centre de recherches nucléaires de Strasbourg

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A STUDY OF THE $^{12}C(\alpha, ^{8}Be)^{8}Be$ REACTION IN THE ENERGY RANGE E_{α} = 17 - 33 MeV

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Excitation functions and angular distributions for the $^{12}C(\alpha,{}^8Be)^8Be$ reaction were measured for E_α = [illegible] – [illegible] MeV. [illegible] structures were observed, except for a narrow resonance at E_α = [illegible] MeV. Total and l-partial cross sections are deduced from the angular distributions. Below E_α = [illegible] MeV no l = 6 resonance was [illegible]. For higher energies an l = 6 contribution appears, increases gradually and becomes dominant at and above E_α = [illegible]3 MeV. A tentative interpretation of the behavior of $^{12}C(\alpha,{}^8Be)^8Be$ partial cross sections is given in the framework of the Hauser-Feshbach formalism.

NUCLEAR REACTIONS $^{12}C(\alpha,{}^8Be)$, E = [illegible] – 33 MeV, measured $\sigma(E_\alpha,\theta)$. ^{16}O resonances. Natural targets.

I. INTRODUCTION

The large number of resonances identified in the work of Chevallier et al.[1] shows that the $^{12}C(\alpha,{}^8Be)^8Be$ reaction seems to be particularly adapted to study the high energy structure of the ^{16}O nucleus. These results were confirmed by Martin and Ophel[2] who studied the same reaction in the incident energy range E_α = 15 –

[illegible] ^{12}C(α,^{8}Be)^{8}Be [illegible]

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[illegible]

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29 MeV. They showed that in their upper energy region the highest contributing relative angular momentum for $^{12}C + \alpha$ is L = 6. The corresponding partial cross section was found to be dominant up to E_α = 22 MeV simultaneously by James et al.[3] and Brochard et al.[4]

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II. EXPERIMENTAL METHOD

The experiment was performed with the α^{++} beam delivered by the Strasbourg M.P. Tandem accelerator. The beam entered an Ortec scattering chamber through a series of 1 and 2 mm diam collimators. The targets consisted of 20 – 50 μg/cm^2 thick, self-supporting natural carbon foils. Typical beam intensity and integrated charge were respectively 10 – 50 nA and 10 μC per data point.

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[illegible]

[illegible] experimental [illegible] ^{8}Be [illegible] from the ^{8}Be [illegible] kinemati[illegible] ^{8}Be [illegible] the ^{8}Be energy [illegible] ^{8}Be particles [illegible] possible processes give continuum shaped spectra. Two ^{8}Be detection [illegible] were used in our measurements. Each system consisted of two [illegible] silicon surface barrier detectors, [illegible] thick, 30 mm [illegible] mounted with [illegible] mm vertical separation.

A computer program was used to evaluate the ^{8}Be detector efficiency and to optimize the geometry. It was also used in extracting absolute cross sections. The geometry and efficiency calculations were experimentally checked by overlapping the angular range of the two ^{8}Be detectors. In order to match the ^{8}Be efficiencies of the two detectors, the distance to the target was [illegible] mm for the ^{8}Be detector placed at the forward angles and [illegible] mm for the one at backward angles. In this way the ^{8}Be effective solid angle varied no more than a factor of 5 over the whole range of bombarding energies and measured angles (Fig.1). This corresponded to a mean angular aperture for ^{8}Be detection varying from two to three degrees in the c.m. system. The use of these rectangular sized detectors allowed for an efficiency improvement of a factor of about 10 with respect

[illegible]

F... monitor ... and to get information on other reaction channels, ... mm^2 silicon detector was mounted ... mm from the target at [illegible] to the beam axis.

To measure the dead time each preamplifier test input was fed from a pulser triggered by the digital output from a beam current integrator. In the singles and coincident spectra, this pulser peak was used to measure the effective beam charge by taking into account dead time and pile-up effects.

