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Proton cross section for Th-232

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Abstract

In this research, the cross-sections for proton-induced reactions on Th-232 nuclei evaluated for produce radioisotopes like Ac-225 ($t_{1/2}$ =10 d), Th-227 ($t_{1/2}$ =18.7d), Pa-231 ($t_{1/2}$ =32,760 y) and Pa-232 ($t_{1/2}$ =1.31 d). Experimental data obtained from the EXFOR library, which affiliated with (IAEA) for nuclear reactions (p,x), (p,n) and (p,2n) for energy range (6-194) MeV. Theoretical study conducted to calculate the stopping power using Ziegler equations in the range of energy (6-93) MeV. A program for evaluating cross-sections, yield, and stopping power was developed using MATLAB - 2013 in the present work.

Key word: Th-232, cross - section, yield, radioisotopes.
Note: The research is based on a master's thesis or a doctoral thesis (if any). **No**

Introduction:

Th-232 is an important element among the actinides, is a widely distributed radioactive element on Earth's surface, with an estimated natural abundance three times that of uranium.Th-232 captures a neutron to become isotope Th-233 which endures beta decay two consecutive times and results in U-233, This is a fissile isotope that is recyclable and used as nuclear reactor fuel. Th-232 contributes significantly in the production of radioactive isotopes used in nuclear medicine. Proton-induced nuclear reactions are essential for generating these radioisotopes. [1]. The three types of radiation found in nature gamma, beta, and alpha particles pose serious health dangers to living things. Radon gas is one of the most harmful substances to human health. It is an alpha emitter that is 15% of the time linked to lung cancer [2,3].

The human body is mostly unaffected by certain elements, like Tritium. Nevertheless, long-term exposure to a Tritium source can harm the body more seriously than exposure to alpha particles or gamma rays. [4].

One of the modern radiation therapy techniques for cancer treatment that utilizes alpha-emitters is targeted alpha therapy (TAT). This promising application in nuclear medicine delivers a potent radiation dose directly to malignant cells while sparing the surrounding healthy tissues. This approach

reduces the side effects of radiation on healthy tissues and enhances the destructive impact on cancer cells[5]. Alpha emitters are distinguished by their high linear energy transfer, approximately 100 KeV/µm, and their low penetration into living tissue, estimated to be around 50-100 µm[6,7].
Among the candidates α- emitters, Bi- 212($t_{1/2}$ = 60.55 m), Ra-223 ($t_{1/2}$ = 11.4 d) [8,9], Th- 227 ($t_{1/2}$=(18.7 d)[5], Ac-225 ($t_{1/2}$ = 10.0 d), and At -211($t_{1/2}$ = 7.214 h)[10] are of major interest. Nonetheless, taking into account the aggregate nuclear, physical, chemical, and biological characteristics, Ac-225 and its daughter Bi-213 ($t_{1/2}$ = 45.61) are of greatest interest.[11,12]
Th-227 is considered a highly potential agent for therapeutic radiation treatments. In addition, Th-227 is the progenitor of Radium-223 (Ra-223), an alpha-emitting element sanctioned for global medical applications. [5].
The (p,x) reaction results in either Ac-225 or Th-227, both of which are used in medical applications as mentioned above. The reactions (p,n) and (p,2n) produce isotopes Pa-232 and Pa-231 respectively, which are used for scientific purposes. Researchers study isotopes of Protactinium as a material for nuclear fuel [13]. The isotope Pa-231 is stable with a natural abundance of 100% and a half-life of 32,760 y; it decays via alpha emission to produce Ac-227. On the other hand, the isotope Pa-232 is rarer and manufactured in nuclear reactors; it has a half-life of approximately 1.31 d and decays via beta emission to form the isotope U-232.
Many studies have been developed for proton induced cross section for Th-232 by to produced radioisotopes like [14], [1],and[15] for production radioisotopes for medical applications. The aim of this research is to produce radioactive isotopes fromTh-232 through proton induced reactions.

Cross section data

EXFOR is a library of experimental cross-sectional data, cross-sectional data for proton reactions on Th-232 were taken from them, for the following reactions (p,x),(p,n) and (p,2n). Table 1 shows the interactions with the authors and the energy ranges of each of them. The experimental data rearranged with the error ratio of each according to the energy intervals of 0.01 MeV by the energy of each reaction.

