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Calculation of the Cross-Section and Neutron Yield for Production Reactions of Gallium-67

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Abstract

The study of cross-section and the neutron Yield of Gallium–67 isotope is a very necessary choice in the field of nuclear medicine, which is used in radiopharmaceuticals and for medical diagnosis and treatments. The cross-section of 68Zn (p,2n) 67Ga, 67Zn (p, n) 67Ga was calculated for different energies by using different sets of programs using MATLAB language. The cross-section was then used to calculate the neutron yields. The results of the neutron yield distributions have been used to generate polynomial expressions with incident proton energies. We also calculated the stopping power through the Ziegler formula using the computer program (SRIM 2013) to calculate the two reactions mentioned above and also compared the results for stopping +++powers for the above reactions with the computer program (MATLAB 2017). Then, the neutron yield was calculated for these two reactions to find the best reaction with the highest neutron Yield in our study and use it to calculate the isotope production Yield for these reactions and other results within this study.

Keywords: Cross-section, neutron yield, stopping power, polynomial expression.

1. Introduction

The cross-section is considered one of the most important physical quantities, that describe nuclear reactions. In practice, these reactions can be calculated by using various mechanisms and models of nuclear reactors[1].

The reaction usually occurs when the target nucleus is bombarded by an accelerated, charged particle, producing a stable or unstable radioactive isotope. The cross-section here describes and marks the nuclear reaction probability [2, 3]. Units of the cross-section are units of area (the square of the nuclear radius), are measured in units called barns, and are equal to:

1 barn = 10^{-28} m^2 , 1 barn = 10^{-24}cm^2

Microscopic and macroscopic cross-sections are the two types of cross-sections that exist:
(1) The microscopic cross-section is the cross-section of a nuclear reaction that takes place between a particle and its nucleus, or between the active region of the nucleus and the beam of the incident particle. It is known as the nuclear reaction's microscopic cross-section (σ), and it is dependent on particle energy. [4,5]. There are two methods by which the incident particle interacts with matter's atoms. The interaction of all particles with the nucleus occurs via processes such as scattering or absorption. A given atom or nucleus's cross-section of absorbing a particle is the microscopic absorption cross-section, or (σ_a).

The following mathematical connection represents the microscopic scattering cross-section, or (σ_s), and the total cross-section is given by [6,7]:

$$\sigma_T = \sigma_a + \sigma_s \tag{1}$$

The cross-sections of scattering are calculated from the elastic and inelastic scattering cross-sections (σes, σins):

$$\sigma \text{ scattering} = \sigma es + \sigma ins \tag{2}$$

(2) The macroscopic cross-section of a homogeneous mixture of nuclides is equal to the total nuclide density added to the microscopic cross-section, and the macroscopic cross-section of the reaction ($\sum$) is obtained by multiplying the microscopic cross-section (σi) by the numerical density (Ni) of the pertinent nuclides (i) in the macroscopic material, which is given by: [3, 8, 9]

$$\sum = \sum_{i=1}^{n} N_i \sigma_i \tag{3}$$

Where: (N) is the material's atom density (atoms/cm^3), (σ) is the microscopic cross-section (cm^2), ($\sum$) is the macroscopic cross-section (cm^{-1}), and (n) is the number of nuclides in the homogeneous material.

The macroscopic cross-section is the region that all nuclei approach ($\sum$) and is the effective target region within 1 cm^2 of matter. As a result, the probability of a nuclear reaction happening when a group of particles passes through a specific unit area is represented by the macroscopic cross-section [6,10].

