ISTITUTO NAZIONALE DI FISICA NUCLEARE

INFN/BE - 69/3
20 Maggio 1969

F. De Guarrini and R. Malaroda:

DIFFERENTIAL CROSS SECTION FOR THE $^9Be(\alpha,n)^{12}C$ REACTION

340

SERVIZIO RIPRODUZIONE DELLA
SOTTOSEZIONE DI TRIESTE DELL'INFN

DIFFERENTIAL CROSS SECTION FOR THE $^{9}Be(\alpha,n)^{12}C$ REACTION

F. De Guarrini and R. Malaroda

Istituto Nazionale Fisica Nucleare - Sottosezione di Trieste

20 Maggio 1969

341

SUMMARY

A complete list of $^{9}Be(\alpha,n)^{12}C$ cross sections of the g.s., 4.43 and 7.76 MeV levels of the residual nucleus ^{12}C in the 0.5 ÷ 5.4 MeV range of the α energy is given.

THE CROSS SECTIONS OF THE $^{9}Be(\alpha,n)^{12}C$ REACTION

The cross sections of the $^{9}Be(\alpha,n)^{12}C$ measured till now and reported in the literature were compared and partially worked upon in order to have a set of self consistent data available for the most general use.

The detailed procedure followed in handling the data is described below.

For the ^{12}C g.s. in the α-energy range 0.51 - 1.34 MeV angular distributions were calculated as a combination of cos ϑ powers with the coefficients given by D.B. James ([1]) and normalized with the g.s. excitation function as given in the same article.

The ^{12}C ground state angular distributions givenby Risser ([2]) in the range $2.02 \leq E_\alpha \leq 5.07$ MeV and those given by Deconninck ([3]) in the range $1.55 \leq E_\alpha \leq 4.0$ MeV were also considered. At the corresponding E_α energies, the shapes of the distributions given by these authors agree well. The two angular distributions measured by Gale and Garg ([4]) at $E_\alpha = 5.53$ and $E_\alpha = 5.76$ MeV were also taken into account. All these distributions were renormalized at 0° using the 0° cross section for the reaction $^{9}Be(\alpha,n)^{12}C$, as a function of the bombarding energy E_α, given by Miller and Kavanagh ([5,6]). The agreement between these values and those given by Risser is good in the range $2.0 \leq E_\alpha \leq 4.75$ MeV, while the discrepancies of the renormalized values from the data of Gale and Garg are of the order of 10%. Moreover, these data agree within 20% with those of the 0° excitation function recently measured by Groce and Sowerby ([7]) in the range $3.8 \leq E_\alpha \leq 12$ MeV.

A further numerical elaboration was necessary in order to evaluate the angular distributions relative to the 4.43 MeV level of ^{12}C. In the $0 \leq E_\alpha \leq 4$ MeV energy interval, there is not any experimental evidence of neutron production from the higher 7.66 MeV excited level in ^{12}C ([8]). Therefore, the neutron contribution due to the 4.43 MeV state was simply deduced by subtracting from the total 4π cross section given by Gibbons and Macklin ([9]) the 4π ground state cross section alone, in the same E_α interval.

The differential cross sections, averaged over the 0°-20°, 20°-70°, 70°-110° and 110°-180° angular intervals, were then deduced by distributing the 4.43 MeV cross section in these interval. Taking into account the data of the neutron yield as measured by Bonner (17) over the 0°-20° and 70°-110°, the remaining contribution of the first excited level was assigned to the other angular intervals, in such a way that the values of these angular distributions, as a function of the energy E_α, for each fixed angle ϑ, fit those measured by Risser for $E_\alpha \geq 4$ MeV.

In the energy range $4 \leq E_\alpha \leq 5.5$ MeV the angular distributions given by Risser at 4.0, 4.19, 4.65 MeV and that given by Gale and Garg at $E_\alpha = 5.4$ MeV for the 4.43 MeV level of ^{12}C were taken into account. Moreover, in the energy range $4.65 \leq E_\alpha \leq 5.4$ MeV, a new set of angular distributions was derived by graphically interpolating these data.

For the 7.66 MeV level of ^{12}C, which is excited by α-particles only above 4 MeV, angular distributions, averaged over the 0°-20°, 20°-70°, 70°-110° and 110°-180° angular intervals, were calculated by subtracting the sum of the contributions due to the ground and first excited state of ^{12}C from the total 4π cross section measured by Gibbons and Macklin; the difference was distributed among the angular intervals, so that each angular distribution of the 7.66 MeV level was similar to the angular distribution, previously averaged over the same angular intervals, relative to the ground state at the corresponding α energy.

In this way using the data available from the literature on the $^{9}Be(\alpha,n)^{12}C$ reaction, all the neutron angular distributions in the α energy range from 0 to 5.5 MeV energies were separately obtained for the three levels.

* * *

The angular distributions for each state of ^{12}C and increasing α-energy are shown.

Series A refers to the g.s. of ^{12}C in the C.M. reference system; series B and C refer respectively to the 4.43 and 7.66 MeV states in the LAB system.

Finally tridimensional displays of the angular distributions for each state are given.

* * *

The ^{9}Be(α,n)^{12}C cross sections given in the following are deduced from the data of:

A 1 - 9	ref. ([1])
A 10 - 34	" ([3])
A 35 - 46	" ([2,4])
A 47 - 51	" ([2,4])
B 1 - 11	see on the text
B 12 - 18	ref. ([2,4])
C 1 - 8	see on the text

* * *

REFERENCES

([1]) D.B. James, G.A. Jones and D.H. Wilkinson, Phil. Mag., 1-2 (1956) 949.

([2]) J. Risser, J.E. Pricel and C.M. Class, Phys. Rev. 105, 4 (1957) 1288.

([3]) G. Deconninck, Mémories-Académie Roy. Belg., Tome 35,2 N.1775 (1965)

([4]) N.H. Gale and J.B. Garg, Il Nuovo Cimento, 19 (1961) 742.

([5]) R.G. Miller and R.W. Kavanagh, Nucl. Phys. 88 (1966) 492.

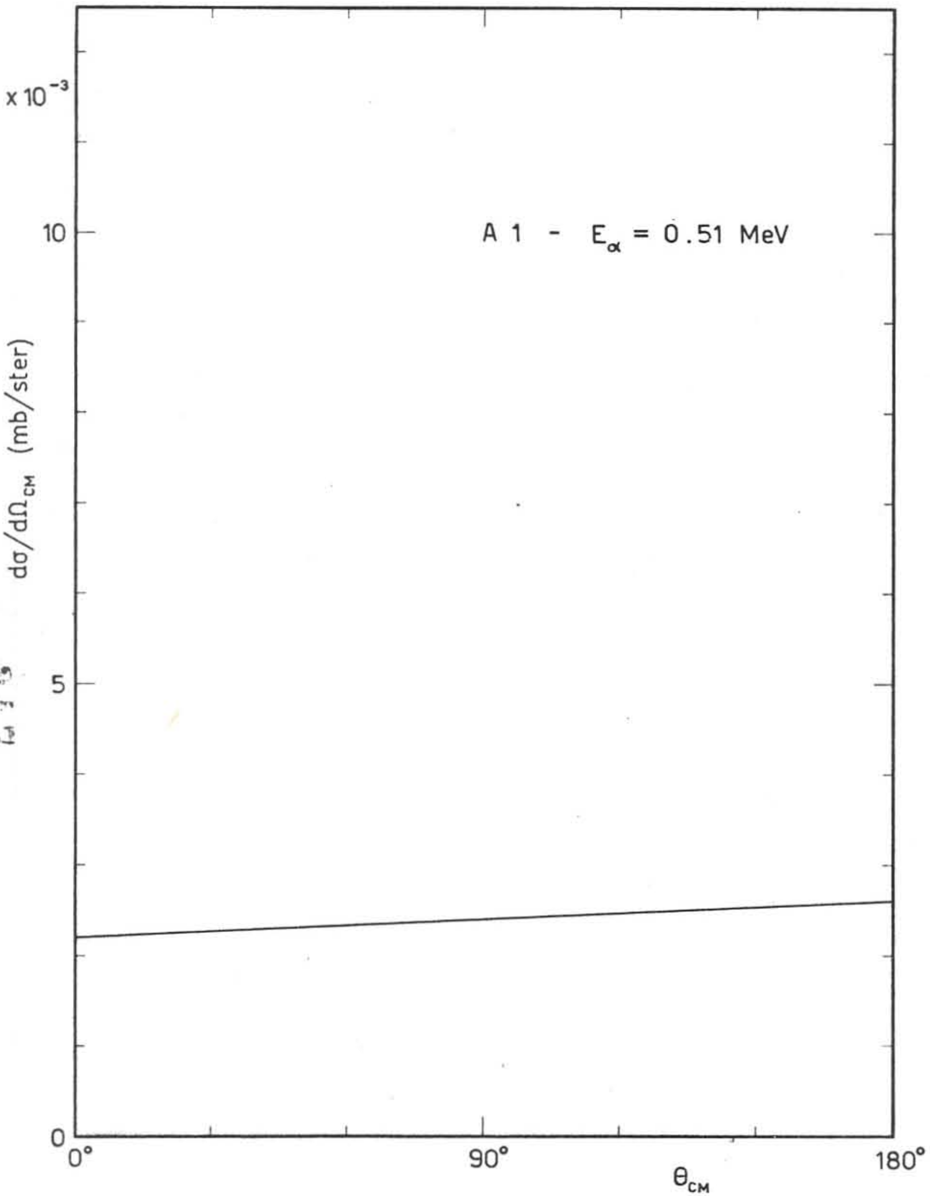
([6]) R.G. Miller and R.W. Kavanagh, Nucl. Inst. and Meth. 48 (1967) 13.

