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MASS - DEPENDENCE FOR DIFFERENT UNCLEAR REACTIONS ON LIGHT NUCLEI

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ABSTRACT

The mass - dependence - effect for one - particle transfer nuclear reactions at three different incident energies is presented and discussed. Particular emphasis is placed on the (^3He, α_o) - reaction on 1p - shell nuclei and a similarity between the features of the mass - dependence relations for the different types of reactions under study is found. Theoretical calculations of spectroscopic factors are presented and discussed to explain this effect.

INTRODUCTION

In certain nuclear reactions the integrated cross - sections for ground states transitions are dependent on the mass number of the targets used. There are remarkable differences between even - even, odd - odd and odd - even nuclei, especially when the reaction is of a direct mechanism.

Takamatus[1] has found, for the (d, α) - reactions on nuclei with atomic mass number A = 14 - 32, that the integrated cross - section for ground states transitions in the case of α - like nuclei is about a factor of three larger than the case of non α - like nuclei. This effect is found also for transitions to the lowest excited states[2,3]. Klabes et. al.[4] have found the same effect in case of (d, α_o) - reactions on ^{12}C and ^{13}C isotopes. Their results were consistent with the mass dependence observed for other nuclei. The integrated cross - section of ground state in ^{13}C (d, α) - reaction at deuteron incident energy E_d = 14 MeV is smaller by a factor of five than that in ^{12}C (d, α) reaction as shown in Fig. 1a[5].

The mass dependence effect and it's energy dependence are studied intensively by the Tuebingen group[5-14] concerning the three nucleons - transfer reactions [(p, α) - and (n, α) - reaction] on light nuclei at incident energies in the range 14 - 45 MeV. They found that the integrated cross - sections for ground states transitions are strongly mass dependence and the mass dependence for the (p, α_o) - reaction is negligibly decreases with increasing energy[7,14]. In the same time they have extended their measurements to the mass region of the 2s - 1d - shell nuclei[7,10]. Figure 1b illustrates the mass dependence for (P, α_o) - reaction on the 1p - shell nuclei at proton incident energy $E_p \approx$ 14 MeV[5] which is similar to that Takamatsu has found in the case of the (d, α_o) - reaction on light nuclei. Figure 2 demonstrates the mass dependence effect with increasing incident energy for (p, α_o) - reactions on the 1p - shell nuclei at three different proton incident energy[14].

The mass dependence for the (n, α_o) - reactions on the 1p - shell nuclei at neutron incident energy $E_n \approx 14$ MeV[5] is given also in Fig. 1c, which has the same characteristics as in both cases of (d, α_o) - and (p, α_o) - reactions presented also in Fig. 1. There is a correspondence between the results of the three considered reactions in this figure where the integrated cross - sections for the ground states transitions of the α - like nuclei as ^{12}C and ^{16}O are considerably large compared to that for the non α - like nuclei.

(^3He, α_0) - REACTIONS

In the present work we are intersted to study more intensively ($^3He,\alpha_o$)-reaction. The experimental data for the mass - dependence of the ($^3He,\alpha_o$)-reaction on 1p - shell nuclei are presented in Fig. 3 and given also in Table1[15-30]. Figure 3 shows that the integrated cross - sections σ_{int} (0-90°) for the angular range (0° ≤ Θ C.M. ≤ 90°) for α - like nuclei as ^{12}C and ^{16}O is large compared to that of the non α - like nuclei (^7Li, ^9Be, ^{10}B, ^{11}B, ^{13}C, ^{14}N, ^{15}N and ^{18}O). The experimental finding of the mass - dependence at ^3He - particle incident energy $E_{^3He} \approx 10$ MeV is obviously clear where the σ_{int} (0 - 90°) for ^{12}C is 20 times larger than that of ^{10}B and ^{13}C nuclei at the same energy and σ_{int} (0 - 90°) for ^{16}O is 10 times larger than that of ^{18}O and is 7 times larger than that of the ^{15}N.

At 25 MeV ^3He - particle incident energy the σ_{int} (0 - 90°) for ^{12}C - nucleus is 14 and 3 time larger than that for ^{13}C and ^9Be respectively and σ_{int} (0 - 90°) for ^{16}O is 2.4 times larger than that of ^{14}N.