2. Material and Methods

The amount that material affects an electrically charged particle's kinetic energy traveling via it is measured by its stopping power. It is frequently connected to a common substance like air or aluminum[11]. The primary causes of the stopping power ability are the target's electrons being ionized, the lowest energy levels being excited, and the target and projectile exchanging charges [12, 13, 14]. When a charged particle interacts with oft electrons at the same time, then the attractive coulomb force will give the electron an impulse when the particle passes inside. When energy is transferred to an electron as a result of acquiring an impulse strong enough to move it to an atom's higher energy level (excitation), and if that energy is high enough to release an electron from the atom, it's referred to as (ionization) [11,15,16], the sum of nuclear-stopping power is given by the relationship :

$$S_{sum} = S_n + S_e \tag{4}$$

Where (Se) represents electronic stopping power and (Sn) represents nuclear stopping power.
(Sn) Atomic nuclei and electrons from the gas interact with the neutral atoms, bombarding them with a beam of charged objects. The percentage of energy lost in this instance when interacting with atomic nuclei (apart from hydrogen) within a gas medium is as follows [17].

$$2m_p/m_e = 4x10^3 \tag{5}$$

Therefore, the energy lost due to interaction with the nucleus is too small, and we could negligible it compared with the loss due to interaction with electrons. For a given thickness, there will be more nuclear interactions in solid targets, (equal to the width of neutron energy), so the nuclear cross-section and the electronic stopping cross-section are comparable.

By using the Ziegler formula, the nuclear-stopping power of an alpha particle at a range of energies has been calculated as follows [18]:

$$S_n = \begin{pmatrix} 1.593 \in^{1/2} & for \in < 0.01 \\ 1.7 \in^{1/2} \dfrac{\ln(\in + \exp 1)}{1 + 6.8 \in + 3.4 \in^{3/2}} & for\, 0.01 \le \in \le 10 \\ \ln(0.47 \in)/2 \in & for \in > 10 \end{pmatrix} \text{ MeV} \tag{6}$$

Where (ϵ) = the reduced ion energy (MeV)

$$\text{Reduced Energy } = \in = \frac{32.53 M_2 E}{Z_1 Z_2 (M_1 + M_2)(Z_1^{2/3} + Z_2^{2/3})^{1/2}} \tag{7}$$

Where: E is the energy of ion (MeV), M_1 is the mass of the projectile (amu), Z_1 is the projectile's atomic number, Z_2 is the target's atomic number, and M_2 is the mass of the target (amu).

If the projectiles are entirely stopped inside the target, as well as if all nuclear reactions were two-particle reactions, we obtain a broad neutron spectrum. In a nuclear encounter, there would be a significantly larger loss of kinetic energy [19].
The Ziegler formula was used to calculate the electronic stopping powers (Se) within the parameters of this work, which give correct expressions for the range of energies (10 – 140 Kev)]18]:

$$(\frac{1}{S_e}) = (\frac{1}{S_{Low}}) + (\frac{1}{S_{High}}) \tag{8}$$

$$S_{Low} = A_1 E^{A_2} \tag{9}$$

$$S_{High} = (\frac{A_3}{E/1000}) \ln[1 + (\frac{A_4}{E/1000}) + (\frac{A_5 E}{1000})] \tag{10}$$

Where the coefficients are provided by Ziegler in (A_i) [20- 22] .

When a beam of accelerated rays falls on a target, the nuclear reaction that occurs, produce a number (N) of particles per unit time [23]:

$$Y_n = (nt)\sigma(E_b)\varepsilon(E_b) \tag{11}$$

Where: (σ) is the cross-section reaction, ($\boldsymbol{\varepsilon}$) is the neutron detection efficiency, and (nt) is the number density of target atoms.

The yield is then calculated as the beam loses energy while passing through a target that is not infinitesimally thin [23]:

$$Y_n = \int_{E_{thr}}^{E_b} \frac{\sigma(E')\varepsilon(E')\, f\, dE'}{\frac{dE}{dX}(E')} \tag{12}$$

$$E_{thr} = Eb - \Delta E \tag{13}$$

Where: ΔE is the beam´s energy loss in the target, f is the number of target atoms in each target molecule, $\frac{dE}{dX}(E')$ is the stopping power per target molecule.

