Science Journal of University of Zakho
DOI: https://doi.org/10.25271/sjuoz

Original Article

TOTAL NEUTRON YIELDS OF ^{9}Be(α,n)^{12}C AND ^{9}Be(d,n)^{10}B REACTIONS USING VARIOS ALPHA EMITTERS*

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ABSTRACT

Received:
03, June, 2025

Accepted:
28, Aug, 2025

Published:
12, Apr, 2026

The cross-sections of ^{9}Be(α,n)^{12}C and ^{9}Be(d,n)^{10}Breactions have been calculated for alpha and deuteron energies from near threshold energy to10 MeV using recently published neutron yields as a Function of alpha and deuteron energies. An α-particle is a type of ionizing radiation consisting of two protons and two neutrons bound together, which is the same as the nucleus of a helium-4.The neutron yields Yo (n/10^{6} α) and Yo (n/10^{6} d) have been calculated using the evaluated cross sections and the stopping powers by applying Simpson's rule. For ^{9}Be(α,n)^{12}C reaction the total neutron yields Y_n(Be)(n/s/$g_{\alpha\text{-emitter}}$/ppm) have been calculated using the various alpha emitters such as ($_{62}$Sm^{147}, $_{64}$Gd^{148} , $_{66}$Dy^{154} , $_{72}$Hf^{174} , $_{76}$Os^{186} , $_{78}$Pt^{190} , $_{84}$Po^{109} , $_{84}$Po^{210} , $_{88}$Ra^{226} ,$_{90}$Th^{232} , $_{91}$Pa^{231} , $_{92}$U^{234} , $_{92}$U^{235} , $_{92}$U^{238} , $_{93}$Np^{237} , $_{94}$Pu^{238} , $_{94}$Pu^{239} , $_{94}$Pu^{242} , $_{94}$Pu^{244} ,$_{95}$Am^{241} , $_{95}$Am^{243} , $_{96}$Cm^{243} , $_{96}$Cm^{244} , $_{96}$Cm^{245} , $_{96}$Cm^{246} , $_{96}$Cm^{247} , $_{96}$Cm^{248} , $_{97}$Bk^{247} , $_{97}$Bk^{248} , $_{98}$Cf^{248} , $_{98}$Cf^{249} , $_{98}$Cf^{250} , $_{98}$Cf^{251} , $_{98}$Cf^{252} , $_{99}$ES^{252} , $_{99}$Es^{253}, $_{99}$Es^{254} , $_{100}$Fm^{257} and $_{101}$Md^{258}.The values of Yo (n/10^{6} α) and Y_n(Be)(n/s/g_α/ppm) have found to be in good agreement with those reported previously. This work evaluates the weighted average cross sections and derives an empirical formula to calculate the stopping powers for (d,n) reactions, enabling the determination of neutron yields Yo (n/10^{6} α) and Yo (n/10^{6} d), as well as the total neutron yield Yn(Be) (n/s/gα-emitter/ppm) for the ^{9}Be(α,n)^{12}C reaction. For the first time, (d,n) neutron yields for various α emitters are reported, with the ^{84}Po^{210} + ^{9}Be reaction yielding ⟨Eα⟩ = 5.30458 MeV, neutron yield 557.2, alpha yield 73.05, and a minimum χ^2 of 0.099. Similar results for other α emitters are summarized in the table, highlighting the reliability and significance of these findings for compact neutron source applications.

KEYWORDS: Cross-Section, Stopping Power, Neutron Yield, Neutron Source, Light Elements.

1. INTRODUCTION

The simplest radioisotope neutron sources utilize (α,n) reactions with light elements, typically consisting of a mixture of an α-emitter (e.g., ^{210}Po, ^{238}Pu, ^{241}Am) and beryllium, as well as (d,n) reactions in which light elements are bombarded by deuterons using charged particle accelerators. Neutrons are produced through reactions such as:

$$ {}^{9}_{4}Be+\alpha \longrightarrow {}^{12}_{6}C+n \quad (Q_o\text{=5.71 MeV}) $$

$$ {}^{9}_{4}Be+d \longrightarrow {}^{10}_{5}B+n \quad (Q_o\text{=4.36 MeV}) $$

The cross sections of the ^{9}Be(α,n)^{12}C reaction have been extensively measured and calculated as a function of α energy by several authors, including (Gibbons& Macklin, 1965; Heaton *et al.*, 1989; Nakasima 1982; Shibata *et al.*, 2002; Hussain, 2020; Koning *et al.*, 2021, 2023). Similarly, the ^{9}Be(d,n)^{10}B cross sections have been recalculated and interpolated for α energies from 0.25 to 10 MeV by (Koning *et al.*, 2021, 2023). The neutron yields Yo(n/10^{6}α) for ^{9}Be(α,n)^{12}C have been reported for various α emitters such as ^{210}Po, ^{226}Ra, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, and ^{241}Am by (Abdullah, 1999; Haji, 2001; Murata & Shibata., 2002; Shibata *et al.*, 2005; Ahmed, 2006; Abdulrahman, 2007).

While neutron yields for ^{9}Be(α,n)^{12}C have been studied extensively, neutron yields for ^{9}Be(d,n)^{10}B using common α emitters have not been reported, representing a clear research gap. The aim of the present work is to determine the weighted average cross sections (adopted) and derive an empirical formula to calculate the stopping powers for (d,n) reactions, and subsequently to establish formulas for the neutron yields Yo(n/10^{6}α) and Yo(n/10^{6}d), as well as the total neutron yields Yn(Be) (n/s/gα-emitter/ppm) for the ^{9}Be(α,n)^{12}C reaction. This study's novelty and significance are noteworthy.

2. THEORY

The Q-values and threshold energies of the ^{9}Be(α,n)^{12}C and ^{9}Be(d,n)^{10}B reactions were calculated using atomic masses from(Huang *et al.*, 2021) and the following expressions:

$$ Q=931.5(M_{\alpha,d}+M_X-M_n-M_Y) \quad (1) $$

$$ E_{thr.} = -Q(\,1+ M_\alpha/M_X) \quad (2) $$

Where:

- M_n=refers to the neutron masses(amu)
- $M_{\alpha,d}$,M_X, M_y=the atomic masses in (amu units) of (alpha-particle, or deuteron),target and product nuclei respectively.
- Q=is Qvalue (in MeV unit).

