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Original Article

Monte Carlo Investigation of Organs Activation in Proton and Heavy Ions Cancer Therapy by Spallation Process

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Abstract

Background: High-energy heavy ions and protons produced by accelerators are used in industrial and medical applications. Recently, Helium (He), Argon (Ar), Krypton (Kr), Carbon (C) and Neon (Ne) heavy ions have been used in the treatment of cancerous tumors. High-energy protons are generally used either directly for the treatment of cancerous tumors or indirectly by neutron production of Lithium (Li), Beryllium (Be) and Thallium (Ta) targets by proton irradiation used for born neutron capture therapy (BNCT) technique. Neutron beams that produced by proton spallation, will activate the brain components before tumors.

Methods: In this study, the neutron brain activation has been investigated using Monte Carlo N Particle X Version (MCNPX). Furthermore, in the direct use of high-energy ions for the treatment of cancerous tumors, the production of radioactive elements by heavy ions spallation process in healthy tissues around tumors was calculated by Monte Carlo simulation.

Results: Proton beams, neutrons, and heavy ions are used to treat internal tumors. Neutron source spallation of Li, Be, Ta, Lead (Pb) targets that were used in the BNCT therapy process can produce radioactive elements in the brain tissue. The results indicate that the Sodium-22 (^{22}Na) ,^{24}Na, Aluminium-28 (^{28}Al), ^{29}Al, Silicon-32 (^{32}Si), Chlorin-34 metastable(^{34m}Cl), Potasium-38 (^{38}K), ^{40}K radioactive elements were produced in brain tissue for BNCT.

Conclusion: In this study, the neutron brain activation has been investigated using MCNPX. Furthermore, in the direct use of high-energy ions for the treatment of cancerous tumors, the production of radioactive elements by heavy ions spallation process in healthy tissues around tumors was calculated by Monte Carlo simulation.

Keywords: Therapy, Radioactive, Protons, Ions, Neutrons, Soft Tissue, Activation.

1. Introduction

Abnormal and uncontrolled cell growth can lead to cancer. In developed countries, cancer is the second leading cause of death and in our country the third leading cause of death (after cardiovascular disease and accidents). For treatment of cancerous tumors, various methods such as surgery, laser radiation, brachytherapy, nuclear radiation or radiation therapy, chemotherapy and etc. Method is used [1-6] .Neutron and photon beams, Electrons, protons and heavy ion accelerators have many applications in radiation therapy [7-10] . Neutron beam was used in the treatment of brain tumors using the BNCT technique[11]. Neutron in the BNCT method is produced in different ways[12] . Reactors and neutron sources due to spallation are more famous in this field[13]. Recently, the possibility of using high-energy ions that are accelerated by certain techniques in the treatment of cancerous tumors has been investigated in various laboratories [14-19] . The research reactors were also used as neutron sources[20, 21]. These neutrons can be converted to thermal energy by passing through different materials and used in the BNCT method [22].The proton spallation process in different targets such as Li, Be and Ta can be produced the neutron beam[23-27] . In the spallation process with energetic charged particles, due to the energy transfer to the target nucleus, evaporation takes place and a wide range of elements with a mass number less than the target nucleus is produced [28].

The energy of neutrons due to the proton spallation process in different targets can be reduced by the attenuation process in brain BNCT process [22]. Recently it is possible to produce different heavy ions such as He, Ar, Kr, Ne and C up to 3.5 Tera electron Volt (TeV) energy [26-30]. In direct application of protons, the high-energy protons have already been used to treat tumors in various organs. High-energy protons and ions, due to their Bragg peak, transfer more energy to the tumor than to healthy organs.

In this research by calculating the spectrum of neutrons produced by proton irradiation on Li, Be and Ta targets and applying of them to healthy brain tissues, the degree of activation of brain is examined and the benefit of producing radioisotopes produced in it, is determined using the MCNPX code. The MCNPX code is a nuclear code based on Monte Carlo method. Also, due to the direct use of heavy ions such as He, Ar, Kr, Ne and C in the treatment of internal tumors of the body, the amount of spallation of these heavy ions and radioactive elements produced in the soft tissue of the body is investigated.