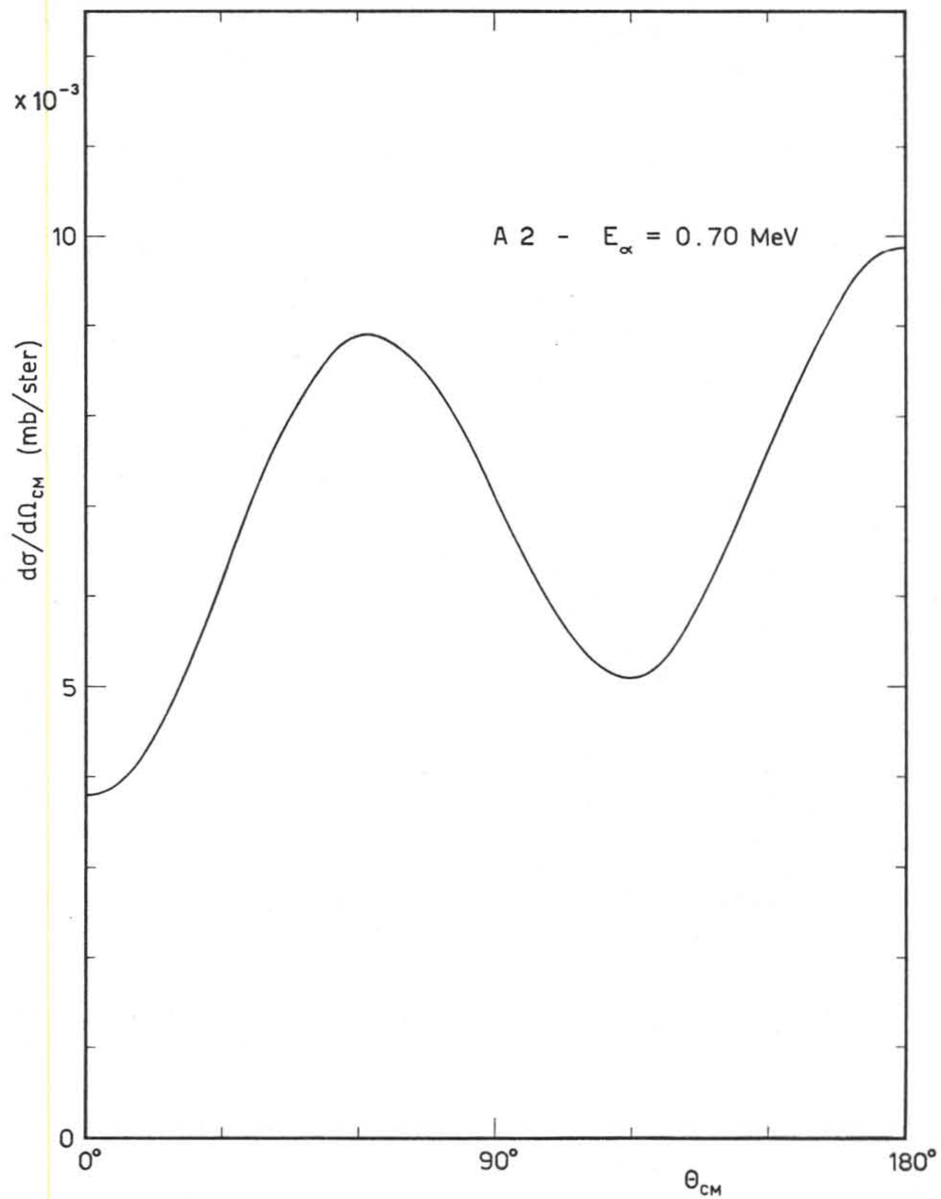
([7]) D.E. Groce and B.D. Sowerby, Nature 206 (1965) 494.

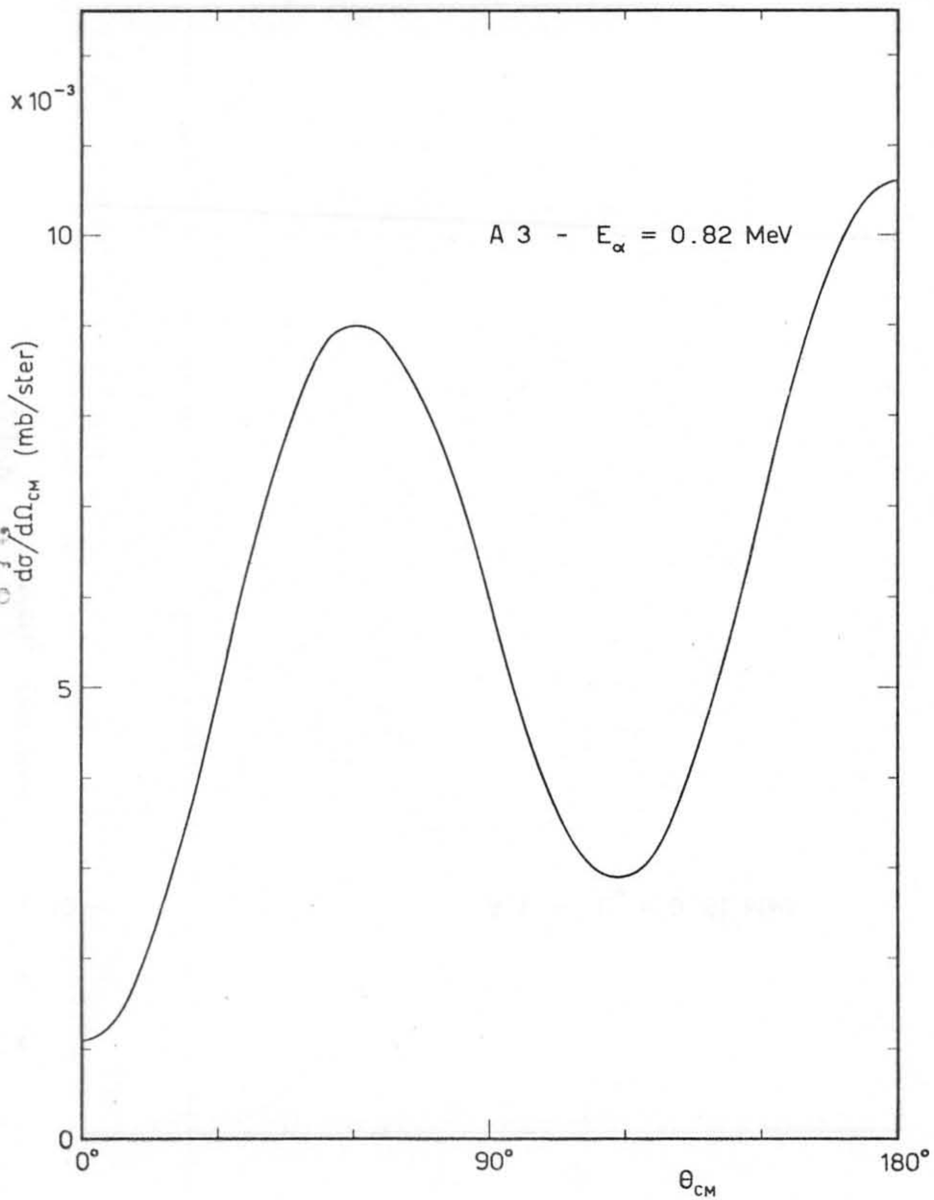
([8]) M.E. Anderson and W.H. Bond, Jr., Nucl. Phys. 43 (1963) 330.