At 33 MeV ^3He - paricle incident energy the σ_{int} (0 - 90°) for ^{12}C - nucleus is 4 and 23 time greater than that for ^{11}B and ^{13}C nuclei respectively.

The accumulated experimental results of the angular distributions of the (^{3}He, α) - reaction on 1p - shell nuclei at $E_{^3He} \approx 10$ MeV are shown in Fig. 4[15-17, 20, 23-26,28].

EXPLANATION FOR THE MASS DEPENDENCE

There are three possibilities for explanation of the mass dependence of the intergrated cross - sections.

a) According to the theory of Hauser - Feshbach[31] for the compound - nucleus formation mechanism at low incident energies, there is a correlation between σ_{int} Q - values in the form.

$$\ln \sigma_{int} (a, \alpha_o) \approx - Q (a, \alpha_o) \qquad (1)$$

where a represents the incident particle, this correlation has been considered as an interpretation for the mass - dependence of the cross section for ground states transitions specially for the compound - nucleus nuclear reactions[5]. The mass dependence of the (p, α_o) cross - sections at higher incident energies is still present[7, 14]. At higher incident energy range in most cases a very small contribution of compound nucleus mechanism may be expected in the reaction or perhaps the reaction goes as a pure direct one[14] (this depends on the incident particle type, on it's incident energy, on reaction type and on the target nucleus).

b) In direct (d, α_o) - reaction on the 1p - shell nuclei the mass dependence could be explained as a consequence of an angular momentum mismatch[2, 4, 32]. The angular momentum is the difference in angular momentum between what is actually transferred to the rest - nucleus and the change in angular momentum between target and rest nucleus. This could be used also as an explanation for (p, α_o) - reaction[14] on the 1p - shell nuclei specially at low incident energies ≈ 14 MeV. The angular momentum mismatch could not applied at higher energies[7, 14].

It found previously that[5, 7, 14], the interpretation of the mass - dependence for the (p, α_o) cross - section together with the strong correlation between σ(p, α_o) and the appropriate Q - values (see Table 1 and 2) by means of either compound - nucleus formation method (a) or an angular momentum mismatch method (b) is insufficient, since in both cases the mass - dependence effect is expected to decrease with increasing incident energy[7].

c) Jahr et. al.[2], have suggested that this effect perhaps due to the cluster structure of the target nucleus. The spectroscopic factors could be used to identify the intensities of the ground and excited states. Calculations hav been done to determine the intensities of the excited states using the spectroscopic factors derived from Kurath and Millener[33] and Cohen and Kurath[34] specially for (p, α)-[7, 11 - 13], (d, α)-[12] and (p, ^{3}He)- reactions[35].

According to the Distorted - Wave Born - Approximation theory (DWBA) of the direct nuclear reactions the relation between the experimental cross - section $\sigma_{exp.}$ and the calculated one by this theory σ_{DWBA} is given by :

$$\sigma_{exp.} = \sigma_{DWBA} \cdot S \qquad (2)$$

where S is the spectroscopic factor. σ_{DWBA} contains all kinematics of the scattered particle and nucleus, as incident energy, Q - value, transferred angular momentum, while S includes the actual information about the structure of the nucleus. The conformity between the values of calculated S according to a certain nuclear - model and the experimental integrated cross-sections of a nucleus can be used as a test for the model itself.

DISCUSSION

The (^{3}He, α_o) - reaction angular distributions for most 1p - shell nuclei exhibit a diffraction pattern as shown in Fig. 4. This could be reproduced by the DWBA - theory calculations. The main mechanism presumable in the (^{3}He, α_o) - reaction on the 1p - shell nuclei $E_{^3He} \approx 10$ MeV is the direct reaction mechanism. So, one can explain this mechanism for each nucleus separately. The angular distributions from the target nuclei ^{7}Li, ^{11}B, ^{12}C, ^{15}N, ^{16}O and ^{18}O sloped down with the outgoing angle of the emitted particle, which expected for the direct mechanism[7, 24, 36]. In the case of ^{7}Li and ^{13}C targets one can suppose that the reaction is going partially as direct reation specially at forward direction and partially as heavy particle pick - up (HP - pick - up) or heavy particle knock out - (HP - knock - out) mechanism in backward direction. Also in the case of the ^{12}C and ^{16}O targets a smaller components of HP - pick - up or HP - knock - out mechanisms existed in case of ^{14}N (^{3}He, α_o) - reaction. Thus, we can conclude that, in most 1p - shell nuclei the reaction (^{3}He, α_o) at $E_{^3He} \approx 10$ MeV is going mainly as a direct reaction and a little component of compound nucleus formation mechanism. The HP - reactions could be neglected.

