ORIGINAL ARTICLE

Monte Carlo Simulation of Damage in Born Neutron Capture Therapy (BNCT) Converter Materials by High-Energy Proton Beam Spallation

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Abstract

Purpose: High-energy protons are generally used for neutron production by Pb, W, Li, Be, and Ta targets that are used for the Born Neutron Capture Therapy (BNCT) technique. Neutron production targets are destroyed by proton spallation (evaporation of nuclei). The purpose of this study is the investigation of neutron activation and proton spallation damage of converter targets using the MCNPX code, which is based on the Monte Carlo method.

Materials and Methods: The MCNPX code was used to extract the activation and spallation information of secondary particle production in Pb, W, Li, Be, and Ta targets. The neutron activation and proton spallation damage, including radioactive elements production in converter targets, was extracted from data in the MCNPX output file.

Results: Results showed that the highest probability of radioactive elements production by proton with low-level energy in the Ta target are 180Hf, 179Hf, and 178Hf, and in the Li target is 7Be, respectively. In addition, the most probable radioactive elements produced by 200, 800, and 1200 MeV proton spallation in lead target are 118Tl and 78Pt, and in tungsten target are 98Hf, 110Ta, and 111Ta, respectively. The calculations showed that the production of radioisotopes in reactions with neutrons is lower than the production in reactions with a proton beam, and with increases in the energy of the proton beam, production of the radioactive elements was increased.

Conclusion: The results illustrated that the radioactive elements are produced in W, Pb, Li, Be, and Te targets in the BNCT method, which should be avoided as radiation hazards.

Keywords: Spallation; Activation; Proton; Neutrons; Radioactive Elements; Born Neutron Capture Therapy.

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1. Introduction

In order to treatment of cancerous tumors, various methods were applied such as surgery, laser radiation, brachytherapy, radiation therapy, chemotherapy Methods, etc. [1-3]. In radiation therapy, the neutron, photon, electron, and heavy-ion beam was used for cancer treatment [4-9]. A neutron beam has been used in the treatment of brain tumors using the BNCT technique [10, 11]. Neutron in the BNCT method is produced in different ways [12-14], such as reactor and spallation processes [15-18]. In neutron therapy, the neutron source can be produced by proton irradiation on special targets. These neutrons converted to thermal energy by passing through different materials for the BNCT method [19]. BNCT treatment works by nuclear capture and fission of nonradioactive materials such as 10B with low thermal neutrons. This procedure produces the 7Li and an alpha particle with high linear energy transfer that deposits all energy in the tumor. By collision of particles with high energy, the spallation process can occur. In this reaction, the light particles were produced with a smaller atomic number. A spallation reaction is comparable to a glass being broken into many pieces. Spallation can be described as a two-step reaction; the target nucleus is heated in the first step, and in the second step, the target is evaporated. stimulated. The neutron beam can be produced by proton spallation of Li, Be, and Ta targets [20-22]. In the spallation process with high-energy particles, due to the energy transfer to the nucleus in the target, the evaporation process takes place and a wide range of elements with a mass number less than the target nucleus is produced [23]. The neutron beam can be produced by proton spallation of Li, Be, and Ta targets [35,36].

In this research, the proton spallation of Pb, W, Li, Be, and Ta targets is investigated for neutron production. In this paper, the MCNPX code which is based on the Monte Carlo principles, is used for the investigation of spallation processes. In fact, the MCNPX code is a coupling of two previous calculations, the MCNP and LAHET codes. This code can transport the neutron and 32 atomic and nuclear particles. Previously, neutron activation surveys on patients following Boron Neutron Capture Therapy (BNCT) were performed [37], but the radioactive elements production in converter targets that are built by neutrons and protons has not been investigated by researchers. Also, the spectrum of neutrons produced by Pb, W, Li, Be, and Ta targets can interact activate with these targets. In addition, the production of radioactive elements is determined by using the MCNPX code. The residual radioactivity in BNCT facilities was studied by neutron activation processes [38,39]. But residual radioactivity in targets is not investigated by spallation processes. The aim and innovation of this research is the calculation of the radiation damage of the material that used for neutron production in BNCT method. By using of the production elements as radiation damage, the radiation hazards caused by target for BNCT workers can be investigated.

2. Materials and Methods

The investigation of the neutron activation process and the spallation of protons in Pb, W, Li, Be, and Ta targets has been performed. The radioactive elements in Li, Be, and Ta targets can be produced by proton spallation. The input file of the MCNPX code, written in the first step, includes the geometry card, surface card, and data card, which contain the following components. The geometry of the cells used consists of Pb, W, Li, Be, and Ta in the spallation and activation mode, which is a sphere with a 2 cm radius. In the data card section, information about the elements' percentage of material, information about proton and neutron sources, as well as how to extract spallation data, and the spectrum of neutrons produced, is given. Table 1 shows the information on proton sources used in this project.

The MCNPX code was used to extract the activation and spallation information. The unit of spallation and activation damage (or spallation yield) is the production mass of secondary particle(g) per one gram(g) of target for a single particle of source(sp) Therefore, the unit of spallation damage is g/(g.sp)=1/sp.

2.1. Validity of the Monte Carlo Simulation Program

In a Monte Carlo simulation project, it is important that the validity of the result is investigated by

Table 1. Information onproton sources and high-energy ions [17, 28, 24,25]

Ion	E(MeV/u)	amu	E(MeV)	Secondary particle	Target 1	Density (g/cm^3)
H	1.91-2.7	1	1.91-2.7	n	Li	0.51
H	9-28	1	9-28	n	Be	1.85
H	50	1	50	n	Ta	19.6
H	178.5	1	200-1200	n	Li	0.51
H	200-1200	1	200-1200	n	Pb	11.34
H	200-1200	1	200-1200	n	W	19.3

comparing the result with other similar research. For this matter, the produced neutron flux by 200 - 1200 MeV proton irradiation on W and Pb targets was extracted by the MCNPX simulation code and was compared with the practical result. The neutron flux generated in W and Pb by 200,800 and 1200 MeV proton irradiation was extracted and is shown in Figures 1 and 2.

Figures 3 and 4 show the neutron flux of Pb and W target S by 1000 MeV proton beam that measured by experimental method [26].

