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Calculation of Excitation Function of Nuclear Data and Reaction Cross-Section for Silicon Isotopes Induced by Alpha

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ABSTRACT

Reaction cross-sections and Excitation Functions were evaluated and calculated for productions of Silicon 28, 29 and 30 isotopes in the energy range from 1 to 20 MeV using EXIFON 2.0 CODE. The shell structure effect on the reaction cross-section were also investigated, the results obtained shows that the cross-section reaction of (*a*, *2n*) for silicon 28 and (*a*, *2n*) for silicon 29, both with shell correction and without shell correction are zeros at energies range considered, this shows that the energy of the incident particle is below the threshold of the reaction due to the present of coulomb repulsive force between the projectile and target nucleus. Results are benchmark and validated with data from the experimental database (EXFOR), and evaluated database (ENDF) from the International Atomic Energy Agency (IAEA) nuclear data bank. From the calculated data obtained, some of the results of the calculated excitation functions are in good agreement with the evaluated data (ENDF), some are in fair agreement, while some disagree with the evaluated data. There are no experimental results (EXFOR) for most of the calculated excitation function.

Keywords: Exifon code, ENDF, EXFOR, Cross-section.

1. INTRODUCTION

Studies of excitation functions of particle-induced reactions are of considerable significance for testing nuclear models as well as for practical applications. Nuclear reaction in the intermediate energy region is a matter of interest in some fields of technology and science such as reactor technology, radiation therapy in nuclear medicine, medical radionuclide production, diagnostic and therapeutic studies, Accelerator Driven Systems, fusion and fission reactor.

The artificially produced radioactive isotopes are important for many different applications. [Srivastava, S.C. 1996, 1971, Sadeghi, M. 2011 and Al-Saleh, *et al.*, 2007].

Nuclear reactions data are mainly needed for optimization of production routes [Abusaleem, K. 2014, Akovali, Y.A. 2004 and Nichols, A.L. 2002]. The cross section data for different nuclide was intensively investigated and up to now, the nuclear databases are accessible online [Basu, S.K., Sonzogni, A.A. 2013, and Menapace, E., *et al.*, 2005].

A nuclear reaction is a process that occurs when a nuclear particle (nucleon or nucleus) gets into close contact with another [Al-Saleh, *et al.,* 2007]. In the general case, an arbitrary number of particles may emerge. The probability of the reaction processes as a function of the energy of the incident particle, in the energy and the direction of the outgoing particles is usually interested in the whole set of reactions.

To calculate the reaction cross section, it is necessary to compute the number of particles that disappear from the elastic channel, what is measured by the flux of the current of probability vector through a spherical surface of large radius centered at the target [Bertulani, C.A. 2009]

Nuclear reaction cross section is one of the most important quantities which we encounter easily in nuclear reactions. It can simply be defined as the probability of interaction. Thus given a reaction of a given type, the cross section for that reaction is the probability that reaction will take place or simply the probability of occurrence of the said reaction. We can define the cross section for absorption, called absorption cross-section, or for scattering called scattering cross section, or fission called fission cross section.

2. CODE AND EQUIPMENT

The EXIFON CODE is based on an analytical model for statistical multistep direct and multistep compound reactions. It predicts emission spectra, angular distributions, and activation cross sections for neutrons, protons, alpha particles, and photons. Multiple particle emissions are considered up to three decays of the compound system.

EXIFON is an easy to handle and fast code which predicts cross sections from one global parameter set. The only adjustable quantity is the pairing shift. The output of EXIFON can also be arranged into ENDF/B-6 format.

For this work the EXIFON code was installed on a Hewlett-Packard (hp), HP 650 Notebook PC, with processor of Intel(R) Pentium(R) CPU B970 @ 2.30GHz, RAM of 2.00GB and ROM of 242GB, with a system type of 32-bit operating system. The system was partitioned to have both a 64 bit windows OS and 32-bits Windows Os. The EXION code was installed in the 32- bits OS for stable running.

3. EXECUTION OF CALCULATION IN EXIFON 2.0 CODE

In Exifon 2.0 code, the following 11 steps for the execution of calculation for Alpha induced reaction cross-section are listed below.

Step 1: INPUT directory c:\exifon\ to be changed < 0-no / 1-yes >

0

Step 2: INPUT directory c:\exifon\ to be changed < 0-no / 1-yes >

0

Step 3: Target Nucleus <Input file>

Si28, 29 and 30.

Step 4: Incident Particle?

Alpha ———→ 2

Step 5: GENERAL OPTION

Excitation function ———→ 2

Step 6: Number of Incident Energies

20

Step 7: 1st Incident Energy <in MeV>

1

Step 8: Incident energy step <in MeV>

1

Step 9: MODIFICATIONS

Shell structure effects ———→ 2

Step 10: Shell effects

With ———→ 0

OR

Without ———→ 1

Step 11: MODIFICATIONS

No ———→ 0

Step 12: Repeat step 1 through 11 with different target nucleus and incident particle.

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The option with shell effect is selected for each target nucleus, an output data (OUTEXI) for the calculation is then stored in the set output directory. Also DAT file name A2N, ALF, and AP (for Alpha-2Neutron, Alpha-Alpha, and Alpha-Proton reaction respectively) are stored in the set output directory.

Secondly, the option without shell effect is then also for each target nucleus, also an output data (OUTEXI) for the calculation is then stored in the set output directory. Also DAT file name A2N, ALF, and AP (Alpha-2Neutron, Alpha-Alpha, and Alpha-Proton reaction respectively) are stored in the set output directory.

4. SHELL STRUCTURE EFFECTS

The shell structure effects are considered in SMC processes. Under such a situation, the single particle state density g, in Equation g = 4ρ (EF) is multiplied by the factors

$$(1+\frac{\delta W}{E_X}\,[\,1-exp\,(-\gamma E_X)]) \qquad (1)$$

With γ = 0.05MeV^{-1} and δW as the shell correction energy, where the quantity E_X= E or U which denotes the excitation energy of the composite or residual systems respectively.

The calculations in this study were performed with ($\delta W \neq 0$) and without ($\delta W = 0$) shell corrections. The procedures WITH and WITHOUT shell correction were repeated several times and the results of cross sections were obtained.