Table 2 contains the Q - values for the (^{3}He, α_o) - reaction, which are always positive and the binding energies of the last neutron in 1p - shell nuclei. It is clear from Tables 1 and 2 that the integrated cross - section is large for small Q - values and vice versa. This phenomena was observed also previously in (p, α_o) - reactions on the 1p -[14] and 2s -1d - shell nuclei[7].

The (^{3}He, α_o) - reaction on the 1p - shell nuclei in the forward direction (0 - 90°) is a direct 1p - neutron pick - up. In α - like nuclei ^{12}C, ^{16}O and ^{20}Ne the picked - up neutron is strongly bound in the nucleus in comparison with their neighbors [see Table 2], because this neutron is picked - up from an α - cluster in the target nucleus. Therefore the (^{3}He, α_o) - reaction on these nuclei have small Q - values [1.8566, 4.909 and 3.7130 MeV for the nuclei ^{12}C, ^{16}O and ^{20}Ne respectively] and great cross - sections, contrary to the case of the non α - like nuclei as ^{9}Be, ^{13}C, ^{17}O and ^{21}Ne (α - like nucleus + 1 neutron) where the picked - up neutron is weakly bound to these nuclei (the neutron exist as an unpaired particle in these nuclei). Therefore the (^{3}He, α_o) - reactions on these nuclei have large Q - values [18.912, 15.632, 16.4361 and 13.817 MeV for the nuclei ^{9}Be, ^{13}C, ^{17}O and ^{21}Ne respectively] and small cross - sections. This means that, in the ground states transitions for the non α - like tatgets, the picked - up neutron is weakely bound to the core of the target nucleus, specially those lead to α - like as residual nuclei. Consequently the cross - sections for the ground states transitions in the cases of non α - like nuclei are very small compared with that of the α - like nuclei, where the probability of the picking - up of a neutron from the α - clusters in these nuclei is very high and has many different possibilities with the same probability[7]. Between nuclei lie the values of integrated cross - sections of α - like - and the (α - like + 1 neutron) - nuclei lie the values of integrated cross - sections of the nuclei ^{6}Li, ^{10}B, ^{11}B, ^{14}N, ^{15}N, ^{18}O, ^{19}F and ^{22}Ne. Also one can expect that, there is a similarity between the integrated cross - sections of ($^{3}He,\alpha_{o}$)-reaction on the nuclei ^{11}B, ^{15}N, ^{19}F and ^{23}Na [(α - like - 1 proton) - nuclei].

Table 1 contains also the spectroscopic factors for single - particle transfer for 1p - shell - nuclei, which are calculated according to the shell - model predictions (Cohen and Kurath[34]). Also the intensities for the ground states transitions and also for excited states could be estimated by means of the values of the spectroscopic factors. Figure 3 illustrates a good correspondence between the integrated cross - sections and the values of the spectroscopic factors, which indicates that, the integtrated cross - sections are dependent on the structure of the target nucleus. This is in consistent with what found in the case of (p, α) - [7, 10 - 12, 14], (d, α) - [12] and (p, ^{3}He) - reactions[35] on the 1p - shell nuclei and ((p, α) - reactions on the 2s - 1d - shell nuclei[7,13]. The mass dependence in (^{3}He, α_{o}) - reaction at three energies 10, 25, 33 MeV is shown in Fig. 5.

Both of the two Figs. 3 and 5 are two different methods representing the mass - dependence effect for the (^{3}He, α) - reactions on 1p - shell nuclei at (^{3}He - particle incident energies of 10, 25 and 33 MeV. It is clear from the two figures that, the integrated cross - section for ground states transition on ^{12}C and ^{16}O are greater than that for their neighbors nuclei.