2. Material and Methods

The study of neutron activation, protons and heavy ions spallation in brain and soft tissues and neutron production due to protons and heavy ions spallation has been performed in two stages. In the first stage, the neutron spectrum energy production by proton spallation of Li, Be, Ta, Lead (Pb) and Tungsten (W) converters are obtained. Then, by applying produced neutron spectrum to healthy brain tissues in the BNCT process, the neutron activation rate and the elements produced in the tissue are investigated. The input file of MCNPX code written in the first step includes geometry card, surface card and data card are contained of the following components. The geometry of the cells used consist Li, Be, Ta, Pb and W in the spallation mode and the brain tissue sphere with 2 cm radius in the activation mode. In the data card section, information about the element's percentage of material, information about proton and neutron sources, as well as how to extract spallation data, and the spectrum of neutrons produced are given. Table 1 shows the materials density that used in this study. Table 2 shows the information of proton sources and high energy ions used in this project.

Table 1. Materials density of Tissue[31]

Tissue	Density g/cm3	Hydrogen (H)	Carbon (C)	Nitrogen (N)	Oxygen (O)	Sodium (Na)	Phosphor (P)	Sulfur (S)	Chlorine (Cl)	Potassium (K)
Brain	1.04	0.107	0.145	0.022	0.712	0.002	0.004	0.002	0.003	0.003
Soft tissue	1.05	0.102	0.143	0.034	0.708	0.002	0.003	0.003	0.002	0.003

Table 2. Information of proton sources and high ions energy[32]

Ion	E (MeV/u)	Atomic Weight Unit(u)	E(MeV)	Second particle	Target 1	Density (g/cm³)	Target 2	Density (g/cm³)
Helium (He)	150	4	600	-	-	-	soft tissue	1.05
Carbon (C)	430	12	5160	-	-	-	soft tissue	1.05
Neon (Ne)	230	20.17	4639	-	-	-	soft tissue	1.05
Argon (Ar)	550	39.94	21967	-	-	-	soft tissue	1.05
Kripton (Kr)	400	83.8	33360	-	-	-		1.05
Hydrogen (H)	1.91-2.7	1	1.91-2.7	Neutron	Li	0.51	brain	1.04
Hydrogen (H)	9-28	1	9-28	Neutron	Be	1.85	brain	1.04
Hydrogen (H)	50	1	50	Neutron	Ta	19.6	brain	
Hydrogen (H)	178.5	1	200-1200	Neutron	Li	0.51		-
Hydrogen (H)	200-1200	1	200-1200	Neutron	Pb	11.34	-	-
Hydrogen (H)	200-1200	1	200-1200	Neutron	W	19.3	-	-

3. Results

The results are also presented in 3 steps. In the first step, the neutron energy spectrum by proton spallation of the Li, Be and Ta targets was calculated.

In the second and third steps, the proton spallation yield productions by neutron and high-energy heavy ions in soft tissue before internal tumors are investigated.

The neutron energy spectrum by the spallation of the Li, Be and Ta targets by proton irradiation was calculated. Protons with energy 1.9-2.5 Mega electron Volt (MeV) 9-28 MeV and 50 MeV hit the Li, Be and Ta targets respectively. Also neutron flux or neutron yield production by 50 MeV proton irradiation on Li target was calculated. The neutron yield of Li, Be and Ta targets by proton irradiation was calculated. Also, neutron flux or neutron yield production by 50 MeV proton irradiation on Li target was calculated. By defining the flux of neutrons produced due to the collision of energetic protons with Li, Be, and Ta targets using Tally FT8 in MCNPX code, the neutron activation of brain in the treatment of BNCT of tumors was calculated. By applying the spectrum of neutrons produced in the Ta, Be and Li targets, the activation or spallation in brain is calculated. The amount of radioactive elements produced in the composition of the brain is calculated and the results are listed in Table 3.

Table 3. Radioactive elements produced by neutron activation in Brain Ta, Be and Li targets

Target	Element	Neutron Number(N)	Proton Number(Z)	Decay mode	Half life
Ta	7Be	4	3	ε	53.12 d
	^{10}Be	4	6	β⁻	1.51E+6 y
	^{11}C	6	5	ε+β+	20.39 m
	^{14}C	6	8	β–	5730 y
	^{13}N	7	6	ε+β⁺	9.965 m
	^{18}F	9	9	ε+β⁺	109.77 m
Be	^{14}C	6	8	β⁻	5730 y
Li	^{15}O	8	7	ε+β+	122.24 s
	^{40}K	19	21	β⁻,ε+β⁺	1.277E+9 y

The spallation yield of isotope production in soft tissue before internal tumors by high-energy heavy ions. In the second step, the spallation yield of isotope production in soft tissue before.