5. RESULTS AND DISCUSSION

Table 1: Cross section for Alpha induced reactions of ^{28}Si in the 1-20MeV energy range from EXIFON code.

Element	Energy (Mev)	Cross Section With Shell Correction (mb)			Cross Section Without Shell Correction (mb)		
		(a, p)	(a, a)	$(a, 2n)$	(a, p)	(a, a)	$(a, 2n)$
	1.00	0.00	0.00	0.00	0.00	0.00	0.00
	2.00	0.00	0.00	0.00	0.00	0.00	0.00
	3.00	0.00	0.00	0.00	0.00	0.00	0.00
	4.00	46.31	1.33	0.00	46.57	1.30	0.00
	5.00	132.38	9.33	0.00	131.79	9.98	0.00
	6.00	241.10	37.04	0.00	241.21	36.97	0.00
	7.00	376.68	82.09	0.00	376.51	82.28	0.00
	8.00	488.11	147.15	0.00	488.57	146.71	0.00
	9.00	552.56	217.27	0.00	552.56	217.28	0.00
^{28}Si	10.00	591.84	278.61	0.00	590.87	280.04	0.00
	11.00	606.59	334.93	0.00	605.25	337.87	0.00
	12.00	612.41	380.58	0.00	610.60	385.45	0.00

	13.00	619.90	415.51	0.00	617.21	422.27	0.00
	14.00	623.65	445.15	0.00	620.09	453.67	0.00
	15.00	626.39	467.88	0.00	622.21	477.96	0.00
	16.00	629.27	485.75	0.00	624.45	479.17	0.00
	17.00	633.37	497.72	0.00	627.17	511.00	0.00
	18.00	638.81	503.62	0.00	631.70	518.39	0.00
	19.00	643.77	507.14	0.00	635.76	523.28	0.00
	20.00	648.80	507.36	0.00	639.94	524.83	0.00

Silicon 28, which has an Even-Even Nucleus (proton-14, neutron-14), it is clearly seen that in the energy range of 1 – 20MeV, the (*a, p*) reaction is the most dominant reaction channel in the interaction. Looking at the data from the table 1 above, the (*a, p*) reaction has the highest cross section in 20MeV. With comparison in term of the shell correction, it shows that cross section is higher when the shell correction is considered.

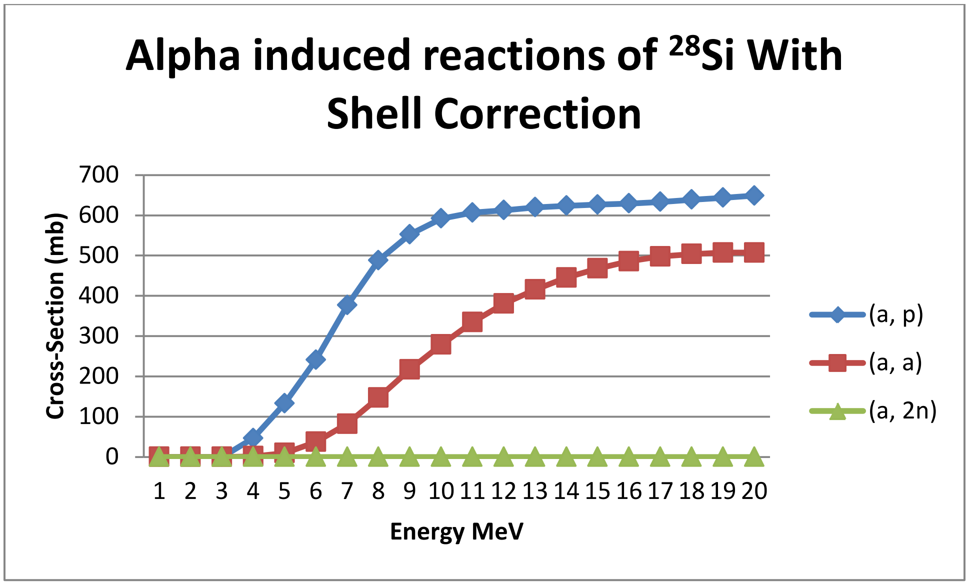

Fig 1: Excitation function of Alpha induced reactions of ^{28}Si with shell correction. It is clearly seen that (*a, p*) reaction is the dominant reaction channel in the interaction, with peak cross-section of 648.80mb, with a corresponding energy of 20MeV. The threshold energy of (*a, p*) reaction is 3.40 MeV, cross section of 0.1 mb. With comparison in terms of the shell correction, it shows that cross section is higher when the shell correction is considered.

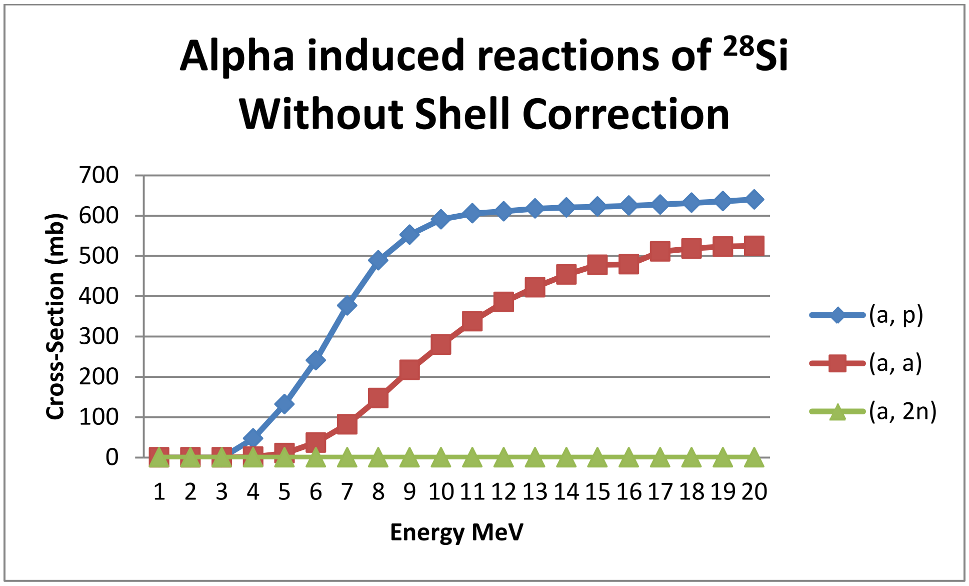

Fig 2: Excitation function of Alpha induced reactions of ^{28}Si without shell correction. It is clearly seen that (*a*, *p*) reaction is the dominant reaction channel in the interaction, with peak cross-section of 639.94mb, with a corresponding energy of 20MeV. The threshold energy of (*a*, *p*) reaction is 3.40 MeV, with cross section of 0.1 mb.