Comparison of Figures 3 and 4 with Figures 1 and 2 shows a good agreement between the results of this paper and other works. Therefore, the validity of this research is satisfied.

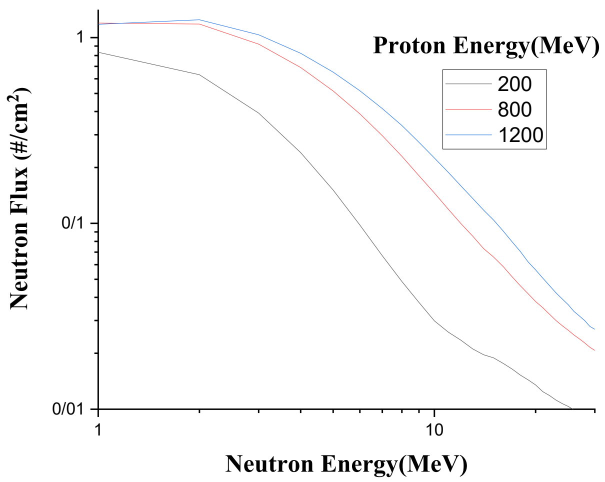

Figure 1. The neutron flux of the W target by 200 - 1200 MeV Proton irradiation

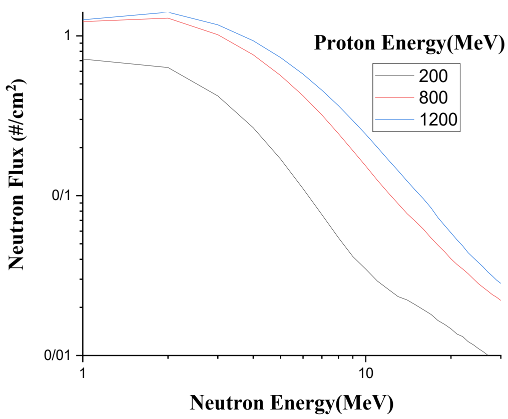

Figure 2. The neutron flux of Pb target by 200 - 1200 MeV proton irradiation

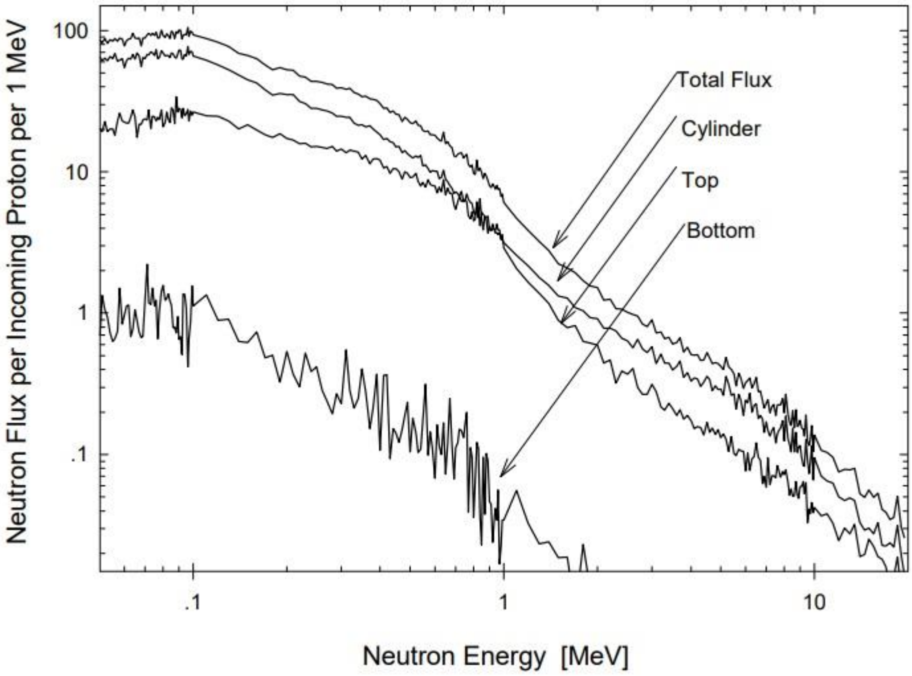

Figure 3. Neutron flux of lead target by 1000 MeV proton beam irradiation [26]

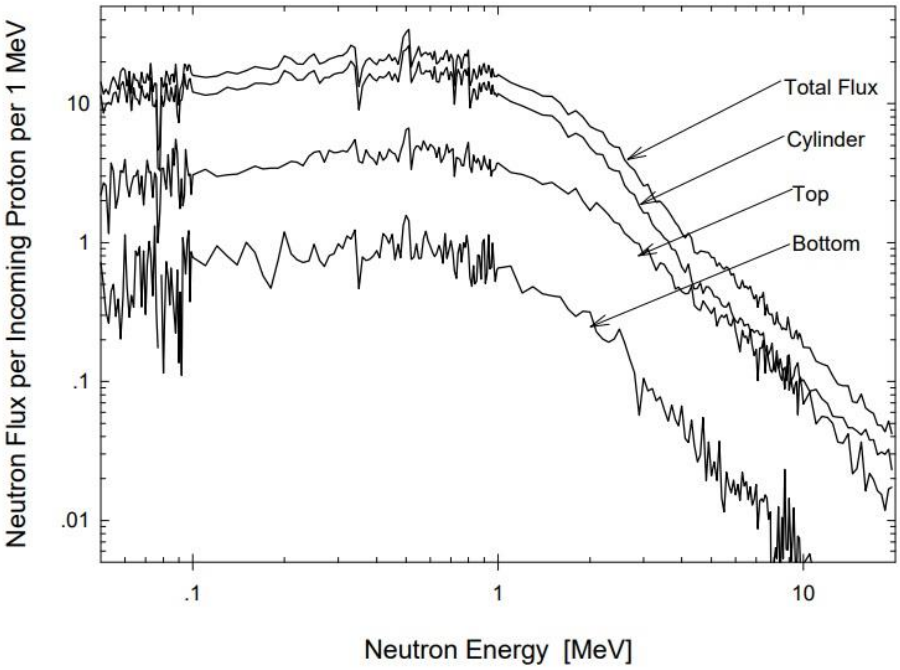

Figure 4. Neutron flux of Tungsten target by 1000 MeV proton beam irradiation [26]

3. Results

The results are presented in 2 steps. In the first step, the proton spallation and activation yield of the Li, Be, and Ta targets were calculated. In the second step, the proton spallation yield of W and Pb by 200,800 and 1200 MeV Protons for neutron production was investigated.