B. Data acquisition

In the sum spectrum of coincident α-energies, the ^{8}Be(g.s.) peak from the ^{16}O decay into two ^{8}Be particles in their ground state can be obscured by other possible processes as for example when the ^{8}Be particles are emitted in their first excited state or from the ^{8}Be + α decay of $^{12}C^*$. A two dimensional spectrum $E_{\alpha 1}$ versus $E_{\alpha 2}$, as shown in Fig.2, gives more information and allows better peak separation. The energy resolution (~4%) needs at least 128 channels for each dimension. This required too many channels to handle simultaneously coincidence and random spectra for two ^{8}Be detectors. However, based on the fact that the two dimensional spectrum is symmetrical with respect to the line $E_{\alpha 1} = E_{\alpha 2}$ (for identical gains) and that over the whole energy range of this study, the maximum energy difference between the two α-particles from a ^{8}Be(g.s.) decay is nearly constant (≈2 MeV), the occupied memory size can be reduced by a coordinate change from $E_{\alpha 2}$, $E_{\alpha 1}$ into $\Sigma = (E_{\alpha 1} + E_{\alpha 2})$,

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[illegible]

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[illegible] final state spins are [illegible] the angular distribution [illegible] emitted [illegible] issuing from a state of spin [illegible] the form [illegible] where $P_l(\cos\theta)$ is a Legendre polynomial of order [illegible]. From the [illegible] symmetry [illegible] is restricted to even values. This implies that [illegible] to a function at [illegible] will show only [illegible] resonances.

A. Excitation Functions

Two excitation functions at [illegible] were measured simultaneously for the ^{12}C[illegible] reaction from [illegible] = 17 to 33 MeV. Steps of 10–40 keV with thin targets were taken in some regions where narrow resonances could be expected, while 100 keV steps were used otherwise. The [illegible] angle, which corresponds to a zero of $P_6(\cos\theta)$, was chosen to identify any J^{π} = [illegible] level. A [illegible] state [illegible] [illegible] was found to be dominant [illegible] E_α = [illegible] MeV (Ref. [illegible]). The measured excitation functions are shown in Fig.3. The [illegible] better known geometry and target thickness estimat[illegible], taking into account carbon buildup, both absolute and relative cross sections differ slightly from our earlier work[1]. Below E_α = [illegible] MeV and at [illegible] the results are in good agreement with those of Martin and Ophel[8] and differ from those of James et al.[6] by about 20%. Our absolute cross sections are estimated to be accurate to within 20%.

Excitation functions corresponding to the elastic and inelastic [illegible] channels from the [illegible] placed at [illegible] are represented in Fig.4. They show no strong inter-channel correlation, except for a narrow resonance at E_α = 22.30 MeV (E_x = 23.86 MeV) found previously by Hayward and Schmidt[7] in elastic α scattering and which corresponds to a $J^\pi = 6^+$ level[6]. The decays of this level were measured simultaneously in the $^{12}C + \alpha_0$, $^{12}C + \alpha_1$, $^{12}C + \alpha_2$, $^8Be(g.s.) + {}^8Be(g.s.)$ and $^{15}N + p$ channels. All the resulting excitation functions show a resonant behavior (Fig.5). It should be pointed out that this level has both a proton and a ^8Be width. Such a situation has already been observed for a $J^\pi = 4^+$ state excited at E_α = 14.52 MeV (Ref.1). The analysis of the elastic scattering data (Fig.5) using the phase shifts determined by Carter[9], leads to the ratio Γ_{α_0}/Γ = 0.06 ± 0.02 for the $J^\pi = 6^+$ level. If we describe in a crude way the resonance at E_α = 22.30 MeV in the $^{12}C + \alpha_2$ and $^8Be(g.s.) + {}^8Be(g.s.)$ channels through Breit-

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taking into [illegible]

The results [illegible] in Table I.

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[illegible] Fig. [illegible]

[illegible] energy [illegible] when the excitation [illegible]

Fig. [illegible] shows [illegible]

[illegible] decreasing [illegible]

energies.

Despite the low efficiency for detecting ^{7}Be(2.4 MeV) [illegible] ^{7}B [illegible] in their first excited state, which was [illegible] smaller than that for detecting ^{7}Be(g.s.), it was still possible to measure some such angular distributions. In calculating the efficiency for the ^{7}Be(2.4 MeV) detection, we assumed an isotropic correlation between the ^{7}Be(2.4 MeV) and the emitted [illegible] particle. In the energy range of the measurements [illegible] MeV, large cross sections are observed as can be seen in Fig. 7. Some angular distributions are strongly peaked near [illegible] and [illegible] decay to ^{8}Be(g.s.), show a weak energy dependence.

