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

## Amin Kadhum Amin[1*] 📧, Huda Majeed Tawfeek[2] 📧 and Khalid Hadi Mahdi [3] 📧

[1,2]Department of Physics, College of Education for Pure Science (Ibn Al-Haitham), University of Baghdad, Baghdad, Iraq.

[3]Department of Physics, Sciences Faculty, University of Karabuk, Karabuk, Türkiye.

Corresponding author*

## 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 ($\sigma$), 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 ($\sigma_a$).

The following mathematical connection represents the microscopic scattering cross-section, or ($\sigma_s$), 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 ($\sigma$es, $\sigma$ins):

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

(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 ($\sigma$i) 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$^3$), ($\sigma$) 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].

$$2m_p/m_e = 4 \times 10^3 \tag{5}$$

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]:

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

Where ( $\in$ ) = the reduced ion energy ( MeV )

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

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]:

$$Y_n = (nt)\,\sigma(E_b)\,\varepsilon(E_b)$$

(11)

Where: ($\sigma$) is the cross-section reaction, ($\varepsilon$) 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]:

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

(12)

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

(13)

Where: $\Delta E$ 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 $\varepsilon$ (E) equal to 1 and assuming that the target is sufficiently thick, with one atom per molecule (i.e., f equal 1).

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

(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)
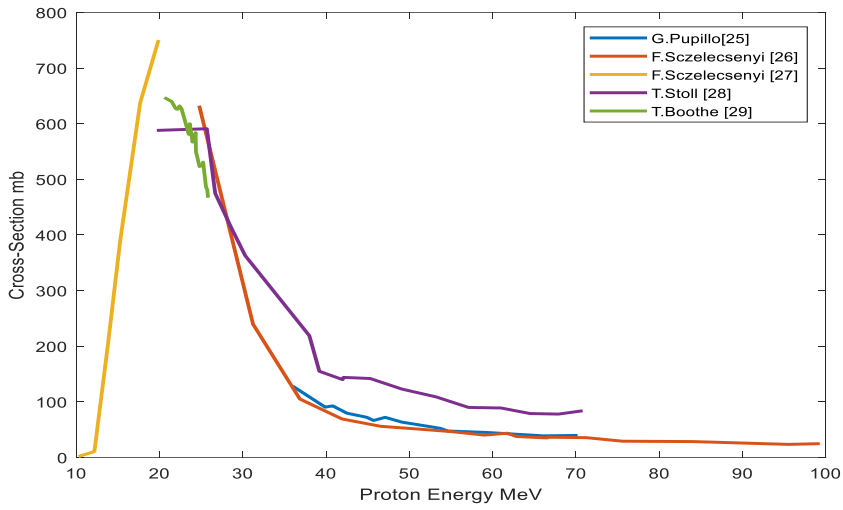for the 67Zn (p,n) 67Ga