3.1. Proton Spallation and Activation Yield of the Li, Be, and Ta Targets

The spallation and activation yield of the Li, Be, and Ta targets by proton irradiation was calculated with 1.9-2.5 MeV, 9-28 MeV, and 50 MeV protons that hit the targets, respectively. The radioactive elements produced in the Li, Be, and Ta targets were also calculated, and the major radioactive elements with half-lives longer than a day in every target are listed in Tables 2-5. In Table 2, Z and N are the atomic and neutron numbers.

Table 2. Radioactive elements produced by Proton activation in Li and Be

Element	N	Z	Decay Mode	Half-life
^{7}Be	4	3	ε	53.12 d

Table 2 shows that the ^{7}Be radioactive element with a half-life d of 53.12 is produced as a result of proton interaction with Li and Be targets.

Table 3 shows the radioactive elements produced in the Ta target as a result of proton radiation with an energy of 50 MeV.

Table 3. Radioactive elements produced by proton and neutron activation in Ta

Element	N	Z	Decay mode	Half-Life
^{175}Ta	73	102	ε+β⁺	10.5 h
^{176}Ta	73	103	ε+β⁺	8.09 h
^{177}Ta	73	104	ε+β⁺	56.56 h
^{178}Ta	73	105	ε+β⁺	9.31 m
^{178m}Ta	73	105	ε+β⁺	2.36 h
^{178m2}Ta	73	105	IT	60 ms
^{179}Ta	73	106	ε	1.82 y
^{180}Ta	73	107	ε,β⁻	8.152 h
^{180m}Ta	73	107	β⁻	>1.2E+15 y
^{173}Hf	72	101	ε+β⁺	23.6 h
^{174}Hf	72	102	α	2.0E15 y
^{175}Hf	72	103	ε	70 d
^{177}Hf	72	105	IT	51.4 m
^{178}Hf	72	106	IT	31 y
^{179}Hf	72	107	IT	25.05 d
^{180}Hf	72	108	IT, β⁻	5.5 h

3.2. Proton Spallation Yield of W and Pb Target

Neutron spallation source facility for BNCT and industrial application used the proton beam for neutron generation that hit to the W and Pb targets. In the final step, the neutron production and spallation yield of W and Pb by 200,800 and 1200 MeV proton irradiation were calculated. The spallation yield of W and Pb by 1200 MeV proton was shown in Figures 5 and 6.

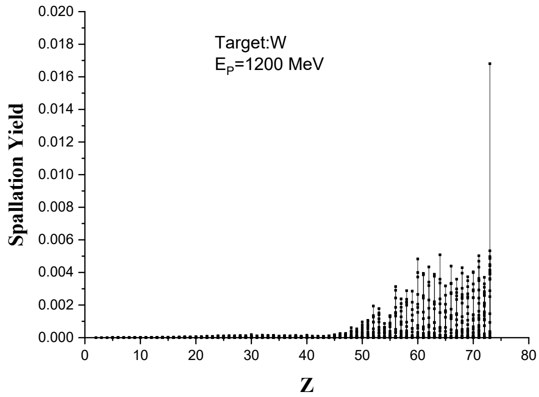

Figure 5. The spallation yield (1/sp) of W by 1200 MeV proton irradiation

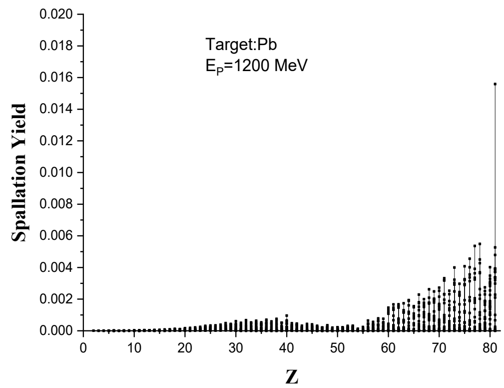

Figure 6. The spallation yield (1/sp) of Pb by 1200 MeV Proton

Figure 5 shows the spallation yield of the elements produced in the tungsten target by proton irradiation with 1200 MeV energy. All produced elements have an atomic number less than 74. The yield of producing elements decreases with decreasing atomic number. The 45 - 74 atomic numbers interval has a higher production yield than the 0-45 atomic numbers range. Also, the spallation yield of elements in each atomic number includes several different isotopes. For example, for 60 atomic number, about 10 isotopes are produced. Also, with the reduction of proton energy, the spallation yield of the produced elements decreases.

Figure 6 shows that the produced elements have an atomic number less than 82. This spectrum of produced elements has two peaks. The first peak is in the atomic number range of 0-50, and the second peak is in the range of 50-82. By decreasing the atomic number from 80 to 55, the production of elements decreases. Also, by decreasing the atomic number from 55 to 40, the yield of element production increases and then decreases for the 0 – 40 interval. With the reduction of proton energy, the yield of element production due to proton spallation decreases. At the same time, several isotopes are produced for each atomic number. The number of isotopes produced for larger atomic numbers is greater than others.

4. Discussion

According of the result, the production yield of ^{7}Be element is 0.16 that means 16% of the lithium target is used to produce neutrons due to proton irradiation. The ^{7}Be element produced is a beta-emitter and emits beta radiation after the proton source is turned off. Also, results showed that the ^{179}Ta, ^{180m}Ta radioactive element and 174Hf with half-lives 1.2×10^{15} y, 1.82 y, and 2×10^{17} year produced in the Ta target by a proton beam that has a high half-life. Other radioactive elements, such as 175Hf, have a shorter half-life of less than 70d. Therefore, cooling of the target after turning off is necessary, and radioactivity of the 7Be and Ta targets is one of the radiation hazard problems for staff and workers.