IV. ANALYSIS

[illegible] the [illegible], because [illegible] a general expression for the differential cross section is[5]

$$\frac{d\sigma}{d\Omega}(E,\theta) = \left| \sum_{\text{even } L}^{L_{MAX}} a_L(E)\sqrt{2L+1}\,P_L(\cos\theta) \right|^2 \qquad (4.1)$$

where the $a_L(E)$ are complex numbers.

From (4.1) the total cross section is

$$\sigma(E) = 4\pi \sum_{\text{even } L}^{L_{MAX}} |a_L(E)|^2 \qquad (4.2)$$

In this decomposition, each term represents the L-partial cross section.

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In Fig.8, we show the total and partial cross sections deduced from the angular distributions measured in this work (Fig.6), in the work of Chevallier et al.[1], and that of Martin and Ophel[2]. Several sets of $a_L(E)$ values corresponding to about the same minimum χ^2 value were obtained for each angular distribution. The origin of this multiplicity arises from the fact that there is at least one ambiguity in the formula (4.1) for $L < L_{MAX}$ and also

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We used three different [illegible] each measured angular distribution [illegible] the one level interpretation [illegible] while the others are [illegible] phases of these [illegible] when passing through [illegible]

V. DISCUSSION

We consider [illegible] our data together with [illegible] obtained in the incident energy range [illegible] similar decomposition of the cross sections, [illegible] $J = 2 - 6$ were observed to lie approximately [illegible] line. This suggested the existence of an [illegible] rotational band with a very high moment of inertia, interpreted later as an 8 particle-5 hole band[5]. One purpose of this study was to locate its $J^{\pi} = 8^{+}$ member.

A. Search for a $J^{\pi} = 8^{+}$ level

[illegible] excitation functions measured in the energy region E_i [illegible] MeV in [illegible] keV steps failed to show evidence for [illegible]. The same conclusion is reached after a search for an [illegible] term in the angular distributions. Up to E_i = 20 MeV no evidence [illegible] a term is found. Above this energy, a weak but slowly increasing l = 8 component appears and becomes dominant at E_i = 23 MeV (Fig.8). Above E_i = 27 MeV the non-linear fit indicates the presence of an l = 10 component. This implies that if a $J^{\pi} = 8^{+}$ level belonging to the predicted 8 particle-8 hole band exists below E_i = 20 MeV, it would have a very different width from the other members of the band. One possibility to explain this difference in width is that the formation of this level might be inhibited either in the entrance or outgoing channels.

To test this hypothesis we report in Fig.8 the energies corresponding to the grazing angular momentum given by the semi-classical formula

$$l(l+1) = k^2R^2(1-2\eta/kR) \qquad (5.1)$$

where $R = Ro(A_1^{1/3} + A_2^{1/3})$, k and η are respectively the wave number and the Sommerfeld parameter for the considered channel. In the entrance channel (Ro = 1.4fm) the possibility of an inhibition for l = 8 is important below E_d = 20 MeV. In the $^8Be(g.s.) + {}^8Be(g.s.)$ exit channel, the observed structures appear for each L value about 5 MeV below energies calculated with formula (5.1) and Ro = 1.4fm. However the agreement becomes quite satisfactory (Fig.8) if we use

larger radius parameter Ro = [illegible] fm, which might take [illegible] for the loose α-cluster structure of the ^8Be nucleus[?] and the linear configuration [illegible] of the two ^8Be. Hence [illegible] particular inhibition can be expected in the outgoing channel.

B. Reaction mechanism

The broad structures [illegible] Fig. [illegible] are characterized by their appearance near the energies corresponding to the grazing angular momentum for the outgoing channel and by their energy localization for each l value. This behavior, where a single partial wave dominates within a restricted range of energy, is typical of a surface mechanism and can be explained by the formation of quasimolecular states. This hypothesis is strengthened by the low cross sections for a direct mechanism estimated by extrapolation from higher incident energy results[1] (E_i = [illegible] MeV). These cross sections are about an order of magnitude lower than the observed ones.

