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Calculation the Cross Sections for $^{64}Cu(n,p)^{64}Ni$ Reaction By Reciprocity Theory

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Abstract: In this study intermediate elements ^{64}Ni , ^{64}Cu for $^{64}Ni\ (p,n)^{64}Cu$ reaction with proton energy from (1.0) MeV to (132) MeV with threshold energy (2.496) MeV are used according to the available data of reaction cross sections. We calculated the cross sections for $^{64}Cu(n,p)^{64}Ni$ reaction by application in nuclear technology (reciprocity theory). In reciprocity theory we derive the mathematical formula for $^{64}Cu(n,p)^{64}Ni$ and we deduced high probability to produced ^{64}Ni because it is very important such as it used in technology field .The evaluated cross sections as a functions of neutron energy between (E_n =0.504MeV) to (E_n=129.506MeV) of (0.0106barn) (0.254barn) respectively and statistical factor ($g_{p,n}$=1 and $g_{n,p}$=1/3) .

Introduction

When two charged nuclei, overcoming their Coulomb repulsion, a rearrangement of the constituents of the nucleus may occur. Similar to the rearrangement of atoms in reacting molecules during a chemical reaction this may result as a nuclear reaction. Nuclear reactions are usually produced by bombarding a target nucleus with a nuclear projectile , in most cases a nucleon (neutron or proton) or a light nucleus such as a deuteron or an α-particle *[1]*.

At low excitation energies (< 10 MeV), the majority of nuclear reactions involve the formation of two nuclei, one nearly equal in charge and mass number to the target nucleus. Such reactions are represented by an equation of the type :

$$a + X \rightarrow b + Y \qquad \text{------ (1)}$$

Or $X(a,b)Y$

Where (a) is the light projectile nucleus (proton , neutron, deuteron, 3H, 3He, or 4He) and (X) is the target nucleus at rest in the laboratory system. (Y) is the produced nucleus and (b) is a light nuclear particle which carries away the major share of the kinetic energy. If the product nucleus (Y) is left in an excited state after the emission of the light particle (b), it usually subsequently decays by radiating one or more gamma rays. Alternatively if (Y) is beta unstable, it decays at some later date by electron or positron emission followed by gamma emission [2].

Nuclear reactions of low excitation energies include the following types : (n,γ) , (n,p) , (n,α) , (α,n) , (p,γ) , (p,n) , (d,n) , (d,p) , …..etc.

$$X + a \rightarrow \begin{cases} X + a, \\ X^* + a, \\ Y + b, \\ Y^* + b, \end{cases} \qquad \text{------ (2)}$$

In the first two reactions of the set (2) the outgoing particle is of the same kind as the incident particle, and the process is called scattering. The first reaction represents elastic scattering and the second reaction represents inelastic scattering in which the target nucleus (*X*) is raised into an excited state *(X*)*. The other reactions of the set represent different possible nuclear transmutations in which the product nuclei may be found in their ground states or, more often, in excited states. The excited product nucleus usually decays very quickly to the ground state with the emission of γ-rays.

Cross Sections Of Nuclear Reactions:

To characterize the probability that a certain nuclear reaction will take place, it is customary to define an effective area of the nucleus for that reaction, called a cross section *[1]*. The reaction cross section data provides information of fundamental importance in the study of nuclear systems. The cross section is defined by *[3]*:

$$\sigma = N_r / N_i \qquad \text{------ (3)}$$

where (σ) is the cross section,

(N_r) is the number of reactions per unit time per nucleus.
(N_i) is the number of incident particles per unit time per unit area,=flux

The cross section has the units of area and is of the order of the square of nuclear radius and a commonly used unit is the barn:

$$1 \text{ barn} = 10^{-24} \text{ cm}^2$$

In general, a given bombarding particle and target can react in a variety of ways producing a variety of light reaction products per unit time. The total cross section is then defined as ***[4]***:

$$\sigma_{tot} = \sum_i \sigma_i \quad \text{------- (4)}$$

Where σ_i is the partial cross section for the process[1].