Table 2: Cross section for Alpha induced reactions of ^{29}Si in the 1-20MeV energy range from EXIFON code.

Element	Energy (MeV)	Cross Section With Shell Correction (mb)			Cross Section Without Shell Correction (mb)		
		(*a*, *p*)	(*a*, *a*)	(*a*, *2n*)	(*a*, *p*)	(*a*, *a*)	(*a*, *2n*)
^{29}Si	1.00	0.00	0.00	0.00	0.00	0.00	0.00
	2.00	0.00	0.00	0.00	0.00	0.00	0.00
	3.00	0.00	0.00	0.00	0.00	0.00	0.00
	4.00	1.91	14.88	0.00	2.10	15.42	0.00
	5.00	117.66	27.80	0.00	114.50	30.30	0.00
	6.00	199.51	51.63	0.00	193.58	51.82	0.00
	7.00	287.58	92.32	0.00	284.18	92.50	0.00
	8.00	372.07	137.93	0.00	366.40	137.00	0.00
	9.00	438.57	175.29	0.00	428.35	174.96	0.00
	10.00	478.07	212.48	0.00	464.02	212.08	0.00
	11.00	508.43	244.15	0.00	490.11	244.41	0.00
	12.00	526.04	274.61	0.00	504.18	275.45	0.00
	13.00	538.36	301.38	0.00	513.22	302.65	0.00
	14.00	547.92	324.14	0.00	519.81	326.00	0.00
	15.00	553.47	344.66	0.00	522.84	346.98	0.00
	16.00	557.63	362.14	0.00	524.76	364.93	0.00
	17.00	559.95	377.27	0.00	525.19	380.47	0.00
	18.00	561.45	389.99	0.00	525.03	393.53	0.00
	19.00	562.61	400.42	0.00	524.70	404.32	0.00
	20.00	563.06	409.09	0.07	523.86	413.31	0.06

Silicon 29, which has an Even-Odd Nucleus (proton-14, neutron-15), it is clearly seen that in the energy range of 1 – 20MeV, the (*a*, *p*) reaction is the most dominant reaction channel in the interaction. Looking at the data from the table 2 above, the (*a*, *p*) reaction has the highest cross section in 20MeV. With comparison in term of the shell correction, it shows that cross section is higher when the shell correction is considered.

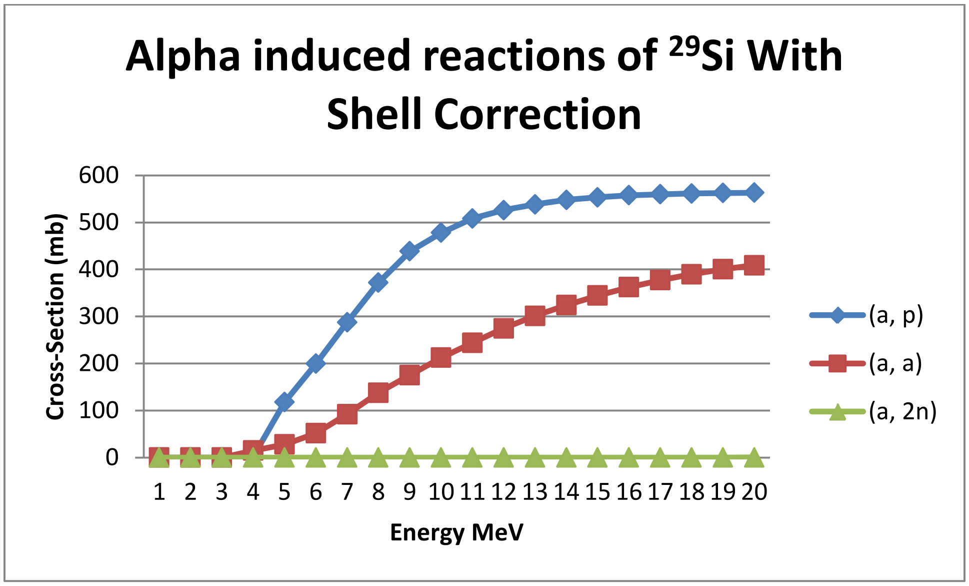

Fig 3: Excitation function of Alpha induced reactions of ^{29}Si with shell correction. It's clearly shows that (*a*, *p*) reaction is the dominant reaction channel in the interaction, with peak cross-section of 563.06mb, with a corresponding energy of 20MeV. The threshold energy of (*a*, *p*) reaction is 3.93 MeV, with cross section of 1.90 mb.