According to the Figures 5 and 6, the half-life of radioactive elements produced in the lead and tungsten spallation by 200- 1200 MeV proton irradiation for neutron production was calculated and is shown in Tables 4 and 5.

Table 4 shows the half-life of radioactive elements produced in the proton spallation of a tungsten target. About 150 radioactive elements were produced, of which 37 have a half-life of more than a year, 65 have a half-life of less than a day, and the rest have a half-life of less than an hour. Table 5 shows the half-life of the elements produced as a result of the proton spallation process of lead targets. About 525 radioactive elements with a half-life longer than an hour are listed in this Table. About 250 radioactive elements have a half-life of less than a day, 103 elements have a half-life of more than a year, and 372 radioactive elements have a half-life of less than a year and more than a day. The results of Tables 5 and 6 show that the tungsten and lead targets, for neutron production due to the proton spallation process, will be activated by a wide range of radioactive elements. After turning off the proton source, the radiation emitted in tungsten and lead targets will pose serious risks for the staff. Therefore, when changing targets, this point should be taken into account, and the occurrence of radiation risks should be prevented by installing a suitable shield. If it is necessary to change the target, the protection principles must be fully obeyed. According to the Monte Carlo simulation result, the spallation yield of radioactive production in lead and tungsten by 200-1200 MeV proton was, and the spallation yield of radioactive production in tungsten for 1200 MeV is shown in Figure 7.

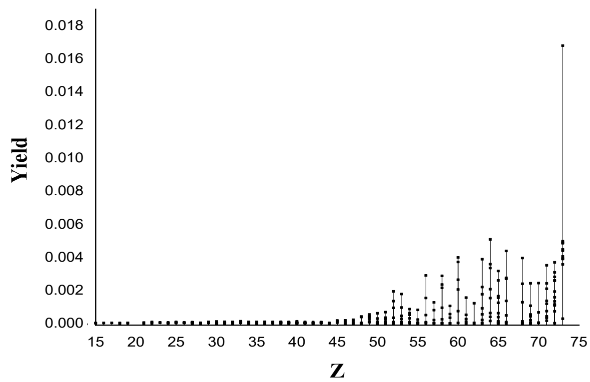

Figure 7. Spallation yield (1/sp) of radioactive production in tungsten by 1200 MeV proton irradiation

Figure 7 shows the benefit of producing radioactive elements as a result of the spallation process with protons with an energy of 1200 MeV in the tungsten target. As it is clear in Figure 7, the radioactive elements with the highest production yield are in the 45-74 atomic number range. It is also clear that the radioactive elements with atomic numbers 15 to 45 have equal spallation yield. The most probable spallation yield of radioactive production in tungsten by 200,800 and 1200 MeV proton was extracted and is shown in Table 6.

The most probable spallation yield of radioactive production in lead by 200,800 and 1200 MeV proton was extracted and is shown in Table 7.

Table 4. Half-life of radioactive elements produced in tungsten spallation by high-energy proton irradiation for neutron production

Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life
^{182}Os	22.10 h	169Yb	32.026 d	96Zr	>3.8E19 y	^{145}Sm	340 d	107Cd	6.50 h	70Zn	>5E14 y
^{183}Os	13.0 h	175Yb	4.185 d	97Zr	16.91 h	^{146}Sm	1.03E8 y	101Pd	8.47 h	^{71m}Zn	3.96 h
^{183m}Os	9.9 h	176mLu	3.635 h	85Y	2.68 h	^{152}Eu	13.537 y	103Pd	16.991 d	72Zn	46.5 h
^{174}Ta	1.05 h	177Lu	6.734 d	85mY	4.86 h	^{152m}Eu	9.3116 h	107Pd	6.5E6 y	61Cu	3.333 h
		177mLu	160.4 d	86Y	14.74 h	^{154}Eu	8.593 y	109Pd	13.7012 h	64Cu	12.700 h
^{175}Ta	10.5 h	179Lu	4.59 h	87Y	79.8 h	^{155}Eu	4.7611 y	112Pd	21.03 h	67Cu	61.83 h
^{176}Ta	8.09 h	128Ba	2.43 d	87mY	13.37 h	^{146}Gd	48.27 d	99Rh	16.1 d	56Ni	6.077 d
^{177}Ta	56.56 h	123Xe	2.08 h	88Y	106.65 d	^{147}Gd	38.06 h	99mRh	4.7 h	55Fe	2.73 y
^{178m}Ta	2.36 h	124Xe	>1.6E+14 y	90Y	64.00 h	^{148}Gd	74.6 y	100Rh	20.8 h	59Fe	44.503 d
^{180m}Hf	5.5 h	125Xe	16.9 h	90mY	3.19 h	^{149}Gd	9.28 d	101Rh	3.3 y	60Fe	1.5E6 y
^{181}Hf	42.39 d	127Xe	36.4 d	83Rb	86.2 d	^{150}Gd	1.79E6 y	101mRh	4.34 d	52Mn	5.591 d
^{182}Hf	9E6 y	129mXe	8.88 d	84Rb	32.77 d	^{151}Gd	124 d	102Rh	207 d	44mSc	58.6 h
^{183}Hf	1.067 h	121I	2.12 h	86Rb	18.631 d	^{152}Gd	1.08E14 y	99Tc	2.111E5 y	46Sc	83.79 d
^{132}La	4.8 h 2	121mTe	154 d	87Rb	4.75E10 y	^{153}Gd	240.4 d	99mTc	6.01 h	47Sc	3.3492 d
^{133}La	3.912 h	123Te	>1E13 y	76Kr	14.8 h	^{157}Tb	71 y	90Mo	5.56 h	36Cl	3.01E5 y
^{140}Nd	3.37 d	123mTe	119.7 d	79Kr	35.04 h	^{158}Tb	180 y	93Mo	4.0E3 y	35S	87.32 d
^{141}Nd	2.49 h	125mTe	57.40 d	81Kr	2.29E5 y	^{160}Tb	72.3 d	93mMo	6.85 h	32P	14.262 d
^{144}Nd	2.29E15 y	127Te	9.35 h	75Se	119.779 d	^{152}Dy	2.38 h	99Mo	65.94 h	33P	25.34 d
^{143}Pm	265 d	128Te	2.2E24 y	79Se	1.13E6 y	^{153}Dy	6.4 h	100Mo	1.00E+19 y	32Si	150 y
^{144}Pm	363 d	117Sb	2.80 h	82Se	1.08E20 y	^{167}Tm	9.25 d	89Nb	1.9 h	26Al	7.17E5 y
^{145}Pm	17.7 y	118mSb	5.00 h	71As	65.28 h	^{168}Tm	93.1 d	86Zr	16.5 h	28Mg	20.91 h
^{146}Pm	5.53 y	111In	2.8047 d	72As	26.0 h	^{170}Tm	128.6 d	87Zr	1.68 h	22Na	2.6019 y
^{147}Pm	2.6234 y	113mIn	1.6582 h	73As	80.30 d	^{171}Tm	1.92 y	88Zr	83.4 d	24Na	14.9590 h
^{148}Pm	5.370 d	114mIn	49.51 d	74As	17.77 d	^{172}Tm	63.6 h	89Zr	78.41 h	14C	5730 y
^{148m}Pm	41.29 d	115In	4.41E14 y	65Zn	244.26 d	^{173}Tm	8.24 h	93Zr	1.53E6 y	10Be	1.51E6 y
^{149}Pm	53.08 h	115mIn	4.486 h	69mZn	13.76 h	^{166}Yb	56.7 h	95Zr	64.02 d		

