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Research Paper

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Possibilities of Exchanging the Cross-Section Area in (p, n) and (p, 2n) Reaction

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***Abstract*—** on extracting the data obtained from IAEA-NDS-2019, for study the nature of the single proton-neutron reaction and single proton-2 neutron reaction, narrowband range of cross-section area, and energy presence is seen. The narrowband region is seen, when the cross-section area is on decreasing order with increasing the energy of incidence particle. This narrowband helps to exchange the cross-section area of the element in each reaction. The sharpness of the graph in a single proton-neutron reaction shows that vibration energy after absorption of incidence particle on target is absent while in single proton-2 neutron reaction is present due to which the graph of single proton-2 neutron reaction is fattened. The cross-section area of the single proton-2 neutron reaction is greater than the single proton-neutron reaction and energy for the single proton-neutron reaction is less than a single proton-2 neutron reaction.

***Keywords*—** Cross-section area, narrowband region, vibration energy, absorption, single proton-neutron reaction, single proton-2neutron reaction, etc.

I. INTRODUCTION

The shifting of energy level can be interpreted in terms of necessary domains of energy to excite typical nuclear processes, in which they considered A_N as the mass number, related to the strong interaction range $R_{Strong} = 1.2 \times 10^{-13} A_N^{\frac{1}{3}} cm$. The threshold energy E_{Th} of the of a material is determined by considering and equilibrium the condition $E_{strong} = E_{Coulomb}$, where E_{strong} is due to nuclear force short ranges while Ecolumb represents the coulomb energy due to long-range charge separation. The shifting of energy can be obtained using a linear combination of Gaussians that incorporate a possible representation of Fermi-Dirac statistics. During this shifting and nuclear excitations, another particle is formed which may know secondary or tertiary particles so on [1 - 3]. To understand the cross section area, let us consider a foil with density n atoms/cm^3, width Δx, bombarded with a beam area A , on which the neutrons incidence with intensity I (neutrons/sec.), with different velocity v_n, then the possible cross section area can be represented with relation (1) as given below,

$$\sigma = \pi R_n^2 \dots\dots\dots\dots\dots (1)$$

In equation (1), R_n represent the nuclear radius, now the total cross section area for the incidence of particles can be represented with the help of equation (1) as,

$$\sigma_T = A\Delta x\, n\sigma \dots\dots\dots\dots\dots\dots (2)$$

Also, the rate of removing neutrons from the target is given by relation (3) as

$$\frac{dN}{dt} = \left(\frac{I}{A}\right)(A\Delta x\; n\; \sigma_T) \dots\dots\dots\dots (3)$$

On combing and arranging the relation (2) and (3) the total microscopic neutron cross section expression is given by relation (4) as, this relation shows how the intensity, density, area, thickness, and rate of production of the neutron are related during a nuclear reaction.

$$\sigma_T = \frac{\frac{dN}{dt}}{\left[\left(\frac{I}{A}\right) n\; A\; \Delta x\right]} \dots\dots\dots\dots (4)$$

On using the neutron flux, defined as $\varphi = \frac{I}{A}$ (neutrons/sec.cm^2), and using this relation in (4), the rate of production of neutron during reaction with time is obtained as

$$\frac{dN}{dt} = \varphi\; (A\; \Delta x\; n\; \sigma) \dots\dots\dots (5)$$

During the nuclear reaction numbers of phenomena are observed, like scattering, absorption, and fission. Therefore, the total cross sections $\sigma_T(E)$ during this reaction are obtained as the sum of all possible cross section area of nuclear reaction can be written [4] as $\sigma_T(E) = \sigma_s(E) + \sigma_a(E) + \sigma_f(E)$, where $\sigma_s(E)$ for scoring cross section area during nuclear reaction similarly, $\sigma_a(E)$ and $\sigma_f(E)$ represent the cross section area during absorption and fission.

The binding energy per nucleon is given below in figure 1, this represents how the binding per nucleon goes on increasing and decreasing among the existence elements [5].