3. Reverse Reaction:

If the cross-sections of the reaction *A(p,n)B* are measured as a functions of T_p (T_p = Kinetic energy of incident proton), the cross–sections of the inverse reaction *B(n,p)A* can be calculated as a function of T_n (T_n = Kinetic energy of neutron) using the reciprocity theorem ***[5]*** which states that :

$$\frac{\sigma_{(p,n)}}{\sigma_{(p,n)} \lambda_p^2} = \frac{\sigma_{(n,p)}}{g_{(n,p)} \lambda_n^2} \quad \text{------ (5)}$$

Where $\sigma_{(p,n)}$ and $\sigma_{(n,p)}$ represent cross-sections of *A(p,n)B* and *B(n,p)A* reactions respectively, $g_{(p,n)}$ and $g_{(n,p)}$ represent a statistical factors of *A(p,n)B* and *B(n,p)A* reactions respectively λ is the de–Broglie wave length divided by 2π and is given by ***[6]***

$$\lambda = \frac{\hbar}{MV} \quad \text{--------- (6)}$$

Where $\hbar$ is Dirac constant ($h/2\pi$), h is Plank constant, M and V are mass and velocity of p or n .

From eq.(6) ,we have

$$\lambda^2 = \frac{\hbar^2}{2MT} \quad \text{------ (7)}$$

The statistical g-factors are givens by ***[5]***

$$g_{(p,n)} = \frac{2J_c + 1}{(2I_A + 1)(2I_p + 1)} \quad \text{------ (8)}$$

and

$$g_{(n,p)} = \frac{2J_c + 1}{(2I_B + 1)(2I_n + 1)} \quad \text{---- (9)}$$

The conservation low of the momentum and parity implique that :

$$I_A + I_p = J_c = I_B + I_n \quad \text{------ (10)}$$

and

$$\pi_A \cdot \pi_p (-1)^{\ell p} = \pi_c = \pi_B \cdot \pi_n (-1)^{\ell n} \quad \text{---- (11)}$$

J_c and π_c are total angular momentum and parity of the compound nucleus .
I_A and π_A are total angular momentum and parity of nucleus *A*.
I_B and π_B are total angular momentum and parity of nucleus *B*.
I_p and π_p are total angular momentum and parity of proton.
I_n and π_n are total angular momentum and parity of neutron .

$$\pi_p = \pi_n = +1 \quad \text{------ (12)}$$

$$I_p = s_p + \ell_p \quad \text{------ (13)}$$

$$I_n = s_n + \ell_n \quad \text{---------- (14)}$$

where
s_p is spin of proton = ½
ℓ_p is the orbital angular momentum of proton
s_n is spin of neutron = ½
ℓ_n is the orbital angular momentum of neutron

From eq.(10) ,we have :

$$|J_c - I_A| \le I_p \le J_c + I_A \quad \text{---- (15)}$$

and

$$|J_c - I_B| \le I_n \le J_c + I_B \quad \text{---- (16)}$$

The reactions *A(p,n)B* and *B(n,p)A* can be represented with the compound nucleus C as in the following schematic diagram. It is clear that there are some important and useful relations between the kinetic energies of the neutron and proton.

$$E = S_p + \frac{M_A}{M_A + M_p} T_p \quad \text{---- (17a)}$$

$$E = S_n + \frac{M_B}{M_B + M_n} T_n \quad \text{----- (17b)}$$

One can calculate the separation energies of proton (S_p) and neutron (S_n) using the following relations:

$$S_p = 931.5 [M_A + M_p - M_c] \text{------- (18)}$$

$$S_n = 931.5 [M_B + M_n - M_c] \text{ ----- (19)}$$

Combining (17a) , (17b) , (18) , (19)
And the equation of Q- value of the reaction *A(p,n)B* which is given by :

$$Q = 931.5 [M_A + M_p - M_B - M_n] \quad \text{---- (20)}$$

We get that :

$$Q = \frac{M_B}{M_B + M_n} T_n - \frac{M_A}{M_A + M_p} T_p \quad \text{---- (21)}$$