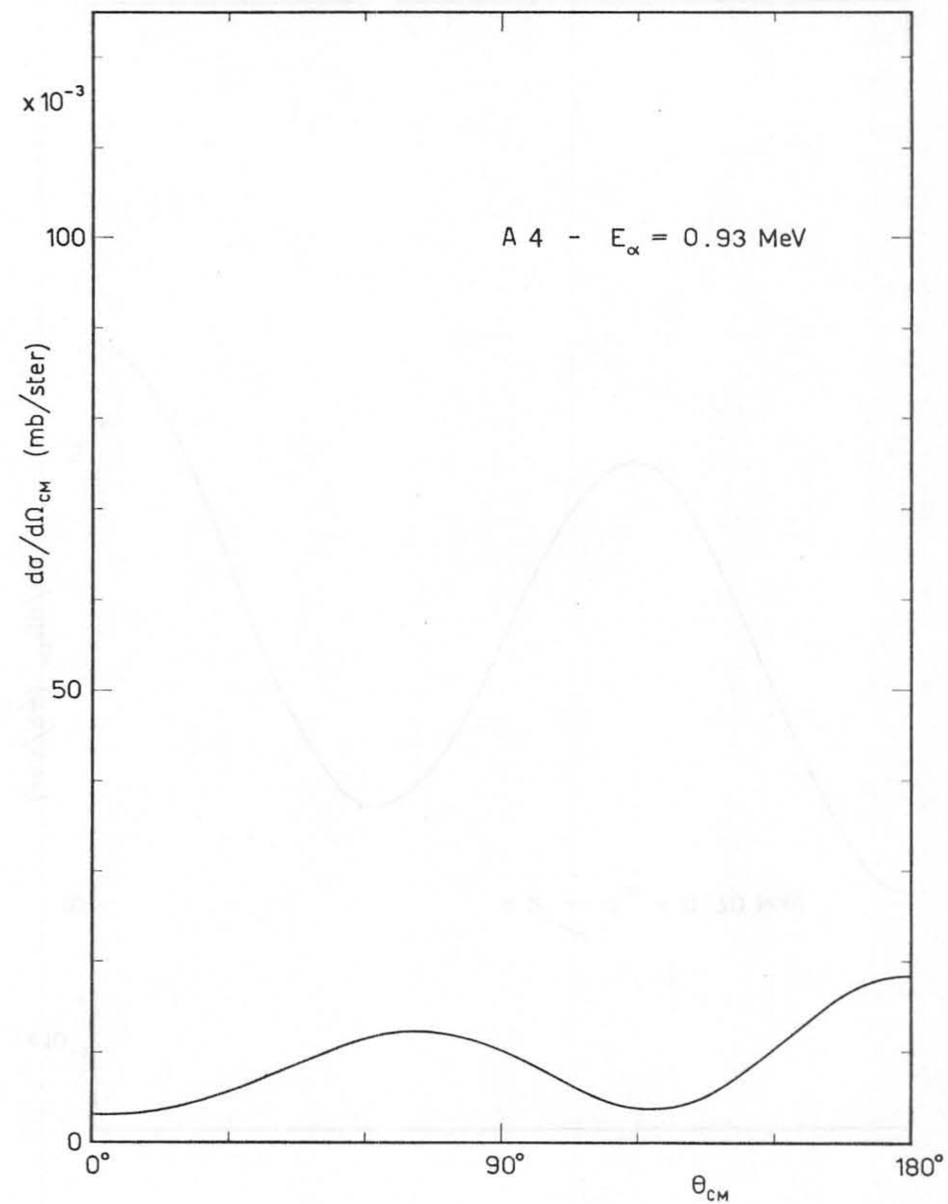
([9]) J.H. Gibbons and R.L. Macklin, Phys. Rev. 137, 6B (1965) 1508.
J.H. Gibbons and R.L. Macklin, private communication.

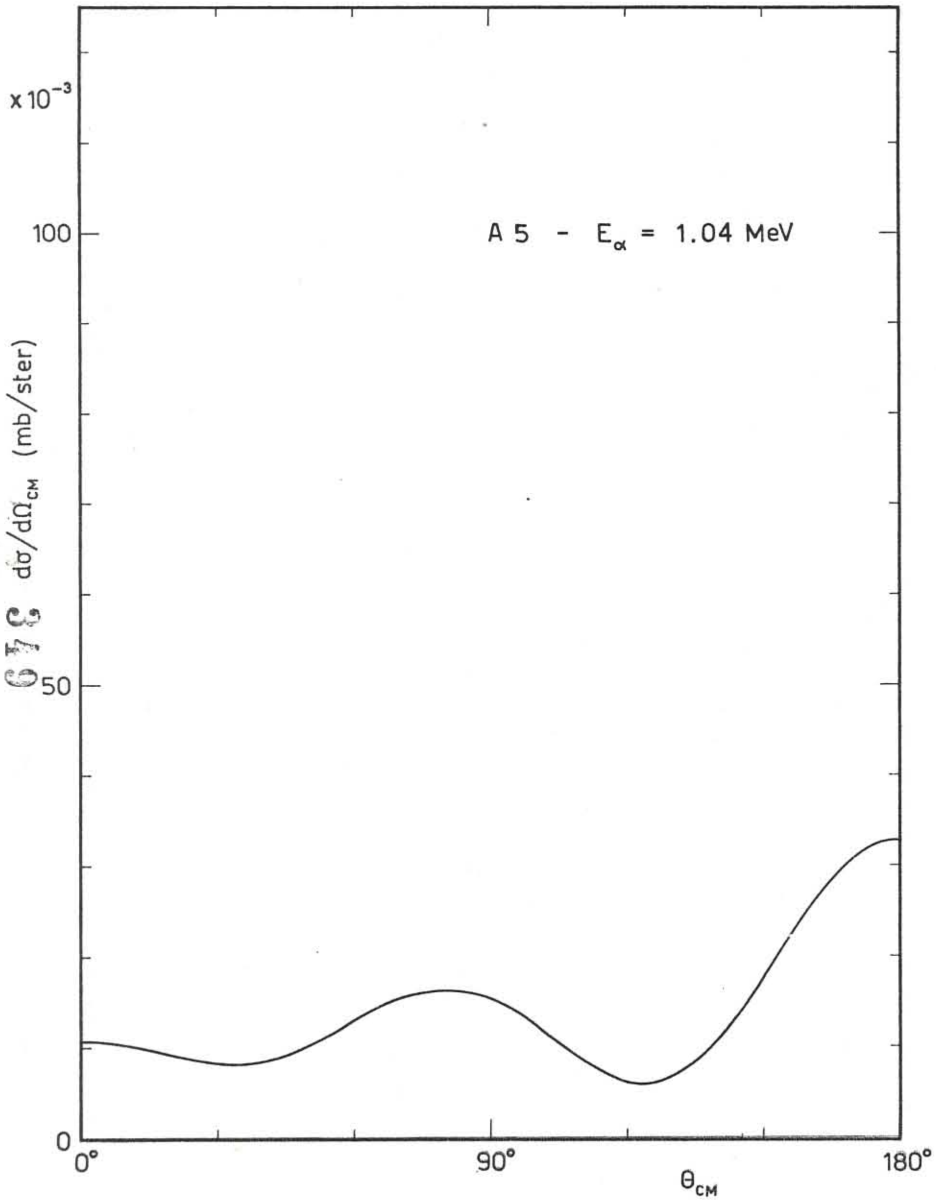
([10]) T.W. Bonner, A.A. Kraus Jr., J.B. Marion and J.P. Schiffer, Phys. Rev. 102, (1956) 1348.