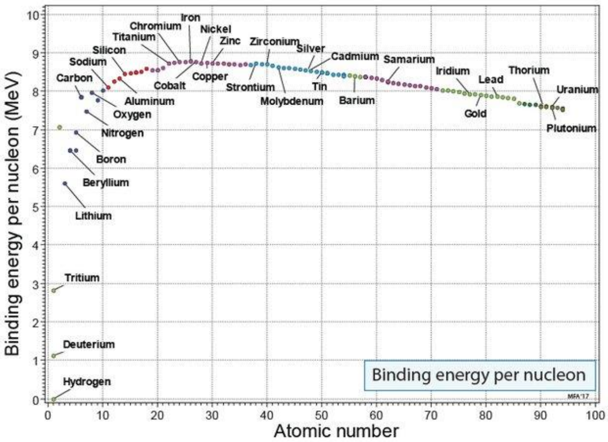


Figure 1: Binding energy per nucleon diagram of element vs atomic number

Note: single proton-2 neutron reaction means (p, 2n) reaction, and single proton-neutron reaction means (p, n) reaction.

II. RELATED WORK

The total nuclear reaction cross section of (p, xn) reaction of low energies i.e. <12 MeV gives the direct information about the proton reaction, but not for (p, pn) reaction, which was verified by Cohen et al. Also, the proton capture cross sections were calculated by Shapiro with the help of nucleus radius relation and calculated minimum 60 to maximum 470 millibarns. This calculation also agreed with the total reaction cross-section of (p, n) interaction proceeds, in which compound nucleus at low energies and direct interaction interference is negligible.

Cross-sections for the nuclear reactions Y^{89}(p, n)Zr^{89}m, Y^{89} (p, n) Zr^{89}g, Pr^{141}(p, n)Nd^{141}m, Pr^{141}(p, n) Nd^{141}g, Au^{197}(p, n)Hg^{197}m, and Au^{197}(p, n)Hg^{197}g were measured to study the mechanism of nuclear reactions (p, n) with incident-particle threshold energies for (p, n) reaction up to 20 MeV [6].

The modified semi-empirical formula for non-elastic scattering and Coulomb effects for the (α, n) reaction cross-section was obtained in different experiment systematics by different researchers and scientists. In a nuclear reaction, the dependence between the cross section and asymmetry are taken into account, for the (α, n) reaction at $18.5 \pm 3\ MeV$ energies classifying the target nuclei into odd and even. The relation between asymmetry and cross-sections obtained from the modified semi-empirical formula with new coefficients as R^2 [7].

Some researchers measured the cross sections for ^{147,149}Sm(p, n)^{147,149}Eu and ^{147,149}Sm(p, γ)^{148,150}Eu using the activation method, and they compared the result with the Hauser-Feshbach statistical model. Also, for different γ-ray, the cross-sections for (p, γ) reactions at energies below the Coulomb barrier are valuable for p-process nucleosynthesis calculations [8].

The comparison of the ratio of the cross-sections for the $(p, 2n)$ reaction and (p, n) reaction at 400 MeV was calculated for a different system, theoretically and experimental, and large variations were observed within the small mass region. For the isobaric system, the separation energies of the least bound neutrons, the variations of the cross-section ratios with a mass number are again taken into account. This indicates that the enhanced population of the isobaric in the p-n scattering event does indeed enhance the (p, n) cross-section for the systems and thereby reduce the ratio considerably [9].

Nuclear reactions induced with the help of photon call as photonuclear reactions, which have great importance in many fields of nuclear, radiation physics, and related fields. The cross-sections of reaction induced by photon (γ, xn) and (γ, xn) were calculated by using TALYS 1.2 and found to be 2 to 20 times larger than that of the photo-proton reaction. On increasing the photon energy, $(\gamma, 2n)$ the reaction becomes dominant according to the (γ, n) after about 20 MeV [10].