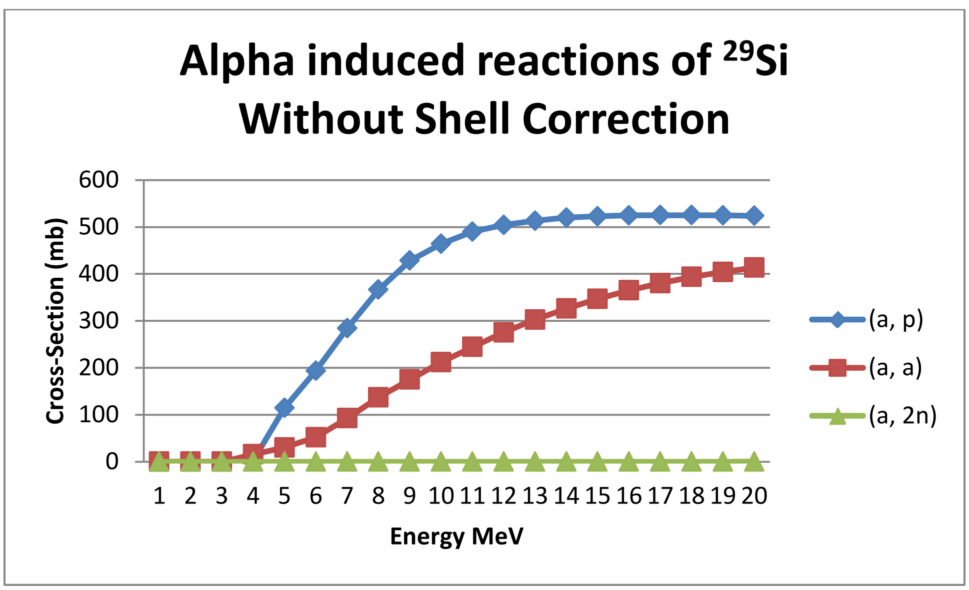

Fig 4: Excitation function of Alpha induced reactions of ^{29}Si without shell correction. It is clearly seen that (*a, p*) reaction is the dominant reaction channel in the interaction, with peak cross-section of 523.86mb, with a corresponding energy of 20MeV. The threshold energy of (*a, p*) reaction is 3.93 MeV, with cross section of 2.1 mb.

Table 3: Cross section for Alpha induced reactions of ^{30}Si in the 1-20MeV energy range from EXIFON code.

Element	Energy (Mev)	Cross Section With Shell Correction (mb)			Cross Section Without Shell Correction (mb)		
		(*a, p*)	(*a, a*)	(*a, 2n*)	(*a, p*)	(*a, a*)	(*a, 2n*)
^{30}Si	1.00	0.00	0.00	0.00	0.00	0.00	0.00
	2.00	0.00	0.00	0.00	0.00	0.00	0.00
	3.00	0.00	0.00	0.00	0.00	0.00	0.00
	4.00	0.00	5.35	0.00	0.00	5.40	0.00
	5.00	2.76	3.71	0.00	2.80	4.16	0.00
	6.00	16.76	14.41	0.00	16.93	15.43	0.00
	7.00	44.56	35.32	0.00	44.85	36.59	0.00
	8.00	73.78	68.85	0.00	74.06	71.12	0.00
	9.00	99.23	107.36	0.00	99.46	110.83	0.00
	10.00	125.02	150.05	0.00	124.80	154.87	0.00
	11.00	142.80	190.76	0.00	142.37	197.29	0.00
	12.00	159.65	229.13	0.00	158.83	237.21	0.00
	13.00	173.06	260.36	0.00	171.98	270.07	0.00
	14.00	185.37	283.33	0.00	184.10	294.72	0.00
	15.00	197.43	302.05	1.84	195.87	315.05	1.93
	16.00	208.20	315.16	18.28	206.43	329.77	19.19
	17.00	218.91	324.46	34.63	216.87	340.62	36.86
	18.00	228.88	329.95	52.08	226.62	347.63	56.03
	19.00	238.48	333.26	80.20	235.97	352.39	85.91
	20.00	247.30	335.45	94.54	244.56	355.97	101.86

Silicon 30, which has an Even-Even Nucleus (proton-14, neutron-16), it is clearly seen that in the energy range of 1 – 20MeV, the (*a, a*) reaction is the most dominant reaction channel in the interaction. Looking at the data from the table 3 above, the (*a, a*) reaction has the highest cross section in 20MeV. With comparison in term of the shell correction, it shows that cross section is higher when the shell correction is not considered.

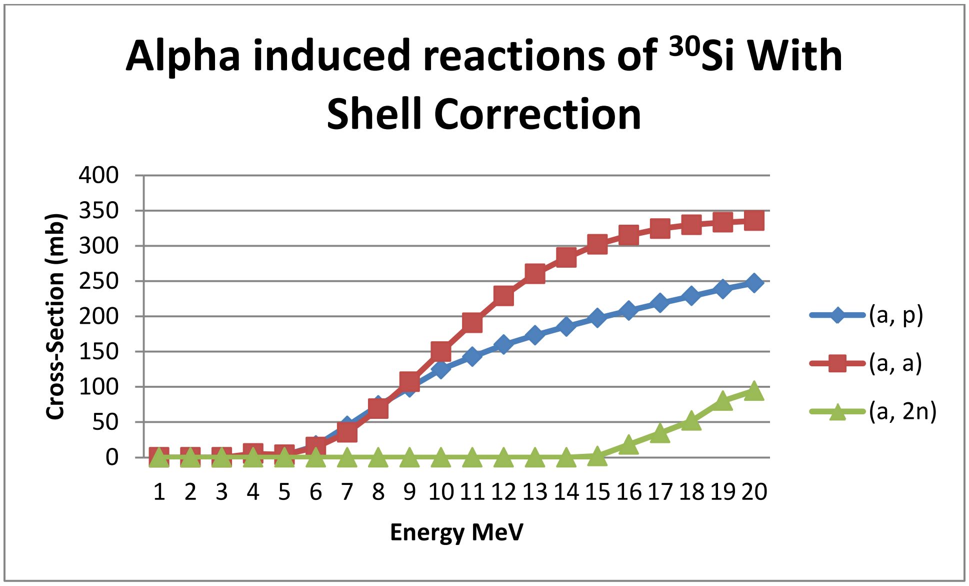

Fig 5: Excitation function of Alpha induced reactions of ^{30}Si with shell correction. It is clearly seen that (*a*, *a*) reaction is the dominant reaction channel in the interaction, with peak cross-section of 335.45mb, with a corresponding energy of 20MeV. The threshold energy of (*a*, *a*) reaction is 3.70 MeV, with cross section of 0.2 mb.