Tables 6 and 7 show that with increasing proton energy, the spallation yield of radioactive elements increases. Also, the atomic and mass numbers of the elements produced with the highest spallation yield increase with increasing proton energy and reach elements with higher mass and atomic numbers. For the tungsten target, ^{170}Hf, ^{184}Ta, and ^{180}Ta elements have the highest spallation yield, and for the lead target, ^{199}Tl and ^{186}Pt elements have the highest spallation yield.

5. Conclusion

A neutron beam was produced by proton irradiation of special targets that were used for the treatment of internal tumors. The proton spallation of W, Li, Be, Ta, Pb targets used in the BNCT therapy process can produce the radioactive elements in these materials. The proton-to-neutron spallation converter materials for the neutron production process can be damaged by this converter. The radioactive elements that exist in proton spallation converters must be considered in the BNCT method. The results showed that the radioactive elements are produced in W, Pb, Li, Be,

Table 5. Half-life of radioactive elements production in lead spallation by high energy proton irradiation for neutron production

Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life	Radioactive Elements	Half-Life
^{202}Bi	1.72 h	^{148}Sm	7E+15 y	^{103}Pd	16.991 d	^{189}Re	24.3 h	^{129m}Xe	8.88 d	^{74}As	17.77 d
^{203}Bi	11.76 h	^{149}Sm	>2E+15 y	^{107}Pd	6.5E6 y	^{176}W	2.5 h	^{131m}Xe	11.84 d	^{76}As	1.0778 d
^{204}Bi	11.22 h	^{151}Sm	90 y	^{109}Pd	13.7012 h	^{178}W	21.6 d	^{133}Xe	5.243 d	^{77}As	38.83 h
^{205}Bi	15.31 d	^{153}Sm	46.284 h	^{111m}Pd	5.5 h	^{181}W	121.2 d	^{133m}Xe	2.19 d	^{66}Ge	2.26 h
^{206}Bi	6.243 d	^{156}Sm	9.4 h	^{112}Pd	21.03 h	^{183}W	>1.1E17 y	^{135}Xe	9.14 h	^{68}Ge	270.8 d
^{207}Bi	31.55 y	^{145}Eu	5.93 d	^{99}Rh	16.1 d			^{136}Xe	2.36E21 y	^{69}Ge	39.05 h
^{208}Bi	3.68E5 y	^{146}Eu	4.61 d	^{99m}Rh	4.7 h	^{184}W	>3E17 y	^{121}I	2.12 h	^{71}Ge	11.43 d
^{198}Pb	2.40 h	^{147}Eu	24.1 d	^{100}Rh	20.8 h	^{185}W	75.1 d	^{123}I	13.27 h	^{77}Ge	11.30 h
^{200}Pb	21.5 h	^{148}Eu	54.5 d	^{101}Rh	3.3 y	187W	23.72 h	^{124}I	4.1760 d	^{66}Ga	9.49 h
^{201}Pb	9.33 h	^{149}Eu	93.1 d	^{101m}Rh	4.34 d	^{188}W	69.4 d	^{125}I	59.408 d	^{67}Ga	3.2612 d
^{202}Pb	5.25E4 y	^{150}Eu	36.9 y	^{102}Rh	207 d	^{173}Ta	3.14 h	^{126}I	13.11 d	^{72}Ga	14.10 h
^{202m}Pb	3.53 h	^{150m}Eu	12.8 h	^{102m}Rh	~2.9 y	^{174}Ta	1.05 h	^{129}I	1.57E7 y	^{73}Ga	4.86 h
^{203}Pb	51.873 h	^{152}Eu	13.537 y	^{105}Rh	35.36 h			^{130}I	12.36 h	^{62}Zn	9.186 h
^{204}Pb	>1.4E17 y	^{152m}Eu	9.3116 h	^{95}Ru	1.643 h	^{175}Ta	10.5 h	^{131}I	8.02070 d	^{65}Zn	244.26 d
^{205}Pb	1.53E7 y	^{154}Eu	8.593 y	^{97}Ru	2.9 d	^{176}Ta	8.09 h	^{132}I	2.295 h	^{69m}Zn	13.76 h
^{195}Tl	1.16 h	^{155}Eu	4.7611 y	^{103}Ru	39.26 d	^{177}Ta	56.56 h	^{132m}I	1.387 h	^{70}Zn	>5E14 y
^{196}Tl	1.84 h	^{156}Eu	15.19 d	^{105}Ru	4.44 h	^{178m}Ta	2.36 h	^{133}I	20.8 h	^{71m}Zn	3.96 h
^{196m}Tl	1.41 h	^{157}Eu	15.18 h	^{106}Ru	373.59 d	^{179}Ta	1.82 y	^{135}I	6.57 h	^{72}Zn	46.5 h
^{197}Tl	2.84 h	^{146}Gd	48.27 d	^{93}Tc	2.75 h	180Ta	8.152 h	^{116}Te	2.49 h	^{61}Cu	3.333 h
^{198}Tl	5.3 h	^{147}Gd	38.06 h	^{95}Tc	20.0 h	^{180m}Ta	>1.2E15 y	^{118}Te	6.00 d	^{64}Cu	12.700 h
^{198m}Tl	1.87 h	^{148}Gd	74.6 y	^{95m}Tc	61 d	^{182}Ta	114.43 d	^{119}Te	16.03 h	^{67}Cu	61.83 h
^{199}Tl	7.42 h	^{149}Gd	9.28 d	^{96}Tc	4.28 d	^{170}Hf	16.01 h	^{119m}Te	4.70 d	^{56}Ni	6.077 d
^{200}Tl	26.1 h	^{150}Gd	1.79E6 y	^{97}Tc	2.6E6 y	^{171}Hf	12.1 h	^{121}Te	16.78 d	^{57}Ni	35.60 h
^{201}Tl	72.912 h	^{151}Gd	124 d	^{97m}Tc	90.1 d	^{172}Hf	1.87 y	^{121m}Te	154 d	^{59}Ni	7.6E4 y
^{202}Tl	12.23 d	^{152}Gd	1.08E14 y	^{98}Tc	4.2E6 y	^{173}Hf	23.6 h	^{123}Te	>1E+13 y	^{63}Ni	100.1 y
^{204}Tl	3.78 y	^{153}Gd	240.4 d	^{99}Tc	2.111E5 y	^{174}Hf	2.0E15 y	^{123m}Te	119.7 d	^{65}Ni	2.5172 h
^{192}Hg	4.85 h	^{147}Tb	1.7 h	^{99m}Tc	6.01 h	^{175}Hf	70 d	^{125m}Te	57.40 d	^{66}Ni	54.6 h
^{193}Hg	3.80 h	^{149}Tb	4.118 h	^{90}Mo	5.56 h	^{178m}Hf	31 y	^{127}Te	9.35 h	^{55}Co	17.53 h
^{193m}Hg	11.8 h	150Tb	3.48 h	^{93}Mo	4.0E3 y	^{179m}Hf	25.05 d	^{127m}Te	109 d	^{56}Co	77.27 d
^{194}Hg	444 y	^{151}Tb	17.609 h	^{93m}Mo	6.85 h	^{182}Hf	9E6 y	^{128}Te	2.2E24 y	^{57}Co	271.79 d
^{195}Hg	9.9 h	^{152}Tb	17.5 h	^{99}Mo	65.94 h	^{183}Hf	1.067 h	^{129m}Te	33.6 d	^{58}Co	70.86 d
^{195m}Hg	41.6 h	^{153}Tb	2.34 d	^{100}Mo	1.00E19 y	^{184}Hf	4.12 h	^{130}Te	7.9E20 y	^{58m}Co	9.04 h
^{197}Hg	64.14 h	^{154}Tb	21.5 h	^{89}Nb	1.9 h	^{132}La	4.8 h	^{131m}Te	30 h	^{60}Co	5.2714 y
^{197m}Hg	23.8 h	^{154m}Tb	9.4 h	^{89m}Nb	1.18 h	^{133}La	3.912 h	^{132}Te	3.204 d	^{61}Co	1.650 h
^{203}Hg	46.612 d	^{154m2}Tb	22.7 h	^{90}Nb	14.60 h	^{135}La	19.5 h	^{117}Sb	2.80 h	^{52}Fe	8.275 h
^{191}Au	3.18 h	^{155}Tb	5.32 d	^{91}Nb	680 y	^{137}La	6E4 y	^{118m}Sb	5.00 h	^{55}Fe	2.73 y
^{191m}Au	0.92 s	^{156}Tb	5.35 d	^{91m}Nb	60.86 d	^{138}La	1.05E11 y	^{119}Sb	38.19 h	^{59}Fe	44.503 d
^{192}Au	4.94 h	^{156m}Tb	24.4 h	^{92}Nb	3.47E7 y	^{140}La	1.6781 d	^{120m}Sb	5.76 d	^{60}Fe	1.5E6 y
^{193}Au	17.65 h	^{156m2}Tb	5.3 h	^{92m}Nb	10.15 d	^{141}La	3.92 h	^{122}Sb	2.7238 d	^{52}Mn	5.591 d