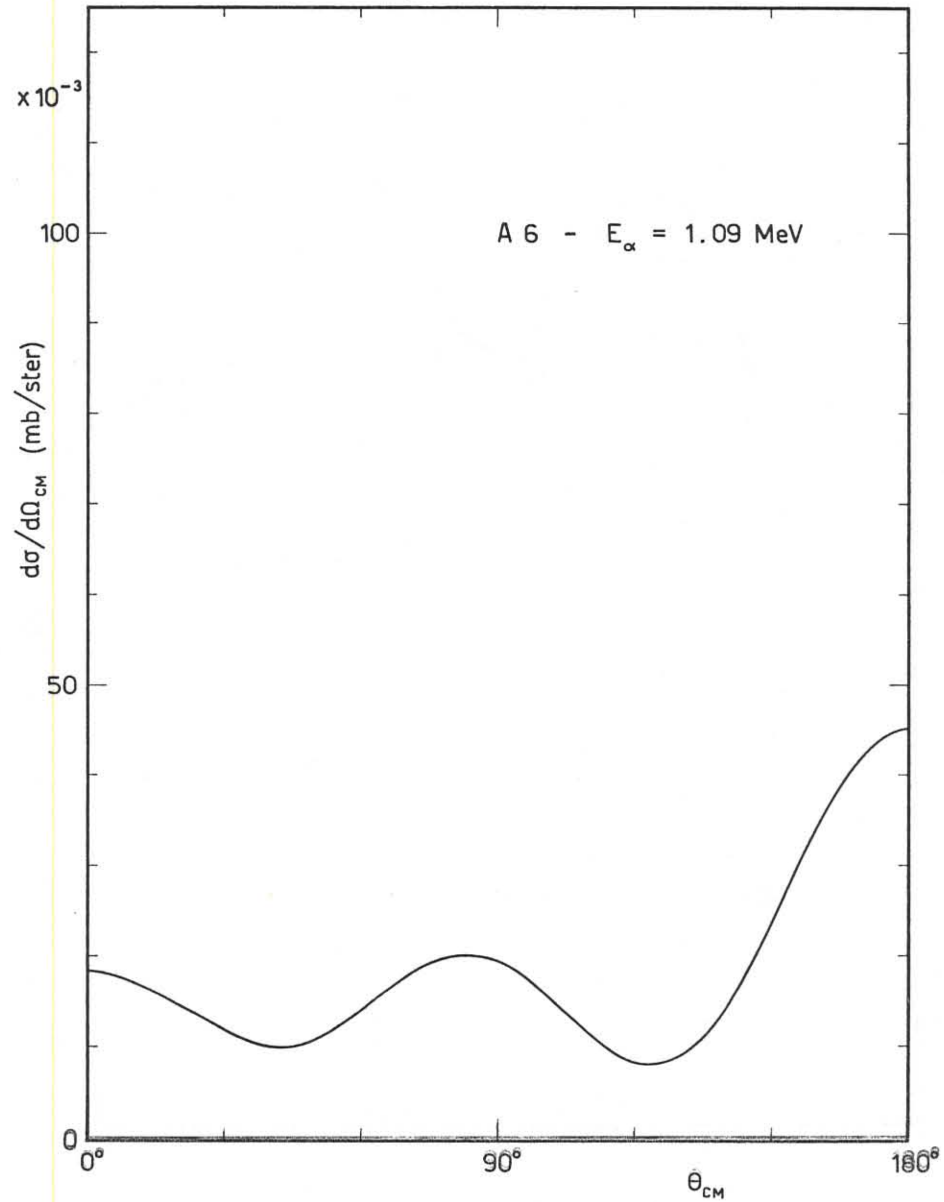

x 10^-3
10
5
0
dσ/dΩ_CM (mb/ster)
A 1 - E_α = 0.51 MeV
0°
90°
180°
θ_CM

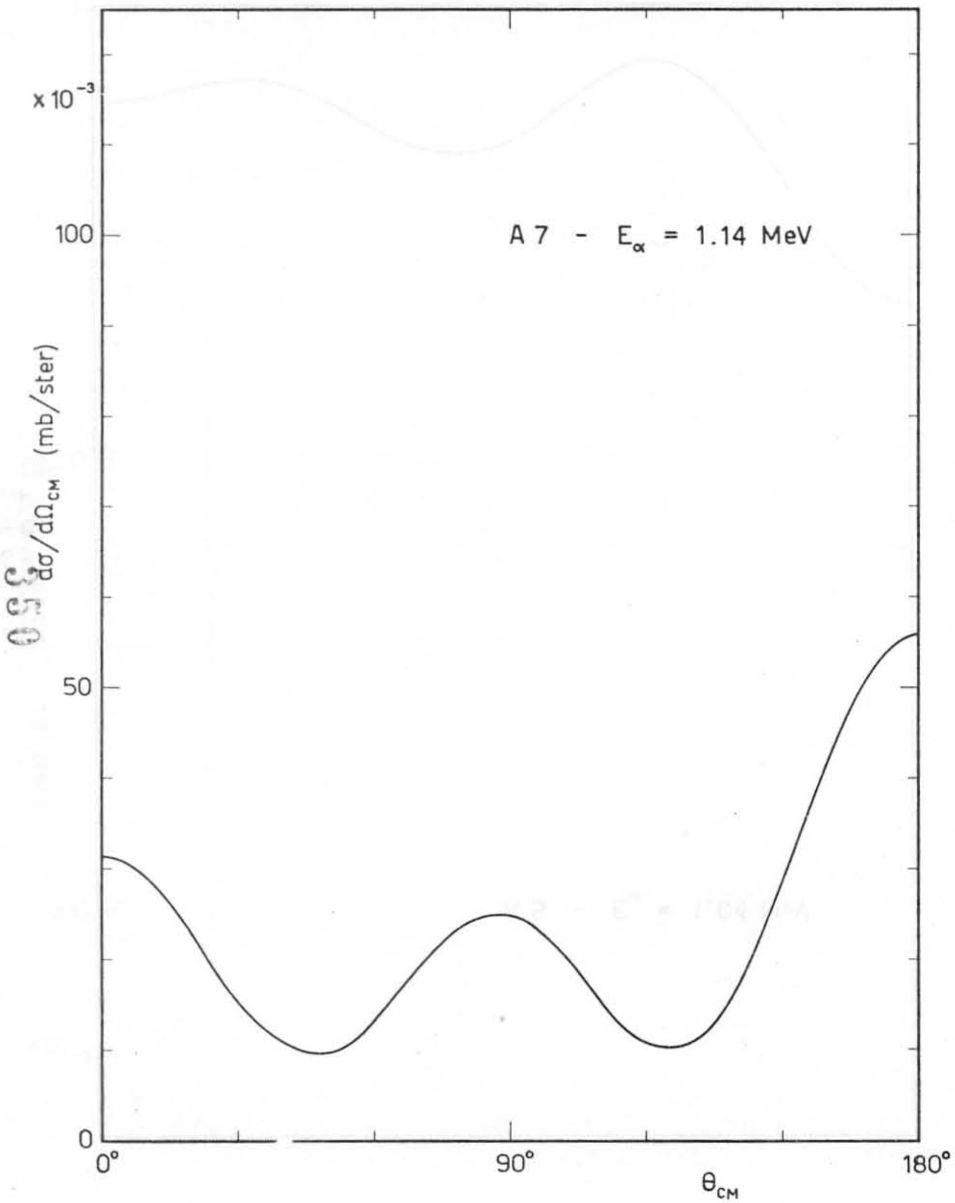

x 10^-3
10
5
0
dσ/dΩ_CM (mb/ster)
A 2 - E_α = 0.70 MeV
0°
90°
180°
θ_CM