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



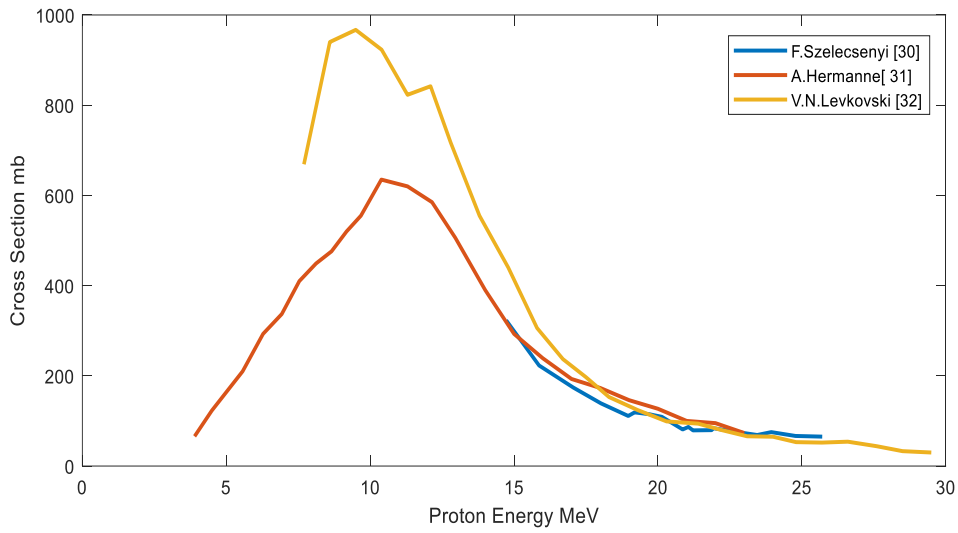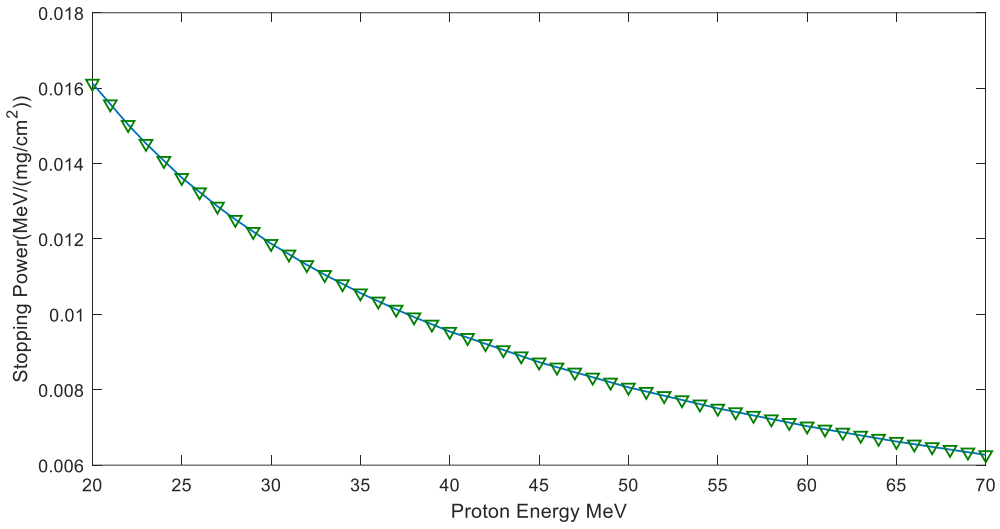**Figure 2**. Cross-section of 67Zn (p,n) 67Ga.

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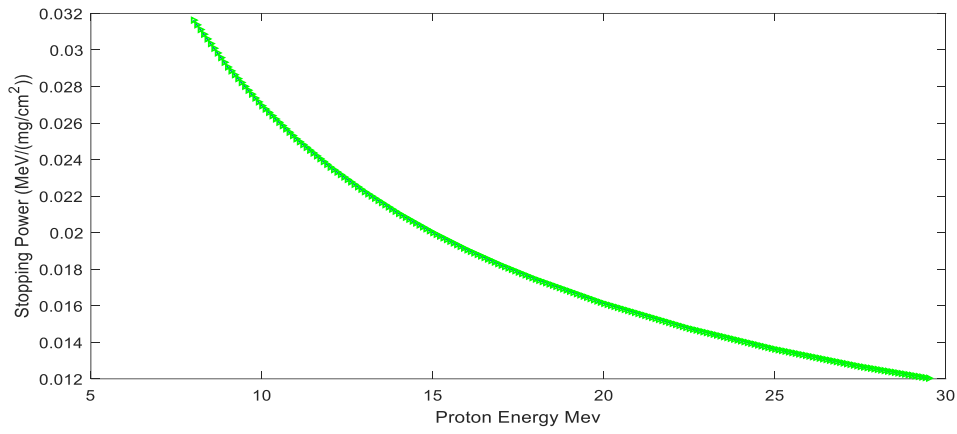