The thick-target yield, which is given by [22][23], is the result of taking the efficiency of ε (E) equal to 1 and assuming that the target is sufficiently thick, with one atom per molecule (i.e., f equal 1).

$$Y(E_b) = \int_{E_{thr}}^{E_b} \frac{\sigma(E)dE}{dE/dX} \tag{14}$$

Where: the reaction threshold energy is (E_{thr}) [24].

3. Results and Discussion

In this study, the nuclear reaction cross-sections, 68Zn (p,2n) 67Ga and 67Zn (p,n) 67Ga, that are found in the literature are plotted for the specified energy level as illustrated in **Figures 1,2**, respectively and listed in **Tables 1,2**. We found via the first figure that the best probability in this reaction occurs with values ranging between (19–30) MeV regarding the energy of incident protons on the isotope (68Zn) where the cross-section after this energy, begins to decrease until the minimum calculated value (24.8 m barn) at the energy value (99.26 MeV). The stopping power values are calculated by (SRIM program -2013) as shown in **Figures 3,4** and **Table 3**.

Depending on the values of the cross-section of these reactions and the values of the calculated stopping power based on (Ziegler formula) [18], as in Figures (3,4), the Neutron Yields for these reactions were calculated according to equation (14) and as in **Figures 5,6** and as in **Tables 4,5**. We found the empirical formula for the results of Neutron Yields, and they were as follows:

(y = - 0.1*x^{4} + 26*x^{3} - 2.6e+03*x^{2} + 1.3e+05*x - 1.7e+06)

for the68Zn (p,2n) 67Ga,,

(y = 1.5*x^{4} – 63*x^{3} – 7.4e+02*x^{2} + 6.5e+04*x – 4.6e+05)