A similar situation where resonance-like structures are observed near the Coulomb barrier is encountered in the study of reactions like $^{12}C + {}^{12}C$ or $^{12}C + {}^{16}O$ (Ref.12). Most of the models developped to explain such behavior are based on two different hypotheses. The first assumes the formation of α-particle molecules[13,14]. The conditions[14] for the existence of these *molecules are also fulfilled for the* $^{12}C(\alpha, {}^8Be(g.s.)){}^8Be(g.s.)$ reaction. However the lack of apparent correlations with other exit channels like $^{12}C + \alpha_0$, $^{12}C + \alpha_1$ and $^{12}C + \alpha_2$ disfavor this hypothesis in our case. The second possibility is based on the creation of

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VI. CONCLUSION

In the energy range E_{α} = 17 - 33 MeV of this study only one narrow resonance, corresponding to a $J^{\pi} = 6^{+}$ level, is found at E_{α} = 22.30 MeV. Below E_{α} = 20 MeV, the existence of a $J^{\pi} = 8^{+}$ level cannot be definitively ruled out, as it may be possible that the limited amount of angular momentum in the entrance channel inhibits quasimolecular states. Several tentative interpretations to reproduce the observed resonance-like structures have been done with optical model calculations using very shallow potentials[15-18]. We have made such an interpretation for the $^{12}C(\alpha,{}^8Be(g.s.))^8Be(g.s.)$ reaction by using a statistical Hauser-Feshbach model calculation with the parameters given in Table II. This calculation is not well adapted to all the incident energies of this study due to the small level densities and number of open channels in the ^{16}O nucleus for lower excitation energies. The heavy ion optical potential used to describe the ^8Be + ^8Be scattering must have a very small imaginary part in order to reproduce the observed structures which are only produced by the transmission coefficients relevant to the outgoing channel. In Fig.8 the calculated curves (dashed lines) are compared to the experimental data. The similitude between the broad predicted structures and the behavior of the experimental cross sections is in surprising agreement with the nuclear molecule hypothesis. Recent results obtained for the $^{16}O(\alpha,{}^8Be)^{12}C$ reaction[22] show a different behavior which could imply that the structures are due to the simultaneous presence of two ^8Be nuclei.

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[illegible]

Table 1. Parameters of the [illegible] = 6^+ level at E_x = 24.68 MeV in [illegible]

E_r (MeV)	Γ (keV)	[illegible] Be (keV)	Γ [illegible] (keV)	Γ [illegible] (keV)
22.295 ± 0.015	25 ± 5	3.5	.5 ± 0.5	≥ 6
22.3[illegible] ± [illegible] [a]	26 ± 4 [a]			

[a] Ref. [illegible]

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E_r (MeV)	[illegible] (keV)	[illegible] Be (keV)	[illegible] (keV)	[illegible] (keV)
22.295 ± 0.015	25 ± 5	3.5	.5 ± 0.5	≥ 6
22.3[illegible] ± [illegible] [a]	2[illegible] ± [illegible] [a]			

[a] Ref. [illegible]

Table II. [illegible] parameters [illegible] calculation. The level density [illegible] are those defined by Gilbert and [illegible][4]. [illegible] potentials are [illegible].

Channel	[illegible] (MeV)	R_U [a] (fm)	a_U (fm)	W [b] (MeV)	R_W [a] (fm)	a_W (fm)	V_{so} (MeV)	R_{so} [a] (fm)	a_{so} (fm)	[illegible] MeV
$^{15}N+p$	[illegible] [c]	[illegible].25	0.65	13.5	[illegible].25	[illegible]	5.5	[illegible]	[illegible]	[illegible]
[illegible] $+n$	[illegible]	[illegible].25	0.65	8.5	1.25	0.48	5.5	[illegible].25	[illegible]	[illegible]
[illegible] $+d$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]
[illegible] $+^3He$	158 [d]	0.91	0.61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	150 [c]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]
[illegible]	185 [c]	[illegible]	0.52	25	[illegible]	[illegible]				[illegible]
$^8Be+^8Be$	[illegible] [e]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]

[a] $R = R_U\, A_2^{1/3}$ except in the $^8Be + ^8Be$ channel where $R = R_U$ [illegible] (A_1 and A_2 are respectively the mass number of the light and heavy particles in the considered channel). The Coulomb radius is equal to the radius of the real well.

[b] The imaginary well is of the surface type for the [illegible] and [illegible] channels, of the Gaussian type in the [illegible] channel and all others are of the volume type.

[c] Ref. 20.

[d] Ref. 23.

[e] The $^8Be + ^8Be$ optical potential is adapted from the one used by Maher *et al.*[21]

[f] Energy above which continuum level densities are used.