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https://doi.org/10.25271/sjuoz.2026.14.2.1611

Printed ISSN 2663-628X;
Electronic ISSN 2663-6298

- E_{thr}=threshold energy (in MeV unit).

The weighted averages (adopted values) of the cross sections for $^9Be(\alpha,n)^{12}C$ and $^9Be(d,n)^{12}C$ reactions of various references have been calculated using the following relationship(Bevington, 1969):

$$\sigma\,(\text{mb})=\frac{\sum_i \frac{\sigma_i}{\Delta_i^2}}{\sum_i \frac{1}{\Delta_i^2}} \qquad (3)$$

The uncertainty in (σ) is:

$$\Delta\sigma=\pm\frac{1}{\sqrt{\sum_i \frac{1}{\Delta_i^2}}} \qquad (4)$$

Where:

- (σ_i)=is the cross sections of i^{th} references.
- (Δ_i)=is the errors of the i^{th} references.

The neutron yield can be calculated using the following relationship (Norman *et al.*, 1982):

$$Y(E)=\int_{E_{th}}^{E_{\alpha,d}}\frac{\sigma(E)}{dE/dx}dE \qquad (5)$$

Where:

- $\sigma(E)$= cross – sections (in mb)
- dE/dx= stopping power in units of MeV / (10^{21} atoms/cm^2)
- Y(E)=neutron yield (n/$10^6\alpha$) or (n/10^6d).

The cross – sections, $\sigma(E)$, is usually measured in mb (millibarrns). Then if the stopping power, dE/dx, is determined in units of MeV / (10^{21} atoms/cm^2), using the Zeigler formula (Ziegler, 1977).While the new empirical formula of the deuteron stopping power has been derived using the Bethe formula as shown in the following equation(Tsoulfanidis & Landsberger, 2015):

$$dE/dx=0.479(Z/E_d)Ln[0.001091(E_d/I_{av})] \qquad (6)$$

Where:

- (Z)=is the atomic number of the target nucleus.
- (E_d)=is the deuteron energy
- ($I_{av.}$)=is the average ionization potential ofthe target nucleus ,for (Be)($I_{av.}=6.52\times10^{-5}$ MeV) (Tsoulfanidis & Landsberger, 2015).

Then the neutron yields, Y(E), would be calculated in (n/$10^6\alpha$) or (n/10^6d) using alpha or deuteron particles. The total neutron yields Y_n(Be) (n/sec/$g_{\alpha\text{-emitter}}$ /ppmBe) can then be calculated using the following relationship(TaherZadeh M. & Gingo, 1972):

$$Y_n(Be)(n/s/g_x/ppm)=10^{-6}k\lambda_x N_A\left[\frac{Y_o(Be)}{A_{Be}}\right]\left[\frac{Z_{Be}}{Z_x}\sqrt{\frac{Z_x+7}{Z_{Be}+7}}\right]f_{Be} \qquad (7)$$

where :

- k=is the fraction of the α-emitter
- (λ_x)=is the decay constant (ln2/$t_{1/2}$)(S^{-1}).
- (N_A) =is Avogadro No. =6.022×10^{23} atom/mole.
- A_{Be} = is mass No. of Be=9.
- Z_x = is atomic No. of α-emitter.
- Z_{Be} =is atomic No. of Be=4
- f_{Be} =is fractional weight of Be=1
- $Y_{n(Be)(n/s/gx/ppm)}$ = total neutron yields, (ppm is part per million)

In the present work, all α-emitters have been taken into consideration separately, Hence, k=1 and eq. (4) become:

$$\left[Y_n(Be)(n/s/g_x/ppm)=8.07\times10^{16}\lambda_x\frac{\sqrt{Z_x+7}}{Z_x}Y_o(Be)\times10^{-6}\right] \qquad (8)$$

where:

- Y_o(Be)= is the neutron yield in (n/α) measured for α-energies from the threshold to E_α from the α-emitter x.
- $Y_{n(Be)(n/s/gx/ppm)}$ = total neutron yields,(ppm is part per million)
- Z_x = is atomic No. of α-emitter.
- (λ_x)=is the decay constant (ln2/$t_{1/2}$)(S^{-1}).

In α-decay, a parent nucleus in its ground state (P) emits α-particle to the ground state of a daughter nucleus (D) as follows (Tsoulfanidis & Landsberger, 2015):

$${}^{A}_{Z}P\longrightarrow{}^{A-4}_{Z-2}D+\alpha$$

From the conservation of energy:

$$931.5M_P=931.5[M_D+M_\alpha]+T_\alpha+T_D \qquad (9)$$

Where:

- M_P=mass of parent nucleus.
- M_D=mass of daughter nucleus.
- M_α= the atomic masses in (amu units) of (alpha-particle).
- T_α =The kinetic energy of the alpha particles.
- T_D=The kinetic energy of the daughter.

DOI: https://doi.org/10.25271/sjuoz.2026.14.2.1611

Q-value of any decay is defined as the sum of the kinetic energies after the decay minus the sum of kinetic energies before the decay. In α-decay (Tsoulfanidis & Landsberger, 2015):

$$Q_{\alpha o} = T_{\alpha o} + T_D \qquad (10)$$

Then:

$$Q_{\alpha o}=931.5[M_p-M_D-M_\alpha] \qquad (11)$$

Where:

- T_o =The kinetic energy of the initial particles

From the conservation of momentum, it can be shown that:

$$T_{\alpha_o} = \frac{A-4}{A} Q_{\alpha_o} \qquad (12)$$

Where:

- (A)=represents the mass No. of the parent nucleus.

If the daughter nucleus is left in an excited state E_i, Then:

$$Q_{\alpha i} = Q_{\alpha o} - E_i \qquad (13)$$

Where:

- E_i =energy in excited state

and

$$T_{\alpha i} = \frac{A-4}{A} Q_{\alpha i} \qquad (14)$$

Mean $<T_\alpha>$ may then be calculated by:

$$MeanT_\alpha = \frac{T_{\alpha o}.BR_o + T_{\alpha i}.BRi + \cdots}{BR_o + BR_i + \cdots} \qquad (15)$$

Where:

- (BR_o) and (BR_i)= represent the branching ratios of α-particles leading to the ground state and ith excited state respectively.
- $<T_\alpha>$ =mean kinetic energy.