for the 67Zn (p,n) 67Ga

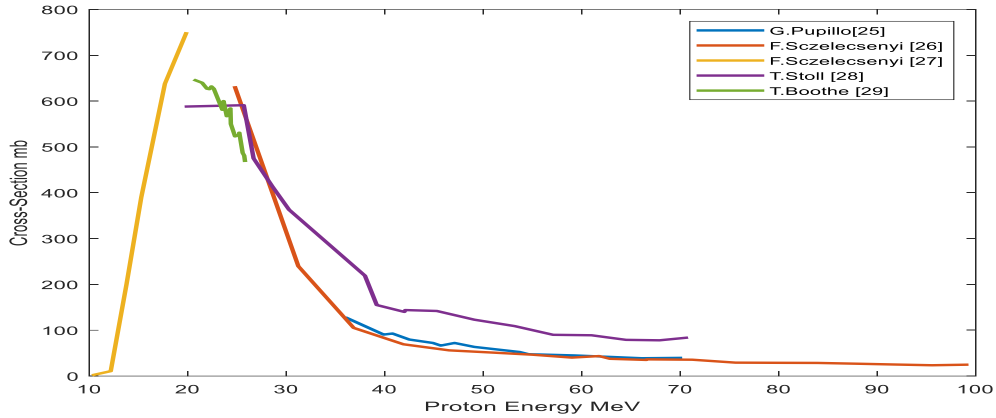

Figure 1. Cross-section of ^{68}Zn (p,2n) ^{67}Ga**.**

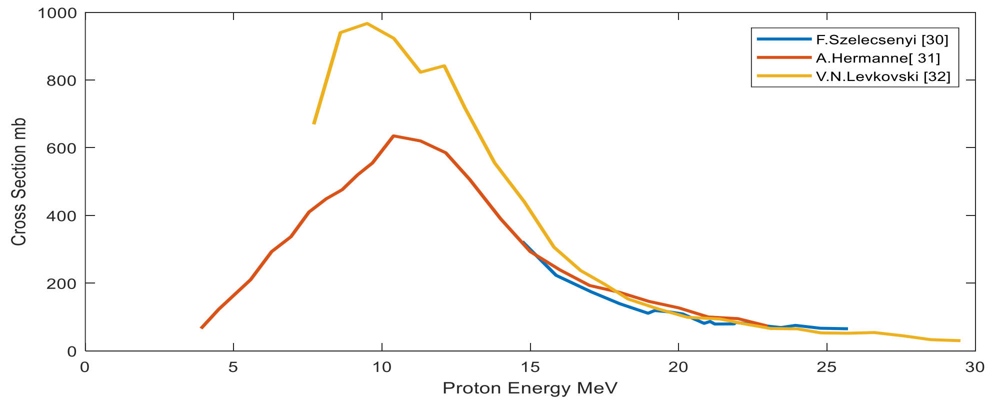

Figure 2. Cross-section of 67Zn (p,n) 67Ga.