**Figure 4.** Stopping power of proton in zinc $^{67}$Zn (p,n) $^{67}$Ga
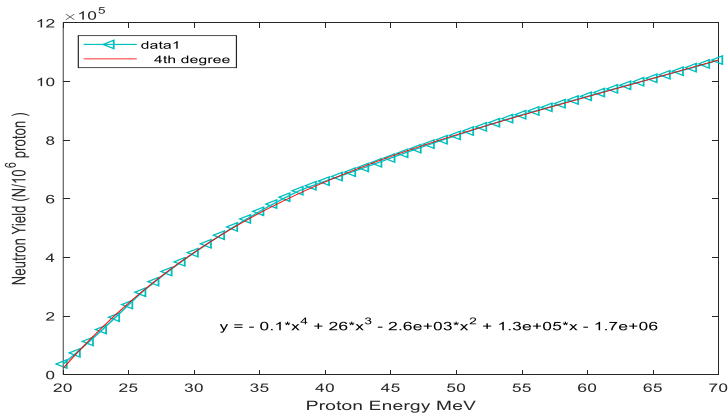


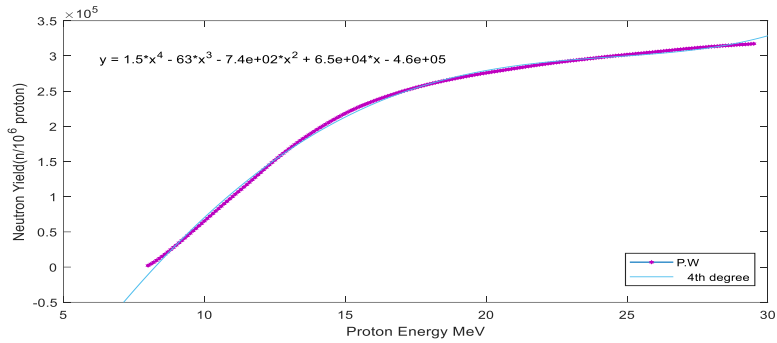**Figure 5.** Neutron Yield for $^{68}$Zn (p,2n) $^{67}$Ga

**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) $^{67}$Ga reaction.

| 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 |
| 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 |
| 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.

## Acknowledgment

## Conflict of Interest

The authors declare that they have no conflicts of interest.

## Funding

## References

1. Audi, G. and Wapstra, A.H.. The 1995 update to the atomic mass evaluation. *Nuclear Physics A*. **1995**, *595(4),* 409-480. https://doi.org/10.1016/0375-9474(95)00445-9

2. Jawad, E.A.; Jassim, M.K.; Tawfeek, H.M. Calculating the Sputtering Yield of Lithium, Sodium and Krypton Bombarded by Same Target Ion Using TRIM Simulation Program. *Ibn AL-Haitham Journal for Pure and Applied Science.* **2017**, *29*, 3, 26-35. https://doi.org/10.1063/5.0172339.

3. Meyerhof, W.E. Elements of Nuclear Physics. *McGraw–Hill.* **1967**, *22*, 174.

4. Samira, A.E.; Firas, M.H.; Mustafa, K.J.; Huda, M.T. Simulation Study of Sputtering Yield of Zn Target Bombarded by Xenon Ions, *Ibn AL-Haitham Journal for Pure and Applied Science.* **2016**, *29*(*2*), 12-23. https://doi.org/10.1063/5.0172339.

5. Mohammed, N.A.; Samira, A.E. Study of Lung Cancer Hazard Due to Radiate Radon Gas for Two Factories in Industrial Region (Shaikh Omar) of Baghdad Governorate. *Ibn AL-Haitham Journal for Pure and Applied Science*. **2020**, *33*(*4*), 34-45. https://doi.org/10.30526/33.4.2522.

6. James, J.D.; Louis, J.H. Nuclear Reactor Analysis. *John Wiley & Sons, Inc*. **1975**, *12*, 234.

7. Shirokov, M.; Yadin, N. Nuclear Physics. *Mir Publisher Moscow.* **1982**, *11*, 1244.

8. Lilley, J. Nuclear physics. *John Wiley & Sons, Ltd.* **2001**, 764.

9. Shaimaa, A.A.; Seham, H.S.; Samira, A.E.; Huda, M.T. Investigation of the Nuclear Structure of Some Ni and Zn Isotopes with Skyrme Hartree-Foc. *Baghdad Science Journal*. **2022**, *19*(*4*), 914-921. http://dx.doi.org/10.21123/bsj.2022.19.4.0914.

10. Burcham, W.E.; Jobes, M. Nuclear and particles physics. *Books. Org.* **1994**, 2343.

11. Arora, E.D. Dictionary of Physics. *Low Textbook Publishers*, *Delhi, India.* **2003**, 2244.

12. Mohammed, N.A.; Ebrahiem, S.A. Assessment of radiation risk parameters for natural radon in three Iraqi institutions for February. *AIP Conference Proceedings.* **2020**, 2307, 020003. https://doi.org/10.1063/5.0035396.

13. Bariq, H.W.; Sameera, A.E. Study of the nuclear properties of an aluminum isotope in the production of third cycle elements. *AIP Conference Proceedings.* **2022**, 2437, 020087. https:// doi.org/10.1063/5.0094228.