On collecting the data from IAEA-NDS-Monitor Reaction 2017, the cross-section area with the incidence of particles with kinetic energy (MeV) is shown in figure 1. It is seen on increasing the energy of incidence particle the cross-section area also goes on an increase in both reaction (p, n) and (p, 2n) of the same element but the nature is different i.e. ^{124}Te(p, n)^{124}I and ^{123}Te(p, n)^{123}I has same nature while ^{124}Te(p, 2n)^{123}I has a difference. The peak of (p, n) reaction is likely to be very closure with a difference of 1MeV energy and 9.5mb while peak value of (p, n) and (p, 2n) reaction of the same element has vast difference for same element i.e. in compare with ^{124}Te(p, n)^{124}I and ^{124}Te(p, 2n)^{123}I energy difference 11MeV and cross-section area 401.7mb, ^{123}Te(p, n)^{123}I and ^{124}Te(p, 2n)^{123}I energy difference 10.5MeV and cross-section area 411.2mb. *Note the data is updated in august 2019.*

III. MATERIALS AND METHODS

To understand the nature of cross section area and energy in a nuclear reaction, the authors are focusing on the nuclear reaction in which the emitted neutrons area consider as a resultant particle or secondary particles.
As binding energy of nucleon play an important role in specifying the cross sectional area during the nuclear

reaction for this role, one can't neglect the nucleon binding energy given by relation (6), since the relation is quite familiar therefore relation (6) is direct, representing

$$E_{nuc} = \{M_{nuc}(N,Z) - NM_n - ZM_p\}c^2 \dots\dots\dots\dots (6)$$

Similarly, the atomic mass can be calculated from the nuclear mass using the relationship $M_{at} = M_{nuc}(N,Z) + ZM_e - B_e(Z)$, where M_e is the electron mass and B_e is the total atomic binding energy of all electrons. Also, for $(N+Z)$ and $(N-Z)$ can be written as $\frac{N^2-Z^2}{Z}$ appears for the nucleon asymmetry and coulomb correction, the nuclear binding energy of all elements:

$$B(Z,N) = \left\{\left(\frac{3^2}{3^2+1}\right)\left[A - \left(\frac{((N^2-Z^2)+\delta(N-Z))}{Z} + 3\right)\right] \times \frac{m_N C^2}{100}\right\} A > 5 \dots\dots (7)$$

where δ stands for nuclear beta-stability line condition and is defined as follows:

$$\delta(N-Z) = \begin{Bmatrix} 0 \ for\ N \neq Z \\ 1 \ for\ N = Z \end{Bmatrix}$$

The constant factor $\frac{3^2}{(3^2+1)}$ in binding energy equation (7) may be explained in two different contexts. One has to do with the defined nuclear region [11],[12] in which the density remains constant.

Since nuclear reaction can't occur directly i.e. it found a compound nucleus at a transition state and after this state, the production of secondary particle and another nucleus take place, therefore the cross sectional area of the compound nucleus or transition state is given by relation (8) given below

$$\sigma(a,b) = \frac{\sigma_c(a)P_b}{\sum_{b'} P_{b'}} \dots\dots\dots\dots\dots\dots (8)$$

Where $\sigma_c(a)$ is the cross-section for the compound nucleus formed by projectile a, and P_b is the probability of the compound nucleus decaying into the corresponding outgoing channel b. After the formation of the compound nucleus during the nuclear reaction, the compound nucleus goes decay or formed secondary particle and daughter nucleus, hence the probabilities of this decay are given by relation (9) as

$$P_b(e_b) = \frac{g_b \mu_b e_b \sigma_c^*(e_b)}{\pi^2 \hbar^3} \frac{\rho_b(U_b)}{\rho_c(U_c)} \dots\dots\dots\dots (9)$$

Where e_b is the energy of the emitted particle, $g_b = 2s_b + 1$ is the statistical factor connected with the spin sb of the particle, μ_b is the reduced mass, $\sigma_c^*(e_b)$ is the cross-section for the inverse reaction, and ρ_b ρ_c are the level densities for the residual and compound nucleus at the corresponding excitation energies. All component energies are connected by the relationship $U_c = U_b + B_b + e_b$, where B_b is the binding energy of the particle in the compound nucleus. Equation (9) is very similar to those for the particle evaporation from a liquid surface, and, for this reason, the above equation is referred to as the evaporation model or Weisskopf-Ewing formula [13]. A more rigorous consideration of the nuclear process defines compound reaction cross-sections in terms of the Hauser-Feshbach-Moldauer formula [14],[15],[16],[17].