^{194}Au	38.02 h	^{157}Tb	71 y	^{93m}Nb	16.13 y	^{132}Ce	3.51 h	^{124}Sb	60.20 d	^{53}Mn	3.74E6 y
^{195}Au	186.09 d	^{158}Tb	180 y	^{94}Nb	2.03E4 y	^{133m}Ce	4.9 h	^{125}Sb	2.7582 y	^{54}Mn	312.3 d
^{196}Au	6.183 d	^{160}Tb	72.3 d	^{95}Nb	34.975 d	^{134}Ce	3.16 d	^{126}Sb	12.46 d	^{56}Mn	2.5785 h
^{196m}Au	9.6 h	^{161}Tb	6.88 d	^{95m}Nb	86.6 h	^{135}Ce	17.7 h	^{127}Sb	3.85 d	^{48}Cr	21.56 h
^{198}Au	2.69517 d	^{152}Dy	2.38 h	^{96}Nb	23.35 h	^{137}Ce	9.0 h	^{128}Sb	9.01 h	^{50}Cr	>1.8E17 y
^{198m}Au	2.27 d	^{153}Dy	6.4 h	^{86}Zr	16.5 h	^{137m}Ce	34.4 h	^{129}Sb	4.40 h	^{51}Cr	27.7025 d
^{199}Au	3.139 d	^{154}Dy	3.0E+6 y	^{87}Zr	1.68 h	^{139}Ce	137.640 d	^{110}Sn	4.11 h	^{48}V	15.9735 d
^{200m}Au	18.7 h	^{155}Dy	9.9 h	^{88}Zr	83.4 d	^{141}Ce	32.501 d	^{113}Sn	115.09 d	^{49}V	330 d
^{186}Pt	2.2 h	^{157}Dy	8.14 h	^{89}Zr	78.41 h	^{142}Ce	>5E16 y	^{117m}Sn	13.60 d	^{50}V	1.4E17 y
^{187}Pt	2.35 h	^{159}Dy	144.4 d	^{93}Zr	1.53E6 y	^{143}Ce	33.039 h	^{119m}Sn	293.1 d	^{44}Ti	63 y
^{188}Pt	10.2 d	^{165}Dy	2.334 h	^{95}Zr	64.02 d	^{144}Ce	284.893 d	^{121}Sn	27.06 h	^{43}Sc	3.891 h
^{189}Pt	10.87 h	^{166}Dy	81.6 h	^{96}Zr	>3.8E19 y	^{137}Pr	1.28 h	^{121m}Sn	55 y	^{44}Sc	3.927 h
^{190}Pt	6.5E11 y	^{158}Er	2.29 h	^{97}Zr	16.91 h	^{138m}Pr	2.12 h	^{123}Sn	129.2 d	^{44m}Sc	58.6 h
^{191}Pt	2.802 d	^{160}Er	28.58 h	^{85}Y	2.68 h	^{139}Pr	4.41 h	^{125}Sn	9.64 d	^{46}Sc	83.79 d
^{193}Pt	50 y	^{161}Er	3.21 h	^{85m}Y	4.86 h	^{142}Pr	19.12 h	^{126}Sn	~1E+5 y	^{47}Sc	3.3492 d
^{193m}Pt	4.33 d	^{165}Er	10.36 h	^{86}Y	14.74 h	^{143}Pr	13.57 d	^{127}Sn	2.10 h	^{48}Sc	43.67 h
^{195m}Pt	4.02 d	^{163}Tm	1.810 h	^{87}Y	79.8 h	^{145}Pr	5.984 h	^{109}In	4.2 h	^{41}Ca	1.03E5 y
^{197}Pt	19.8915 h	^{165}Tm	30.06 h	^{87m}Y	13.37 h			^{110}In	4.9 h	^{45}Ca	162.61 d
^{200}Pt	12.5 h	^{166}Tm	7.70 h	^{88}Y	106.65 d	^{138}Nd	5.04 h	^{111}In	2.8047 d	^{47}Ca	4.536 d
^{184}Ir	3.09 h	^{167}Tm	9.25 d	^{90}Y	64.00 h	^{139m}Nd	5.50 h	^{113m}In	1.6582 h	^{48}Ca	>6E18 y
^{185}Ir	14.4 h	^{168}Tm	93.1 d	^{90m}Y	3.19 h	^{140}Nd	3.37 d	^{114m}In	49.51 d	^{40}K	1.277E9 y
^{186}Ir	16.64 h	^{170}Tm	128.6 d	^{91}Y	58.51 d	^{141}Nd	2.49 h	^{115}In	4.41E14 y	^{42}K	12.360 h
^{186m}Ir	1.90 h	^{173}Tm	8.24 h	^{92}Y	3.54 h	^{144}Nd	2.29E15 y	^{115m}In	4.486 h	^{43}K	22.3 h