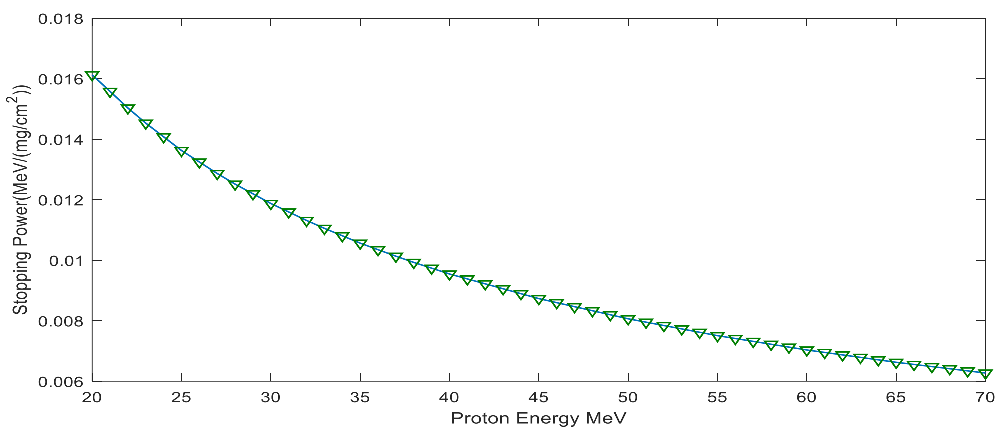

Figure 3. Stopping power of proton in zinc 68Zn (p,2n) 67Ga

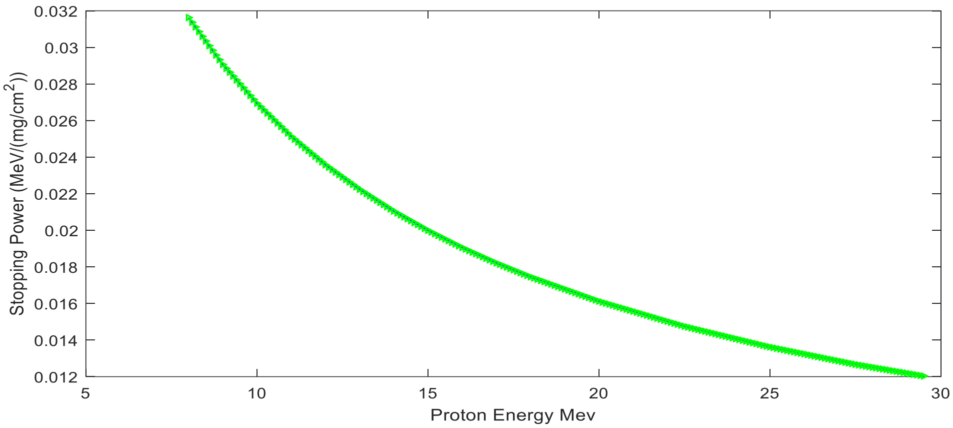

Figure 4. Stopping power of proton in zinc ^{67}Zn (p,n) ^{67}Ga

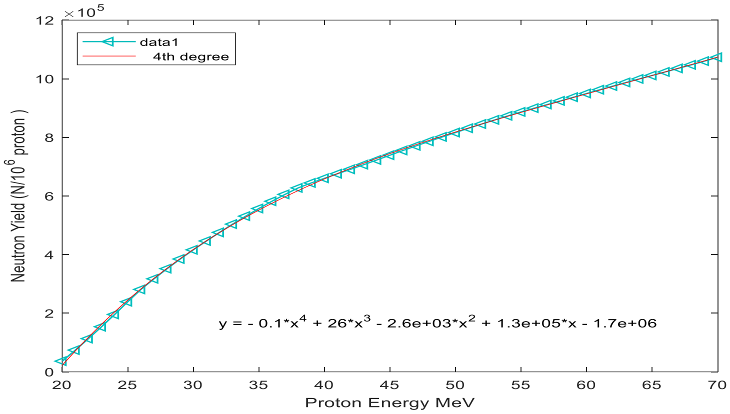

Figure 5. Neutron Yield for ^{68}Zn (p,2n) ^{67}Ga

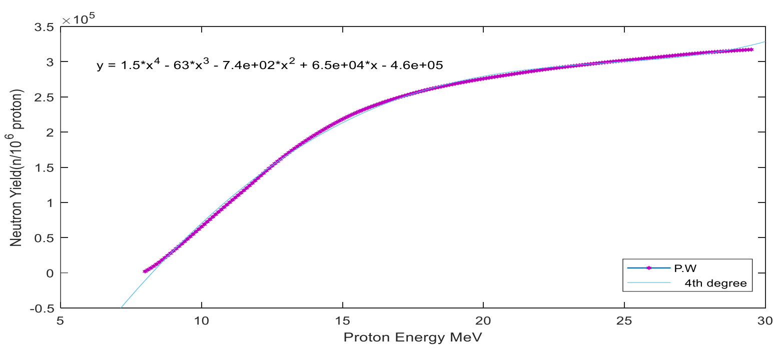

Figure 6. Neutron Yield for 67Zn (p,n) 67Ga

Table 1. The cross-section of (p,2n) ^{67}Ga ^{68}Zn reaction

Proton Energy MeV	Cross Section mb	Proton Energy MeV	Cross Section mb	Proton Energy MeV	Cross Section mb
19.7	588	36.7	243.3117	53.7	106.5641
20.2	588.25	37.2	233.961	54.2	104.1282
20.7	588.5	37.7	224.6104	54.7	101.6923
21.2	588.75	38.2	208.3333	55.2	99.2564
21.7	589	38.7	181.6667	55.7	96.8205
22.2	589.25	39.2	155	56.2	94.3846
22.7	589.5	39.7	152.3214	56.7	91.9487
23.2	589.75	40.2	149.6429	57.2	89.9744
23.7	590	40.7	146.9643	57.7	89.8462
24.2	590.25	41.2	144.2857	58.2	89.7179
24.7	590.5	41.7	141.6071	58.7	89.5897
25.2	590.75	42.2	143.9375	59.2	89.4615
25.7	591	42.7	143.625	59.7	89.3333
26.2	533	43.2	143.3125	60.2	89.2051
26.7	475	43.7	143	60.7	89.0769
27.2	458.9474	44.2	142.6875	61.2	88.4286
27.7	442.8947	44.7	142.375	61.7	87
28.2	426.8421	45.2	142.0625	62.2	85.5714
28.7	411	45.7	140	62.7	84.1429
29.2	396	46.2	137.5	63.2	82.7143
29.7	381	46.7	135	63.7	81.2857
30.2	366	47.2	132.5	64.2	79.8571
30.7	355.5195	47.7	130	64.7	78.9412
31.2	346.1688	48.2	127.5	65.2	78.7941
31.7	336.8182	48.7	125	65.7	78.6471
32.2	327.4675	49.2	122.6585	66.2	78.5
32.7	318.1169	49.7	120.9512	66.7	78.3529
33.2	308.7662	50.2	119.2439	67.2	78.2059
33.7	299.4156	50.7	117.5366	67.7	78.0588
34.2	290.0649	51.2	115.8293	68.2	78.6207
34.7	280.7143	51.7	114.122	68.7	79.6552
35.2	271.3636	52.2	112.4146	69.2	80.6897
35.7	262.013	52.7	110.7073	69.7	81.7241
36.2	252.6623	53.2	109	70.2	82.7586

Table 2. The cross-section of ^{67}Zn (p,n) ^{67}Gareaction.