If α-particle is emitted from the meta stable state (m) of the parent nucleus, then:

$$Q_m = Q_g + E_m \qquad (16)$$

Where:

- Q_m=is the decay energy of the meta stable state.
- Q_g =is the decay energy of the ground state (=$Q_{\alpha o}$).
- E_m= is the energy of meta stable.

Then eq. (14) becomes:

$$T_{\alpha m} = \frac{A-4}{A} Q_m \qquad (17)$$

The following polynomial fit expression has been considered in the present work (Ahmed, 2006):

$$Y_o(n/10^6\alpha) = \sum_{i=0}^{N} C_i E^i \qquad (18)$$

Where:

- (c_1, c_2, c_3 …) =are Free parameters,
- i=0, 1, 2,3,…...
- (N) =represents the No. of data points.

The set of parameters giving minimum value of chi-squared (x^2) (CHISQ) in the following expression, has been used to calculate the neutron yield (Y_o) (Belgaid *et al.*, 2005):

$$x^2(CHISQ) = \frac{1}{(N-M)} \sum_{i}^{N} \left(\frac{Y^i_{exp.} - Y^i_{cal.}}{\Delta Y^i_{exp.}} \right)^2) \qquad (19)$$

Where:

- (N) =represents the No. of data points.
- (m)=is No. of fitting parameters.
- ($Y_{exp.}$) is (adopted) of neutron yields.
- ($Y_{cal.}$)= is the calculated neutron yields.
- x^2 = minimum chi-square

3. DATA REDUCTION AND ANALYSIS

The Q-values and threshold energies of ${}^{9}_{4}$Be(α,n)${}^{12}_{6}$C and ^{9}Be(d,n)^{10}B were calculated using the atomic masses taken from ref (Huang *et al.*, 2021) and using the equations (1) and (2) respectively. The cross sections of ^{9}Be(α,n)^{12}C reaction published in references (Gibbons & Macklin, 1965; Heaton *et al.*, 1989; Nakasima, 1982; Shibata *et al.*, 2002; Shibata *et al.*, 2005; Hussain, 2020; Koning *et al.*, 2021,2023) as functions of α-energies have been rearranged and interpolated in steps of 50 keV using a linear interpolation method from near the threshold energy to 10000 keV. (for example, if values were available at 2 MeV and 4 MeV, the value at 3 MeV was estimated linearly).The uncertainties associated with the interpolated cross-sections were propagated and included in the analysis.The results were then used to calculate the weighted average cross-sections and the errors using the eq. (3) and (4) respectively. The obtained results of the interpolated cross sections of $^{9}Be(\alpha,n)^{12}C$ are shown in Figure1.

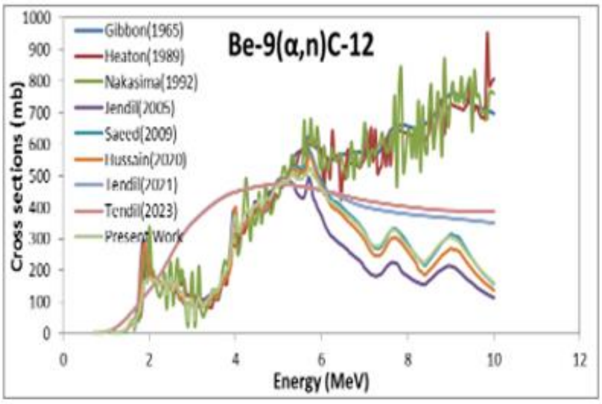


Figure 1 : The cross sections of $^{9}Be(\alpha,n)^{12}C$ reaction as a function of alpha particle Energies for different references.

While the cross sections of $^{9}Be(d,n)^{10}B$ reaction published in references (Koning *et al*., 2021,2023) as functions of deuteron energies have been rearranged and interpolated in steps of 50 keV using the same linear interpolation method. Uncertainties were also included for all interpolated values from near the threshold energy to 10000 keV.The weighted average cross-sections and errors were then calculated using equations (3) and (4), and the obtained interpolated cross-sections of $^{9}Be(d,n)^{10}B$ are shown in Figure 2.

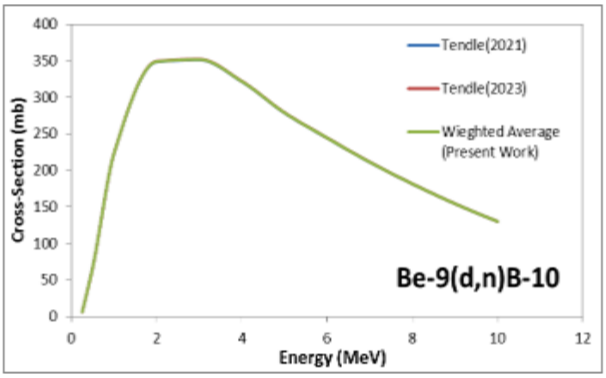


Figure 2: The cross sections of $^{9}Be(d,n)^{10}B$ reaction as a function of deuteron particle Energies for different references.

The ($Q_{\alpha o}$) calculated from eq. (11) using the atomic masses published by (Huang *et al*., 2021) are presented in table 1.

Table 1: The Values of ($Q_{\alpha o}$) , ($T_{\alpha o}$) , ($< E >$) , ($t_{1/2}$) and (λ) for various α-emitters.