Table (1) :Properties and experimental information for proton-induced reactions on Th-232 that can be found in the EXFOR library.

Target	Reactions	Product	Rang of Energy (MeV)	Author ref. no.
$^{232}_{90}Th$	(p,x)	$^{225}_{89}Ac$	56.32-194.57 90-135	Weidner et al.[16] Zhuikov et al.[17]
$^{232}_{90}Th$	(p,x)	$^{227}_{90}Th$	56.32-194.57 90-135	Weidner et al.[16] Zhuikov et al.[17]
$^{232}_{90}Th$	(p,n)	$^{232}_{91}Pa$	11.1-17.5 13-39.9 14.1-19.9	Roshchin et al.[18] Griswold et al.[19] Kmak et al.[20]
$^{232}_{90}Th$	(p,2n)	$^{231}_{91}Pa$	7.23-20.23 11.42-20.55	Celler et al.[21] Kudo et al.[22]

The distribution of cross-sectional errors was standardized based on the respective cross-sectional values obtained. Which was then determined using interpolated values, calculated through the weighted average method.

$$\sigma_{w.a.} = \frac{\sum_{i=1}^{n} \frac{\sigma_i}{(\Delta\sigma_i)^2}}{\sum_{i=1}^{n} \frac{1}{(\Delta\sigma_i)^2}} \qquad (1)$$

The standard deviation (S.D) error expressed as:

$$S.D. = \frac{1}{\sqrt{\sum_{i=1}^{N} \frac{1}{(\Delta\sigma_i)^2}}} \qquad (2)$$

Stopping power and Yield

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Stopping power is the term for the energy loss that occurs when charged particles go through a material. This can be characterized as the mean energy dissipation of charged particles per unit route length within the investigated material. [23]. Radiative and electrical components make up stopping power. The interaction of the charged particle with the medium's nucleus produces the radiative stopping power, which is usually insignificant at high energies. We shall concentrate on electronic stopping power, which is produced when atomic electrons in the medium collide with incident charged particles [24].
Stopping power of the Proton calculated using the Ziegler equations and programmed using MATLAB-2013 according to the following energy ranges [25-27]:

1. Energy range (0.0001-0.001)MeV.

$$-\frac{dE}{dx} = A_1 E^{1/2} \quad (3)$$

2. Energy range (0.001-9.99)MeV.

$$\left(-\frac{dE}{dx}\right)^{-1} = \left(-\frac{dE}{dx}\right)_{Low}^{-1} + \left(-\frac{dE}{dx}\right)_{High}^{-1} \quad (4)$$

$$\left(-\frac{dE}{dx}\right)_{Low} = A_2 E^{0.45} \quad (5)$$

$$\left(-\frac{dE}{dx}\right)_{High} = \left(\frac{A_3}{E}\right)\ln\left[1+\left(\frac{A_4}{E}\right)+A_5 E\right] \quad (6)$$

3. Energy range (10-100) MeV.

$$\left(-\frac{dE}{dx}\right) = \left(\frac{A_6}{\beta^2}\right)\left[\ln\left(\frac{A_7\beta^2}{1-\beta^2}\right) - \beta^2 - \sum_{i=0}^{4} A_{i=8}(lnE)^i\right] \quad (7)$$

Where: E is energy of proton in (MeV). A_i is Ziegler coefficients, Table (2) shows the Ziegler coefficients for the proton on Thorium that were used in this work. β is the proportion of incident particles velocities and velocity of the light.

TABLE (2): coefficients given by Ziegler for proton on Thorium [28].

Coe	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8

.								
$^{232}_{90}Th$	5.24536	0.0039744	6.79689	0.48542	4586.31	0.87794	2481.50	0.011282

The ratio of the number of nuclei created during the reaction to the number of incoming particles impacting the target is known as the nuclear reaction's yield. The Y of product nuclei represented as a function of the cross section as for any energy (e) [29]:

$$Y = i(\emptyset\, n)H\left(1 - e^{-\lambda t}\right)\int_{e\ out}^{e\ in} \sigma\ (e)\left(\frac{dE}{dx}\right)^{-1}$$

(8)

Where:

Y: the activity in Bq. i: the current of incident beam in µA.

