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The systematics of (n, α) reaction cross-sections at 14.5 MeV neutron energy

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Abstract : A comprehensive review of the experimental data for 14.5 MeV neutron induced reaction cross-sections for (n, α) reaction has been made for the isotopes having Z up to 82. Two different parameter groups have been considered by the classification of nuclei into odd-mass and even-even nuclei. The empirical formulae with two parameters for the evaluation of (n, α) reaction cross-sections are discussed in the present study. The odd-even effects have been observed as the cross-sections of odd-mass nuclei are higher as compared to their neighboring even-even nuclei. The shell effects have also been established at magic nucleon numbers for these reaction cross-sections.

Keywords : Cross-sections, shell effects, odd-even effects, magic numbers.

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1. Introduction

When a nucleon interacts with a nucleus, different processes can take place. The primary reactions like (n, n'), (n, p) and (n, α) induced by 14 MeV neutrons are quite prominent for the designing concept of fusion and fission reactors, study of reaction mechanism, in extracting useful information about nuclear structure, neutron dosimetry, radiation damage to materials, activation analysis, shielding *etc.* For fast neutron dosimetry *via* multiple foil activation technique, an extensive knowledge of activation cross-sections, especially in the energy range of 14 MeV, is needed. In studies on low yield reactions like (n, d), (n, t) and (n, He^3), where thick samples are commonly used, the (n, p) and (n, α) reactions leading to activation products are ideally suited as internal flux monitor reactions.

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Nuclear cross-section data are generated mostly by nuclear physics experiments and also by nuclear theory using nuclear reaction model codes. Many of the nuclides produced in the reactor have short half lives, so they are unstable and it is not possible to measure their cross-sections directly. A large number of empirical and semi-empirical formulae with different parameters for cross-section calculation of the reactions like (*n, p*), (*n,* α) and (*n*, 2*n*) at the different neutron energies have been proposed by several authors [1–16]. Belgaid and Asghar [17] obtained a semi-empirical formulae which includes five parameters and have shown for the first time a strong dependence of the (*n, p*) cross-sections in terms of the parameter $(2Z - 1)/A$. In the present work, an attempt has been made to develop an empirical relation for (*n,* α) reaction cross-sections at 14 MeV neutron energy using least square fitting which shows the Z/A dependence of the (*n,* α) cross-sections. Such empirical relation can be very useful for predicting cross-sections of the isotopes when experimental data are not available. The odd-even effects have been shown by the plots of $\sigma_{n,\alpha}$ *vs. Z*. The shell effects have also been established at magic nucleon numbers.

2. Results and discussion

The experimental data for (*n,* α) reaction cross-sections at 14.5 MeV neutron energy have been collected from the references listed in CINDA-2007 [18] and from the report by Pashchenko [19].

2.1. Odd-even effect :

The nuclei with even number of both protons and neutrons are most stable, while odd-odd nuclei are the least stable. The nuclei having even number of protons and odd number of neutrons and *vice-versa* are known as odd-mass nuclei and have intermediate degree of instability. Hence, the odd-even nuclei have higher cross-sections than their neighboring even-even nuclei and this odd-even effect is distinctly marked when neutron excess is small *i.e.*, for lighter nuclei.

The plots of $\sigma_{n,\alpha}$ *vs. Z* for “the most abundant isotopes or the isotopes having comparable abundances” have been shown in Figures 1(a) and 1(b) for even-even, odd-mass and odd-odd isotopes and are discussed below.

In Figure 1(a), for Z up to 45, the odd-even effect is clearly visible, as the cross-section values are less for even-even nuclei as compared to their neighboring odd-mass nuclei. The cross-sections of odd-even isotopes $^{37}Cl_{20}$, $^{51}V_{28}$, $^{87}Rb_{50}$, $^{89}Y_{50}$ following the behavior of magic neutron numbers N = 20, 28 and 50 are low as compared to their neighboring even-even isotopes. There are few exceptions in the lower mass region which are difficult to explain. The cross-section of odd-odd nuclei are also higher as compared to their neighboring even-even and odd-mass nuclei.