Or :

$$T_n = \frac{M_B + M_n}{M_B} \left[\frac{M_A}{M_A + M_p} T_p + Q \right] \text{----- (22)}$$

Then the threshold energy E_{th} is :

$$E_{th} = \left| -Q \frac{M_A + M_P}{M_A} \right| \quad \text{------- (23a)}$$

Or

$$Q = -\frac{M_A}{M_A + M_p} E_{th} \quad \text{------ (23b)}$$

Then

$$T_n = \frac{M_B + M_n}{M_B} \times \frac{M_A}{M_A + M_p}(T_p - E_{th})$$ -----(24)

Thus eq . (5) can be written as follows:

$$\sigma_{(n,p)} = \frac{g_{(n,p)} M_p T_p}{g_{(p,n)} M_n T_n} \sigma_{(p,n)}$$ -----(25)

It is clear from this equation that the cross sections of reverse reaction are related by a variable parameters which can be calculated if the nuclear characteristics of the reactions are known.

Results and Discussion:

The evaluated cross sections as a function of proton energy are listed in table (1) and these data are plotted in fig (2)[7] .
By using the reciprocity theory we derive the mathematical formula for ^{64}Cu *(n,p)* ^{64}Ni reaction by ground state :

$$\sigma_{(n,p)} = \frac{g_{(n,p)} M_p T_p}{g_{(p,n)} M_n T_n} \sigma_{(p,n)}$$

Where $g_{(p,n)}=1$ $g_{(n,p)}=1/3$
M_p=proton mass M_n=neutron mass

The evaluated cross sections as a function of neutron energy from (0.504 MeV) to (129.506MeV) of present work are listed in table (2) .These data are plotted in fig.(3). From fig . (3) we observed the maximum cross section in neutron energy (27.5043 MeV) is (0.3692 barn) to produced ^{64}Ni by bombard ^{64}Cu by neutron .
The cross sections are increased when neutron energy between(0.504 – 27.5043)MeV but these are decreased smoothly and we get mathematical formula representing the cross sections distribution in the indicate range of neutron energy as follow :

$$y = 3.7*10^{-13}x^6 + 1.3*10^{-6}x^5 - 9*10^{-8}x^4 + 1.6*10^{-5}x^3 - 0.0011x^2 + 0.035x + 0.00068$$

Reference:

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[6] Ebrahiem S. A. ; " Calculation the Cross Sections of *(n,α)* and *(n,p)* Reactions by Using the Reciprocity Theory for the First Exited State" P-6 , (2011).
[7]Chiba,Chadwick,ate. ; ENDF/B-VII Library ; (1999)

Table (1):The cross sections of ^{64}Ni *(p,n)*^{64}Cu reaction as a function of proton energy

p -energy (MeV)	Cross sections (mbarn)	p -energy (MeV)	Cross sections (mbarn)	p -energy (MeV)	Cross sections (mbarn)
1.000	0.000	25.4724	1.1545	51.000	1.0102
1.367	0.000	26.000	1.1563	52.000	1.001
2.000	0.0008	26.8478	1.1579	52.2242	0.999
2.4956	0.0087	27.000	1.1581	52.7024	0.9946
3.000	0.0332	27.0237	1.1581	53.000	0.992
4.000	0.1407	27.252	1.1583	53.2015	0.9902
5.000	0.2719	28.000	1.1581	54.000	0.9832
6.000	0.3096	29.000	1.1568	54.0587	0.9827
7.000	0.2947	29.0552	1.1567	55.000	0.9747
7.285	0.3108	30.000	1.1542	55.1698	0.9733
7.5493	0.333	30.5876	1.1521	56.000	0.9667
8.000	0.3822	30.9737	1.1507	57.000	0.9589
8.1398	0.4001	31.000	1.1506	57.5302	0.955
8.245	0.4146	31.0905	1.1503	58.000	0.9515
8.7951	0.4921	31.5171	1.1487	59.000	0.9444
9.000	0.5154	32.000	1.1468	59.9699	0.9379
10.000	0.6088	32.9088	1.1429	60.000	0.9377
10.5366	0.6549	33.000	1.1425	61.000	0.9311
11.000	0.6941	33.2392	1.1414	62.000	0.9249