CONCLUSION

The mass - dependence effect found previously in the direct two - particles transfer (d, α) - reactions on light nuclei at 14 MeV incident energy[1 - 4], which was also found later for the direct three - paticles transfer reactions from the two - types (n, α) and (p, α) on light nuclei at the same incident particle energy[5]. In this study a similarity between the features of the mass - dependence effect for these three types of reactions is obtained, which shows that, the integrated cross - section for ground states transitions in the case of the α - like nuclei are greater than those of the non α - like nuclei. Also our study concerning the direct one - particle transfer (^{3}He, α) - reaction on 1p - shell nuclei at three different incident energies shows that, the results obtained in this work is in consistence with that found previously for the other types of transfer reactions. It is also found the integrated cross - sections for ground states transitions on the α - like nuclei ^{12}C and ^{16}O are relatively large in comparison to that for the non α - like nuclei. As a method for explaining this effect is the cluster structure for the target - nucleus, where the spectroscopic factors for target nuclei calculated theoretically by Cohen - Kurath using the shell - model wave - functions are used. A remarkable correlation between the values of integrated cross - sections for ground states transitions and that of the spectroscopic factors for the 1p - shell nuclei is obtained.

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FIGURE CAPTIONS

Fig. 1: Mass dependence for the reactions[5]:

a) (d, α_o) - reactions.

b) (p, α_o) - reactions.

c) (n, α_o) - reactions.

Fig. 2: Energy dependence for the mass dependence of the reaction (p, α_o) on 1p - shell nuclei at Ep = 14, 22.5 and 45 MeV[14].

Fig. 3: A comparison between the one - particle transfer spectroscopic factors as given by Cohen et. al. 1965, 1967 and the integrated cross-section σ_{int} (0 - 90°) for the (^{3}He, α_o) - reaction on the 1p - shell nuclei (Table 1).

Fig. 4: Angular distributions for the (^3He, α_o) - reactions on the 1p - shell nuclei at $E_{^3He} \approx 10$ MeV[15 - 17, 20, 23 - 26, 28].

Fig. 5: Futher representation for the comparison between the integrated cross - sections for the (^3He, α_o) - reactions and the one - particle transfer spectroscopic factors for the 1p - shell nuclei.

خلاصة

الإعتماد على عدد الكتلة للتفاعلات النووية المختلفة على الأنوية الخفيفة

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يقوم هذا البحث على دراسة ظاهرة إعتماد احتمالية حدوث تفاعل نووى ما على عدد كتلة نواة الهدف المستخدم فيه وذلك فى حالة التفاعلات النووية الخاصة بإنتقال جسيم واحد خلالها عند طاقات سقوط مختلفة للجسيم أو النويه المستخدمه لإحداث هذا التفاعل. ولقد وجه إهتمام خاص خلال هذا البحث للتفاعل النووى المباشر من نوع (^{3}He, α) على أنوية القشرة 1P - ولقد وجد تشابه تام بين سلوك تلك الظاهرة فى حالة التفاعلات المدروسة فى هذا البحث. وكأحدى طرق تفسير لظاهرة إعتماد احتمالية حدوث تفاعل نووى على عدد كتلة النواه المستخدمة كهدف فيه تم فى هذا البحث إستخدام ما يسمى "بالمعادلة الموجية التى تصف التركيب الداخلى لنواة ذلك الهدف وعلاقتها بمعادلات النواه النهائية والجسيم المنتقل فى التفاعل" والتى أمكن بحسابات نظرية تبعاً للنموذج القشرى للنواه The shell model استنتاج ما يسمى بالمعاملات المطيافية Spectroscopic factors كدلالة على تلك العلاقة وإستخدام قيم المعاملات المطيافية لتفسير هذه الظاهرة.

Table 1 : The integrated cross-sections of the ($^3He,\alpha_o$)-reaction at $E_{^3He} \approx 10$, 25 and 33 MeV on the 1p-shell nuclei and the corresponding spectroscopic factors for one particle transfer.