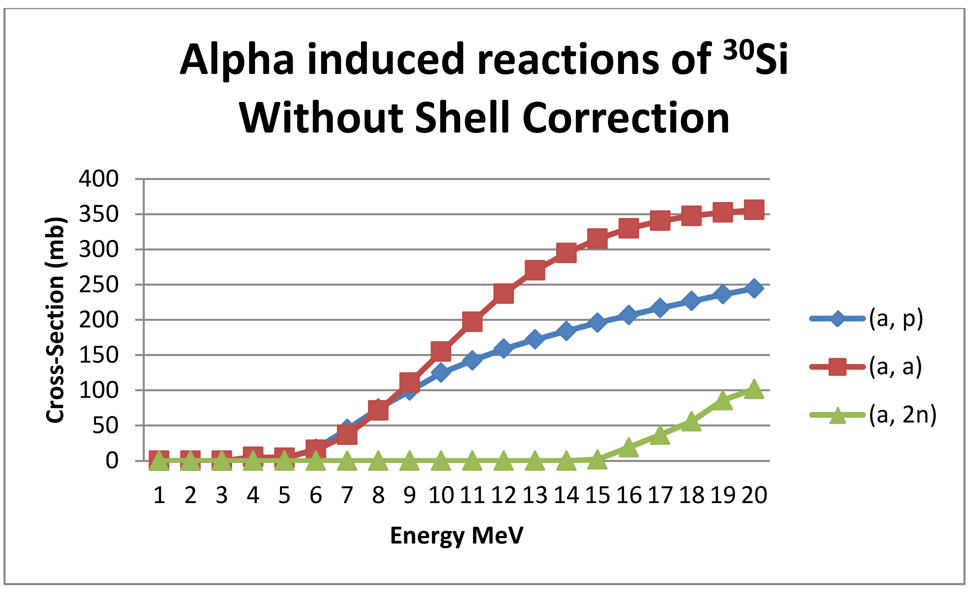

Fig 6: Excitation function of Alpha induced reactions of ^{30}Si without shell correction. It is clearly seen that (*a*, *a*) reaction is the dominant reaction channel in the interaction, with peak cross-section of 355.97mb, with a corresponding energy of 20MeV. The threshold energy of (*a*, *a*) reaction is 3.70 MeV, with cross section of 0.2 mb. With comparison in terms of the shell correction, it shows that cross section is higher when the shell correction is considered.

6. BENCHMARKING AND VALIDATION OF RESULTS

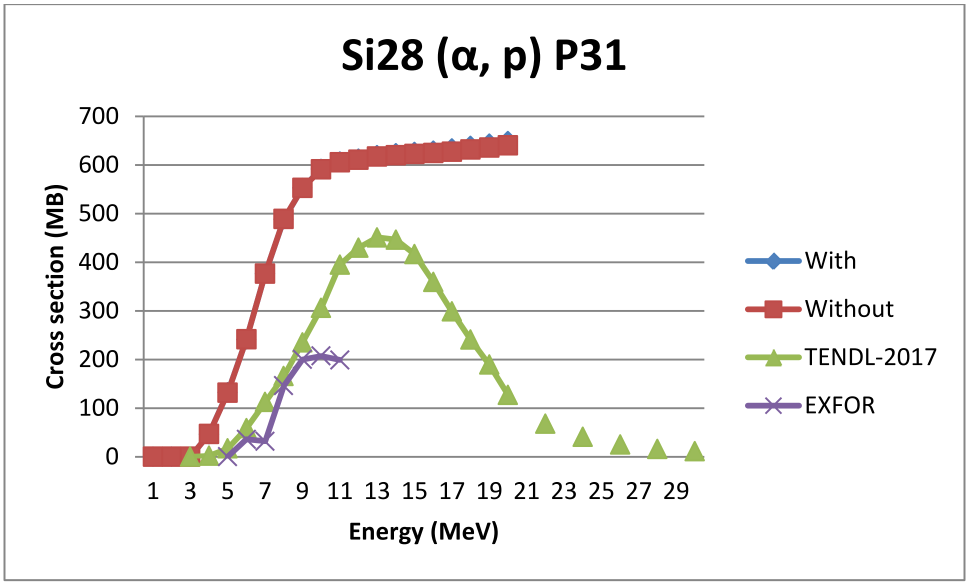

Fig. 7: Cross-section against energy for the $^{28}Si\ (a, p)\ ^{31}P$ reaction

The $^{28}Si\ (a, p)\ ^{31}P$ reaction cross-section starts to generate values at 4 MeV. Evaluated data are available up to 30 MeV. Comparison with EXFOR values could only be made from 5.24571-11.4971 MeV (M.A. Buckby and J.D. King 1984). The calculations from EXIFON over predict the evaluated data. Fig.10 shows that the calculations from EXIFON over predict the experimental data of Buckby and King (1984)

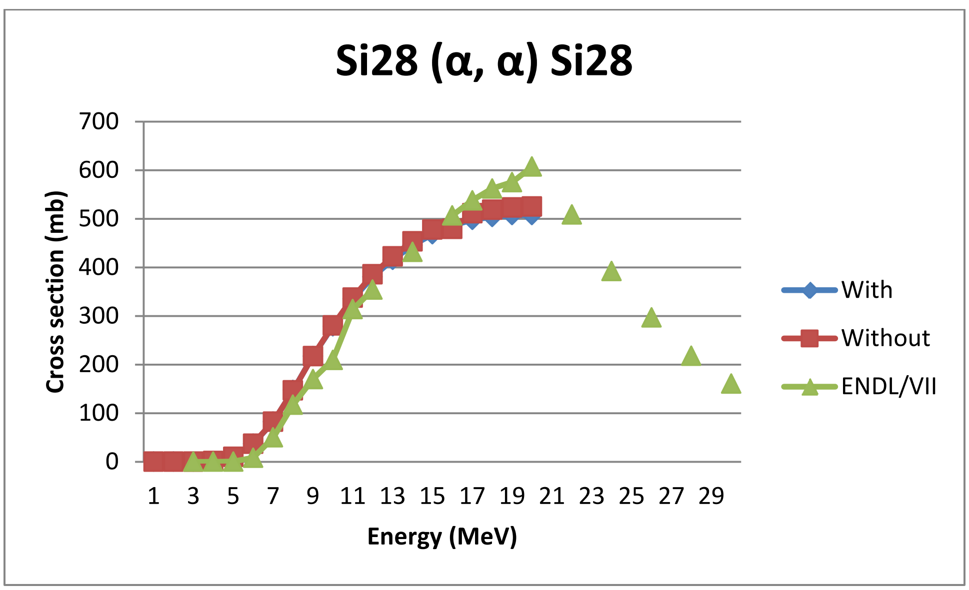

Fig. 8: Cross-section against energy for the $^{28}Si\ (a, a)\ ^{28}Si$ reaction

The ^{28}Si *(a, a)* ^{28}Si reaction cross-section starts to show values at 4 MeV. Evaluated data are available up to 30 MeV. There are no experimental results for the $28_{Si}\ (\alpha,\ \alpha)\ 28_{Si}$ reaction cross-section in the EXFOR database. Fig. 8 shows that results of the EXIFON code calculation are in fair agreement with evaluated data From 4 – 16 MeV energy regions.