12.000	0.7757	33.8455	1.1385	62.2834	0.9232
12.746	0.8319	34.000	1.1377	62.6094	0.9212
13.000	0.8498	35.000	1.1321	63.000	0.9189
14.000	0.9089	35.7318	1.1277	63.9594	0.9135
14.9404	0.95	35.7499	1.1276	64.000	0.9132
15.000	0.9522	36.000	1.1261	65.000	0.9079
15.2692	0.9619	37.000	1.1200	65.8714	0.9035
15.4781	0.9693	38.000	1.1139	66.000	0.9028
16.000	0.9866	38.4161	1.1113	67.000	0.898
16.0724	0.9889	39.000	1.1077	67.6484	0.895
16.4052	0.9991	40.000	1.1016	68.000	0.8934
16.9206	1.0142	40.9735	1.0957	69.000	0.8891
17.000	1.0164	41.000	1.0955	70.000	0.885
18.000	1.0425	42.000	1.0894	71.000	0.8812
18.9043	1.0636	42.2024	1.0881	72.000	0.8775
19.000	1.0657	42.4818	1.0864	73.000	0.874
19.1076	1.0681	42.7427	1.0848	74.000	0.8708
20.000	1.0865	42.9243	1.0837	75.000	0.8677
21.000	1.1048	43.000	1.0832	75.8149	0.8654
21.561	1.114	44.000	1.077	76.000	0.8649
21.6725	1.1157	44.614	1.073	77.000	0.8621
22.000	1.1208	45.000	1.0705	78.000	0.8595
23.000	1.1343	46.000	1.0625	79.000	0.857
23.0364	1.1347	47.000	1.0523	80.000	0.8547
23.0475	1.1349	47.2876	1.0491	81.000	0.8525
23.4577	1.1394	47.5581	1.046	82.000	0.8504
24.000	1.1446	48.000	1.041	83.000	0.8484
24.0905	1.1454	49.000	1.0297	84.000	0.8465
25.000	1.152	50.000	1.0195	85.000	0.8447
25.3017	1.1537	50.4733	1.0151	86.000	0.843

Table (1):The cross sections of 64Ni (p,n)64Cu reaction as a function of proton energy

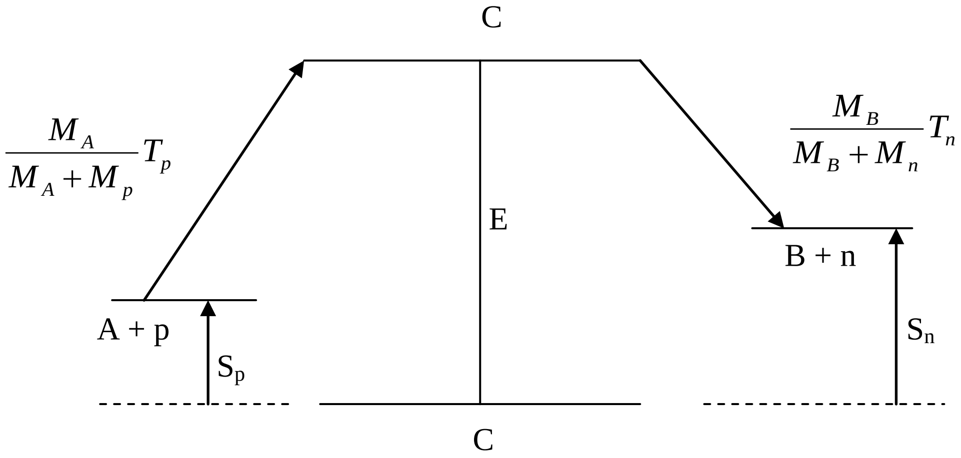
p -energy (MeV)	Cross sections (mbarn)	p -energy (MeV)	Cross sections (mbarn)	p -energy (MeV)	Cross sections (mbarn)
87.000	0.8413	97.000	0.8278	114.000	0.8105
88.000	0.8397	98.000	0.8266	116.000	0.8086
89.000	0.8382	99.000	0.8255	118.000	0.8067
90.000	0.8368	100.000	0.8244	120.000	0.8049
91.000	0.8354	102.000	0.8223	122.000	0.8031
92.000	0.834	104.000	0.8202	124.000	0.8013
93.000	0.8327	106.000	0.8182	126.000	0.7995
94.000	0.8314	108.000	0.8162	128.000	0.7977
95.000	0.8302	110.000	0.8143	130.000	0.7959
96.000	0.829	112.000	0.8124	132.000	0.7941

