An Investigation on γ-Induced Activation Reactions on Human Essential Elements: Postprint

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Abstract

In radiotherapy, the energy of the γ rays used could be larger than 10 MeV, which would potentially activate stable nucleus into a radioactive one. The γ induced reactions on some of the human essential elements are studied to show the probability of changes of nuclei. The Talys1.4 toolkit was adopted as the theoretical model for calculation. The reactions investigated include the (γ, n) and (γ, p) channels for the stable Na, Mg, Cl, K, Ca, and Fe isotopes, with the incident energy of γ ranging from 1 to 30 MeV. It was found that the cross sections for the reactions are very low, and the maximum cross section is no larger than 100 mb. By considering the threshold energy of the channel, the half-life time of the residue nucleus, and the percentage of the element accounting for the weight and its importance in the body, it is suggested to track the radioactive nuclei 22Na, 41Ca, and 42,43K after γ therapy. The results might be useful for medical diagnosis and disease treatment.

Full Text

Preamble

An Investigation on γ-Induced Activation Reactions on Human Essential Elements

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In radiotherapy, the energy of γ rays used can exceed 10 MeV, which may potentially activate stable nuclei into radioactive ones. This study investigates γ-induced reactions on several human essential elements to assess the probability of nuclear transformations. The Talys 1.4 toolkit was adopted as the theoretical model for calculations. The reactions investigated include (γ, n) and (γ, p) channels for stable isotopes of Na, Mg, Cl, K, Ca, and Fe, with incident γ energies ranging from 1 to 30 MeV. The results show that reaction cross sections are very low, with maximum values not exceeding 100 mb. By considering the channel threshold energy, the half-life of the residual nucleus, the element' s weight percentage in the body, and its biological importance, we suggest tracking the radioactive nuclei ^{22}Na, ^{41}Ca, and ^{42},^{43}K after γ therapy. These results may be useful for medical diagnosis and disease treatment.

Keywords: Photon activation, γ therapy, Human essential element, Optical model, Talys
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Introduction

Nuclear technology has found extensive applications in medical diagnosis and disease treatment, including X/γ-CT, γ therapy, and positron emission tomography (PET). In radiation therapy, most side effects are predictable and expected, making them avoidable in normal tissues. Understanding the origin of these side effects and developing methods to reduce unwanted complications is therefore highly desirable. Beyond the complex biochemical effects of γ rays on molecules —primarily through ionization and Compton scattering—γ rays can also induce nuclear reactions via positron-electron pair production and photon activation reactions. Although the probability is quite low, high-energy γ rays ($E_\gamma \gtrsim 10$ MeV) can induce nuclear activation reactions that transform stable nuclei into radioactive ones. It is well known that around 15 MeV, nuclei exhibit strong γ-absorption due to the giant dipole resonance, through which stable nuclei can be activated to unstable states via (γ, n) or (γ, p) reactions. For nuclei with small mass numbers, the (γ, n) cross section may peak below 15 MeV, as observed in ^{13}C, ^{17}O, ^{18}O, and ^{29}Si. Since γ rays used in radiotherapy can exceed 10 MeV, they may potentially induce γ-activation reactions. The residual nuclei from such reactions could represent a form of internal radioactivity harmful to normal tissue if they possess long half-lives. This motivates investigation of γ-induced reactions on elements composing the human body within the energy range used in γ therapy. In this article, we examine γ-induced reactions on isotopes of essential human elements and discuss possible nuclear activation pathways.

Methods

γ-Induced reactions on nuclei, known as photonuclear reactions, have attracted considerable attention in nuclear physics. Numerous γ-induced reactions on various isotopes have been measured for different purposes. The optical model has proven highly successful in predicting these reactions for outgoing particles. In the Talys toolkit, the ECIS-06 code is implemented as a subroutine to handle optical model calculations. Talys is commonly used for experimental analysis and nuclear data generation. With appropriate adjustable parameters, it can reproduce neutron-induced reactions on nuclei with A $>$ 30, while for A $<$ 30, parameters require adjustment to match experimental results. This work adopts Talys version 1.4. We omit detailed model description as our aim is not to introduce Talys physics; complete documentation is available in the user manual. Our focus is on radioactive nuclei with long half-lives produced from stable nuclei via γ-activation reactions. We calculate (γ, n) and (γ, p) channels based on whether the residual nucleus is unstable and has a long half-life. Results are compared with experimental data from the EXFOR library. Default Talys 1.4 parameters are used, as our goal is not exact reproduction of measured data, which would require careful parameter tuning. Natural abundance data and isotope half-lives are taken from the National Nuclear Data Center (NNDC). Information about human elements is extracted from the Micronutrient Information Center of the Linus Pauling Institute (MICLPI).

Results and Discussion

In medical experimentation, blood and hair samples are commonly analyzed. We study γ-induced reactions on isotopes of Na, Cl, Ca, K, and Mg due to their relatively high abundance in the human body.

^{23}Na(γ, n)^{22}Na

Sodium has only one stable isotope, ^{23}Na. In adults, sodium constitutes 0.15% of body weight, distributed primarily in bones (40–47%), extracellular fluids (44–50%), and blood (9–10%). Sodium maintains osmotic pressure balance and cellular fluid homeostasis, and supports normal nerve, heart, muscle, and other physiological functions. Sodium retention time in the body is short, with excretion occurring mainly through sweat and the renal system. Normal blood Na^+ levels range from 136–146 mmol/L.