In the second step, the spallation yield of isotope production in soft tissue before internal tumors by high-energy heavy ions is investigated. The radioactive elements produced in healthy soft tissue before tumor by the heavy ions therapy process was shown in Tables 4-6.

4. Discussion

Proton beams, neutrons, and heavy ions are used to treat internal tumors[11, 14-19]. Neutron source spallation of Li, Be, Ta, Pb targets that were used in the BNCT therapy process can produce radioactive elements in the brain tissue[28]. These radioactive elements in the brain tissue will create a radiation dose and will produce more damage to it. Cancerous tumors with abnormal growth of cells increase in size over time. Radiation methods are used to prevent the growth of cancerous tumors in the organs of the body. The BNCT method is a nuclear method to kill cancer cells. In this method, boron is injected into the body and enters the circulatory system. Due to the tendency of cancerous tissue to absorb boron 10, this element accumulates in cancerous tumors. Boron 10 is a neutron-absorbing element and decays due to neutron absorption. It emits an alpha particle. Due to its short range, this particle leaves all its energy in the cancerous tissue and tumor and causes the destruction of tumor material and its destruction. To do this, a neutron beam is needed. Usually, neutron beams are produced by reactors or nuclear reactions. One of the methods of production is spallation targets of Li, Ta and ... which cause the production of neutron beams. The produced neutrons pass through healthy tissue until it reaches the tumor and make its elements radioactive. In this study, the production of radioactive elements in healthy tissues before tumor was investigated by BNCT method. It is also possible to use direct ions where cancer ions are used to treat cancerous tumors. The tumor is treated. The radioactive elements produced by BNCT and ion therapy cause radiation hazards in human organs and its risks exist for a long time due to the long half-life of the radioactive elements produced

Table 4. The radioactive elements produced in healthy soft tissue before the tumor by Ar Spallation

Element	Neutron Number (N)	Proton Number (Z)	Decay mode	Half life	Element	(N)	(Z)	Decay mode	Half life
^{7}Be	4	3	e	53.12 d	^{30}P	15	15	e+β+	2.498 m
^{10}Be	4	6	β-	1.51E+6 y	^{32}P	15	17	β-	14.262 d
^{11}C	6	5	e+β+	20.39 m	^{33}P	15	18	β-	25.34 d
^{14}C	6	8	β-	5730 y	^{35}S	16	19	β-	87.32 d
^{13}N	7	6	e+β+	9.965 m	^{37}S	16	21	β-	5.05 m
^{18}F	9	9	e+β+	109.77 m	^{38}S	16	22	β-	170.3 m
^{24}Ne	10	14	β-	3.38 m	^{34}mCl	17	17	e+β+,IT	32.00 m
^{22}Na	11	11	e+β+	2.6019 y	^{36}Cl	17	19	β-,e+β+	3.01E5 y
^{24}Na	11	13	β-	14.9590 h	^{38}Cl	17	21	β-	37.24 m
^{27}Mg*	12	15	β-	9.458 m	^{39}Cl	17	22	β-	55.6 m
^{28}Mg	12	16	β-	20.91 h	^{40}Cl	17	23	β-	1.35 m
^{26}Al	13	13	e+β+	7.17E+5 y	^{37}Ar	18	19	e	35.04 d
^{28}Al	13	15	β-	2.2414 m	^{39}Ar	18	21	β-	269 y
^{29}Al	13	16	β-	6.56 m	^{38}K	19	19	e+β+	7.636 m
^{31}Si	14	17	β-	157.3 m	^{40}K	19	21	β-, e+β+	1.277E9 y
^{32}Si	14	18	β-	150 y					

*Mg: Magnesium.