Proton Energy MeV	Cross Section mb	Proton Energy MeV	Cross Section mb	Proton Energy MeV	Cross Section mb
7.7	669	15.1	399.8	22.5	75.3333
7.9	729.2222	15.3	373	22.7	72.2222
8.1	789.4444	15.5	346.2	22.9	69.1111
8.3	849.6667	15.7	319.4	23.1	66
8.5	909.8889	15.9	298.3333	23.3	65.7778
8.7	943	16.1	283	23.5	65.5556
8.9	949	16.3	267.6667	23.7	65.3333
9.1	955	16.5	252.3333	23.9	65.1111
9.3	961	16.7	237	24.1	63.5
9.5	967	16.9	227	24.3	60.5
9.7	957.2222	17.1	217	24.5	57.5
9.9	947.4444	17.3	207	24.7	54.5
10.1	937.6667	17.5	197	24.9	52.8889
10.3	927.8889	17.7	186	25.1	52.6667

Complete table 2. The cross-section of ^{67}Zn (p,n) ^{67}Gareaction

10.5	911.8889	17.9	175	25.3	52.4444
10.7	889.6667	18.1	164	25.5	52.2222
10.9	867.4444	18.3	153	25.7	52
11.1	845.2222	18.5	147.2	25.9	52.4444
11.3	823	18.7	141.4	26.1	52.8889
11.5	827.75	18.9	135.6	26.3	53.3333
11.7	832.5	19.1	129.8	26.5	53.7778
11.9	837.25	19.3	124	26.7	53
12.1	842	19.5	119	26.9	51
12.3	806.2857	19.7	114	27.1	49
12.5	770.5714	19.9	109	27.3	47
12.7	734.8571	20.1	104	27.5	45
12.9	700.8	20.3	99	27.7	42.7778
13.1	668.4	20.5	98.0909	27.9	40.3333
13.3	636	20.7	97.1818	28.1	37.8889
13.5	603.6	20.9	96.2727	28.3	35.4444
13.7	571.2	21.1	95.3636	28.5	33
13.9	543.5	21.3	94.4545	28.7	32.4
14.1	520.5	21.5	92.25	28.9	31.8
14.3	497.5	21.7	88.75	29.1	31.2
14.5	474.5	21.9	85.25	29.3	30.6
14.7	451.5	22.1	81.75	29.5	30
14.9	426.6	22.3	78.4444	---------------	----------------

Table 3. The stopping power of proton (1.5 – 98.5 MeV) in zinc.