Table (2):The cross sections of 64Cu (n,p) 64Ni reaction as a function of neutron energy

n -energy (MeV)	Cross sections (barn)	n -energy (MeV)	Cross sections (barn)	n -energy (MeV)	Cross sections (barn)
-1.496	0.0028	22.9766	0.3693	48.5046	0.3231
-1.129	0.0003	23.5043	0.3699	49.5046	0.3202
-0.496	0	24.3521	0.3704	49.7288	0.3195
-0.0004	0	24.5043	0.3704	50.2071	0.3182
0.504	0.0106	24.528	0.3704	50.5046	0.3173
1.504	0.045	24.7563	0.3705	50.7061	0.3167
2.504	0.087	25.5043	0.3704	51.5046	0.3145
3.504	0.099	26.5043	0.37	51.5633	0.3143
4.5041	0.0943	26.5595	0.37	52.5047	0.3118
4.789	0.0994	27.5043	0.3692	52.6744	0.3113
5.0533	0.1065	28.092	0.3685	53.5047	0.3092
5.5041	0.1223	28.4781	0.3681	54.5047	0.3067
5.6439	0.128	28.5044	0.3681	55.0349	0.3055
5.749	0.1326	28.5949	0.3679	55.5047	0.3044
6.2992	0.1574	29.0214	0.3674	56.5047	0.3021
6.5041	0.1649	29.5044	0.3668	57.4746	0.3000
7.5041	0.1947	30.4131	0.3656	57.5047	0.2999
8.0407	0.2095	30.5044	0.3655	58.5047	0.2978
8.5041	0.222	30.7436	0.3651	59.5047	0.2958
9.5041	0.2481	31.3499	0.3642	59.7882	0.2953
10.2501	0.2661	31.5044	0.3639	60.1142	0.2947
10.5041	0.2718	32.5044	0.3621	60.5048	0.2939
11.5041	0.2907	33.2362	0.3607	61.4642	0.2922
12.4445	0.3039	33.2543	0.3607	61.5048	0.2921
12.5042	0.3046	33.5044	0.3602	62.5048	0.2904
12.7733	0.3077	34.5044	0.3582	63.3762	0.289
12.9823	0.3101	35.5044	0.3563	63.5048	0.2888
13.5042	0.3156	35.9206	0.3555	64.5048	0.2872
13.5765	0.3163	36.5045	0.3543	65.1532	0.2863
13.9094	0.3196	37.5045	0.3524	65.5048	0.2858
14.4248	0.3244	38.478	0.3505	66.5048	0.2844
14.5042	0.3251	38.5045	0.3504	67.5048	0.2831
15.5042	0.3335	39.5045	0.3485	68.5048	0.2819
16.4085	0.3402	39.7069	0.3481	69.5049	0.2807
16.5042	0.3409	39.9863	0.3475	70.5049	0.2796
16.6118	0.3416	40.2472	0.347	71.5049	0.2785
17.5042	0.3475	40.4288	0.3466	72.5049	0.2776
18.5042	0.3534	40.5045	0.3465	73.3198	0.2768
19.0652	0.3563	41.5045	0.3445	73.5049	0.2766
19.1768	0.3569	42.1185	0.3432	74.5049	0.2758
19.5042	0.3585	42.5045	0.3424	75.5049	0.2749
20.5043	0.3628	43.5045	0.3399	76.5049	0.2741
20.5407	0.363	44.5046	0.3366	77.505	0.2734
20.5518	0.363	44.7922	0.3356	78.505	0.2727
20.9619	0.3645	45.0627	0.3346	79.505	0.272
21.5043	0.3661	45.5046	0.333	80.505	0.2714
21.5948	0.3664	46.5046	0.3294	81.505	0.2708
22.5043	0.3685	47.5046	0.3261	82.505	0.2702
22.806	0.369	47.9779	0.3247	83.505	0.2697