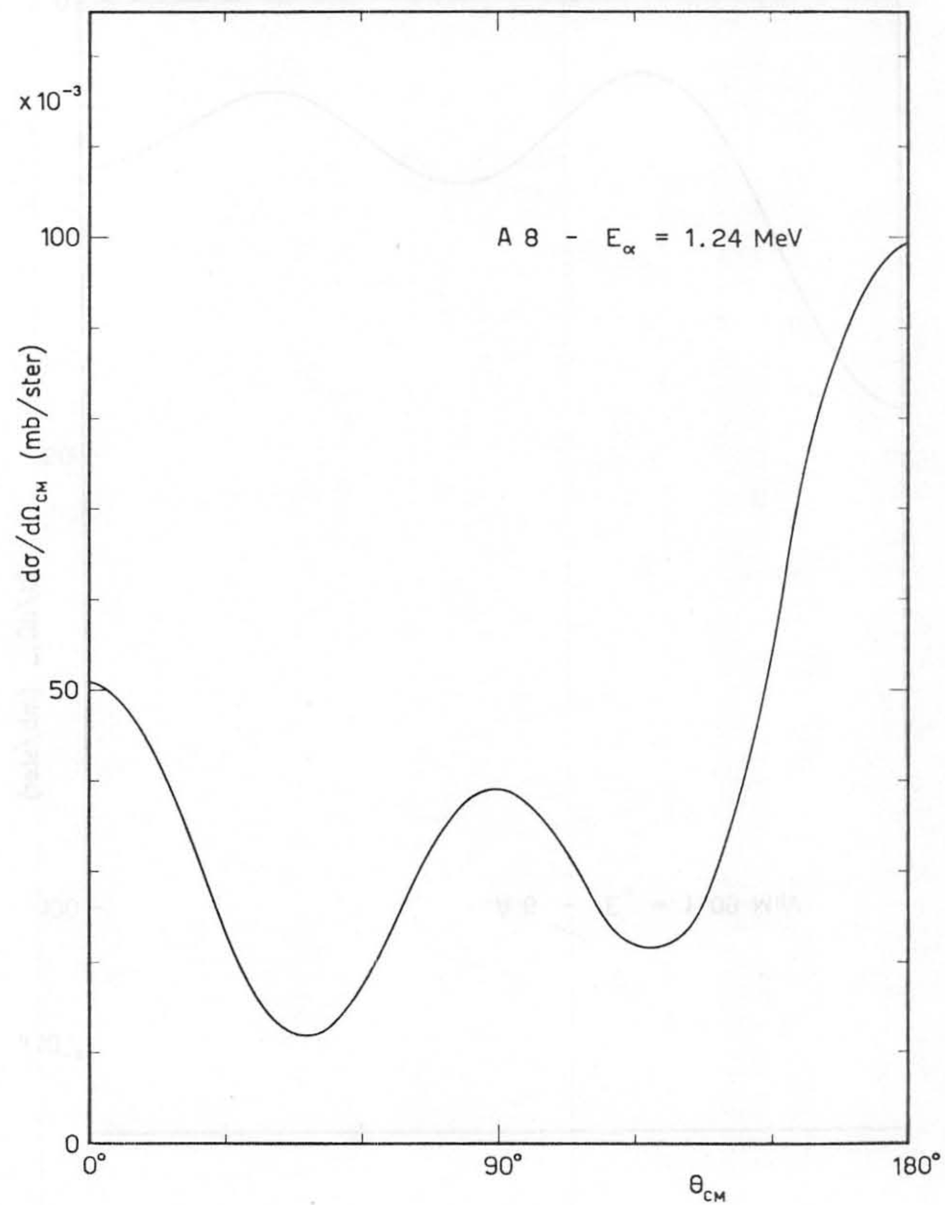

A 3 - E_α = 0.82 MeV
x 10^{-3}
$d\sigma/d\Omega_{CM}$ (mb/ster)
0
5
10
0°
90°
180°
θ_{CM}

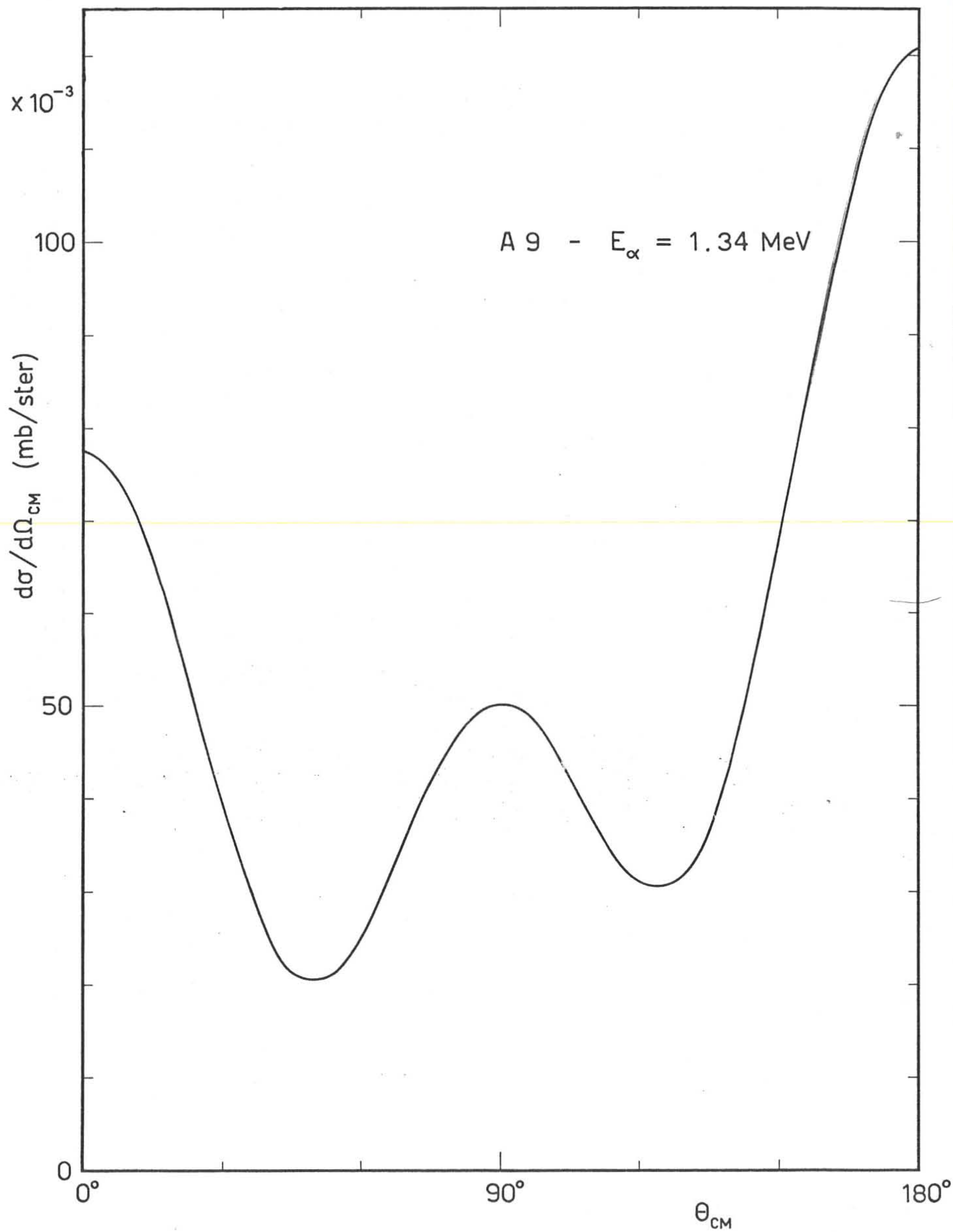

A 4 - E_α = 0.93 MeV
x 10^{-3}
$d\sigma/d\Omega_{CM}$ (mb/ster)
0
50
100
0°
90°
180°
θ_{CM}