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FIGURE [illegible]

Fig.1 [illegible] dependence [illegible] the [illegible] angle [illegible] of the ^{8}Be [illegible] distances [illegible] the [illegible] line shows the energy range [illegible] covered by [illegible]. The ^{8}Be [illegible] expressed [illegible] the [illegible] system, is defined as [illegible] where [illegible] is the [illegible] to detect [illegible] two [illegible] particles from the breakup [illegible] of [illegible] ^{8}Be nucleus emitted [illegible]

Fig.2 Schematic representation [illegible] [illegible] and [illegible] The [illegible] labelled "1" corresponds to the detection of ^{8}Be [illegible] from the [illegible] ^{8}Be(g.s.) + ^{8}Be(g.s.) [illegible] labelled "2" [illegible] the detection [illegible] ^{8}Be [illegible] MeV [illegible] [illegible] ^{8}Be(2.9 MeV) + ^{8}Be(g.s.) [illegible]. The group "3" corresponds to the detection of ^{8}Be(g.s.) [illegible] and from the ^{12}C [illegible] ^{8}Be(g.s.) [illegible]

Fig.3 Incident [illegible] particle energy dependence of the angles [illegible] the differential cross section for the [illegible] ^{8}Be(g.s.) [illegible] reaction.

Fig.4 Incident [illegible] particle energy dependence [illegible] differential cross section for the [illegible]

Fig.5 Energy dependence of the differential cross section [illegible] the ^{12}C + [illegible] reaction for several decaying channels around the $J^\pi = 6^+$ level in ^{16}O at E_x = 23.88 MeV. The solid lines are the results of calculations done with the parameters of Table I.

(see Sec.III A). The dashed lines are to guide the eye.

Fig.6 Angular distributions in the c.m. observed at several bombarding energies for the ^{12}C([illegible],^{8}Be(g.s.))^{8}Be(g.s.) reaction. The solid lines are the results of a non-linear fit to the data with the formula [illegible] (see Sec.IV). Here EB stands for the [illegible] bombarding energy.

Fig.7 Angular distributions in the c.m. measured at several bombarding energies for the ^{12}C([illegible],^{8}Be(2.9 MeV))^{8}Be(g.s.) reaction.

Fig.8 Total and l-partial cross sections of the ^{12}C([illegible],^{8}Be(g.s.))$^{[illegible]}Be$(g.s.) reaction for E_{i} = 12 − 34 MeV. The solid lines are to guide the eye and correspond to the general trend of the measured differential cross sections. The dashed lines correspond to the results of a statistical Hauser-Feshbach compound nuclear calculation done with the parameters given in Table II. The solid and open triangles represent respectively the energies corresponding to the grazing angular momentum (see Sec.V(A)) for the entrance and outgoing channels. The arrows show the position of the J^{π} = 2^{-} − 5^{+} levels of the 8 particle-8 hole band[5] and the predicted position of the J^{π} = 8^{+} member of this band assuming a $\Delta J = 2$ rule. The solid bars correspond to the decomposition of the angular distributions measured in this work [illegible]. The dashed bars correspond to the decomposition of the measurements of Martin and Oppel[2].

(see Sec.III A). The dashed lines are to guide the eye.

Fig.6 Angular distributions in the c.m. observed at several bombarding energies for the $^{12}C(\alpha,{}^{8}Be(g.s.))^{8}Be(g.s.)$ reaction. The solid lines are the results of a non-linear fit to the data with the formula ([illegible]) (see Sec.IV). Here EB stands for the α bombarding energy.

Fig.7 Angular distributions in the c.m. measured at several bombarding energies for the $^{12}C(\alpha,{}^{8}Be(2.9\ MeV))^{8}Be(g.s.)$ reaction.

Fig.8 Total and L-partial cross sections of the $^{12}C(\alpha,{}^{8}Be(g.s.))^{8}Be(g.s.)$ reaction for E_{α} = [illegible]2 – 3[illegible] MeV. The solid lines are to guide the eye and correspond to the general trend of the measured differential cross sections. The dashed lines correspond to the results of a statistical Hauser-Feshbach compound nuclear calculation done with the parameters given in Table II. The solid and open triangles represent respectively the energies corresponding to the grazing angular momentum (see Sec.V(A)) for the entrance and outgoing channels. The arrows show the position of the J^{π} = 2^{-} – [illegible] levels of the 8 particle-8 hole band[5] and the predicted position of the J^{π} = 8^{+} member of this band assuming a J(J+1) rule. The solid bars correspond to the decomposition of the angular distributions measured in this work at [illegible]. The dashed bars correspond to the decomposition of the measurements of Martin and Ophel[7].