ϕ : flux of beam in (1/s). ϕ. In a nuclear power plant the flux is ~ 10^{12} to $10^{14}\ n/cm^2 \cdot s$. n: atomic density $(\frac{N}{A})$. N: Avogadro's number. A: mass number in (amu). H: relative abundance of isotopes of the target. λ: Radioactive decay coefficient of the product = $(\frac{0.693}{t_{1/2}})$ in (h^{-1}). t : irradiation duration in (h). $\frac{dE}{dx}$: stopping power. $\sigma(e)$: cross section at e in (mb).

Results and Discussion

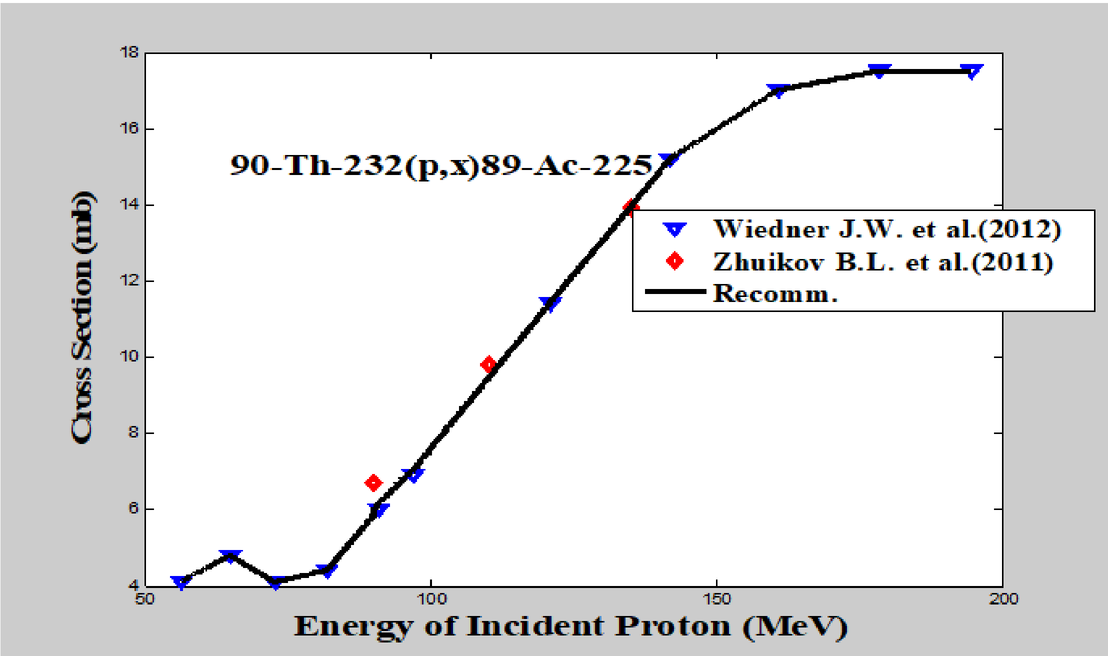
The experimental data presented in Table (1) is utilized to compute the cross-sections of nuclear reactions sourced from the EXFOR Library, associated with the (IAEA). These reactions are induced by protons on the Th-232 target nucleus. The recommended cross section for Th-232 calculated by Matlab-2013. It is worth noting that range of energy for the reactions derived from various sources and is not the same, so a recalculation performed in the energy interval 0.01MeV. Recalculated cross-sections are appear in the following figures (1 - 4).

The reaction Th-232(p,x) Ac-225 the nuclear data show agree with [16], with energy range (56-194) MeV, for[16] and [17], the high cross section (17.5)mb at optimum energy E_P=194MeV, and production yield is (1.43x10^{30}) MBq/µAh for proton energy(56.37)MeV ,as shown in figure (1).

The reaction Th-232(p,x) Th-227 the nuclear data show agree with [16], with energy range (56-194) MeV, for [16] and [17], the high cross section (49.5)mb at optimum energy range E_P=(70-80)MeV, and production yield is (5.51x10^{31})MBq/µAh for proton energy (65.37)MeV as shown in figure (2).

The reaction Th-232(p,n) Pa-232 the nuclear data show agree with [20], with energy range (11-39.8)MeV, for[18], [19] and [20]. The high cross section (18.84) mb at optimum energy E_P =17.41 MeV, and production yield is ($4.86x10^{25}$) MBq/µAh, as shown in figure (3).