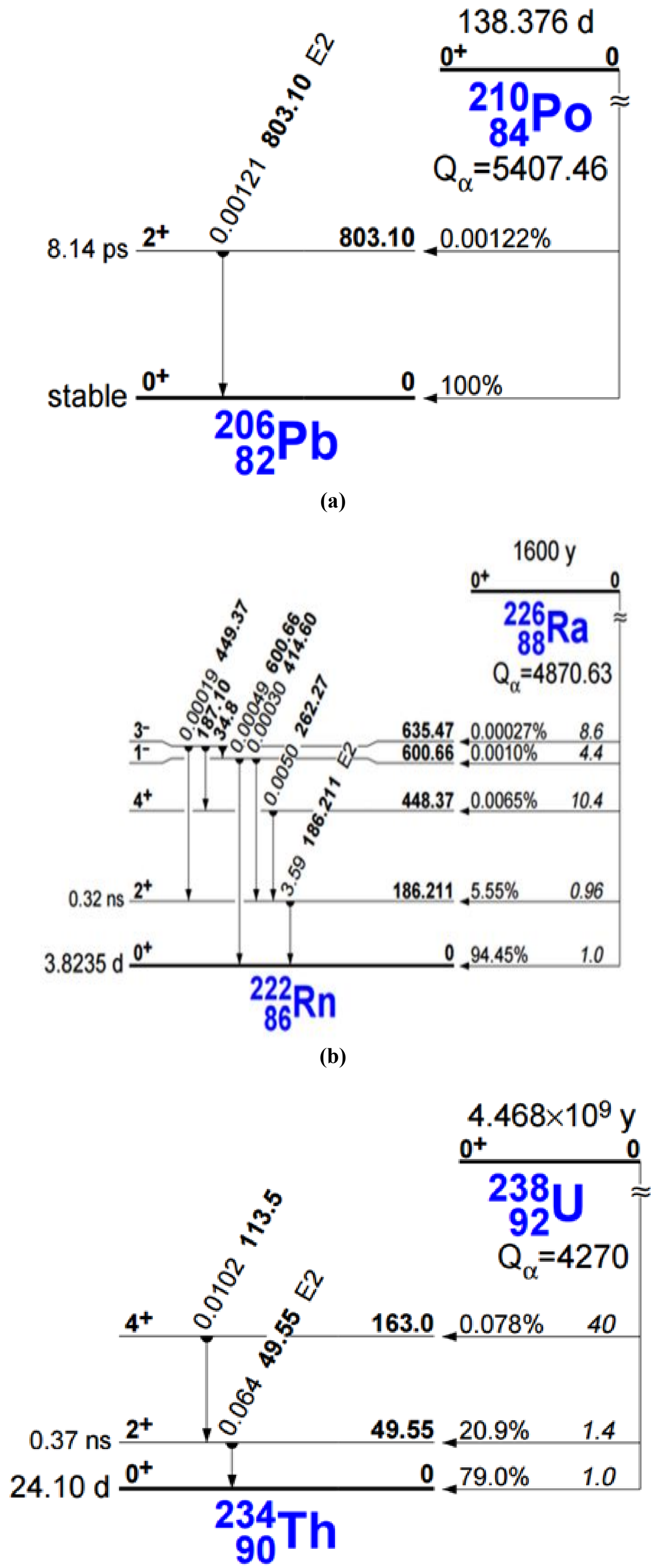
α-emitter	$Q_{\alpha o}$ (MeV)	$T_{\alpha o}$(MeV)	Mean energy<E> (MeV)	Half-life $t_{1/2}$ (sec)	Decay constant λ (sec^{-1})
$_{62}Sm^{147}$	2.3114	2.248	2.24848	3.34511E+18	2.07212E-19
$_{64}Gd^{148}$	3.2713	3.183	3.18287	2237433840	3.09796E-10
$_{66}Dy^{154}$	2.9452	2.869	2.86867	9.46728E+13	7.3215E-15
$_{72}Hf^{174}$	2.4945	2.437	2.43712	6.31152E+22	1.09823E-23
$_{76}Os^{186}$	2.8213	2.761	2.7606	6.31152E+22	1.09823E-23
$_{78}Pt^{190}$	3.2686	3.2	3.19977	2.05124E+19	3.37916E-20
$_{84}Po^{209}$	4.9793	4.884	4.87982	3218875200	2.15338E-10
$_{84}Po^{210}$	5.4076	5.305	5.30458	11947392	5.80166E-08
$_{88}Ra^{226}$	4.8708	4.785	4.77437	50492160000	1.37278E-11
$_{90}Th^{232}$	4.0816	4.011	3.99747	4.41806E+17	1.56889E-18
$_{91}Pa^{231}$	5.1499	5.061	4.98472	1.03383E+12	6.70467E-13
$_{92}U^{234}$	4.8575	4.775	4.7593	7.74739E+12	8.94685E-14
$_{92}U^{235}$	4.678	4.598	4.41117	2.22166E+16	3.11996E-17
$_{92}U^{238}$	4.2699	4.198	4.18778	1.40999E+17	4.91596E-18
$_{93}Np^{237}$	4.9573	4.874	4.76907	6.76595E+13	1.02446E-14
$_{94}Pu^{238}$	5.5933	5.499	5.48672	2767601520	2.5045E-10
$_{94}Pu^{239}$	5.2446	5.157	5.14878	7.60854E+11	9.11012E-13
$_{94}Pu^{242}$	4.9843	4.902	4.89185	1.18341E+13	5.8572E-14
$_{94}Pu^{244}$	4.6656	4.589	4.58057	2.52461E+15	2.74556E-16

$_{95}Am^{241}$	5.6379	5.544	5.4787	13651817760	5.07733E-11
$_{95}Am^{243}$	5.4392	5.35	5.27886	2.3258E+11	2.98026E-12
$_{96}Cm^{243}$	6.1688	6.067	5.8101	918326160	7.54794E-10
$_{96}Cm^{244}$	5.9017	5.805	5.79492	571192560	1.21351E-09
$_{96}Cm^{245}$	5.6244	5.533	5.35942	2.6581E+11	2.60768E-12
$_{96}Cm^{246}$	5.4751	5.386	5.37824	1.4851E+11	4.66734E-12
$_{96}Cm^{247}$	5.3539	5.267	4.94939	4.92299E+14	1.40798E-15
$_{96}Cm^{248}$	5.1619	5.079	5.05572	1.0982E+13	6.31164E-14
$_{97}Bk^{247}$	5.8897	5.794	5.61106	43549488000	1.59163E-11
$_{97}Bk^{248}$	5.8255	5.731	5.7315	284018400	2.4405E-09
$_{98}Cf^{248}$	6.3613	6.259	6.25054	28814400	2.40556E-08
$_{98}Cf^{249}$	6.2933	6.192	5.84439	11076717600	6.25769E-11
$_{98}Cf^{250}$	6.1286	6.031	6.02369	412773408	1.67924E-09
$_{98}Cf^{251}$	6.1765	6.078	5.78785	28338724800	2.44594E-11
$_{98}Cf^{252}$	6.217	6.118	6.11126	83469852	8.30416E-09
$_{99}ES^{252}$	6.741	6.634	6.6085	40754880	1.70077E-08
$_{99}Es^{253}$	6.7393	6.633	6.63271	1768608	3.91917E-07
$_{99}Es^{254}$	6.6171	6.513	5.69173	23820480	2.90988E-08
$_{100}Fm^{257}$	6.8631	6.756	6.53202	8683200	7.98262E-08
$_{101}Md^{258}$.	7.272	7.159	6.82982	4449600	1.55777E-07