Table 5. The radioactive elements produced in healthy soft tissue before the tumor by carbon and He Spallation

Spallation Target	Element	Proton Number(Z)	Neutron Number(N)	Decay mode	Half life
	^{7}Be	4	3	ε	53.12 d
	^{10}Be	4	6	β–	1.51E+6 y
	^{11}C	6	5	ε+β+	20.39 m
	^{14}C	6	8	$β^-$	5730 y
	^{13}N	7	6	ε+β+	9.965 m
Carbon	^{18}F	9	9	ε+β+	109.77 m
	^{24}Ne	10	14	β–	3.38 m
	^{30}P	15	15	ε+β+	2.498 m
	^{34m}Cl	17	17	ε+β+, IT	32.00 m
	^{37}Ar	18	19	ε	35.04 d
	^{38}K	19	19	ε+β+	7.636 m
	^{7}Be	4	3	ε	53.12 d
	^{10}Be	4	6	β–	1.51E+6 y
Helium	^{11}C	6	5	ε+β+	20.39 m
	^{14}C	6	8	β–	5730 y
	^{13}N	7	6	ε+β+	9.965 m
	^{18}F	9	9	ε+β+	109.77 m

	^{22}Na	11	11	$\varepsilon+\beta+$	2.6019 y
	^{31}Si	14	17	$\beta-$	157.3 m
	^{30}P	15	15	$\varepsilon+\beta+$	2.498 m
	^{32}P	15	17	β^-	14.262 d
	^{36}Cl	17	19	$\beta^-\varepsilon+\beta^+$	3.01E+5 y
	^{38}K	19	19	$\varepsilon+\beta^+$	7.636 m

Table 6. The radioactive elements produced in healthy soft tissue before the tumor by Ne Activation and spallation

Interaction Process	Element	Proton Number(Z)	Neutron Number(N)	Decay mode	Half life
Activation	^{22}Na	11	11	$\varepsilon+\beta^+$	2.6019 y
	^{24}Na	11	13	β^-	14.9590 h
	^{28}Al	13	15	$\beta-$	2.2414 m
	^{29}Al	13	16	$\beta-$	6.56 m
	^{32}Si	14	18	$\beta-$	150 y
	^{34m}Cl	17	17	$\varepsilon+\beta+$, IT	32.00 m
	^{38}K	19	19	$\varepsilon+\beta+$	7.636 m
	^{40}K	19	21	$\beta-$, $\varepsilon+\beta+$	1.277E+9 y
Spallation	^{7}Be	4	3	ε	53.12d
	^{10}Be	4	6	β^-	1.51E+6y
	^{11}C	6	5	$\varepsilon+\beta+$	20.39m
	^{14}C	6	8	β^-	5730y
	^{13}N	7	6	$\varepsilon^+\beta^+$	9.965m
	Fluorine(^{18}F)	9	9	$\varepsilon^+\beta^+$	109.77m

5. Conclusion

Increasing the energy of the proton beam, the gain of the radioactive elements production was increased. By using directly high-energy ions to treat internal tumors, healthy soft tissue is considered as the most common tissue at risk. The results show that when using He, C and Ar ions, the radioactive elements, are produced with high yields respectively, where the results are shown in the Tables 4-6. Therefore, in the treatment of cancerous tumors with high-energy heavy ions, because of radioactive element production, the healthy tissues are at high risks and the tissue has high radiation hazards.

Authors' contributions

Ali Nouraddini Shahabadi and Mohammad Reza Rezaie designed and simulated this study and Saeed Mohammadi analyzed the data. Ali Nouraddini Shahabadi proceeded to the data quality control and the manuscript drafting. Mohammad Reza Rezaie revised the final version.

Consent for publications

All authors agree to have read the manuscript and authorize the publication of the final version of the manuscript

Conflict declaration

The authors declare that there is no conflict.

Conflict of interest

None of the authors have any conflict of interest to declare.

Availability of data and material

Data are available on request from the authors.

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Ethics approval and consent to participate

Because the simulation of this study, don't need an Ethics approval and consent to participate form. Their work is in the field of the dosimetry effects of radiation in the treatment of cancer in the organs of the body. There is no need to code of ethics.