Reaction Th-232(p,2n) Pa-231 the nuclear data show agree with [21], with energy range (7-20.3)MeV, for [21], and [22]. The high cross section (313.2) mb at optimum energy E_P =14 MeV, and production yield is ($9.59x10^9$) MBq/µAh, as shown in figure (4). In this study, the stopping power of the target element for protons was determined using Matlab-2013 software shown in figure (5). The approximate yield was calculated based on recommended cross-sections for (p,x), (p,n), and (p,2n) reactions obtained from the same software. The objective of the research is to produce radioisotopes from Th-232 through proton-induced reactions. Different beam currents, measured in µAh, were used to evaluate yield of the reactions, with the results depicted in figure (6).



Figure(1): suggested cross section of ${}^{232}_{90}Th(p,x)\,{}^{225}_{89}Ac$ reaction in comparison with other studies.

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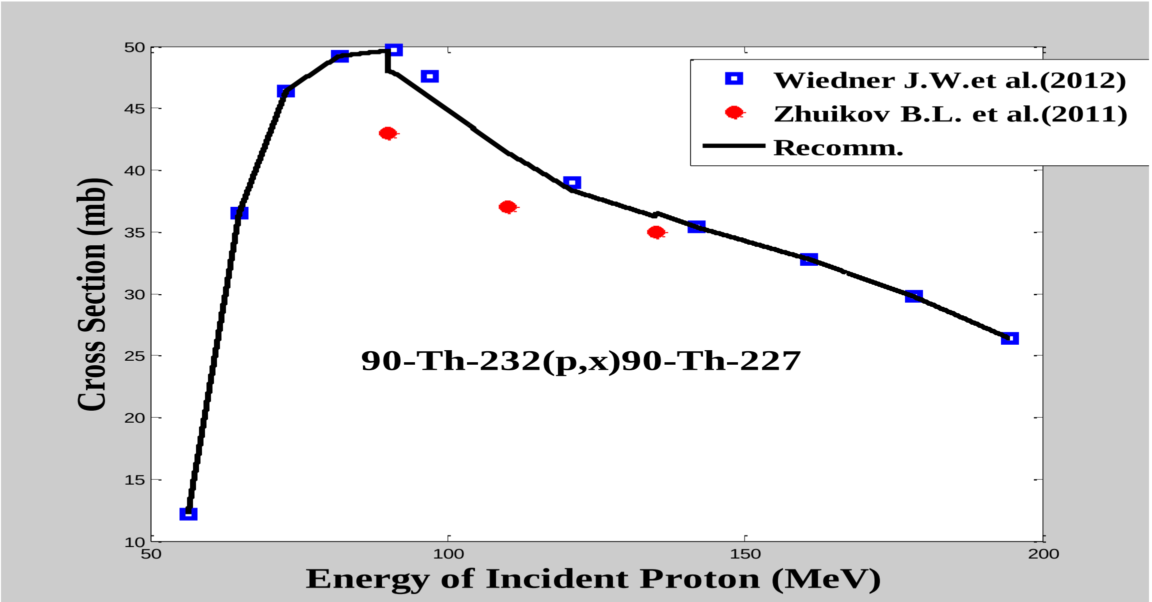
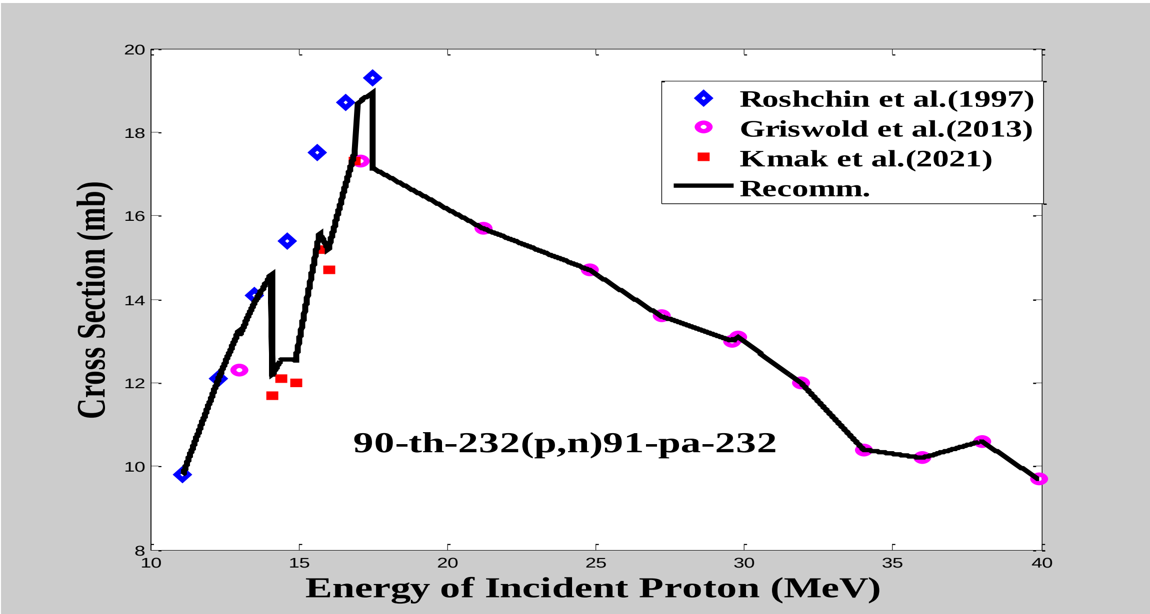
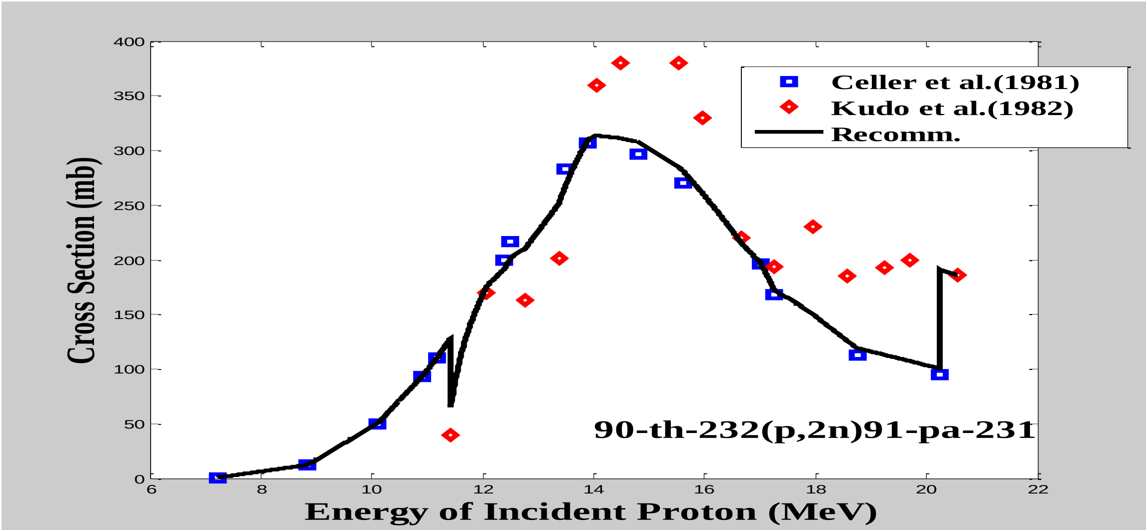