Figure 1(b), for Z = 45–75, clearly shows odd-even effects with the exceptions of $^{139}La_{82}$ and $^{141}Pr_{82}$ which follow the expected behavior of very low cross-sections $\sigma_{n,\alpha}$ having magic neutron number N = 82. In heavy mass region the cross-sections for

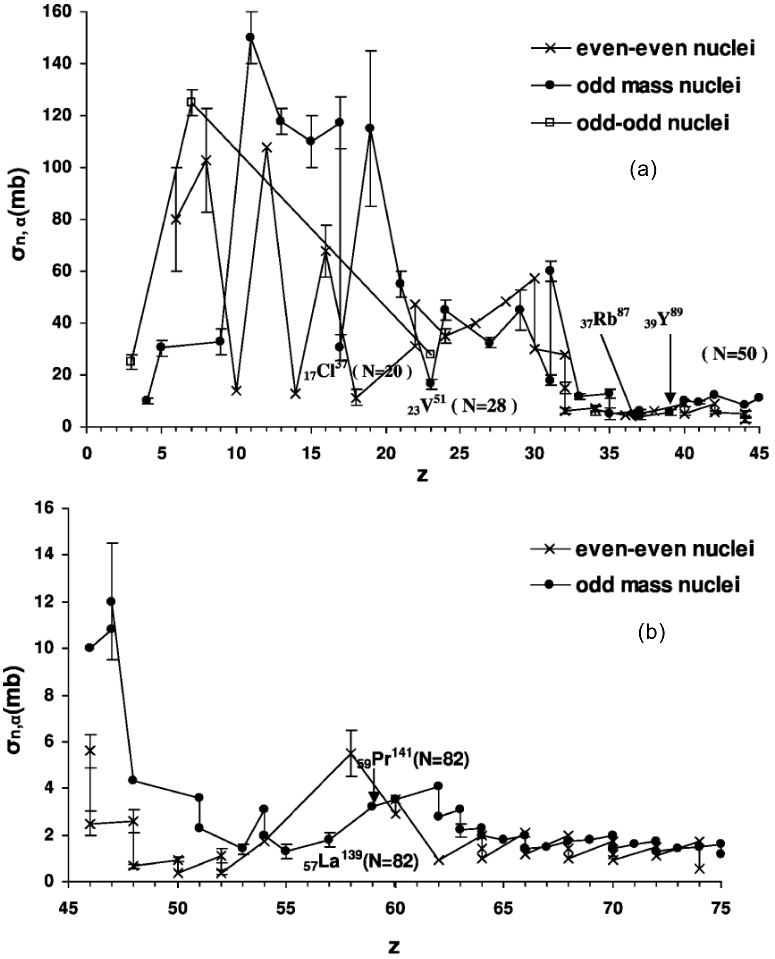

Figure 1. Plot of $\sigma_{n,\alpha}$ *vs.* Z for the isotopes which are most abundant or having comparable abundances for (a) Z = 3–45 and (b) Z = 46–75.

even-even and odd mass nuclei do not differ much. It is noticed that with increase in Z the difference in Q-values is small, the odd-even effects decrease gradually and finally disappear in heavy mass region.

2.2. Empirical relation :

An empirical relation for (n, α) reaction cross-sections have been derived using least squares fitting. A regression model has been developed which predicts the cross-sections *vs.* Z/A for the isotopes having $0.39 \leq Z/A \leq 0.49$. Different regression equations were tried and the exponential trend was found to give the best fit equation as shown in Figure 2(a). The empirical relation thus obtained for (n, α) reaction cross-sections is given by

$$\sigma_{n,\alpha} = a(A^{1/3} + 1)^2 \exp(bZ/A) \qquad \text{(mb)} \qquad (1)$$

where a and b are fitting parameters. They have the following values :

$a = 1.4 \times 10^{-14}$, $b = 70.1596$

The coefficient of determination is given by $R^2 = 0.9419$.

The validity of these fittings is defined by R-square *i.e.* coefficient of determination or square of the correlation coefficient which when equals to 1, indicates the best fit [16,20]. It is the % variability defined by the fitting equation. The model which gives maximum R^2 is selected, as this interprets the maximum variability in data set.