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References

1. Sudhakar A. (2009). History of cancer, ancient and modern treatment methods. *Journal of cancer science & therapy*, 1(2): 1-4.. [Crossref], [Google Scholar], [Publisher]
2. Fitzmaurice C, Allen C, Barber R M, Barregard L, Bhutta Z A, Brenner H, Dicker D J, Chimed-Orchir O, Dandona R, Dandona L. (2017). Global, regional, and national cancer incidence, mortality, years of life lost, years lived with disability, and disability-adjusted life-years for 32 cancer groups, 1990 to 2015: a systematic analysis for the global burden of disease study. *JAMA oncology*, 3(4): 524-548.. [Crossref], [Google Scholar], [Publisher]
3. Wang X, Xiao J, Jiang G. (2021). Real time medical data monitoring and iodine 131 treatment of thyroid cancer nursing analysis based on embedded system. *Microprocessors and Microsystems*, 81: 103660. [Crossref], [Google Scholar], [Publisher]
4. Gogineni E, Bloom B, Molina F D, Villella J, Goenka A. (2021). Radiotherapy dose escalation on pelvic lymph node control in patients with cervical cancer. *International Journal of Gynecologic Cancer*, 31(4). [Crossref], [Google Scholar], [Publisher]
5. Kayani Z, Islami N, Behzadpour N, Zahraie N, Imanlou S, Tamaddon P, Salehi F, Daneshvar F, Perota G, Sorati E. (2021). Combating cancer by utilizing noble metallic nanostructures in combination with laser photothermal and X-ray radiotherapy. *Journal of Drug Delivery Science and Technology*, 65: 102689. [Crossref], [Google Scholar], [Publisher]
6. Lin Y, Huang G, Huang Y, Tzeng T R J, Chrisey D. (2010). Effect of laser fluence in laser-assisted direct writing of human colon cancer cell. *Rapid Prototyping Journal*., 16, 202-208. [Crossref], [Google Scholar], [Publisher]
7. Loap P, Kirova Y. (2021). Fast Neutron Therapy for Breast Cancer Treatment: An Effective Technique Sinking into Oblivion, *Int J Part Ther.*, 7(3), 61-64. [Crossref], [Google Scholar], [Publisher]
8. Ho S L, Choi G, Yue H, Kim H-K, Jung K-H, Park J A, Kim M H, Lee Y J, Kim J Y, Miao X. (2020). In vivo neutron capture therapy of cancer using ultrasmall gadolinium oxide nanoparticles with cancer-targeting ability. *RSC Advances*, 10(2): 865-874. [Crossref], [Google Scholar], [Publisher]
9. Chen Y-J, Paul A C. (2007). Compact proton accelerator for cancer therapy.

Paper presented at the *2007 IEEE Particle Accelerator Conference (PAC)*. [Crossref], [Google Scholar], [Publisher]