Since most of the α-emitters decay mainly to the ground state of the daughter nuclei and ($T_{\alpha o}$) is larger than ($T_{\alpha i}$). The values of ($T_{\alpha o}$) and ($T_{\alpha i}$) have been taken in to consideration to determine the mean kinetic energy (Mean T_α) from eq. (15) in the present work. These values are also presented in Table (1) together with the half-lives and decay constants of the parent nuclei which are taken from(Fireston *et al*., 1997). Table 2, shows the mean and kinetic energies with the branching ratios of the alpha particles emitted from some various alpha emitters as shown in Figure 3.

Table 2: The kinetic energies and the Branching ratios of the alpha particles emitted from some various alpha emitters

Kinetic energies (MeV)	Po – 210		Ra – 226		U – 238	
	Kinetic Energies(MeV	Branching Ratio(%)	Kinetic Energies(MeV)	Branching Ratio(%)	Kinetic Energies(MeV)	Branching Ratio(%)
Tαo	5.305	100	4.785	94.45	4.198	79
Tα1	4.517	0.00122	4.602	5.55	4.149	20.9
Tα2	—	—	4.344	0.0065	4.038	0.078
Tα3	—	—	4.195	0.001		
Tα4	—	—	4.160	0.00027		
$\langle E_\alpha \rangle$	5.30458		4.77437		4.18778	



(a)

(b)

(c)

Figure 3 : The decay schemes of (a)Po-210 (b)Ra-226 (c)U-238.

The alpha particle stopping powers of (^{9}Be) used in the present work are the total stopping powers calculated using the formulae presented by (Ziegler, 1977).The obtained results for α-energies from near the threshold energy to (10 MeV) is steps of (50 keV) presented in Figure 4.

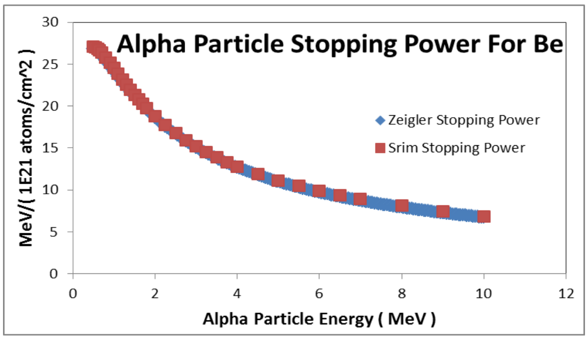


Figure 4: The alpha particle stopping power for (Be) as a function of Alpha energy using Zeigler formula.

Results were compared with those reported previously by SRIM-2008 version (Ziegler & Biersack, 2008).The comparison shows a good agreement. Similarly, the deuteron stopping powers in ^{9}Be used in this work were derived using the Bethe formula (Tsoulfanidis & Landberger, 2015).The results obtained for deuteron energies from near the threshold energy to 10 MeV in steps of 50 keV are presented in Figure 5. and compared with those reported previously by SRIM-2008 (Ziegler & Biersack, 2008).

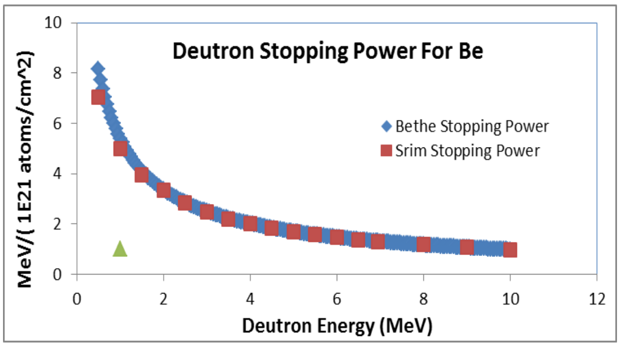


Figure 5 : The deuteron particle stopping power for (Be) as a function of Deuteron energy using the new semi empirical formula.

The comparison shows good agreement. Finally, the adopted values and uncertainties of the neutron yields Yo (n / 10^6 α) and Yo (n / 10^6 d) for the ^{9}Be(α,n)^{12}C and ^{9}Be(d,n)^{10}B reactions as functions of α-particle and deuteron energies were calculated using equation (5). The results are presented in Table 3.

Table 3: The adopted neutron yields $Y_o(n/10^6d)$ of ^{9}Be(d,n)^{10}B and $Y_o(n/10^6\alpha)$ of ^{9}Be(α,n)^{12}C reactions together with the total neutron yield Y_n(Be)(n/s/g_x/ppm) for different neutron sources at mean kinetic energies <E_α> of various alpha emitters