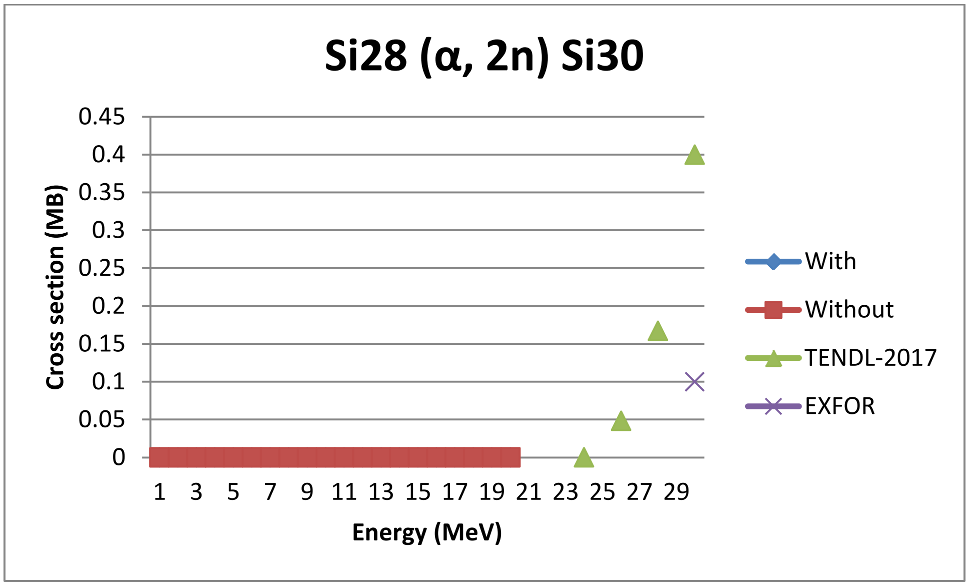

Fig. 9: Cross-section against energy for the ^{28}Si *(a, 2n)* ^{30}Si reaction

The ^{28}Si *(a, 2n)* ^{30}Si reaction cross-section starts to generate values at 4 MeV. Evaluated data are available from 24.2675 to 30 MeV. Comparison with EXFOR values could only be made at 29.95 MeV (D.J. Frantsvog *et al.*, 1982). The calculations from EXIFON under predict the evaluated data.

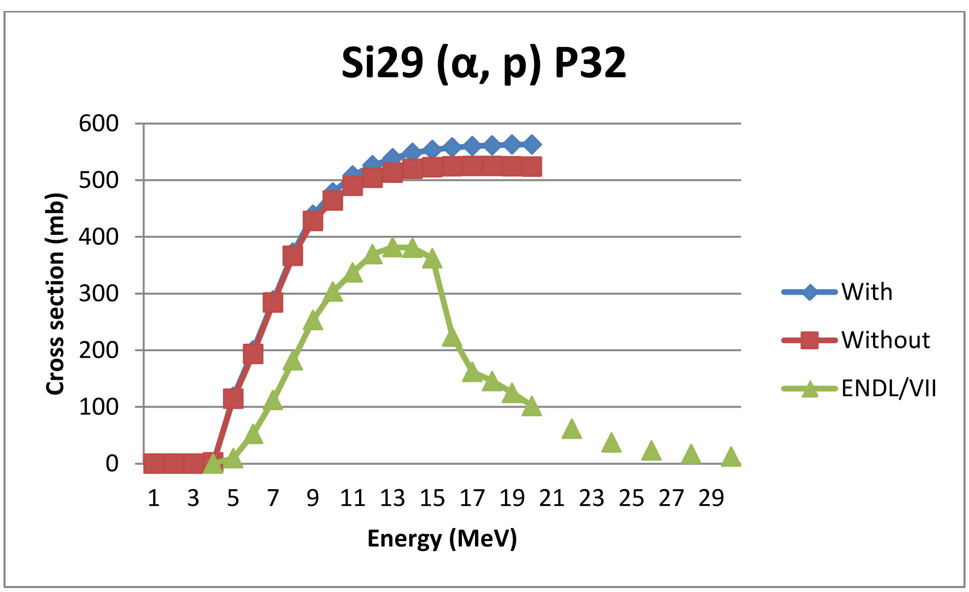

Fig. 10: Cross-section against energy for the ^{29}Si *(a, p)* ^{32}P reaction

The $^{29}Si\ (a, p)\ ^{32}P$ reaction cross-section starts to show values at 4 MeV. Evaluated data are available up to 30 MeV. The calculations from EXIFON over predict the evaluated data.