Target nucleus	$E_{^3He} \approx 10$ MeV		$E_{^3He} \simeq 25$ MeV		$E_{^3He} \approx 33$ MeV		Spectroscopic factors	
	σ (0-90°) mb	Reference	σ (0-90°) mb	Reference	σ (0-90°) mb	Reference	S	Reference
^7Li	1.703 a)	Zander et al 1971	---		---		0.721	Cohen & Kurath (1965, 1967)
^9Be	1.310	Roy et al 1975	9.425	Artemov et al 1968	---		0.58	""
^{10}B	---		---		1.626	Squier et al 1971	0.60	""
^{11}B	5.621	Coker et al 1973	---		7.052	Dehnhard et al 1969	1.094	""
^{12}C	97.606	Schwartz et al 1966	28.006	Fucks & Deschler 1973	27.942	Yamaji et al 1974	2.85	""
^{13}C	6.590	Deshpande 1965	2.006	Artemov et al 1968	1.227	Gaillard et al 1969	0.613	""
^{14}N	6.1366	Guazzoni et al 1971	5.491	" "	---		0.69	""
^{15}N	1.859	Bohne et al 1970	---		2.136	Drumm et al 1986	1.459	""
^{16}O	12.447	Papker Alford et al 1965	13.047	""	7.882 b)	Fucks & Deschler 1973	2.0	Roos et al 1975
^{18}O	1.082 a)	Détraz & Duhm 1969	---		---		0.49	Détraz & Duhm 1969

a) These values are at $E_{^3He} = 16$ MeV, b) This value is at $E_{^3He} = 28$ MeV.

INTRODUCTION

The transfer nuclear reaction is one of the most powerful ways of determining the properties of nuclear states. The one - nucleon - transfer nuclear reactions are the most simple, in this case the shapes of the angular distributions are characteristic for the orbital angular momentum transfer L_{tr} and also for the total angular momentum transfer J_{tr} ([1 - 3]). Using different one - nucleon transfer nuclear reactions on medium weight nuclei from ^{40}Ca up to ^{64}Ni nuclei ([2, 3]), two different J - dependence effects has been reported, one is at forward angle and the second is at backward angle. The origin of the first one is due to spin orbit effect in the wave function of the transferred particle and that of the second effect is due to spin - orbit coupling in the entrance and / or exit channels of the reaction ([2]).

A great value of the J - dependence lies in it's usefulness in determining fixing and correcting the spins of several states using (^3He, α) - nuclear reactions ([4]). Since the spin of the final state is given by $J_f = J_i + J_{tr}$, where J_i is the spin of the target and J_{tr} is the transferred total angular momentum, when $J_i = 0$ this give $J_f = J_{tr}$ and when $J_f = 0$, $J_i = J_{tr}$ in both cases the transferred total angular momentum is clear. Accordingly if the target has a zero spin, the spin of the final state(s) is simply given by the vectorial sum of the orbital and spin angular momenta of the transferred particle and if the final state has a zero spin, the previous vectrorial sum is equal to the target spin. Measurements of the polarization of the outgoing particle together with distorted wave - calculations or a simple comparison with the polarizations of the outgoing particle in reactions leaving the residual nucleus in states of known spins resolves the ambiguity in the determination