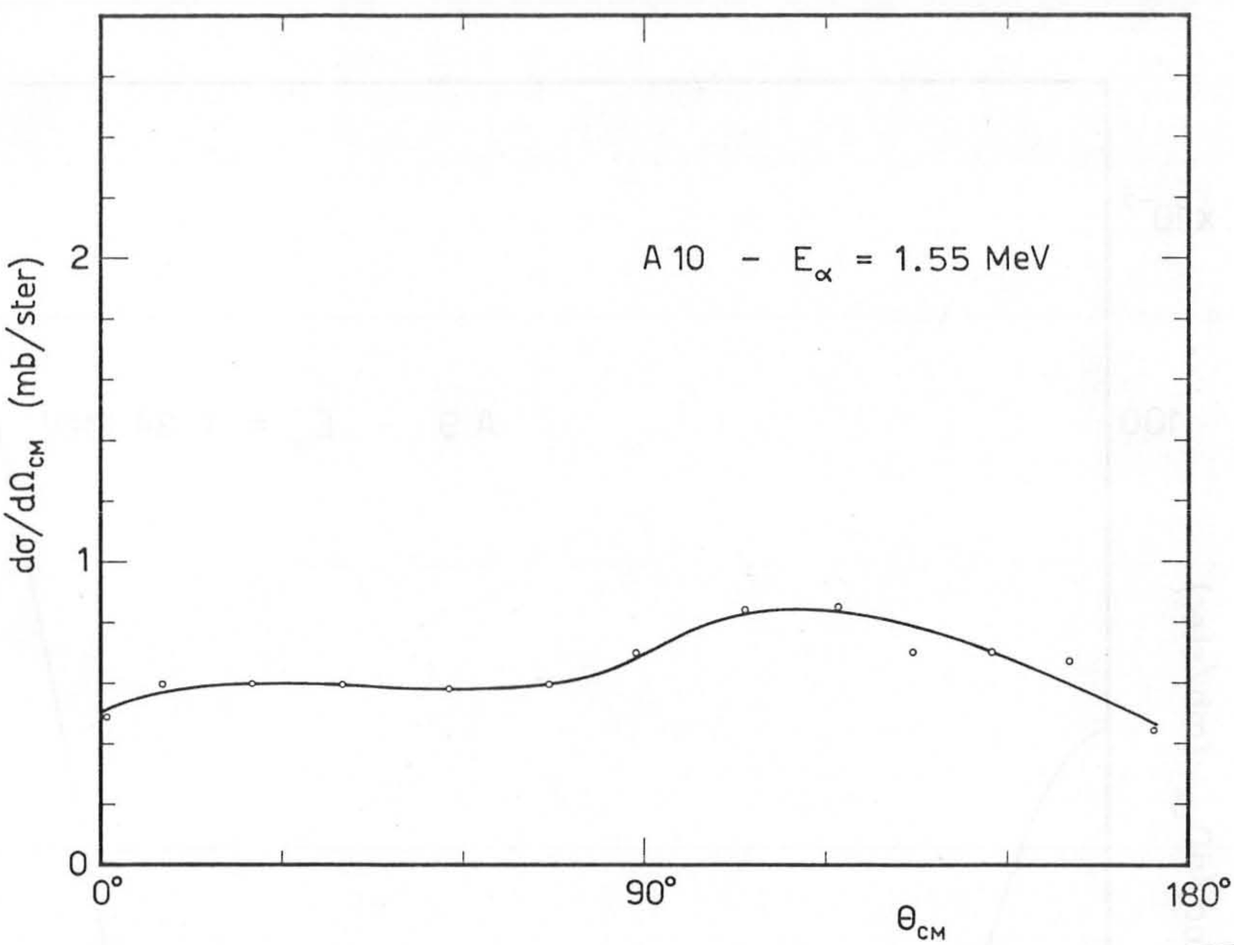

A 5 - E_α = 1.04 MeV
x 10^{-3}
100
50
0
$d\sigma/d\Omega_{CM}$ (mb/ster)
0°
90°
180°
θ_{CM}

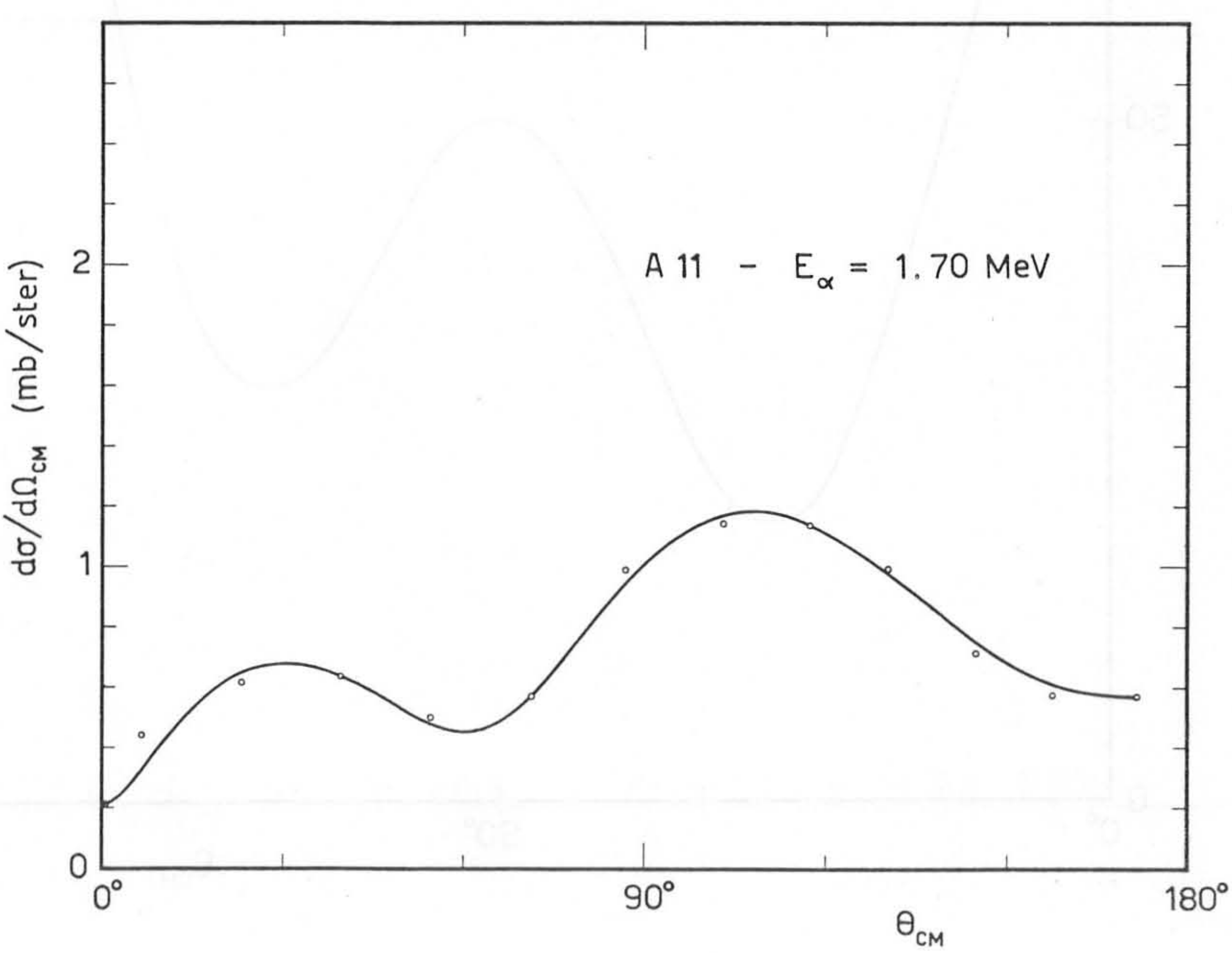

A 6 - E_α = 1.09 MeV
x 10^{-3}
100
50
0
$d\sigma/d\Omega_{CM}$ (mb/ster)
0°
90°
180°
θ_{CM}

