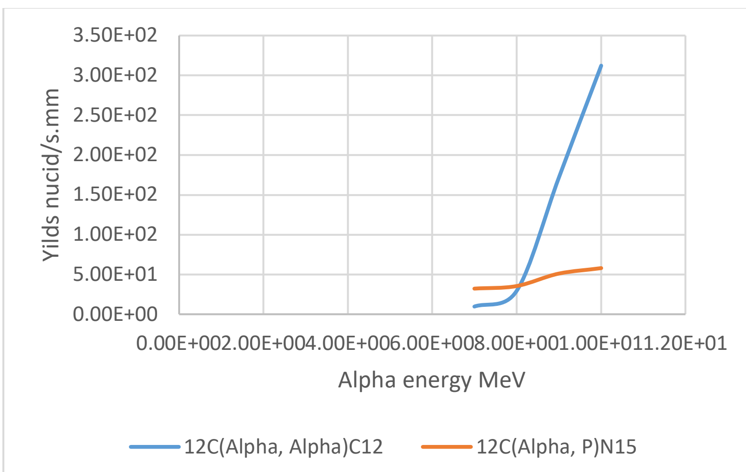

Fig. 7: The values of proton yields versus alpha particle energy

Using Eq. (16) and cross-section for the reaction and the yield of resulting protons, the absorbed dose can be calculated and equal to 12.35×10^5 Gy. Then the annual effective dose was calculated equal to 24.70×10^5 Sv. In many previous studies concerned with measuring the concentration of radium and uranium and their relationship to the increased incidence of cancerous tumors, these studies end with no clear relationship because the compositions found are few. However, we find that there is a large number of cancerous diseases even in areas with a low concentration of radionuclides. When radon is present, even if it is in a small concentration, it will lead to the release of alpha particles, which in turn will interact with carbon and proton fluxes with high energy and radiation doses.

Conclusion

The conclusion regarding the effective dose of protons produced from the $^{12}C(\alpha,p)^{15}N$ reaction would depend on various factors including the energy of the incident alpha particles, the target material (^{12}C), and the resulting proton energy spectrum. This reaction typically occurs in the context of nuclear reactions and may have implications in fields such as nuclear physics, astrophysics, or even medical physics in the context of proton therapy.

The findings of this work, show the values of the annual effective dose for exposure to protons produced from $^{12}C(\alpha,p)^{15}N$ reaction is dependent on the composition and thickness of the target material, and the resulting proton energy spectrum. The annual effective dose for protons with energy 7.5 MeV is 24.70×10^{5} Sv, and its values depend on the energy distribution of the protons.

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