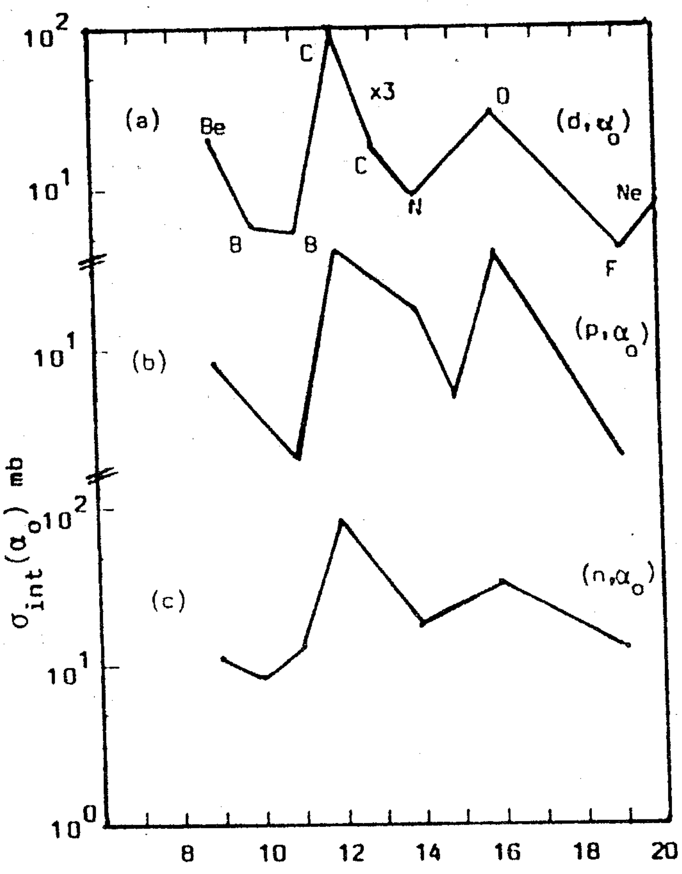

10^2
10^1
10^1
10^2
10^1
10^0
$\sigma_{int}(\alpha_o)$ mb
(a)
(b)
(c)
Be
B
B
C
C
x3
N
O
F
Ne
(d,α_o)
(p,α_o)
(n,α_o)
8
10
12
14
16
18
20
Mass Number

Fig. 1

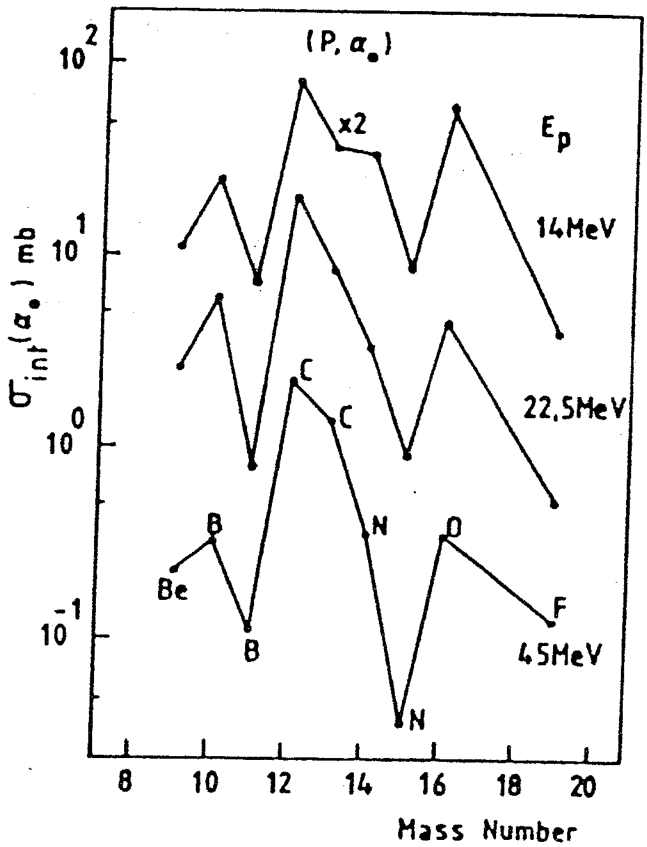

(P, α₀)
x2
Ep
14MeV
22.5MeV
45MeV
Be
B
B
C
C
N
N
O
F
10^2
10^1
10^0
10^{-1}
$\sigma_{int}(\alpha_0)$ mb
8
10
12
14
16
18
20
Mass Number