Alpha Emitter	Atomic Number (Z)	Mass Number (A)	Mean Energy <Eα> (MeV)	^{9}Be(d,n)^{10}B Neutron yield $Y_o(n/10^6d)$	^{9}Be(α,n)^{12}C Neutron yield $Y_o(n/10^6\alpha)$	^{9}Be(α,n)^{12}C Total Neutron yield ±Errors Y_n(Be)(n/s/g_x/ppm)
$_{62}Sm^{147}+_4Be^9$	62	147	2.24848	108.7	4.115	1.02E-09
$_{64}Gd^{148}+ {}_4Be^9$	64	148	3.18287	227.2	11.87	4.00E+01
$_{66}Dy^{154}+ {}_4Be^9$	66	154	2.86867	184.3	10.58	8.00E-04
$_{72}Hf^{174}+ {}_4Be^9$	72	174	2.43712	130.2	7.534	6.03E-13
$_{76}Os^{186}+ {}_4Be^9$	76	186	2.7606	170.2	10.14	1.03E-12
$_{78}Pt^{190}+ {}_4Be^9$	78	190	3.19977	229.6	11.96	3.94E-09
$_{84}Po^{209}+ {}_4Be^9$	84	209	4.87982	488.2	53.74	1.04E+02
$_{84}Po^{210}+ {}_4Be^9$	84	210	5.30458	557.2	73.05	3.83E+04
$_{88}Ra^{226}+ {}_4Be^9$	88	226	4.77437	471.2	49.28	5.95E+00
$_{90}Th^{232}+ {}_4Be^9$	90	232	3.99747	348	23.23	3.19E-07
$_{91}Pa^{231}+ {}_4Be^9$	91	231	4.98472	505.2	58.34	3.38E-01
$_{92}U^{234}+ {}_4Be^9$	92	234	4.7593	468.7	48.66	3.74E-02
$_{92}U^{235}+ {}_4Be^9$	92	235	4.41117	413	35.42	9.49E-06
$_{92}U^{238}+ {}_4Be^9$	92	238	4.18778	377.7	28.31	1.20E-06
$_{93}Np^{237}+ {}_4Be^9$	93	237	4.76907	470.3	49.06	4.29E-03
$_{94}Pu^{238}+ {}_4Be^9$	94	238	5.48672	586.8	81.73	1.74E+02
$_{94}Pu^{239}+ {}_4Be^9$	94	239	5.14878	531.8	65.77	5.09E-01
$_{94}Pu^{242}+ {}_4Be^9$	94	242	4.89185	490.1	54.26	2.70E-02
$_{94}Pu^{244}+ {}_4Be^9$	94	244	4.58057	440	41.57	9.68E-05
$_{95}Am^{241}+_4Be^9$	95	241	5.4787	585.5	81.35	3.49E+01
$_{95}Am^{243}+_4Be^9$	95	243	5.27886	553	71.84	1.81E+00
$_{96}Cm^{243}+_4Be^9$	96	243	5.8101	639.6	97.27	6.18E+02
$_{96}Cm^{244}+_4Be^9$	96	244	5.79492	637.1	96.55	9.86E+02
$_{96}Cm^{245}+ Be^9$	96	245	5.35942	566.1	75.65	1.66E+00
$_{96}Cm^{246}+_4Be^9$	96	246	5.37824	569.2	76.55	3.00E+00
$_{96}Cm^{247}+_4Be^9$	96	247	4.94939	499.5	56.77	6.71E-04

$_{96}Cm^{248}+_4Be^9$	96	248	5.05572	516.7	61.52	3.26E-02
$_{97}Bk^{247}+ _4Be^9$	97	247	5.61106	607.1	87.71	1.17E+01
$_{97}Bk^{248}+ _4Be^9$	97	248	5.7315	626.7	93.5	1.91E+03
$_{98}Cf^{248}+ _4Be^9$	98	248	6.25054	711.1	117.9	2.36E+04
$_{98}Cf^{249}+ _4Be^9$	98	249	5.84439	645.1	98.91	5.15E+01
$_{98}Cf^{250}+ _4Be^9$	98	250	6.02369	674.3	107.4	1.50E+03
$_{98}Cf^{251}+ _4Be^9$	98	251	5.78785	635.9	96.21	1.96E+01
$_{98}Cf^{252}+ _4Be^9$	98	252	6.11126	688.5	111.5	7.70E+03
$_{99}ES^{252}+ _4Be^9$	99	252	6.6085	768.9	133.8	1.88E+04
$_{99}Es^{253}+ _4Be^9$	99	253	6.63271	772.8	134.8	4.36E+05
$_{99}Es^{254}+ _4Be^9$	99	254	5.69173	620.3	91.59	2.21E+04
$_{100}Fm^{257}+_4Be^9$	100	257	6.53202	756.6	130.5	8.55E+04
$_{101}Md^{258}+_4Be^9$.	101	258	6.82982	804.4	143.1	1.82E+05

obtained results of Yo (n / $10^6\alpha$)for $^9Be(\alpha,n)^{12}C$ reaction are used to fabricate the neutron sources by mixing 1 gram of (Be) with 1 gram of various alpha emitters such as ($_{62}Sm^{147}$, $_{64}Gd^{148}$, $_{66}Dy^{154}$, $_{72}Hf^{174}$, $_{76}Os^{186}$, $_{78}Pt^{190}$, $_{84}Po^{109}$, $_{84}Po^{210}$, $_{88}Ra^{226}$,$_{90}Th^{232}$, $_{91}Pa^{231}$, $_{92}U^{234}$, $_{92}U^{235}$, $_{92}U^{238}$, $_{93}Np^{237}$, $_{94}Pu^{238}$, $_{94}Pu^{239}$, $_{94}Pu^{242}$, $_{94}Pu^{244}$,$_{95}Am^{241}$, $_{95}Am^{243}$, $_{96}Cm^{243}$, $_{96}Cm^{244}$, $_{96}Cm^{245}$, $_{96}Cm^{246}$, $_{96}Cm^{247}$, $_{96}Cm^{248}$, $_{97}Bk^{247}$, $_{97}Bk^{248}$, $_{98}Cf^{248}$, $_{98}Cf^{249}$, $_{98}Cf^{250}$, $_{98}Cf^{251}$, $_{98}Cf^{252}$, $_{99}ES^{252}$, $_{99}Es^{253}$, $_{99}Es^{254}$, $_{100}Fm^{257}$ and $_{101}Md^{258}$) to determine the total neutron yields Y(n)(Be)(n/s/$g_{\alpha\text{-emitter}}$/ppm) by using the eq. (8). The obtained results are presented in Table 3.