The values predicted with the above equation are compared with the experimental data. Such comparison [16,21] of the predicted cross-sections with the experimental values shows that the agreement is quite satisfactory.

Figure 2(b) shows the dependence of $\sigma_{n,\alpha}$ on the alpha particle separation energy (S_α) of the target nucleus. The empirical relation thus obtained is given by

$$\sigma_{n,\alpha} = a(A^{1/3} + 1)^2 \exp(bS_\alpha) \qquad \text{(mb)} \qquad (2)$$

Here the fitting parameters a and b have the following values :

$a = 0.064$, $b = 0.3033$

The coefficient of determination is given by $R^2 = 0.4924$.

From Figures 2(a) and 2(b) it is concluded that the quality of fit is not good when we choose S_α over the proton fraction (Z/A). Hence we prefer $\sigma_{n,\alpha}$ *vs.* Z/A plot.

Here it is to mention that when we plot the global data (all the data together), the odd-even effect is not prominent. So we can ignore this effect when we choose the variable as Z/A.

2.3. Shell effect :

The plots of $\sigma_{n,\alpha}$ *vs.* Z and N in the region of magic nuclei $Z = 20, 28, 50$ and $N = 20, 28, 50$ are found to show shell effects.

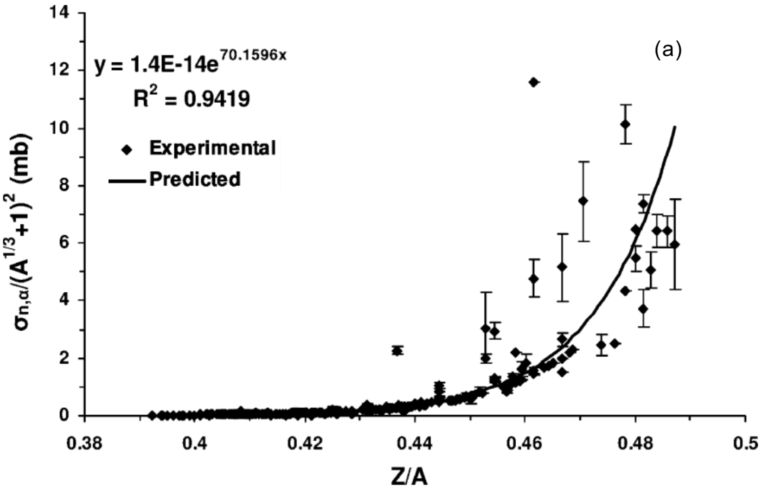

Figure 2(a). Plot of $\sigma_{n,\alpha}$ *vs.* Z/A for nuclei having $0.39 \leq Z/A \leq 0.49$.

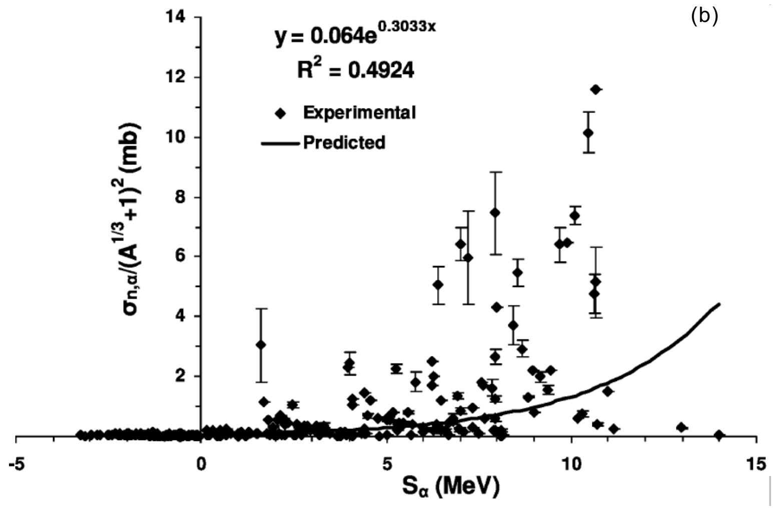

Figure 2(b). Plot of $\sigma_{n,\alpha}$ *vs.* S_α.