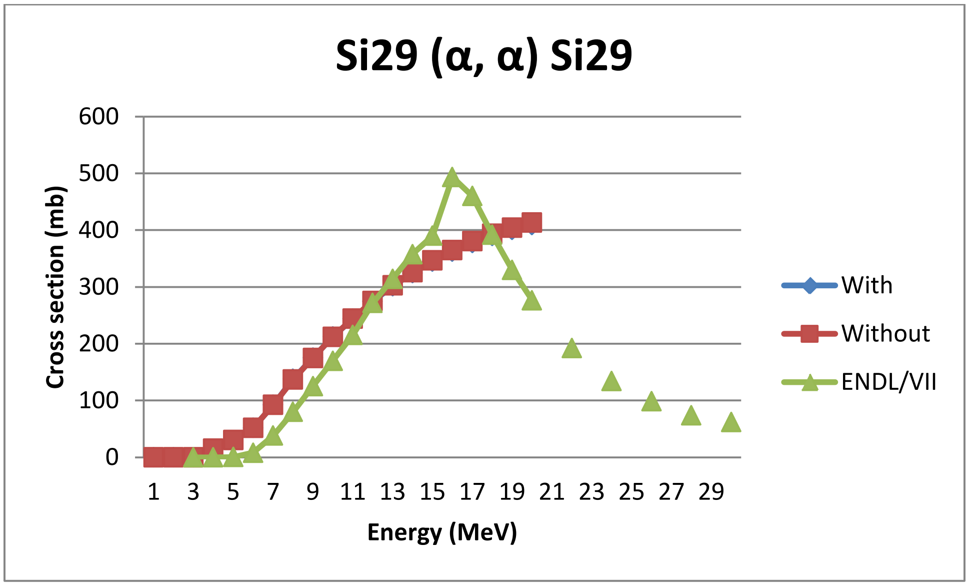

Fig. 11: Cross-section against energy for the $^{29}Si\ (a, a)\ ^{29}Si$ reaction

The $^{29}Si\ (a, a)\ ^{29}Si$ reaction cross-section starts to show values at 4 MeV. Evaluated data are available up to 30 MeV. There are no experimental results for the $29_{Si}\ (\alpha,\ \alpha)\ 29_{Si}$ reaction cross-section in the EXFOR database. Fig. 11 shows that results of the EXIFON code calculation are in good agreement with evaluated data From 12 – 14 MeV energy regions.

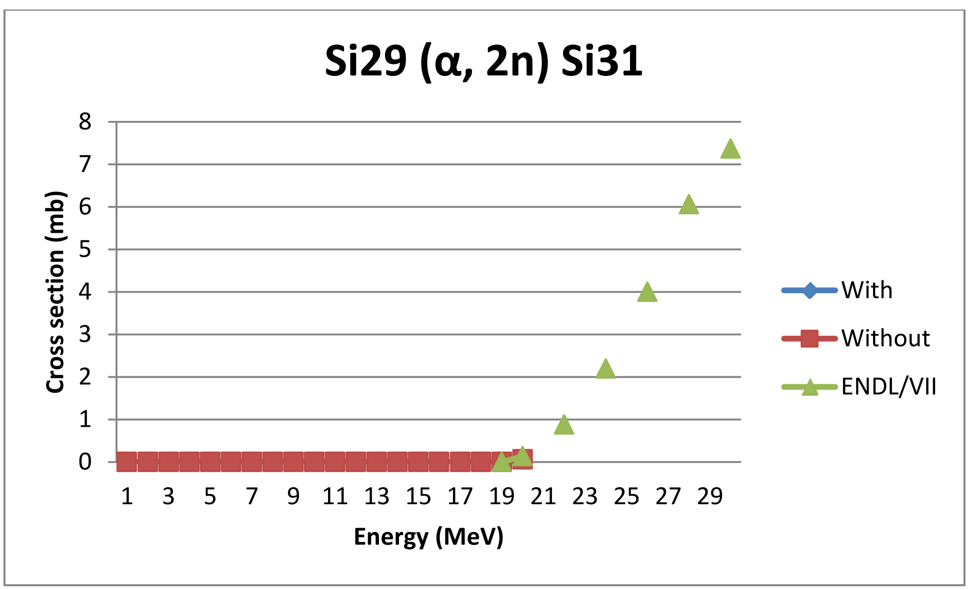

Fig. 12: Cross-section against energy for the $^{29}Si\ (a, 2n)\ ^{31}Si$ reaction

The $^{29}Si\ (a,\ 2n)\ ^{31}Si$ reaction cross-section starts to show values at 20 MeV. Evaluated data are available from 18.868-30 MeV. There are no experimental results for the $29_{Si}\ (a,\ 2n)\ 31_{Si}$ reaction cross-section in the EXFOR database. The calculations from EXIFON under predict the evaluated data.

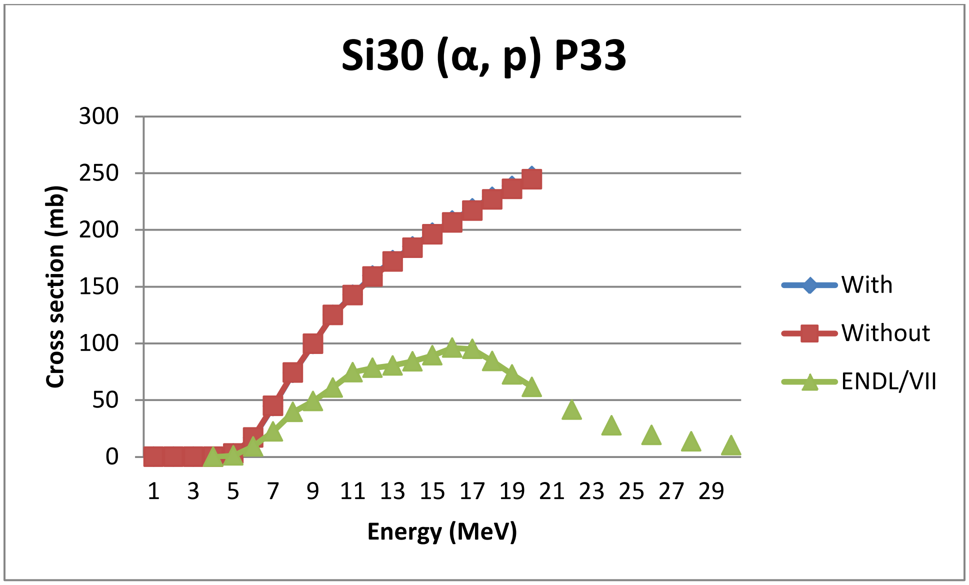

Fig. 13: Cross-section against energy for the $^{30}Si\ (a,\ p)\ ^{33}P$ reaction

The $^{30}Si\ (a,\ p)\ ^{33}P$ reaction cross-section starts to show values at 5 MeV. Evaluated data are available up to 30 MeV. There are no experimental results for the $30_{Si}\ (a,\ p)\ 33_{P}$ reaction cross-section in the EXFOR database. Fig. 13 shows that results of the EXIFON code calculation are in fair agreement with evaluated data From 4 – 6 MeV energy regions. From 5 – 30 MeV, theoretical results over predict cross-sections from evaluated data library.