For the ^{23}Na(γ, n)^{22}Na reaction, the residual nucleus ^{22}Na is radioactive, decaying to ^{22}Ne via positron emission with a half-life of 2.60 years. ^{22}Na is used to create test objects and point sources for PET imaging and serves as an indicator for neutron radiation exposure in nuclear accidents. Measured cross sections for this reaction by Alvarez et al. and Veyssiere et al. show good agreement. When E_γ exceeds the threshold, the measured cross section increases rapidly with energy but forms a plateau above 16 MeV. Calculated results overestimate measurements in the 12.5–16 MeV range. The measured cross section for ^{23}Na(γ,

n)^{22}Na between 16–23 MeV is approximately 10 mb. Tracking ^{22}Na in the body after γ therapy is advisable due to its long half-life and sodium' s relatively high body weight percentage.

[Figure 1: see original paper] (Color online) The results for the ^{23}Na(γ, n)^{22}Na reaction. The calculated result is plotted as the solid line, and measured data are shown as circles and triangles. The calculated threshold energy is 12.50 MeV, which agrees with experimental results.

^{42}Ca(γ, n)^{41}Ca, ^{43}Ca(γ, p)^{42}K, and ^{44}Ca(γ, p)^{43}K

Calcium is the most abundant mineral in the human body, with approximately 99% stored in bones and teeth and the remaining 1% in blood and soft tissues. Calcium is deposited and retained for extended periods. Normal blood calcium levels range from 1.55–2.10 mmol/L.

For γ + Ca reactions, we consider three isotopes: ^{42}Ca, ^{43}Ca, and ^{44}Ca, with natural abundances of 0.647%, 0.135%, and 2.08%, respectively. In the ^{42}Ca(γ, n)^{41}Ca, ^{43}Ca(γ, p)^{42}K, and ^{44}Ca(γ, p)^{43}K channels: ^{41}Ca decays to ^{41}K via electron capture with a half-life of 1.02×10^5 years; ^{42}K decays to ^{42}Ca and ^{43}K decays to ^{43}Ca, both via β^- emission with half-lives of 12.32 h and 22.30 h, respectively. No natural ^{42}K or ^{43}K isotopes exist.

No experimental data were found for the ^{42}Ca(γ, n)^{41}Ca, ^{43}Ca(γ, p)^{42}K, and ^{44}Ca(γ, p)^{43}K reactions. The threshold energies for these channels are 11.48 MeV, 10.68 MeV, and 12.16 MeV, respectively. Cross sections peak around 19.80 MeV, 19.40 MeV, and 20.60 MeV, respectively. Since these reactions have thresholds around 10 MeV and produce relatively long-lived residual nuclei, tracking the decays of ^{41}Ca, ^{42}K, and ^{43}K after γ therapy is necessary.

^{25}Mg(γ, p)^{24}Na

Magnesium is an essential mineral and cofactor for hundreds of enzymes, constituting approximately 0.05% of adult body weight. It is a major bone component and essential mineral element. Normal blood magnesium levels range from 0.6–0.95 mmol/L.

The natural abundance of ^{25}Mg is about 10%. For the ^{25}Mg(γ, p)^{24}Na reaction, ^{24}Na is unstable, decaying to ^{24}Mg via β^- emission with a half-life of 15.00 h. Calculated results are shown in Figure 2. The threshold energy is 12.06 MeV. Cross sections peak around 21 MeV with a maximum value of 6.25 mb, which is very small compared to other elements.

[Figure 2: see original paper] (Color online) The calculated cross section for the ^{25}Mg(γ, p)^{24}Na, ^{37}Cl(γ, n)^{36}Cl, ^{42}Ca(γ, n)^{41}Ca, ^{43}Ca(γ, p)^{42}K, and ^{44}Ca(γ, p)^{43}K reactions.

Results for γ-induced reactions on isotopes of human essential elements are summarized in Table 1. Cross sections are very low, with maximum values

below 100 mb. Table 1 shows that ^{23}Na, ^{37}Cl, and ^{42}Ca can be activated by γ rays with $\sigma > 10$ mb, and the radioactive residual nuclei have long half-lives.

A summary of the results for the γ-induced reactions discussed

Reaction	Eth(MeV)	Decay mode	Half-life time	Final residue	Max. of σ (mb)	High σ range (mb)
^{23}Na(γ, n)^{22}Na	12.50	β^+	2.6027 y	^{22}Ne	12.5	10–23
^{25}Mg(γ, p)^{24}Na	12.06	β^-	15.00 h	^{24}Mg	6.25	–
^{37}Cl(γ, n)^{36}Cl	10.18	β^-	3.01×10^5 y	^{36}Ar	35.0	13–22
^{42}Ca(γ, n)^{41}Ca	11.48	EC	1.02×10^5 a	^{41}K	15.0	13–23
^{43}Ca(γ, p)^{42}K	10.68	β^-	12.32 h	^{42}Ca	8.0	12–23
^{44}Ca(γ, p)^{43}K	12.16	β^-	22.30 h	^{43}Ca	12.0	13–24

Summary

This article presents γ-induced activation reactions on stable nuclei of human essential elements and discusses possible nuclear transformations. In γ therapy, radioactive nuclei produced through γ-induced activation reactions could represent a form of internal radioactivity. Using the Talys 1.4 toolkit to predict reaction cross sections, we investigated (γ, n) and (γ, p) channels for ^{23}Na, ^{25}Mg, ^{37}Cl, and ^{42},^{43},^{44}Ca, focusing on cases where residual nuclei are radioactive with long half-lives. Reaction cross sections are very low, with maximum values below 100 mb. Considering threshold energies, residual nucleus half-lives, elemental weight percentages, and biological importance, we recommend tracking ^{22}Na, ^{42},^{43}K, and ^{41}Ca after γ therapy.

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Note: Figure translations are in progress. See original paper for figures.