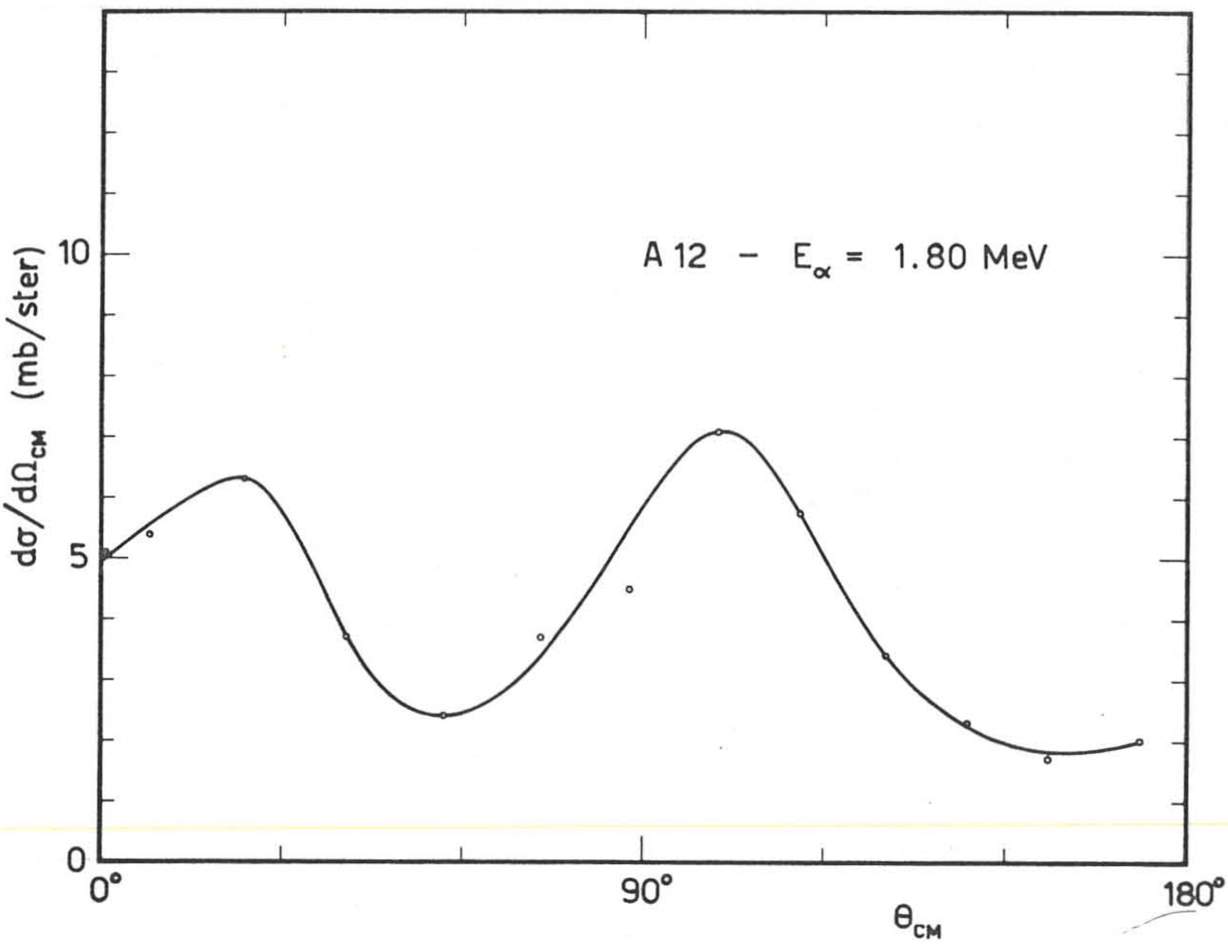

x 10⁻³
100
50
0
dσ/dΩ_CM (mb/ster)
A 7 - E_α = 1.14 MeV
0°
90°
180°
θ_CM

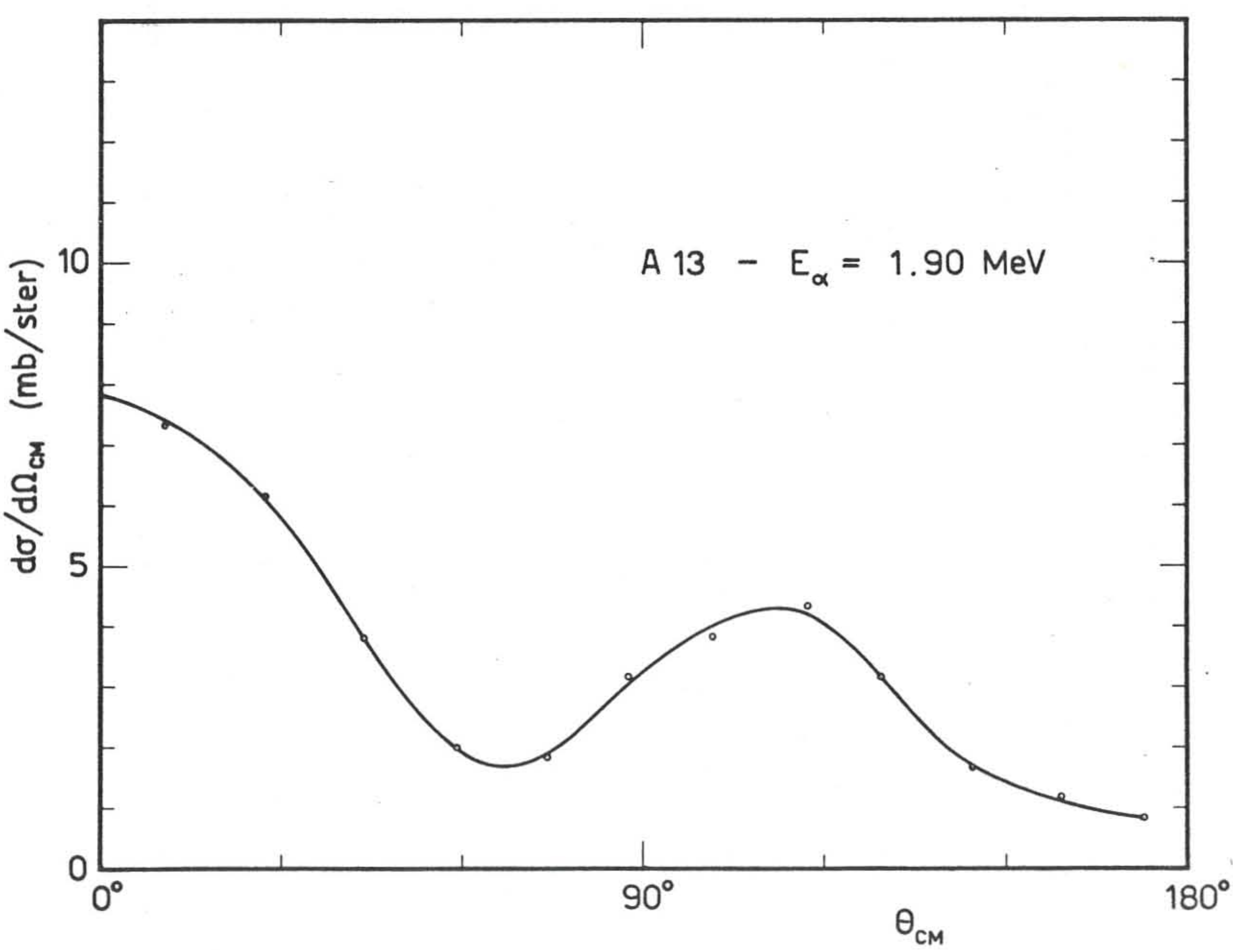

x 10⁻³
100
50
0
dσ/dΩ_CM (mb/ster)
A 8 - E_α = 1.24 MeV
0°
90°
180°
θ_CM