10. Pasler M, Georg D, Wirtz H, Lutterbach J. (2011). Effect of Photon-Beam Energy on VMAT and IMRT Treatment Plan Quality and Dosimetric Accuracy for Advanced Prostate Cancer. *Strahlenther Onkol*, 187, 792–798, 187(12): 792-798. [Crossref], [Google Scholar], [Publisher]
11. Aihara T, Hiratsuka J, Kamitani N, Nishimura H, Ono K. (2020). Boron neutron capture therapy for head and neck cancer: Relevance of nuclear-cytoplasmic volume ratio and anti-tumor effect.-A preliminary report. *Applied Radiation and Isotopes*, 163: 109212. [Crossref], [Google Scholar], [Publisher]
12. Nedunchezhian K, Aswath N, Thiruppathy M, Thirugnanamurthy S. (2016). Boron neutron capture therapy-a literature review. *Journal of clinical and diagnostic research: JCDR*, 10(12): ZE01. [Crossref], [Google Scholar], [Publisher]
13. Yonai S, Baba M, Nakamura T, Yokobori H, Tahara Y. (2005). Investigation of spallation-based epithermal neutron field for BNCT. [Crossref], [Google Scholar], [Publisher]
14. Pompos A, Durante M, Choy H. (2016). Heavy ions in cancer therapy. *JAMA oncology*, 2(12): 1539-1540. . [Crossref], [Google Scholar], [Publisher]
15. Myers F. (1993). A heavy ion accelerator gears up to fight cancer. *Science*, 261(5126): 1270-1270.. [Crossref], [Google Scholar], [Publisher]
16. Schardt D, Kavatsyuk O, Krämer M, Durante M. (2013). Light flashes in cancer patients treated with heavy ions. *Brain Stimulation*, 6(3): 416-417. [Crossref], [Google Scholar], [Publisher]
17. Ma C-M, Veltchev I, Fourkal E, Li J, Luo W, Fan J, Lin T, Pollack A. (2006). Development of a laser-driven proton accelerator for cancer therapy. *Laser Physics*, 16(4): 639-646. [Crossref], [Google Scholar], [Publisher]
18. Sato K, Matsumoto S, Noda K, Miyazawa Y, Suzuki H, Yamada T, Yamada S, Kanai T, Hirao Y, Noda A. (1990). Heavy ion medical accelerator in Chiba (HIMAC). *Part. Accel.*, 33: 147-152. [Google Scholar], [PDF]
19. Scholz M. (2000). Heavy ion tumour therapy. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 161: 76-82.. [Crossref], [Google Scholar], [Publisher]
20. Kasesaz Y, Khalafi H, Rahmani F. (2014). Design of an epithermal neutron beam for BNCT in thermal column of Tehran research reactor. *Annals of Nuclear Energy*, 68: 234-238.. [Crossref], [Google Scholar], [Publisher]
21. Anikin M, Lebedev I, Naymushin A, Smolnikov N. (2020). Feasibility study of using IRT-T research reactor for BNCT applications. *Applied Radiation and Isotopes*, 166: 109243. [Crossref], [Google Scholar], [Publisher]
22. Hassanein A, Hassan M, Mohamed N M, Abou Mandour M. (2018). An optimized epithermal BNCT beam design for research reactors. *Progress in Nuclear Energy*, 106: 455-464. . [Crossref], [Google Scholar], [Publisher]
23. Cheng H-G, Feng Z-Q. (2021). Light fragment and neutron emission in high-energy proton induced spallation reactions. *Chinese Physics C*, 45(8): 084107.. [Crossref], [Google Scholar], [Publisher]
24. Didi A, Dadouch A, Bencheikh M, Jaï O, Hajjaji O E. (2019). New study of various target neutron yields from spallation reactions using a high-energy proton beam. *International Journal of Nuclear Energy Science and Technology*, 13(2): 120-137. [Google Scholar], [Publisher]
25. Esposito R, Calviani M. (2020). Design of the third-generation neutron

spallation target for the CERN's n_TOF facility. *Journal of Neutron Research*, 22(2-3): 221-231.. [Crossref], [Google Scholar], [Publisher]

26. Borne F, Crespin S, Drake D, Frehaut J, Ledoux X, Lochard J, Martinez E, Patin Y, Petibon E, Pras P. (2000). Experimental studies of spallation on thin target: CEA/DAM-Ile de France. [Google Scholar], [Publisher]
27. Zakalek P, Doege P-E, Baggemann J, Mauerhofer E, Brückel T. (2020). Energy and target material dependence of the neutron yield induced by proton and deuteron bombardment. Paper presented at the *EPJ Web of Conferences*. [Crossref], [Google Scholar], [Publisher]
28. Stankovsky A, Saito M, Artisyuk V, Shmelev A, Korovin Y. (2001). Accumulation and transmutation of spallation products in the target of accelerator-driven system. *Journal of nuclear science and technology*, 38(7): 503-510.. [Crossref], [Google Scholar], [Publisher]
29. Kobayashi C, Takada E, Ogawa H, Fujiwara H, Nishimura T, Sano Y. (2001). Operation of HIMAC and cancer therapy. [Google Scholar], [PDF]
30. Washio M, Hama Y, Sakaue K, Kudo H, Oka T, Oshima A, Murakami T. (2011). Fabrication of nano space controlled materials using high-energy heavy ion irradiation. [Crossref], [Google Scholar], [Publisher]
31. Valentin J. (2003). ICRP Publication 89: Basic anatomical and physiological data for use in radiological protection: reference values (Vol. 89): *Elsevier Health Sciences*. . [Crossref], [Google Scholar], [Publisher]
32. Torres-Sánchez P, Porras I, Ramos-Chernenko N, Arias de Saavedra F, Praena J. (2021). Optimized beam shaping assembly for a 2.1-MeV proton-accelerator-based neutron source for boron neutron capture therapy. *Scientific Reports*, 11(1): 1-12. [Crossref], [Google Scholar], [Publisher]

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