4. RESULTS AND DISCUSSION

The adopted neutron yields of $^9Be(\alpha,n)^{12}C$ reaction have been computer fitted to a polynomial expression of the form shown in eq. (18). The values of parameters (c_i) obtained for different values of (i) were as follows:

Y_3=-0.804E^3+16.077E^2-63.222E+74.741 with (χ^2= 30.16)

Y_4 = 0.22E^4 - 6.3479E^3 + 65.852E^2 - 250.3E + 321.1 with (χ^2=19.55)

Y_5 = 0.0136E^5 - 0.2099E^4 - 1.1415E^3 + 35.702E^2- 167.22E + 234.3232 with (χ^2= 13.07)

Y_6 = -0.0296E^6 + 1.1328E^5 - 17.277E^4 + 132.81E^3 - 533.15E^2 + 1068.4E - 835.8 with (χ^2=0.174)

As shown in Fig. 6, the sixth-order polynomial (i = 6) provided the best fit, with the (χ^2 value 0.174).

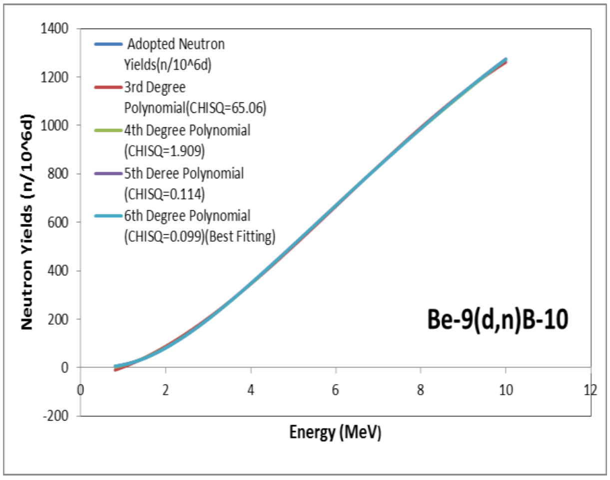


Figure 6 : The best fitting expression of the neutron yields Y_o(n/$10^6\alpha$) of $^9Be(\alpha,n)^{12}C$ reaction as a function of alpha particle energy.

While the adopted neutron yields of $^9Be(d,n)^{10}B$ reaction have been computer fitted to a polynomial expression of the form shown in eq. (18). The values of parameters (c_i) obtained for different values of (i) were as follows:

Y_3 = -1.2374E^3 + 22.813E^2 + 26.243E - 44.582 with (χ^2=65.06)

Y_4=0.1294E^4 - 4.0335E^3 + 43.088E^2 - 29.661E + 1.3642 with (χ^2=(1.909)

Y_5 = -0.0139E^5 + 0.5057E^4 - 7.7654E^3+ 59.664E^2-61.453E + 21.4 with(χ^2=(0.114).

Y_6 = -9E-05E^6 - 0.011E^5 + 0.469E^4 - 7.5392E^3 + 58.959E^2 - 60.427E + 20.875 with (χ^2=(0. 099)

The results, shown in Fig. 7, indicate that the sixth-order polynomial again yields the best fit (χ^2 = 0.099).

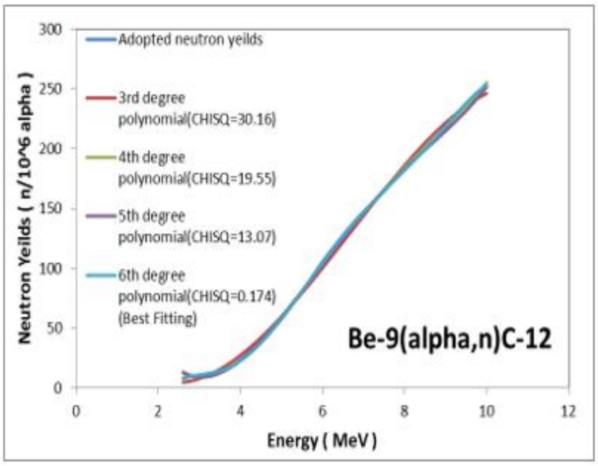


Figure 7: The best fitting expression of the neutron yields Y_o(n/10^6d) of $^9Be(d,n)^{10}B$ reaction as a function of deuteron particle energy.

The adopted neutron yields Y_o(n/$10^6\alpha$) of $^9Be(\alpha,n)^{12}C$ reaction calculated from the best fitting equation of minimum (χ^2 = 0.174) for various α-emitters at mean kinetic energy <E> are presented in table (3) together with the total neutron yields Y_n(Be)(n/s/$g_{\alpha\text{-emitter}}$/$ppm_{Be}$)calculated by using eq. (8).where ppm Be represents the concentration of beryllium in parts per million in the target material.The adopted neutron yields (n/$10^6\alpha$) calculated in the present work for a number of selected neutron sources are presented in table (4) and compared with those reported previously by other authors from references(Abdullah, 1999; Haji, 2001; Murata & Shibata, 2002; Shibata *et al*., 2005; Ahmed, 2006; Abdulrahman, 2007; Abdullah, 2007 ; Sabir, 2016).

DOI: https://doi.org/10.25271/sjuoz.2026.14.2.1611

Table 4: Comparison Between the neutron yields(n/$10^6\alpha$)of present and previous works for Be-9(a,n)C-12 reaction for various alpha emitters.