Fig. 2

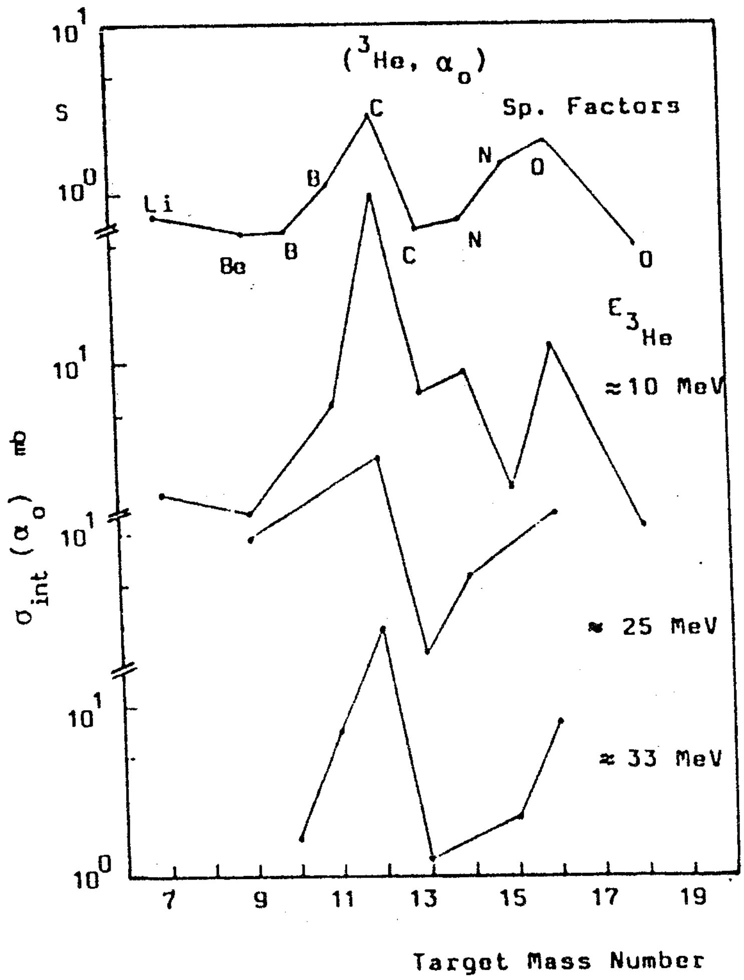

(^{3}He, α_0)
Sp. Factors
S
10^1
10^0
Li
Be
B
B
C
C
N
N
O
O
$E_{^3He}$
≈10 MeV
≈ 25 MeV
≈ 33 MeV
σ_{int} (α_0) mb
7
9
11
13
15
17
19
Target Mass Number