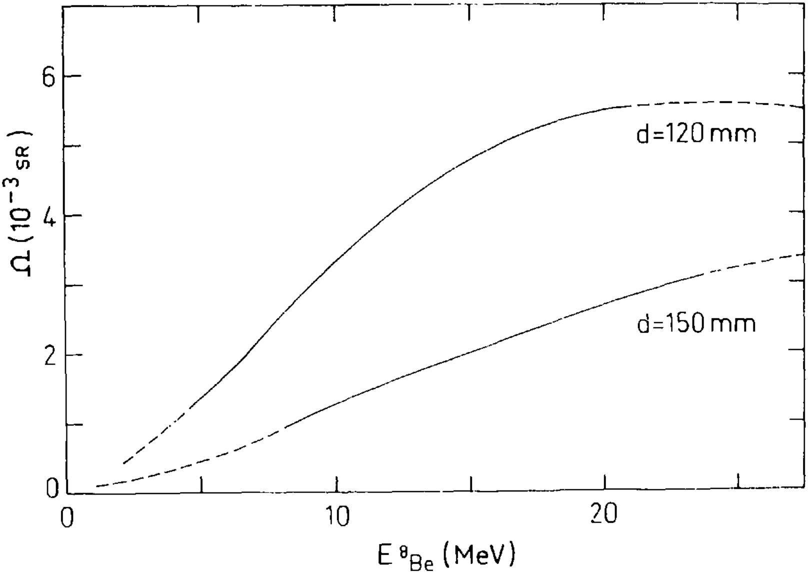
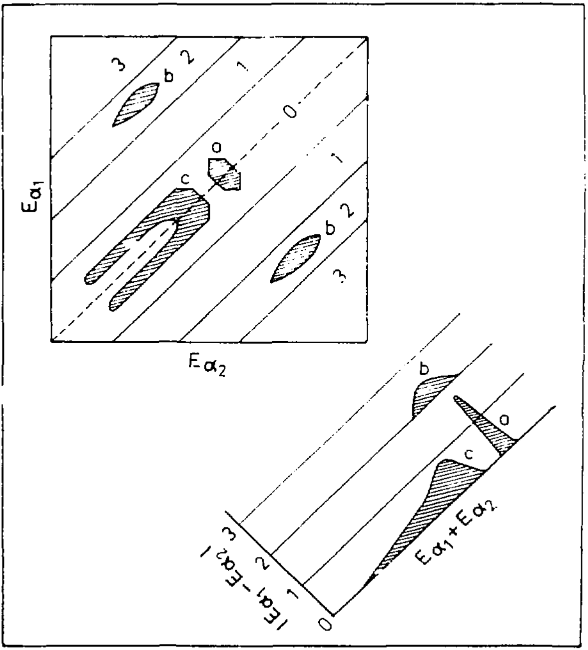
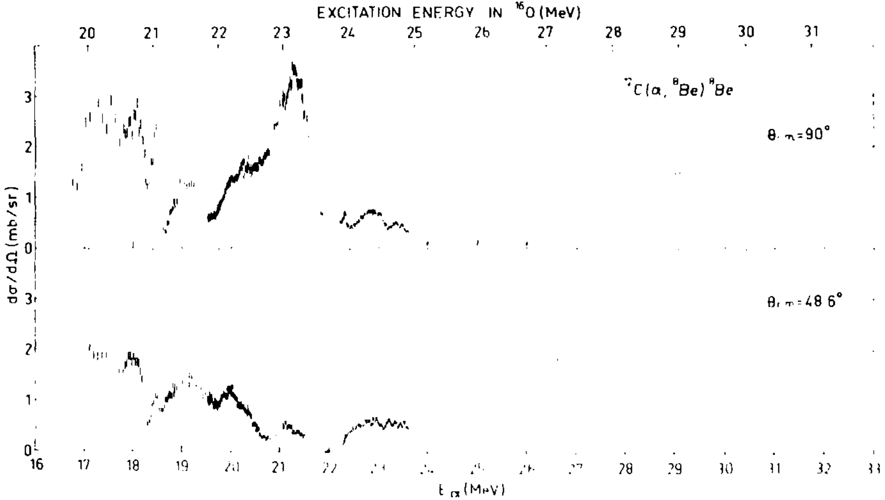


Fig. 1.