$$\sigma(a,b) = \pi \lambda_a^2 \sum_{J\pi} g_s^J \frac{T_a^{J\pi} T_b^{J\pi}}{\sum_c T_c^{J\pi}} F_{ab,c}^{J\pi} \dots\dots\dots\dots (10)$$

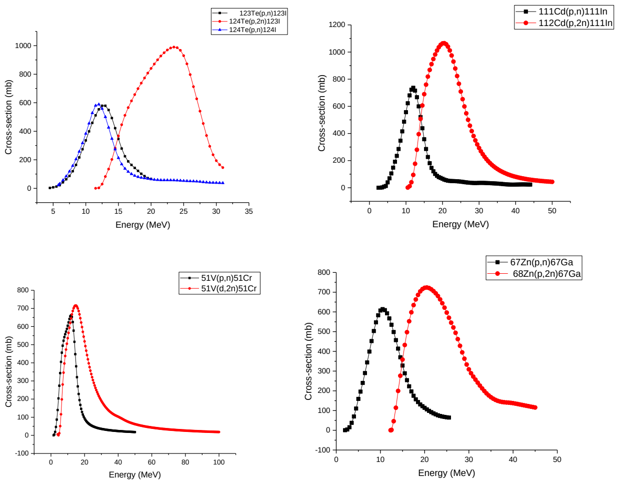
where λ_a is the wavelength of the incident particle, $T_a^{J\pi}$ are the transmission coefficients for the given angular momentum J and parity π, and $F_{ab,\ c}$ is the width fluctuation correction for differences between the averaged ratio of fluctuating decay widths and the ratio of the averaged widths.

On taking into account, angular momentum and spin of reaction production, $\sum_c T_c^{J\pi}$ the term of equation (10) can be replaced by integrals as

$$\sum_c T_c = \sum_{l,\ j,\ I} \int_0^{U_{max}} T_{lj}(E_c)\rho(U,I)dU \dots\dots\dots (11)$$

As we have an internal binding energy equation (6), which depends upon the nucleon and nucleus and binding energy of nucleons in equation (7). The reaction (p, n) and (p, 2n) is only possible if the incidence particle has energy greater than the binding energy of the target nucleon. If the energy of incidence particle energy is absorbed and only a small change in the cross-section area of target in the reaction is observed. Since the threshold energy is needed to emit neutron by incidence particle on target, therefore the energy absorbed by the nucleus for the nuclear reaction cause to change the cross-section area of target nucleus and the cross-section area for this given in equation (1), (2), (4), (8), (10). This equation gives the measurement cross-section and with the help of this equation, we can study the nature of cross-section area in (p, n) and (p, 2n) reaction, with the cross-section area time duration of the reaction.

After the particle incidence on the target, the target interacts with the particle and absorbed the energy and the target goes to change with nuclear excitation which causes to change in the cross-section area shown in figure 2, figure 3, and figure 4. The peak is different is due to the incidence of energy, time of reaction, and vibration, or excitation of the nucleus.



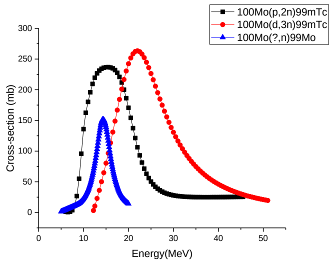


Figure 2: Representation of (p, n), (p, 2n), of the same element

The cross-section area and incidence kinetic energy of particle on the target for nuclear reaction 111Cd(p, n)111In or ^{111}Cd(p, n)^{111}In and 112Cd(p, 2n)111In or ^{112}Cd(p, 2n)^{111}In are shown in figure 2. The peak point of (p, n) reaction is seen at 12MeV and cross-section area 736.5mb while for (p, 2n) reaction is seen at 20.5MeV and cross-section area 1065.3mb. The difference between cross-section and energy of (p, n) and (p, 2n) are 328.8mb and 8.5MeV. The cross-section area of both reaction increase parallels with the increase in particle kinetic energy. The cross-section area just side of peak value for a narrow band is symmetry.