Table (2):The cross sections of 64Cu(n,p)64Ni reaction as a function of neutron energy

n -energy (MeV)	Cross sections (barn)	n-energy (MeV)	Cross sections (barn)	n -energy (MeV)	Cross sections (barn)
84.505	0.2691	95.5052	0.2644	115.505	0.2581
85.5051	0.2686	96.5052	0.2641	117.506	0.2575
86.5051	0.2681	97.5052	0.2637	119.506	0.2569
87.5051	0.2677	99.5052	0.263	121.506	0.2563
88.5051	0.2672	101.505	0.2624	123.506	0.2557
89.5051	0.2668	103.505	0.2617	125.506	0.2552
90.5051	0.2664	105.505	0.2611	127.506	0.2546
91.5051	0.2659	107.505	0.2605	129.506	0.254
92.5051	0.2656	109.505	0.2599	----	----
93.5052	0.2652	111.505	0.2592	----	----
94.5052	0.2648	113.505	0.2587	----	----



Schematic diagram of the reactions

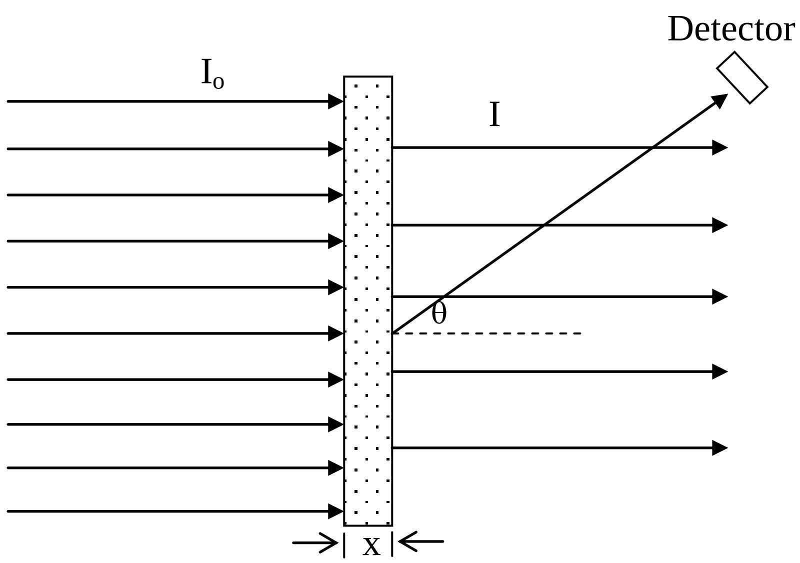
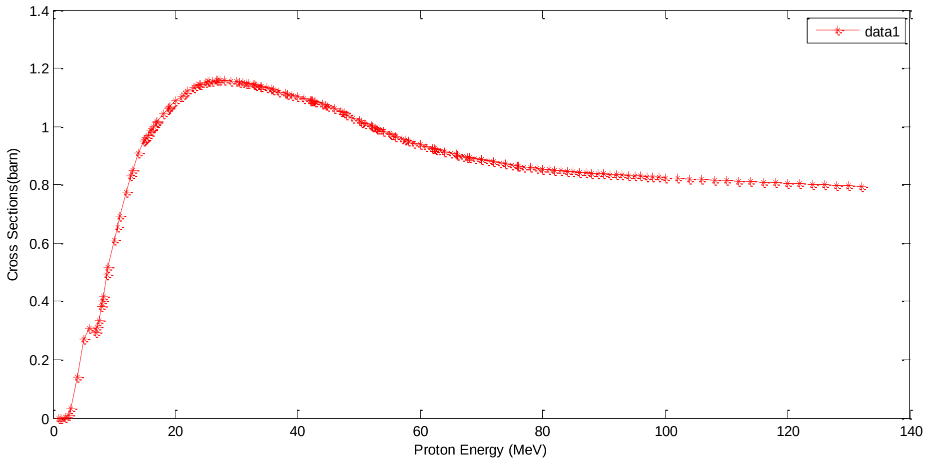
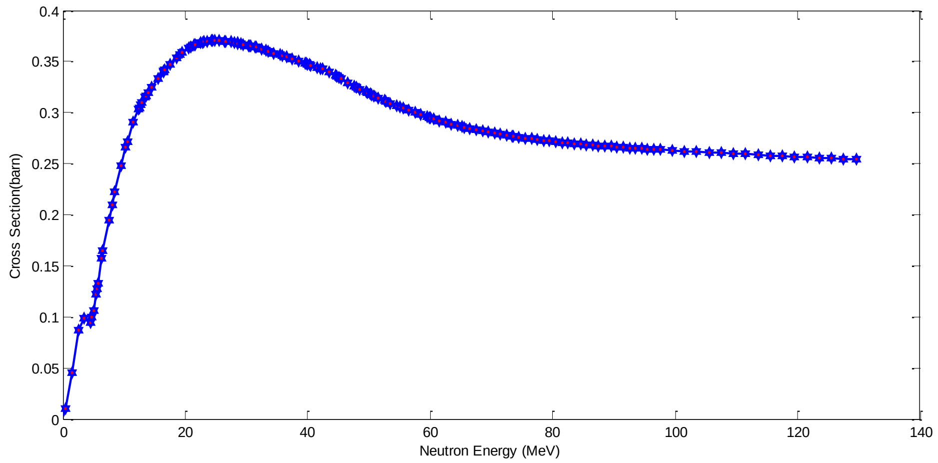


Figure (1): A schematic diagram illustrating the definition of total cross section in terms of the reduction of intensity