In the region from N = 12–52, plots of $\sigma_{n,\alpha}$ *vs.* N have been shown in Figure 3(a) for N–Z = 2, 3 and 8. For N–Z = 2, the shell effect is clearly satisfied with minima at N = 28 for $^{54}Fe_{28}$, as compared to the neighboring isotopes. When N–Z = 3 and 8, one sided minima have been observed at magic neutron numbers N = 20 and 28 as no data are available on their left side.

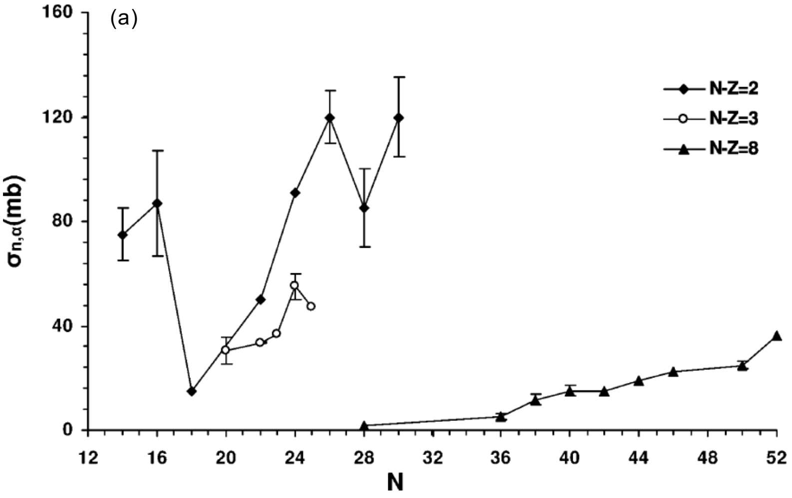

Figure 3(a). Plot of $\sigma_{n,\alpha}$ *vs.* N for the isotopes having N–Z = 2, 3 and 8.

Figure 3(b) shows region from Z = 20–44 with neutron excess N–Z = 5, 6 and 8. When N–Z = 5, the shell effect is distinct for $_{28}Ni^{61}$. It is odd-even nuclei with minimum cross-section when compared with neighboring odd-even nuclei $_{27}Co^{59}$ and $_{29}Cu^{63}$ having the same neutron excess. When N–Z = 6 and 8, at Z = 20 the trend shows one sided minima for $_{20}Ca^{46}$ and $_{20}Ca^{48}$ due to non-availability of data points on

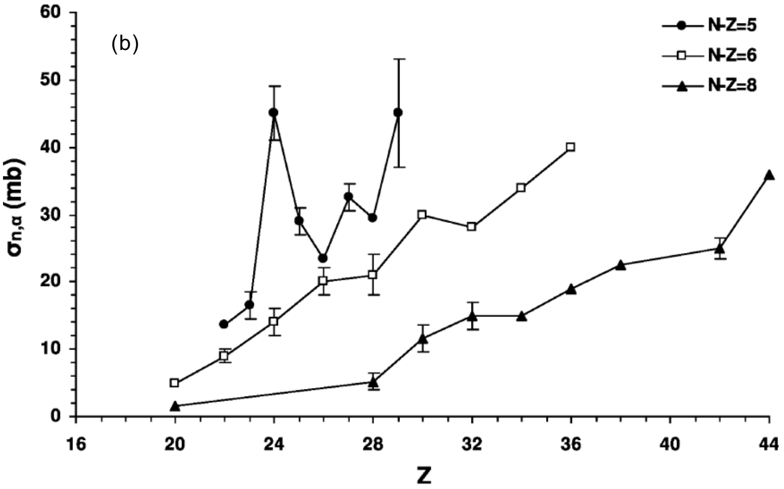

Figure 3(b). Plot of $\sigma_{n,\alpha}$ *vs. Z* for the isotopes having *N–Z* = 5, 6 and 8.

left side of Z = 20 for same neutron excess. Also at *Z* = 28, $_{28}Ni^{64}$ shows minima as compared to the cross-section of $_{30}Zn^{68}$.