Fig. 3

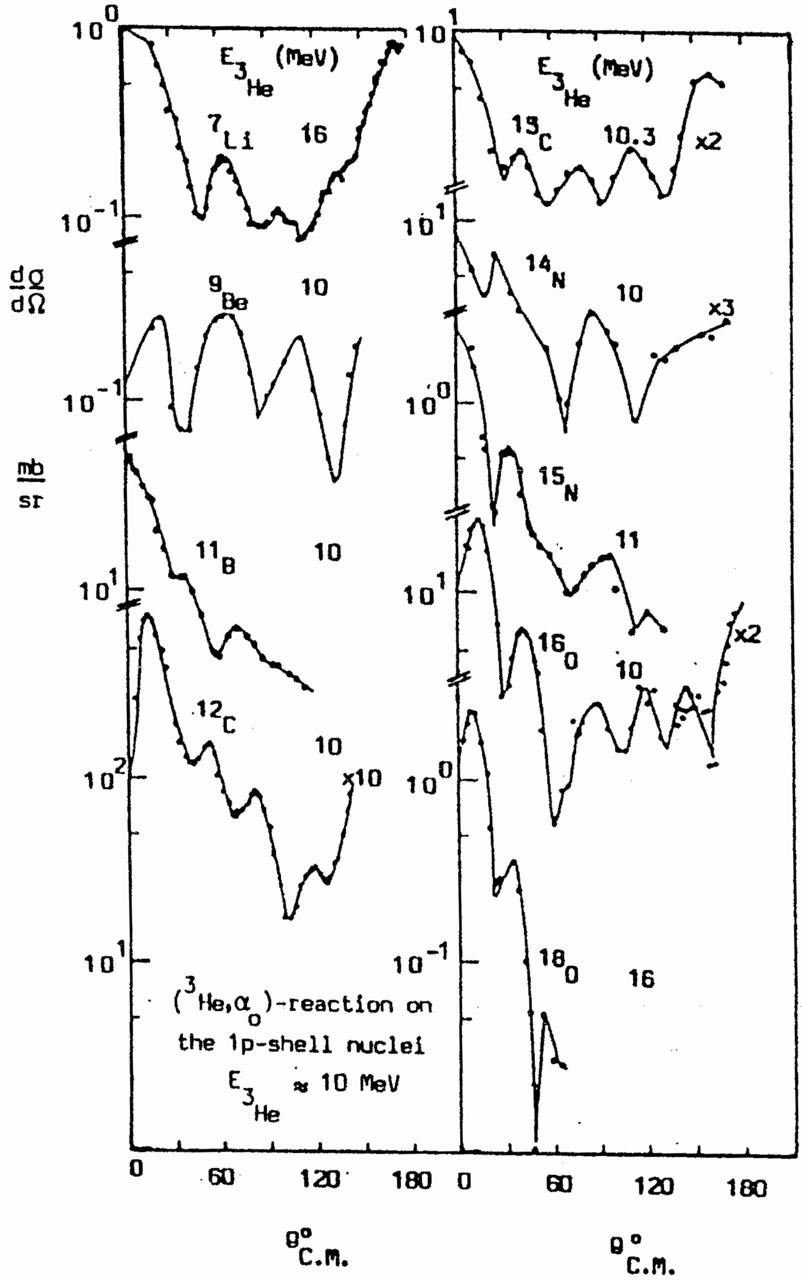
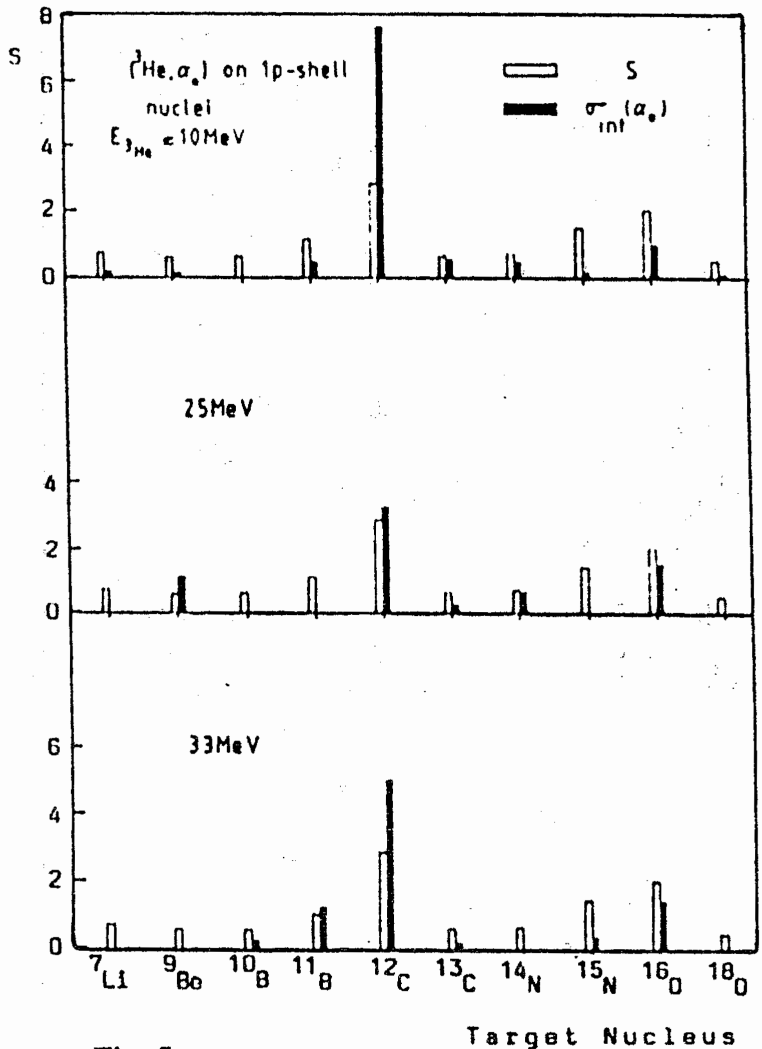

E3He (MeV)
7Li 16
9Be 10
11B 10
12C 10 x10
13C 10.3 x2
14N 10 x3
15N 11
16O 10 x2
18O 16
dσ/dΩ mb/sr
(3He,α0)-reaction on
the 1p-shell nuclei
E3He ≈ 10 MeV
θ°C.M.

Fig. 4



S
(^{3}He, α_0) on 1p-shell nuclei
$E_{^3He}$ = 10MeV
S
$\sigma_{int}(\alpha_0)$
25MeV
33MeV
8
6
4
2
0
7Li 9Be 10B 11B 12C 13C 14N 15N 16O 18O
Target Nucleus

Fig. 5