Proton Energy MeV	**Stopping Power MeV/(mg/cm)**	**Proton Energy MeV**	**Stopping Power MeV/(mg/cm^2)**	**Proton Energy MeV**	**Stopping Power MeV/(mg/cm^2)**
1.5	0.0933	36.5	0.0102	69.5	0.0063
2.5	0.0689	37.5	0.01	70.5	0.0062
3.5	0.0556	38.5	0.0098	71.5	0.0062
4.5	0.0471	39.5	0.0096	72.5	0.0061
5.5	0.0411	40.5	0.0095	73.5	0.0061
6.5	0.0366	41.5	0.0093	74.5	0.006
7.5	0.0332	42.5	0.0091	75.5	0.0059
8.5	0.0303	43.5	0.009	76.5	0.0059
9.5	0.028	44.5	0.0088	77.5	0.0058
10.5	0.026	45.5	0.0087	78.5	0.0058
11.5	0.0244	46.5	0.0085	79.5	0.0057
12.5	0.0229	47.5	0.0084	80.5	0.0057
13.5	0.0216	48.5	0.0083	81.5	0.0056
14.5	0.0205	49.5	0.0081	82.5	0.0056
15.5	0.0195	50.5	0.008	83.5	0.0055
16.5	0.0186	51.5	0.0079	84.5	0.0055
17.5	0.0178	52.5	0.0078	85.5	0.0054
18.5	0.0171	53.5	0.0077	86.5	0.0054
19.5	0.0165	54.5	0.0076	87.5	0.0053
20.5	0.0159	55.5	0.0075	88.5	0.0053
21.5	0.0153	56.5	0.0074	89.5	0.0052
22.5	0.0148	57.5	0.0073	90.5	0.0052
23.5	0.0143	58.5	0.0072	91.5	0.0052
24.5	0.0139	59.5	0.0071	92.5	0.0051
25.5	0.0134	60.5	0.007	93.5	0.0051
26.5	0.0131	61.5	0.0069	94.5	0.005
27.5	0.0127	62.5	0.0068	95.5	0.005
28.5	0.0124	63.5	0.0067	96.5	0.005

Complete **Table 3.** The stopping power of proton (1.5 – 98.5 MeV) in zinc

29.5	0.012	64.5	0.0067	97.5	0.0049
30.5	0.0117	65.5	0.0066	98.5	0.0049
31.5	0.0115	66.5	0.0065	-------------	-----------------
32.5	0.0112	67.5	0.0064	-------------	------------------
33.5	0.0109	68.5	0.0064	------------	-----------------

Table 4. The neutron yield of ^{68}Zn (p,2n) ^{67}Ga.

Proton Energy MeV	**Neutron Yield*10^6 (n/ 10^6 proton)**	**Proton Energy MeV**	**Neutron Yield*10^6 (n/ 10^6 proton)**	**Proton Energy MeV**	**Neutron Yield*10^6 (n/ 10^6 proton)**
19.7	0.0182	36.7	0.5952	53.7	0.8684
20.2	0.0367	37.2	0.6068	54.2	0.8752
20.7	0.0556	37.7	0.6181	54.7	0.8819
21.2	0.0747	38.2	0.6286	55.2	0.8886
21.7	0.0941	38.7	0.6379	55.7	0.8951
22.2	0.1139	39.2	0.6459	56.2	0.9015
22.7	0.134	39.7	0.6538	56.7	0.9077
23.2	0.1544	40.2	0.6616	57.2	0.9139
23.7	0.1752	40.7	0.6694	57.7	0.9201
24.2	0.1963	41.2	0.6772	58.2	0.9263
24.7	0.2177	41.7	0.6848	58.7	0.9326
25.2	0.2395	42.2	0.6926	59.2	0.9389
25.7	0.2616	42.7	0.7005	59.7	0.9452
26.2	0.2819	43.2	0.7085	60.2	0.9515
26.7	0.3002	43.7	0.7165	60.7	0.9579
27.2	0.3181	44.2	0.7245	61.2	0.9643
27.7	0.3357	44.7	0.7326	61.7	0.9706
28.2	0.3528	45.2	0.7408	62.2	0.9768
28.7	0.3695	45.7	0.7489	62.7	0.983
29.2	0.3859	46.2	0.7569	63.2	0.9891
29.7	0.4018	46.7	0.7648	63.7	0.9952
30.2	0.4173	47.2	0.7727	64.2	1.0011
30.7	0.4325	47.7	0.7804	64.7	1.0071
31.2	0.4475	48.2	0.7881	65.2	1.013
31.7	0.4622	48.7	0.7957	65.7	1.019
32.2	0.4768	49.2	0.8032	66.2	1.025
32.7	0.4911	49.7	0.8107	66.7	1.031
33.2	0.5051	50.2	0.8181	67.2	1.0371
33.7	0.5189	50.7	0.8254	67.7	1.0431
34.2	0.5324	51.2	0.8328	68.2	1.0493
34.7	0.5455	51.7	0.84	68.7	1.0555
35.2	0.5584	52.2	0.8472	69.2	1.0619
35.7	0.571	52.7	0.8543	69.7	1.0684
36.2	0.5833	53.2	0.8614	70.2	1.075