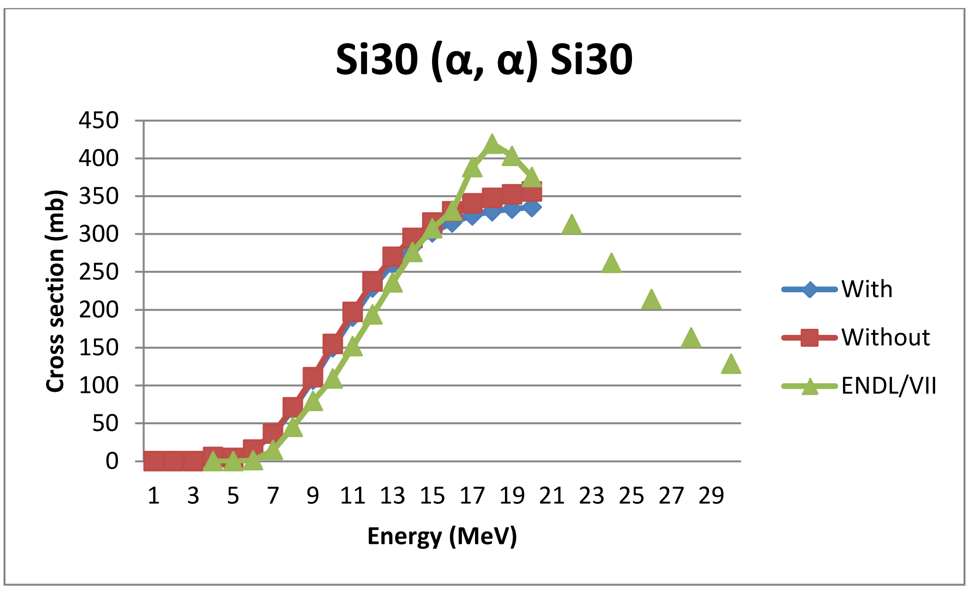

Fig. 14: Cross-section against energy for the $^{30}Si\ (a,\ a)\ ^{30}Si$ reaction

The $^{30}Si\ (a, a)\ ^{30}Si$ reaction cross-section starts to show values at 4 MeV. Evaluated data are available up to 30 MeV. There are no experimental results for the $30_{Si}\ (\alpha,\ a)\ 30_{Si}$ reaction cross-section in the EXFOR database. Fig. 14 shows that results of the EXIFON code calculation are in fair agreement with evaluated data From 14 – 16 MeV energy regions.

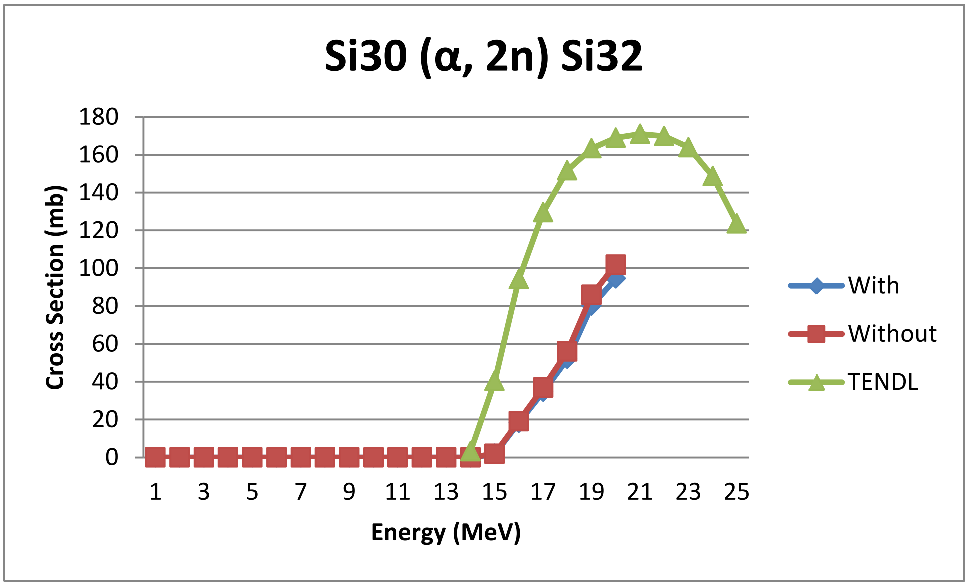

Fig. 15: Cross-section against energy for the $^{30}Si\ (a, 2n)\ ^{32}Si$ reaction

The $^{30}Si\ (a, 2n)\ ^{32}Si$ reaction cross-section starts to show values at 15 MeV. Evaluated data are available from 13.6958 to 30 MeV. There are no experimental results for the $^{30}Si\ (a, 2n)\ ^{32}Si$ reaction cross-section in the EXFOR database. The calculations from EXIFON under predict the evaluated data.

CONCLUSION

Nuclear model calculations of cross-section for alpha induced reactions of silicon isotopes where performed using the statistical multistep reaction code EXIFON. Calculated values have also been compared with experimental data from other authors and evaluated data from the IAEA Nuclear Data Section library. Where there are no experimental and evaluated data, and where existing data are discrepant or scarce, the EXIFON code was able to predict cross-section.

Results obtained differ from experimental data in the input parameter used in EXIFON code.

Due to the lack of measured cross-sections beyond 30 MeV, more experimental data are needed in order to further test the reliability of the theoretical calculations.

The theoretical model code (EXIFON) was able to predict the cross section data where no experimental data exist. Another advantage of the EXIFON code is that it was able to provide information for most of the cross section data for the silicon isotopes. For some set of target nuclides experimental data (EXFOR) were scanty and discrepant. The EXIFON 2.0 CODE is very flexible in predicting reaction cross-section.

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