Figure 3(c) shows plots of $\sigma_{n,\alpha}$ *vs. N* having shell effect with minima at *N* = 50 for the isotopes $^{90}Zr_{50}$, $^{89}Y_{50}$, $^{87}Rb_{50}$ and $^{86}Kr_{50}$ for *N–Z* = 10, 11, 13 and 14 respectively, as compared to their neighboring isotopes.

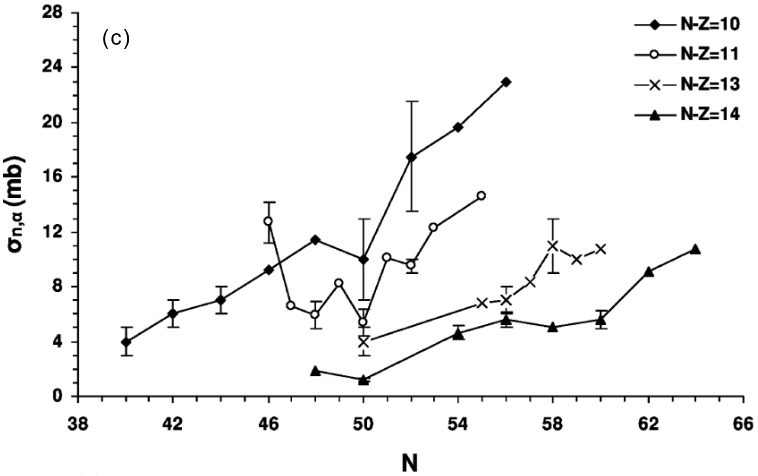

Figure 3(c). Plot of $\sigma_{n,\alpha}$ *vs. N* for the isotopes having *N–Z* = 10, 11, 13 and 14.

For *Z* = 40–62, Figure 3(d) shows the plots of $\sigma_{n,\alpha}$ *vs. Z*, when *N–Z* = 16,19 and 20. The shell effect has been observed with minima at Z = 50 for *N–Z* = 16 and 20. For *N–Z* = 19, the trend shows one sided minima due to non-availability of data points on the left side of *Z* = 50 for the same neutron excess.

Figures 4(a)–4(c) shows the correlation between cross-sections against A for the isotopes having *A* = 4*n* number (*i.e.* for C-12, O-16, Ne-20,…., Ca-40 isotopes), 4*n*+1 number (*i.e.* for Be-9, C-13,…,Si-29), 4*n*+2 number (*i.e.* Mg-26, Si-30,…,Ni-58), 4*n*+3

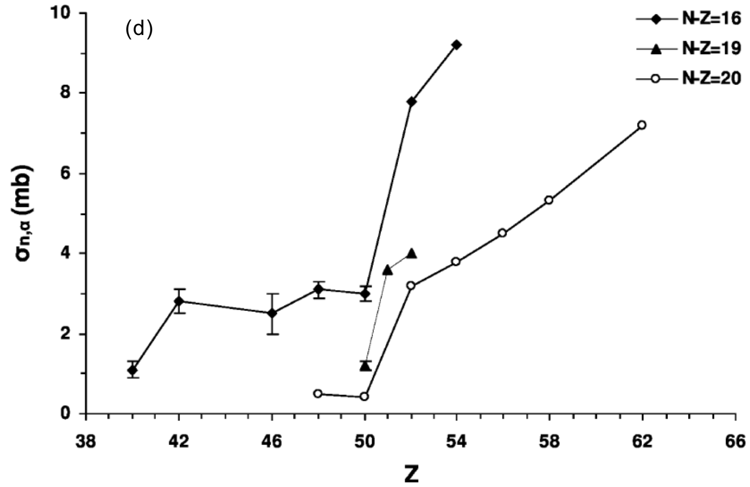

Figure 3(d). Plot of $\sigma_{n,\alpha}$ *vs. Z* for the isotopes having *N–Z* = 16,19 and 20.