Table 5. The neutron yield of ^{67}Zn (p,n) ^{67}Ga

Proton Energy MeV	Neutron Yield*10^5 (n/ 10^6 proton	Proton Energy MeV	Neutron Yield*10^5 (n/ 10^6 proton	Proton Energy MeV	Neutron Yield*10^5 (n/ 10^6 proton
7.7	0.0423	15.1	2.3037	22.5	2.9995
7.9	0.089	15.3	2.3416	22.7	3.0094
8.1	0.1402	15.5	2.377	22.9	3.0189
8.3	0.196	15.7	2.41	23.1	3.028
8.5	0.2566	15.9	2.4412	23.3	3.0371
8.7	0.3202	16.1	2.471	23.5	3.0463
8.9	0.385	16.3	2.4995	23.7	3.0555
9.1	0.4512	16.5	2.5266	23.9	3.0647
9.3	0.5188	16.7	2.5522	24.1	3.0738
9.5	0.5879	16.9	2.577	24.3	3.0824
9.7	0.6573	17.1	2.6009	24.5	3.0907
9.9	0.7271	17.3	2.624	24.7	3.0987
10.1	0.7972	17.5	2.646	24.9	3.1064
10.3	0.8675	17.7	2.6671	25.1	3.1141
10.5	0.9375	17.9	2.687	25.3	3.1219
10.7	1.0068	18.1	2.7059	25.5	3.1297
10.9	1.0753	18.3	2.7236	25.7	3.1375
11.1	1.143	18.5	2.7408	25.9	3.1454
11.3	1.2097	18.7	2.7575	26.1	3.1534
11.5	1.2777	18.9	2.7736	26.3	3.1615
11.7	1.347	19.1	2.7891	26.5	3.1697
11.9	1.4175	19.3	2.804	26.7	3.1779
12.1	1.4893	19.5	2.8185	26.9	3.1858
12.3	1.5589	19.7	2.8324	27.1	3.1934
12.5	1.6262	19.9	2.8459	27.3	3.2008
12.7	1.6911	20.1	2.8588	27.5	3.2079
12.9	1.7537	20.3	2.8713	27.7	3.2147
13.1	1.8141	20.5	2.8836	27.9	3.2211
13.3	1.8723	20.7	2.896	28.1	3.2272
13.5	1.928	20.9	2.9083	28.3	3.2329
13.7	1.9814	21.1	2.9206	28.5	3.2383
13.9	2.0327	21.3	2.9328	28.7	3.2435
14.1	2.0824	21.5	2.9449	28.9	3.2487
14.3	2.1304	21.7	2.9566	29.1	3.2539
14.5	2.1767	21.9	2.9679	29.3	3.2589
14.7	2.2211	22.1	2.9788	29.5	3.2639
14.9	2.2636	22.3	2.9893	-------------	---------

3. Conclusion

The present study detailed a theoretical investigation to study the cross-section and the neutron yield of the Gallium – 67 isotopes by using (MATLAB 2017) and (SRIM 2013) programs, where we studied some of the isotopes that affect the Cross-Section, stopping power, and neutron yields of Gallium-67 and their properties. Regarding the Cross-Section of the proton, the best results are with higher energy values (about 29.3 MeV) in Zinc. Concerning the stopping power, we got the best results (0.0933 MeV / (mg/cm^2) with lower energy (1.5 MeV) from the Proton isotope in zinc. Regarding the neutron yield, the proton isotope had the best results (70 MeV) in Zinc.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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