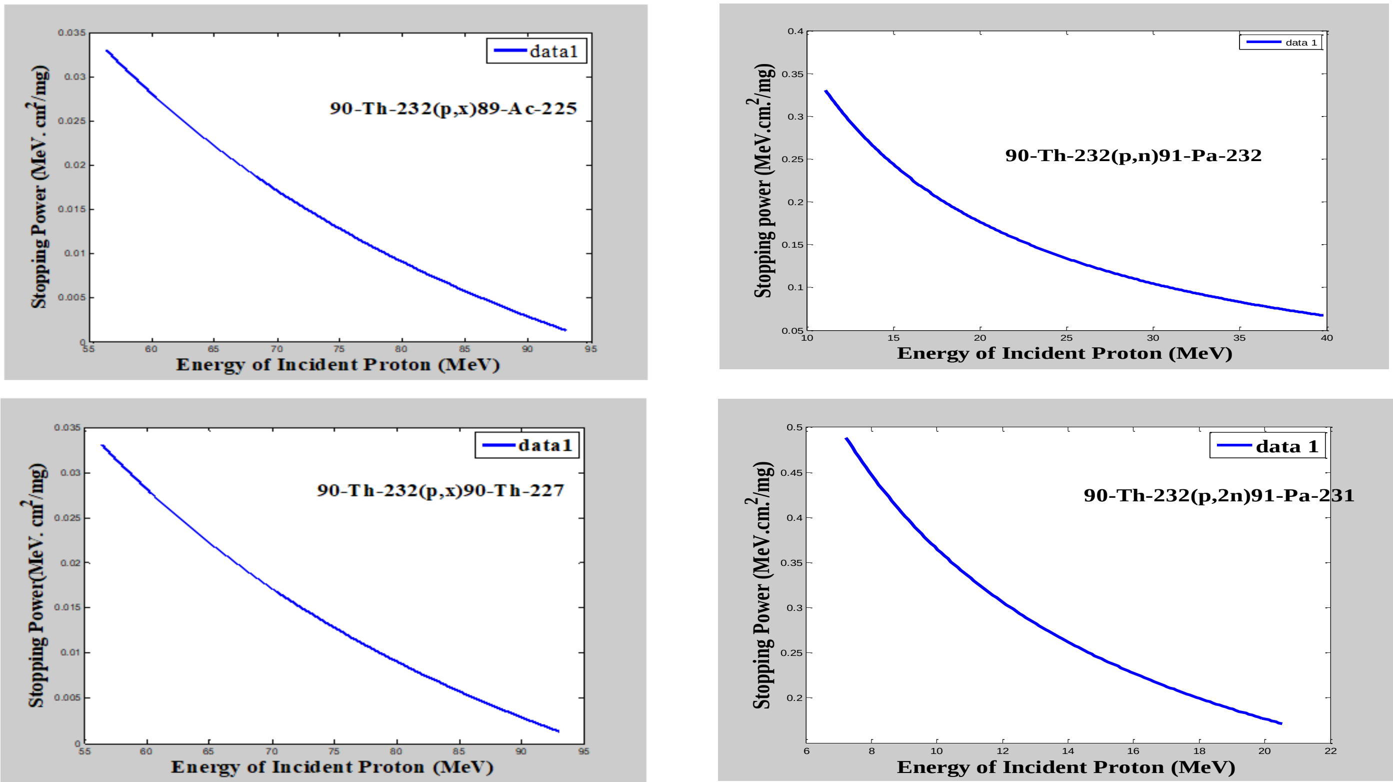
Figure(2): suggested cross section of $^{232}_{90}Th(p,x)^{227}_{90}Th$ reaction in comparison with other studies.