^{187}Ir	10.5 h	^{169}Yb	32.026 d	^{93}Y	10.18 h	^{147}Nd	10.98 d	^{107}Cd	6.50 h	^{37}Ar	35.04 d
^{188}Ir	41.5 h	^{166}Yb	56.7 h	^{82}Sr	25.55 d	^{149}Nd	1.728 h	^{109}Cd	462.6 d	^{39}Ar	269 y
^{189}Ir	13.2 d	^{169}Lu	34.06 h	^{83}Sr	32.41 h	^{150}Nd	>1.1E19 y	^{113}Cd	7.7E+15 y	^{42}Ar	32.9 y
^{190}Ir	11.78 d	^{170}Lu	2.012 d	^{85}Sr	64.84 d	^{143}Pm	265 d	^{113m}Cd	14.1 y	^{36}Cl	3.01E5 y
^{190m}Ir	1.2 h	^{171}Lu	8.24 d	^{87m}Sr	2.803 h	^{144}Pm	363 d	^{115}Cd	53.46 h	^{35}S	87.32 d
^{190m}Ir	3.25 h	^{172}Lu	6.70 d	^{89}Sr	50.53 d	^{145}Pm	17.7 y	^{115m}Cd	44.6 d	^{32}P	14.262 d
^{192}Ir	73.831 d	^{173}Lu	1.37 y	^{90}Sr	28.79 y	^{146}Pm	5.53 y	^{117}Cd	2.49 h	^{33}P	25.34 d
^{192m}Ir	241 y	^{174}Lu	3.31 y	^{91}Sr	9.63 h	^{147}Pm	2.6234 y	^{117m}Cd	3.36 h	^{32}Si	150 y
^{193m}Ir	10.53 d	^{174m}Lu	142 d	^{92}Sr	2.71 h	^{148}Pm	5.370 d	^{106m}Ag	8.28 d	^{26}Al	7.17E5 y
^{194}Ir	19.28 h	^{176}Lu	3.78E10 y	^{81}Rb	4.576 h	^{148m}Pm	41.29 d	^{108m}Ag	418 y	^{28}Mg	20.91 h
^{194m}Ir	171 d	^{176m}Lu	3.635 h	^{82m}Rb		^{149}Pm	53.08 h	^{110m}Ag	249.79 d	^{22}Na	2.6019 y
^{195}Ir	2.5 h	^{177}Lu	6.734 d	^{83}Rb	86.2 d	^{150}Pm	2.68 h	^{111}Ag	7.45 d	^{24}Na	14.9590 h
^{195m}Ir	3.8 h	^{177m}Lu	160.4 d	^{84}Rb	32.77 d	^{151}Pm	28.40 h	^{112}Ag	3.130 h	^{14}C	5730 y
^{196m}Ir	1.40 h	^{128}Ba	2.43 d	^{86}Rb	18.631 d	^{145}Sm	340 d	^{113}Ag	5.37 h	7Be	53.12 d
^{182}Os	22.10 h	^{129}Ba	2.23 h	^{87}Rb	4.75E10 y	^{146}Sm	1.03E8 y	^{100}Pd	3.63 d		
^{183}Os	13.0 h	^{129m}Ba	2.16 h	^{76}Kr	14.8 h	^{147}Sm	1.06E11 y	^{101}Pd	8.47 h	^{10}Be	1.51E6 y
^{183m}Os	9.9 h	^{131}Ba	11.50 d	^{79}Kr	35.04 h	^{182}Re	64.0 h	^{134m}Cs	2.903 h	^{83}Br	2.40 h
^{184}Os	>5.6E13 y	^{133}Ba	10.51 y	^{81}Kr	2.29E5 y	^{182m}Re	12.7 h	^{135}Cs	2.3E+6 y	^{72}Se	8.40 d
^{185}Os	93.6 d	^{133m}Ba	38.9 h	^{85}Kr	10.756 y	^{183}Re	70.0 d	^{136}Cs	13.16 d	^{73}Se	7.15 h
^{186}Os	2.0E15 y	^{135m}Ba	28.7 h	^{85m}Kr	4.480 h	^{184}Re	38.0 d	^{137}Cs	30.07 y	^{75}Se	119.779 d
^{189m}Os	5.8 h	^{140}Ba	12.752 d	^{88}Kr	2.84 h	^{184m}Re	169 d	^{122}Xe	20.1 h	^{79}Se	1.13E6 y
^{191}Os	15.4 d	^{127}Cs	6.25 h	^{76}Br	16.2 h	^{186}Re	3.7183 d	^{123}Xe	2.08 h	^{82}Se	1.08E20 y