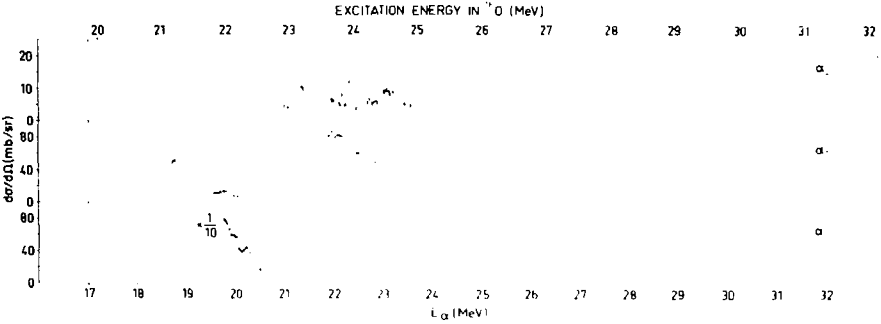


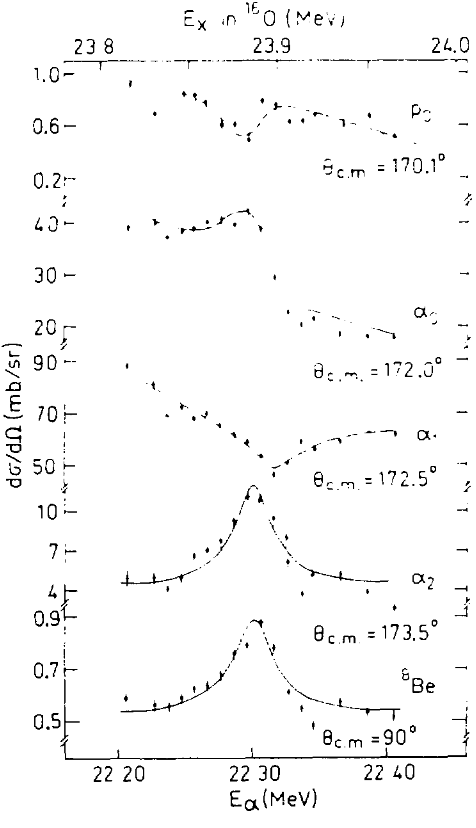
3
b
2
1
0
a
c
1
b
2
3
E_{α_1}
E_{α_2}
b
a
c
3
2
1
0
$|E_{\alpha_1} - E_{\alpha_2}|$
$E_{\alpha_1} + E_{\alpha_2}$

Fig.2.