14. Hassan, I.M.; Ebrahiem, S.A.; Al-Khafaji, R.S. Calculated the Quadrupole Electrical Transmission |M(E2)|2 W.u For Even-Even Nuclides of Strontium (78-100Sr and 66-76Ge). *AIP Conference Proceedings.* **2022**, 2437, 020114. https://doi.org/10.1063/5.0094215.

15. Knoll, G.F.; Radiation detection and measurement. *2nd and 3rd. wiley, New York.* **1989,** 23002.

16. Washington, D.C. International commission on radiation units and measurements. *USA* **1970**.

17. Ebrahiem, S.A.; Falih, E.H.; Mahdi, H.A.; Shaban, A.H. Indoor $^{222}$Rn measurement and hazards indices in houses of Al-Najaf province Iraq. *AIP Conference Proceedings.* **2018**, 030003.

18. https:// doi.org/10.1063/1.5039190.

19. Ziegler, J.F.; Helium: Stopping Powers and Ranges in all elemental Matter. *Peramon Press Oxford* **1977**, *23*(*3*),123-134.

20. Wrean, P.R.; Kavanagh, R.W. The cross-section of this reaction was measured for alpha energy (2.2841-3.0999) MeV for $^{19}$ F($\alpha$,n)$^{22}$Na J, PR/C,62,055805, *Appl. Phys.* **2000**, *12*(*2*), 34-44. https://doi.org/10.1103/PHYSREVC.62.055805.

21. Anderson, M.; Kennett, S.J. Nuclear Physics. *Sec. A,* **1979**, *318*, 471.

22. Norman, E.; Chupp, T.J.; Nuclear Physics. *Sec. A,* **1982**, *390*, 561.

23. Ziegler, J.F.; Biersack, J.P.; Littmark, U. the stopping and range of ions in solids. *Pergamon Press, New York.* **1985**. *12*(*32*), 44-56. https://doi.org/10.1007/978-3-642-68779-2_5.

24. Trim, V.; Ziegler, J.F.; Biersack, J P. Updated version of a computer code for calculating stopping and Ranges, described in Reference, *Applied. Physics.* **2003**. *12*(*4*), 45-56. https://doi.org/10.1016/J.NIMB.2010.02.091.

25. Bowler, M. Nuclear physics. *Pergamon Press Ltd. Oxford* **1973**, 232.

26. Szelecsényi, F., Steyn, G.F., Dolley, S.G., Kovács, Z., Vermeulen, C. and Van der Walt, T.N., 2009. Investigation of the 68Zn (p, 2p) 67Cu nuclear reaction: New measurements up to 40 MeV and compilation up to 100 MeV. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms.* *267*(11),1877-1881. https://doi.org/10.1016/J.NIMB.2017.10.022.

27. Szelecsényi, F.; Steyn, G.F.; Dolley, S.G.; Kovács, Z.; Vermeulen, C. Van der Walt, T.N. Investigation of the 68Zn (p, 2p) 67Cu nuclear reaction: New measurements up to 40 MeV and compilation up to 100 MeV. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms.* **2009**, *267*(*11*), 1877-1881**.** https://doi.org/10.1016/J.NIMB.2009.03.097**.**

28. Szelecsényi, F.; Kovács, Z.; Nagatsu, K.; Fukumura, K.; Suzuki, K.; Mukai, K. Investigation of direct production of $^{68}$Ga with low energy multiparticle accelerator. *Journal Radio-chemical Acta, Germany.* **2012**, *100*, *5*, 34-45. https:// doi.org/10.1524/ract.2011.1896.

29. Stoll, T.; Kastleiner, S. Excitation functions of proton-induced reactions on 68-Zn from threshold up to 71 MeV, with specific reference to the production of 67-Cu. *Journal Radio-chemical Acta, Germany.* **2002**, *l9* (*309*), 33-45. https://doi.org/10.1524/ract.2002.90.6.309.

30. Szelecsenyi, F.; Boothe, T.E.; Takacs, S. Evaluation of direct production of Ga with high energy multiparticle. *Journal Applied Radiation and Isotopes.* **1998**, *49(8)*, 1005-1032. https://doi.org/10.1016/S0969-8043%2897%2910103-8.

31. Hermanne, A. Evaluated cross-section and thick target yield databases of Zn+p processes for practical applications. *Journal Applied Radiation and Isotopes.* **1997**, *49*, 1005, 23-33. https:// doi.org/10.1016/S0969-8043(97)10103-8.