^{191m}Os	13.10 h	^{129}Cs	32.06 h			^{186m}Re	2.0E+5 y	^{124}Xe	1.6E+14 y	^{71}As	65.28 h
^{193}Os	30.11 h	^{131}Cs	9.689 d	^{77}Br	57.036 h	^{187}Re	4.35E10 y	^{125}Xe	16.9 h	^{72}As	26.0 h
^{194}Os	6.0 y	^{132}Cs	6.479 d	^{80m}Br	4.4205 h	^{188}Re	17.005 h	^{127}Xe	36.4 d	^{73}As	80.30 d
^{181}Re	19.9 h	^{134}Cs	2.0648 y	^{82}Br	35.30 h						

Table 6. The most probable spallation yield of radioactive production (SPRP) in tungsten by 200,800 and 1200 MeV proton (E_P) irradiation

Z	**N**	**SPRP for E_P=200 MeV**	**Z**	**N**	**SPRP for E_P=800 MeV**	**Z**	**N**	**SPRP for E_P=1200 MeV**
72	98	0.00409	73	111	0.018218	73	110	0.016805
72	100	0.003931	73	101	0.007474	64	82	0.005084
72	101	0.003341	73	103	0.007048	73	109	0.004973
72	102	0.003286	73	109	0.00589	73	102	0.00489
72	99	0.003263	73	105	0.005878	73	100	0.004855
72	103	0.002551	72	99	0.005794	73	104	0.00448
71	98	0.002075	73	100	0.005722	73	106	0.004398
72	106	0.001758	73	102	0.005659	66	86	0.004387
71	99	0.001485	71	98	0.005576	73	107	0.004053
71	100	0.001347	73	107	0.005507	60	78	0.003994
72	107	0.00112	71	99	0.005458	68	90	0.003958
72	108	0.000922	66	87	0.005139	73	101	0.003928
71	101	0.000906	73	104	0.005093	73	105	0.003896
71	102	0.000696	73	106	0.004884	63	82	0.003887
72	109	0.00049	73	110	0.004849	60	77	0.003718
70	96	0.000444	72	101	0.004471	72	98	0.003694
71	103	0.000409	64	83	0.004404	64	84	0.003586
72	110	0.000291	72	98	0.004395	73	103	0.003574
71	105	0.00016	68	90	0.004232	71	98	0.003517
70	99	0.000152	72	100	0.004107	64	83	0.003354
71	106	0.000145	69	94	0.003921	65	84	0.003175
69	94	0.000102	66	86	0.003789	72	100	0.00309

and Ta targets and must be avoided during radiation hazards calculation. The simulation results show that proton spallation of W and Pb targets produced the (^{170}Hf, ^{184}Ta, ^{180}Ta) and (^{199}Tl,^{186}Pt) radioactive elements with high spallation yield, respectively, which should be considered as radioactive hazards for these targets. With increased energy of the proton beam, the amount of production of the radioactive elements was increased. Also, the Monte Carlo result shows that the production of radioactive elements in reactions with secondary neutrons is lower than in reactions with the primary proton beam.

Table 7. The most probable spallation yield of radioactive production in Lead by 200,800 and 1200 MeV protons

Z	N	SPRP for E_P=200 MeV	Z	N	SPRP for E_P=800 MeV	Z	N	SPRP for E_P=1200 MeV
81	118	0.012081	78	108	0.008673	78	108	0.005488
81	120	0.010675	78	109	0.006797	78	109	0.004507
81	116	0.010262	78	110	0.006741	78	110	0.004274
81	119	0.009813	80	114	0.00612	80	114	0.004019
81	117	0.00969	80	112	0.005897	81	118	0.003936
81	121	0.008471	81	118	0.005782	81	120	0.003922
81	115	0.007583	77	108	0.00567	77	108	0.003914
81	114	0.007011	81	116	0.005622	81	116	0.003731
81	123	0.00642	81	114	0.005378	81	123	0.00371
80	114	0.003784	81	120	0.005118	80	112	0.003481
80	115	0.002871	80	113	0.004956	81	121	0.00338
80	117	0.00266	81	117	0.004851	81	119	0.003366
80	113	0.002614	81	119	0.004749	81	114	0.003343
80	112	0.002609	81	115	0.004678	73	100	0.003225
80	123	0.001019	80	115	0.004343	81	117	0.003193
79	112	0.000697	81	121	0.004325	80	113	0.003098
79	114	0.000602	81	123	0.004239	81	115	0.002986
79	113	0.000555	78	111	0.004023	80	115	0.002823
79	115	0.000399	79	112	0.003958	78	111	0.002636
79	116	0.000368	73	100	0.003512	68	90	0.002618
78	110	0.000367	80	117	0.003351	79	112	0.00251

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