Figure(2): Cross section as a function of proton energy of64Ni (p,n)64Cu Reaction[7]



Figure(3): Cross section as a function of neutron energy of64Cu (n,p) 64Ni Reaction by inverse reaction

حساب المقاطع العرضية للتفاعل 64Cu(n,p)64Ni بواسطة نظرية التعاكس

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الخلاصة

في هذه الدراسة تم حساب المقاطع العرضية للنوى المتوسطة ^{64}Ni , ^{64}Cu للتفاعل $^{64}Ni\ (p,n)^{64}Cu$ للبيانات المتوفرة في الادبيات العالمية وللمدى الطاقي من (1.0) MeV الى (132.0) MeV وبطاقة عتبه مقدارها (2.496)MeV كدالة للمقاطع العرضية .تم حساب المقاطع العرضية للتفاعل $^{64}Cu\ (n,p)\ ^{64}Ni$ بوسطة تقنية التفاعل المعاكس وتم تحديد الاحتمالية الاكبر لأنتاج النيكل لأهميته الكبيرة في التقدم التكنولوجي. بواسطة التفاعل المعاكس تم اشتقاق المعادلة . قيم المقاطع العرضيه كداله لطاقة النيوترون تتراوح ما بين (E_n =0.504MeV) الى (E_n=129.506MeV) تكون (0.0106barn) الى (0.254barn) على التوالي اما العامل الأحصائي فهو ($g_{p,n}$=1) و ($g_{n,p}$=1/3).