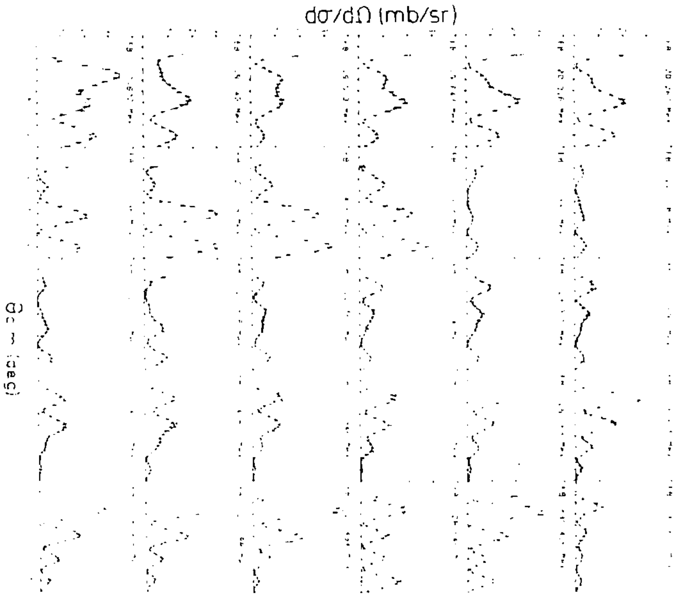


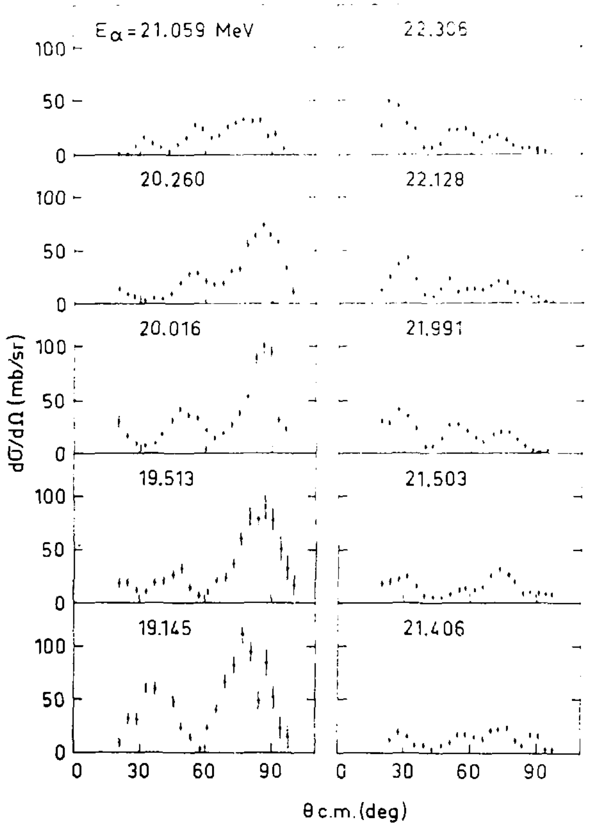
EXCITATION ENERGY IN ¹⁶O (MeV)
20 21 22 23 24 25 26 27 28 29 30 31
C(α, ⁸Be)⁸Be
=90°
=48 6°
dσ/dΩ (mb/sr)
0 1 2 3
0 1 2 3
16 17 18 19 21 28 29 31 32
(MeV)


EXCITATION ENERGY IN O (MeV)
20 21 22 23 24 25 26 27 28 29 30 31 32
dσ/dΩ(mb/sr)
1/10
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
(MeV)

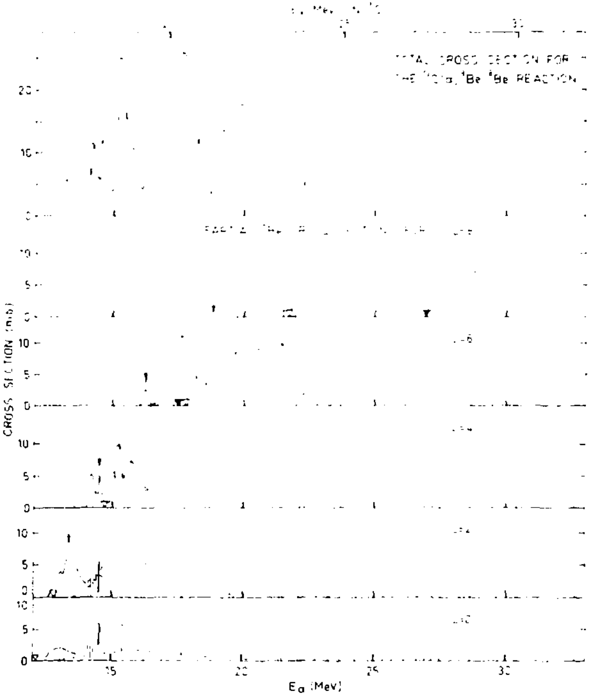


Ex in 16O (MeV)
23.8
23.9
24.0
1.0
0.6
0.2
40
30
20
90
70
50
10
7
4
0.9
0.7
0.5
p0
θc.m = 170.1°
α0
θc.m. = 172.0°
α1
θc.m. = 172.5°
α2
θc.m. = 173.5°
8Be
θc.m = 90°
dσ/dΩ (mb/sr)
22.20
22.30
22.40
Eα (MeV)


dσ/dΩ (mb/sr)



Eα = 21.059 MeV
22.306
20.260
22.128
20.016
21.991
19.513
21.503
19.145
21.406
dσ/dΩ (mb/sr)
θ c.m. (deg)


CROSS SECTION (mb)
Eα (MeV)
15