Different Neutron Sources	Mean Energy <Eα> (MeV)	Abdullah (1999)	Haji (2001)	Murata (2002)	Shibata (2005)	Ahmed (2006)	Abdulrahman (2007)	Abdullah (2007)	Sabir (2016)	Present work
${}_{84}Po^{210}$ + ${}_{4}Be^{9}$	5.30458	68.76 ±4.23	71.66 ±5.206	69.97 ±6.997	66.47 ±6.65	66.501 ±4.702	69.22 ±2.581	70.99 □2.328	70.77 ±2.838	71.97 ±1.569
${}_{88}Ra^{226}$ + ${}_{4}Be^{9}$	4.77437			45.83 ±4.583				48.29 □1.596	46.53 ±1.866	48.46 ±1.056
${}_{92}U^{234}$ + ${}_{4}Be^{9}$	4.7593		49.78 ±3.62	45.23 ±4.523	46.457 ±4.646	46.152 ±3.264	45.68 ±1.705	47.72 □1.578	46.001 ±1.845	47.84 ±1.043
${}_{92}U^{235}$ + ${}_{4}Be^{9}$	4.41117		□□□□ □□□□ □□□□ □□□	32.25 ±3.225	33.317 ±3.332	33.111 ±2.341	33.06 ±1.235	35.14 □1.168		34.84 ±0.76
${}_{92}U^{238}$ + ${}_{4}Be^{9}$	4.18778		29.23 ±2.126	26.41 ±2.641	27.485 ±2.748	26.838 ±1.898	27.19 ±1.016	29.23 □0.974	26.511 ±1.063	27.91 ±0.608
${}_{94}Pu^{238}$ + ${}_{4}Be^{9}$	5.48672	79.48 ±4.89		79.49 ±7.949			78.09 ±2.909	79.93 □2.614	79.805 ±3.2	80.57 ±1.756
${}_{94}Pu^{239}$ + ${}_{4}Be^{9}$	5.14878	59.26 ±3.65		62.36 ±6.236	58.139 ±5.814	59.816 ±4.231	62.07 ±2.314	63.86 □2.099	63.338 ±2.54	64.76 ±1.412
${}_{95}Am^{241}$ + ${}_{4}Be^{9}$	5.4787	79.48 ±4.89		79.12 ±7.912	75.635 ±7.564	76.06 ±5.38	77.74 ±2.897	79.58 □2.603	79.454 ±3.186	80.19 ±1.748

Show good agreement across all selected neutron sources, validating the present calculations. Tables (4 and 5) further confirm this agreement for both Yo(n/$10^6\alpha$) and Yn(Be).

In the same manner, Eq. (5) was applied to the (d,n) reaction, yielding the adopted neutron yields Yo(n/10^6d) for ${}^{9}Be(d,n){}^{10}B$, calculated from the sixth-order polynomial (χ^2 = 0.099). These results are also presented in Table 3, alongside the corresponding α-emitter values for direct comparison.

The analysis highlights that higher-order polynomial fits (i = 6) provide significantly better accuracy (minimum χ^2 values), and the consistency between calculated and previously reported yields underscores the reliability of the proposed method. Agreement with previous works is generally strong ,but deviations arise from differences in stopping power models and target assumptions

Table 5: Comparison Between the neutron yields (n/sec/g of a-emitter/ppm)of present and previous works for Be-9(a,n)C-12 reaction for various alpha emitters

Different Neutron Sources	Mean Energy <Eα> (MeV)	Abdullah (1999)	Abdulrahman (2007)	Abdullah (2007)	Sabir (2016)	Present work
${}_{84}Po^{210}$ + ${}_{4}Be^{9}$	5.30458	3.654E4 ±2.25E3	3.677×10^{4} $\pm1.370\times10^{3}$	3.708´10^{4} ±1.216´10^{3}	3.76×10^{4} $\pm1.51\times10^{3}$	3.83x10^{4} ±0.834x10^{3}
${}_{88}Ra^{226}$ + ${}_{4}Be^{9}$	4.77437			5.926 ± 0.196	5.71 ±0.229	5.95 ±0.13
${}_{92}U^{234}$ + ${}_{4}Be^{9}$	4.7593		0.0357 $\pm1.331\times10^{-3}$	0.0373 ±0.00123	3.59×10^{-2} $\pm1.44\times10^{-3}$	3.74x10^{-2} ±8.15x10^{-4}
${}_{92}U^{235}$ + ${}_{4}Be^{9}$	4.41117		8.999×10^{-6} $\pm3.362\times10^{-7}$	9.572´10^{-6} ±3.182´10^{-7}		9.49x10^{-6} ±2.07x10^{-7}
${}_{92}U^{238}$ + ${}_{4}Be^{9}$	4.18778		1.166×10^{-6} $\pm4.358\times10^{-8}$	1.254´10^{-6} ±4.179´10^{-8}	1.14×10^{-6} $\pm4.56\times10^{-8}$	1.2x10^{-6} ±2.62x10^{-8}
${}_{94}Pu^{238}$ + ${}_{4}Be^{9}$	5.48672	1.378E2 ±8.5	1.687×10^{2} ±6.285	1.727´10^{2} ±5.647	1.72×10^{2} ±6.91	1.74x10^{2} ±3.793
${}_{94}Pu^{239}$ + ${}_{4}Be^{9}$	5.14878	0.0739 ±0.0045	0.488±0.0182	0.502 ±0.0165	0.498 ±0.02	0.509 ±0.0111
${}_{95}Am^{241}$ + ${}_{4}Be^{9}$	5.4787	34.65 ±2.13	33.89 ±1.263	34.70 ±1.135	34.6 ±1.39	34.9 ±0.761

CONCLUSION

This study established an empirical formula for the deuteron stopping powers in ${}^{9}Be$, showing consistency with SRIM calculations. Neutron yields Yo(n/$10^6\alpha$) and Yn(Be) (n/s/gα-emitter/ppm Be) for the ${}^{9}Be(\alpha,n){}^{12}C$ reaction were evaluated for several α-emitters and found to agree well with previous experimental and theoretical results. For the first time, the method was extended to (d,n) reactions, providing reliable estimates of Yo(n/10^6d) for the ${}^{9}Be(d,n){}^{10}B$ reaction with strong polynomial fits. These results contribute valuable data for neutron source modeling and can be applied in the design of compact accelerator-based neutron generators for nuclear technology, medicine, and materials science.

Acknowledgments:

The author would like to thank the University of Salahaddin Kurdistan Region of Iraq, for providing the necessary environment to complete this work. Special thanks are also due to my family for their patience and encouragement.

Ethical statement:

The present study is a theoretical and computational analysis based on established nuclear data libraries and empirical modeling. It did not involve any human participants, animal subjects, or the collection of sensitive personal data. Therefore, no ethical committee approval code was required for this research.

Author Contributions:

D.S.K. was responsible for the study conception, design, methodology, and drafting of the manuscript. D.S.K. performed the data collection, numerical interpolation, statistical analysis, and critical revision of the manuscript. R.H.A. provided scientific supervision, validated the theoretical models, and contributed to the interpretation of the data. Both authors read and approved the final manuscript.

Conflict of Interest:
The authors declare that there are no conflict of interest.

Funding:
None.

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