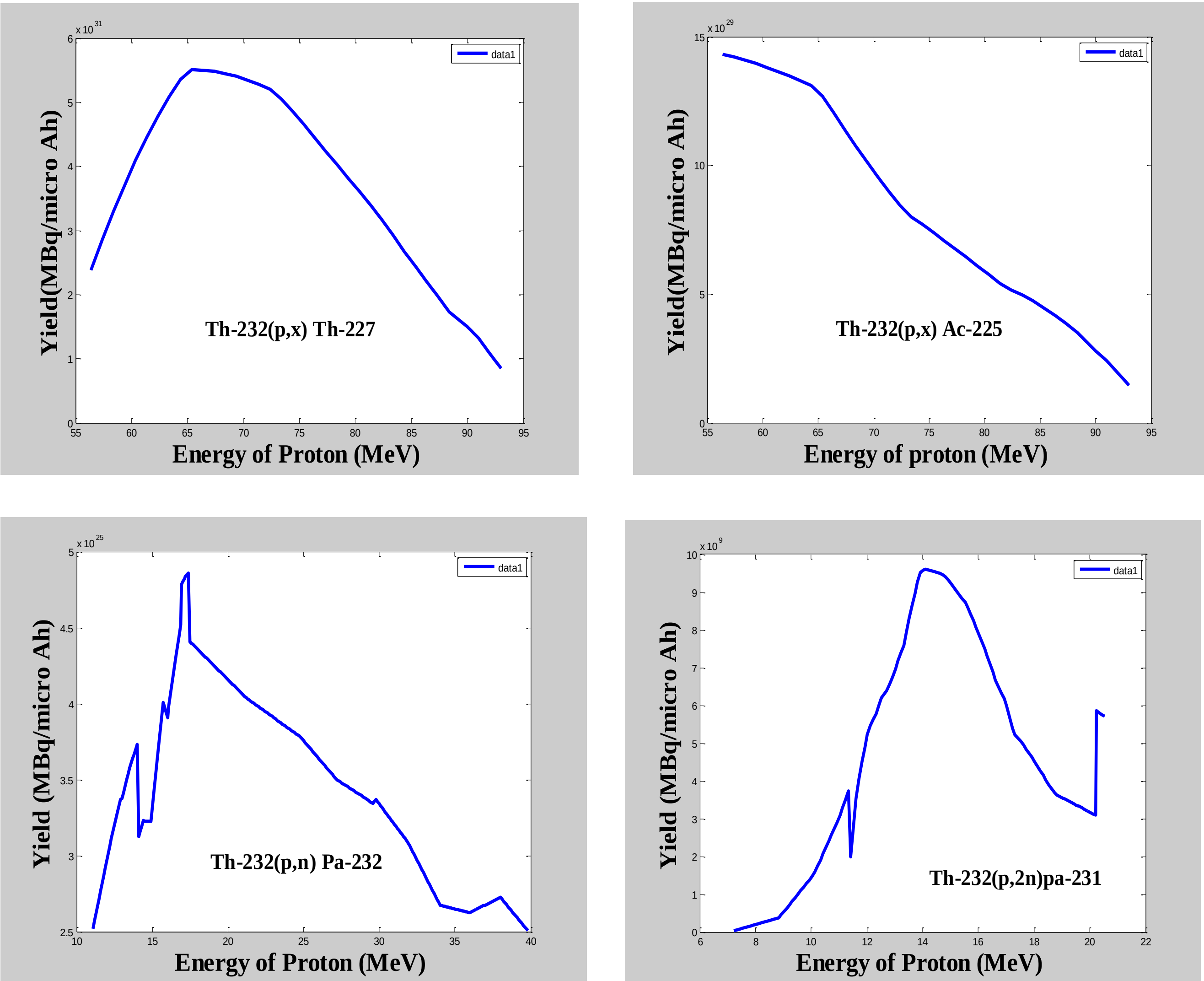
Figure(3): suggested cross section of $^{232}_{90}Th(p,n)^{232}_{91}Pa$ reaction in comparison with other studies.