The cross-section area of 51V(p, n)51Cr or ^{51}V(p, n)^{51}Cr and 51V(d, 2n)51Cr or ^{51}V(d, 2n)^{51}Cr reaction are maximum at 457.5mb and 715.8mb while energy is 12MeV and 14.5MeV, both reaction symmetry on both sides of the peak. The difference in cross-section area of (p, n) and (p, 2n) reaction is 258.3mb and energy is 2.5MeV, the visualization is shown in figure 1. The representation of the cross-section area of (p, n) and (p, 2n) reaction for same element Zn show the cross-section area of both reactions has different peak point i.e. ^{67}Zn(p, n)^{67}Ga has 614mb at energy 10.5MeV and other ^{68}Zn(p,2n)^{67}Ga has 723.8mb at an energy20.5MeV.

The representation of the cross-section area of (p, n), (p, 2n) and (p, 3n) reaction for the same element Mo show the cross-section area of both reactions has different peak point i.e. ^{100}Mo(?, n)^{99}Mo has 151.7mb at energy 14.4MeV, ^{100}Mo(p, 2n)^{99}mTc has 236.8mb at energy 15.5MeV and other ^{100}Mo(d, 3n)^{99}mTc has 263.4mb at an energy 22MeV.

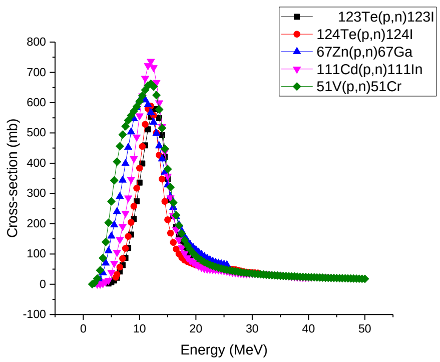


Figure 3: Representation of (p, n) nuclear reaction cross-section vs kinetic energy of incidence particles at the target of a different element

Figure 3 is the representation of five (p, n) reactions of a different element to study the nature of the cross-section area of the element with the emission of a single neutron after energized article incidence on the target. The maximum cross-section area in reaction ^{123}Te(p ,n)^{123}I, ^{124}Te(p ,n)^{124}I, ^{67}Zn(p, n)^{67}Ga, ^{111}Cd(p, n)^{111}In, and ^{51}V(p, n)^{51}Cr are 578.8mb, 588.8mb, 609mb, 662.4mb and 736.5mb respectively with corresponding energies 12.5MeV, 12MeV, 11MeV, 12MeV and 12MeV respectively. This shows that the energies ranges 11MeV to 12.5MeV produce maximum cross-section area of the different element by the emission of a single neutron. Therefore to obtain the maximum cross-section area between 578.8mb to 736.5mb one can select any element or replaced one element with another.

As we increase the kinetic energy of incidence on target the cross-section area goes on the increase and at a certain point the cross-section area of all (p, n) reaction maximum and then with an increase in the energy of incidence particle the cross-section area goes decrease. Decreasing the cross-section area with an increase in energy match with a narrow band of energy and cross-section area where all the cross-section area of difference elements goes likely to be equivalent i.e. cross-section lies in 380mb to 269.8mb and energy 14.5MeV to 16MeV.

This range is quite interesting and this research is also focusing in this narrow band energy, this narrowband region of both energy and cross-section area help to replace one element by another for the study of different field related to cross-section area.