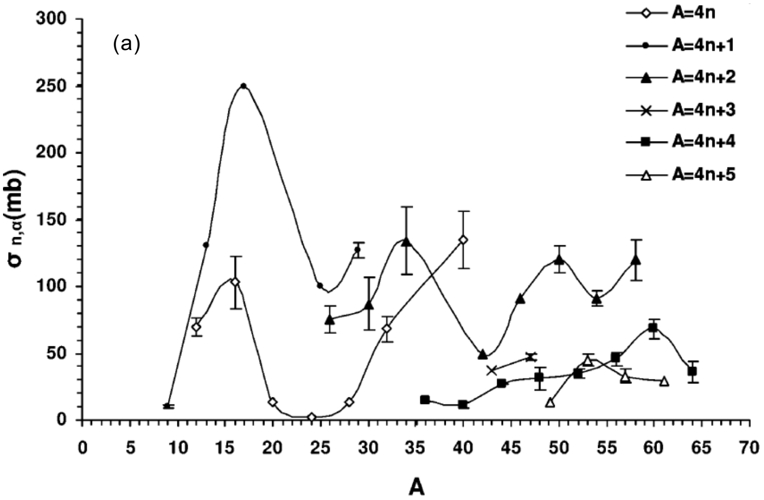

Figure 4(a). Plot of $\sigma_{n,\alpha}$ *vs. A* for the isotopes having *Z*-even and *A* = 4*n* (with *N* = Z), 4*n*+1 (with *N–Z* = 1), 4*n*+2 (with *N–Z* = 2), 4*n*+3 (with *N–Z* = 3), 4*n*+4 (with *N–Z* = 4) and 4*n*+5 (with *N–Z* = 5).

number (*i.e.,* Ca-43 and Ti-47), 4*n*+4 number (*i.e.,* S-36, Ar-40,…, Zn-64), 4*n*+5 number (*i.e.,* Ti-49,…, Ni-61), 4*n*+6 number (*i.e.,* Ca-46, Ti-50,…, Kr-78), 4*n*+8 number (*i.e.,* Ca-48, Ni-64,…, Ru-96), 4*n*+9 number (*i.e.,* Ge-73 and Se-77), 4*n*+10 number (*i.e.,* Zn-70, Ge-74,…, Pd-102), 4*n*+11 number (*i.e.,* Kr-83, Sr-87,…, Ru-99), 4*n*+12 number (*i.e.,* Ge-76, Se-80,…, Sn-112), 4*n*+13 number (*i.e.,* Mo-97, Ru-101 and Pd-105), 4*n*+14 number (*i.e.,* Se-82, Kr-86,…, Sn-114), 4*n*+16 number (*i.e.,* Zr-96, Mo-100,…, Xe-124), 4*n*+17 number (*i.e.* Cd-113 and Sn-117), 4*n*+18 number (*i.e.* Pd-110, Cd-114,…, Ba-130), 4*n*+19 number (*i.e.,* Sn-119 and Te-123) and 4*n*+20 number (*i.e.,* Cd-116, Sn-120,…, Sm-144). For these nuclei the cross-sections behave in a smooth manner as in Figures 4(b) and 4(c). From these Figures we see that no strong odd-even and shell effects have been observed, whereas when we select the data for most abundant