Figure(4): suggested cross section of $^{232}_{90}Th(p,2n)^{231}_{91}Pa$ reaction in comparison with other studies.



Figure(5): the stopping power calculated according to Ziegler's formula.



Figure(6): approximate yield based on the suggested cross section and stopping power for proton induced reactions in Th-232 in the current work.

Conclusion

The production of radioactive isotopes is of great importance in many aspects of life, whether in the field of nuclear medicine or for scientific purposes alike. Proton-induced reactions on Th-232 have shown significant importance in this field. For Ac-225, the production is high at 56 MeV and begins to decrease with increasing energy. As for the th-227 isotope, the results have shown that it can be more efficiently produced within the energy range (60-80) MeV for proton. Similarly, for Pa-231 and Pa-232 isotopes, the production of the isotope increases within medium proton energies and gradually decreases with increasing proton energy.

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المقطع العرضي للبروتون لـTh-232

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مستخلص البحث
في هذا البحث ، تم تقييم المقاطع العرضية للتفاعلات التي يسببها البروتون على نوى Th-232 لإنتاج نظائر مشعة مثل Ac-225 (t1/2 = 10 d) ، Th-227 (t1/2 = 18.7d)، Pa-231 (t1/2 = 32,760 y)و Pa-232 (t1/2 = 1.31 d). البيانات التجريبية التي تم الحصول عليها من مكتبة EXFORالتابعة لـ (IAEA)للتفاعلات النووية (p,x) و (p,n) و (p,2n) لمدى الطاقة) 6-194 (MeV.دراسة نظرية أجريت لحساب قدرة الايقاف باستخدام معادلات زيغلر في مدى الطاقة) 6-93(MeV.تم تطوير برنامج لتقييم المقاطع العرضية والعائد وقدرة الإيقاف باستخدام- MATLAB 2013في العمل الحالي.