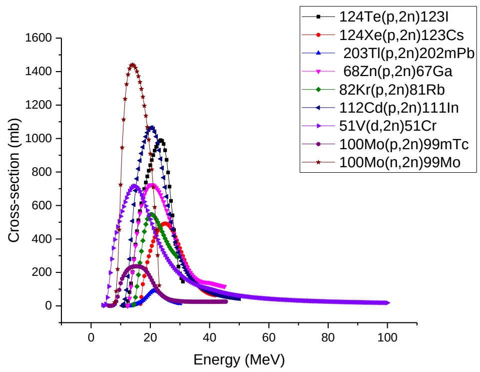


Figure 4: Representation of (p, 2n) nuclear reaction cross-section vs kinetic energy of incidence particles at the target of a different element

The maximum cross-section of (p, 2n) reaction of different elements are given in figure 4, the reaction ^{124}Te(p, 2n)^{123}I, ^{124}Xe(p, 2n)^{123}Cs, ^{203}Tl(p, 2n)^{202m}Pb, ^{68}Zn(p, 2n)^{67}Ga, ^{82}Kr(p, 2n)^{81}Rb, ^{112}Cd(p, 2n)^{111}In, ^{51}V(d, 2n)^{51}Cr, ^{100}Mo(p, 2n)^{99m}Tc, ^{100}Mo(n, 2n)^{99}Mo are 900mb, 492.2mb, 92.7mb, 723.8mb, 547.2mb, 990mb, 715.8mb, 236.8 and 1441.4mb respectively while the corresponding energies are 23.5MeV, 25MeV, 18MeV, 20.5MeV, 20.5MeV, 20.5MeV, 14.5MeV, 15.5MeV and 14MeV respectively.

As we increase the kinetic energy of incidence on target the cross-section area goes on the increase and at a certain point the cross-section area of all (p, 2n) reaction maximum and then with an increase in the energy of incidence particle the cross-section area goes decrease. Decreasing the cross-section area with an increase in energy match with a narrow band of energy and cross-section area where all the cross-section area of difference elements goes likely to be equivalent i.e. cross-section lies in 457.2mb to 348.7mb and energy 27.5MeV, which is our research interest.

The difference in (p, n) and (p, 2n) reaction there is a narrow band region in which cross-section area and energy both in which one can replace by another. Moreover, in (p, 2n) reaction a fixed point for the energy of the corresponding cross-section is seen.

IV. RESULTS AND DISCUSSION

The cross section area of (p, n) and (p, 2n) nuclear reaction of the same element are independent of each other but behavior is the same i.e. cross-section increase with the increase in MeV of incidence particles and decrease after certain value with increase MeV of incidence particles on target. Moreover, the narrowband region is not found throughout the reaction, for the visualization one can see in figure 2 with considering nuclear reaction.

The cross-section area follows the narrowband region in (p, n) reaction when the reaction takes with a different element, one can visualize in figure 3 among considering nuclear reaction. The interesting this about this reaction is the narrow band reaction is formed after the maximum cross-section area. This indicates that in this region the cross-section of the different elements can be exchanged or replaced by one another. The increasing and decreasing cross-section with increasing energy is sharply in (p, n) reaction type. This indicates the nature of all elements involved in (p, n) reaction is the same.

In (p, 2n) reaction also a narrowband region of cross-section and energy is seen as shown in figure 4, but the narrow bandwidth in this type of reaction is greater than (p, 2n) reaction. The sharpness of the graph is not seen as figure 3 of (p, n) reaction. This may be due to the absorption of the incidence energy and vibration of the nucleus after the absorption of energy, which causes to increase in the cross-section area. But in the case of (p, n) the change of vibration of the nucleus is very low because the emission of the single neutron is taken place and the vibration is negligible. Also, the energy needed for (p, n) reaction is less than (p, 2n) reaction.

This study of sharp peak or narrow band of both reactions is showing that the variation of cross section area, which is the objective of this work.

V. CONCLUSION AND FUTURE SCOPE

The narrowband region of the cross-section area in both (p, n) and (p, 2n) reaction show that the cross-section area is exchangeable. The sharpness of figure 3 shows that the vibrational energy of nucleons after the incidence of a particle on target is negligible in (p, n) reaction while the flatten graph seen in figure 4 is due to the vibrational energy of nucleons after absorption of energy from incidence particle on target in (p, 2n) reaction. This also shows that the cross-section area of (p, n) and (p, 2n) has no relation to each other as shown in figure 2, and flatten in the graph show that cross section area of (p, n) is less than (p, 2n).

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