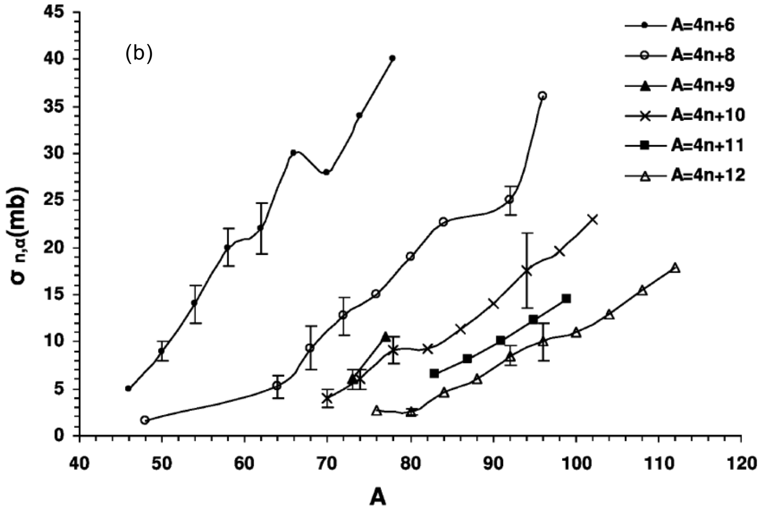

Figure 4(b). Plot of $\sigma_{n,\alpha}$ *vs. A* for the isotopes having Z-even and A = 4*n*+6 (with *N–Z* = 6), 4*n*+8 (with *N–Z* = 8), 4*n*+9 (with *N–Z* = 9), 4*n*+10 (with *N–Z* = 10), 4*n*+11 (with *N–Z* = 11) and 4*n*+12 (with *N–Z* = 12).

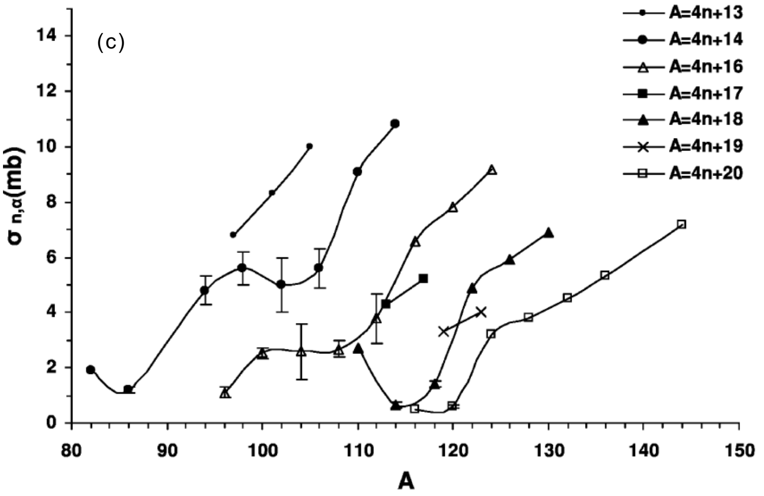

Figure 4(c). Plot of $\sigma_{n,\alpha}$ *vs.* A for the isotopes having *Z*-even and *A* = 4*n*+13 (with *N–Z* = 13), 4*n*+14 (with *N–Z* = 14), 4*n*+16 (with *N–Z* = 16), 4*n*+17 (with *N–Z* = 17), 4*n*+18 (with *N–Z* = 18), 4*n*+19 (with *N–Z* = 19) and 4*n*+20 (with *N–Z* = 20).

isotopes or the isotopes having comparable abundances, the odd-even effects have been observed as in Figures 1(a) and 1(b).

It has been observed from these Figures that, on the average, for the same incident neutron energy, the (*n*, α) reaction cross-sections decrease with the increase in mass number of the target nuclei. The similar variation was observed by Qaim *et al.* [22] in case of (*n*, *t*) reaction cross-sections of ^{27}Al, ^{59}Co and ^{93}Nb. This is due to the fact that for medium and heavy mass nuclei (*Z* between 15 and 92), as a result of high negative *Q*-values and the increasing coulomb barrier for emission of charged particles, the (*n*, charged particle) reaction cross-sections in heavier nuclei are expected to be small.

3. Conclusion

The odd-even effects have been observed as the cross-sections of odd-mass nuclei are higher than their neighboring even-even nuclei. In heavy mass region, the odd-even effect is diluted since with the increase in *Z*, the difference in *Q*-values of odd-mass and even-even nuclei gets smaller and neutron excess becomes larger. So, the odd-even effects decrease gradually and finally disappear.

The new empirical relation obtained may be very useful for the quick estimation of the cross-sections, where experimental data are not available as well as in testing new experimental results. It is found that Z/A is a good parameter to describe the variation of $\sigma_{n,\alpha}$. We have tried plotting $\sigma_{n,\alpha}$ *vs.* S_α, but the overall quality of fits is better with Z/A as the variable. There are few exceptions which cannot be predicted by these formulae and which are difficult to explain. When we plot the global data, the odd-even effect is not prominent. Hence, we can ignore this effect, when we choose variable as Z/A in Figures 1(a) and 1(b). The shell effects have also been predicted at magic nucleon numbers.

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