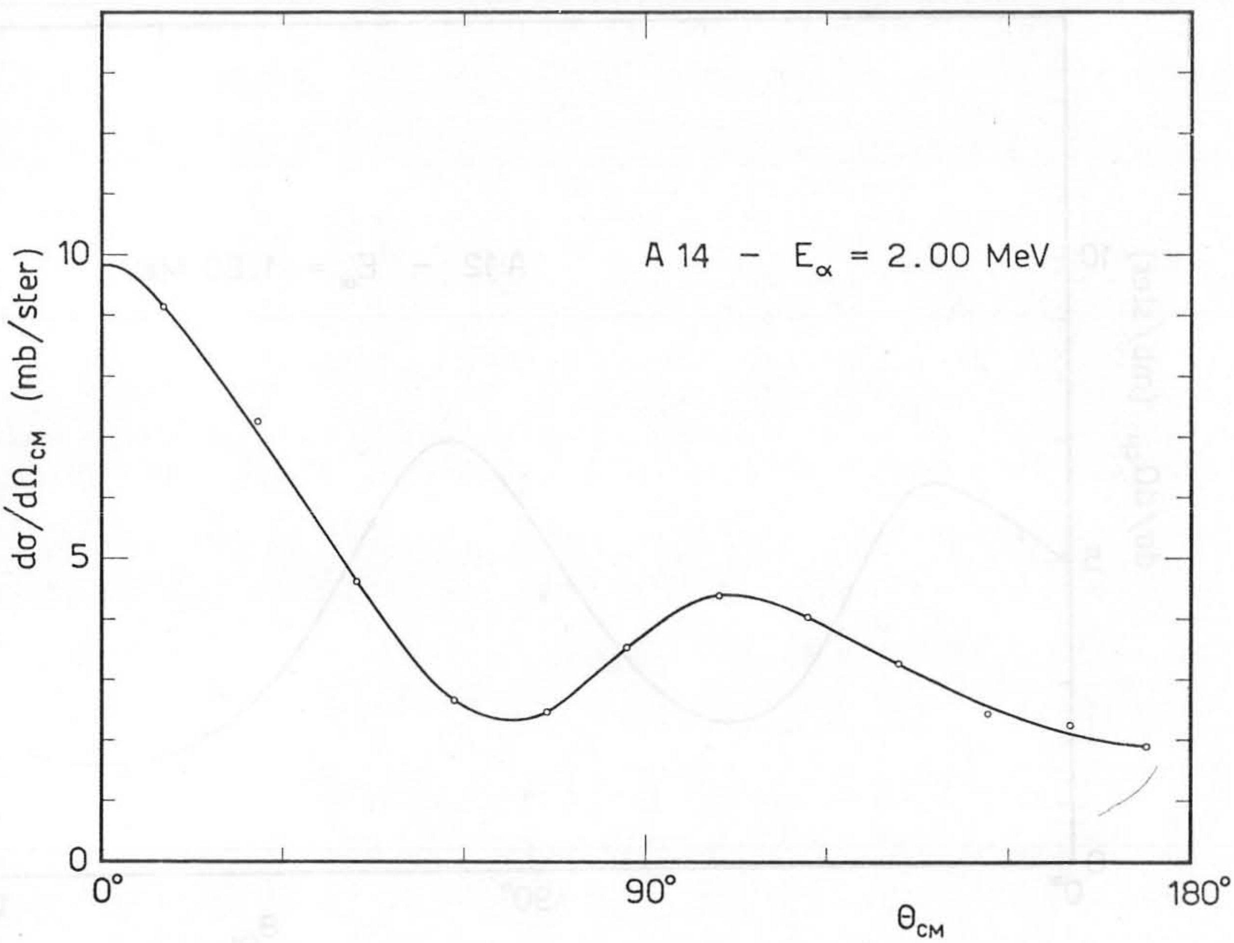

x 10⁻³
100
50
0
dσ/dΩ_CM (mb/ster)
A 9 - E_α = 1.34 MeV
0°
90°
180°
θ_CM

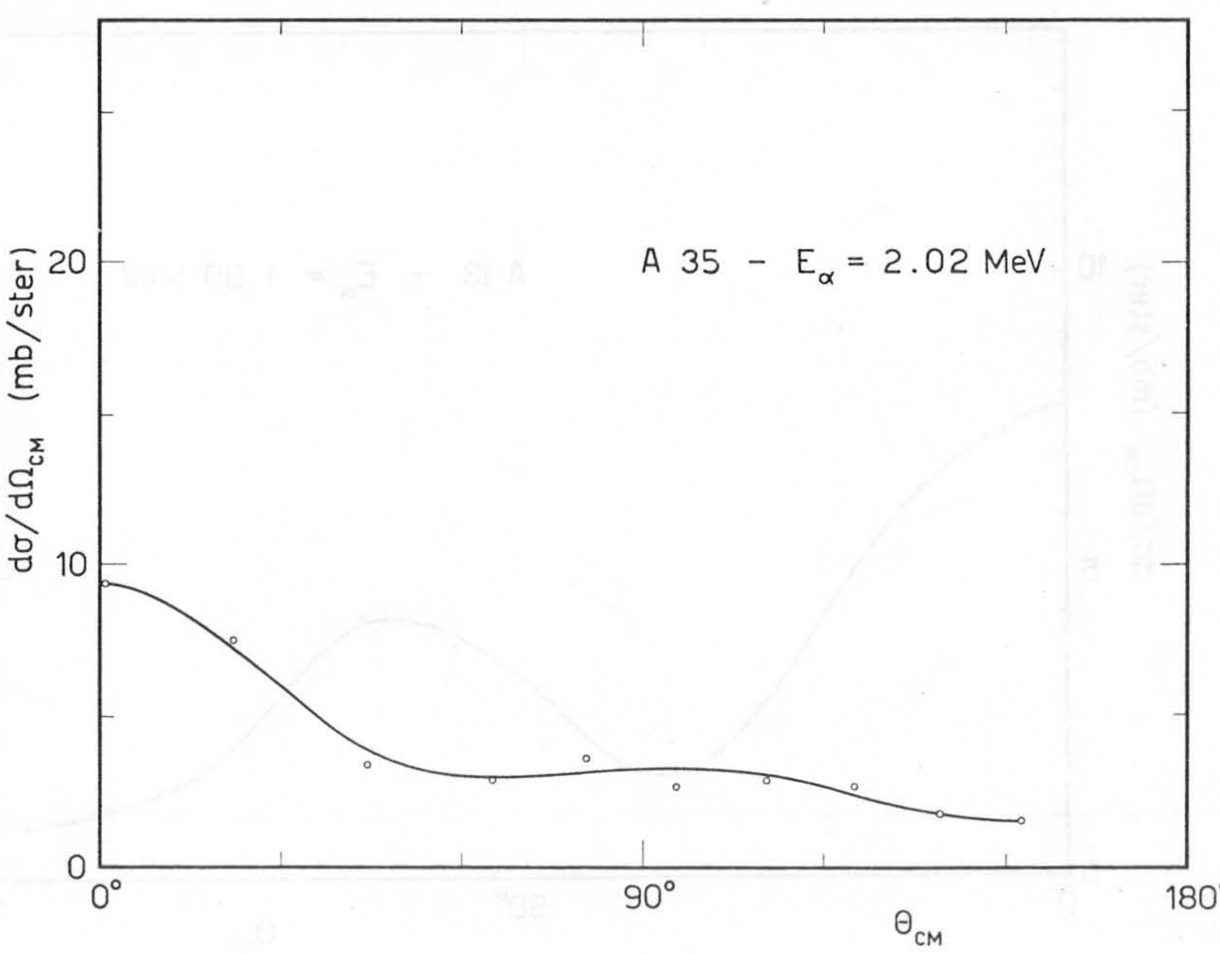

A 10 - E_α = 1.55 MeV
dσ/dΩ$_{CM}$ (mb/ster)
0
1
2
0°
90°
180°
θ$_{CM}$

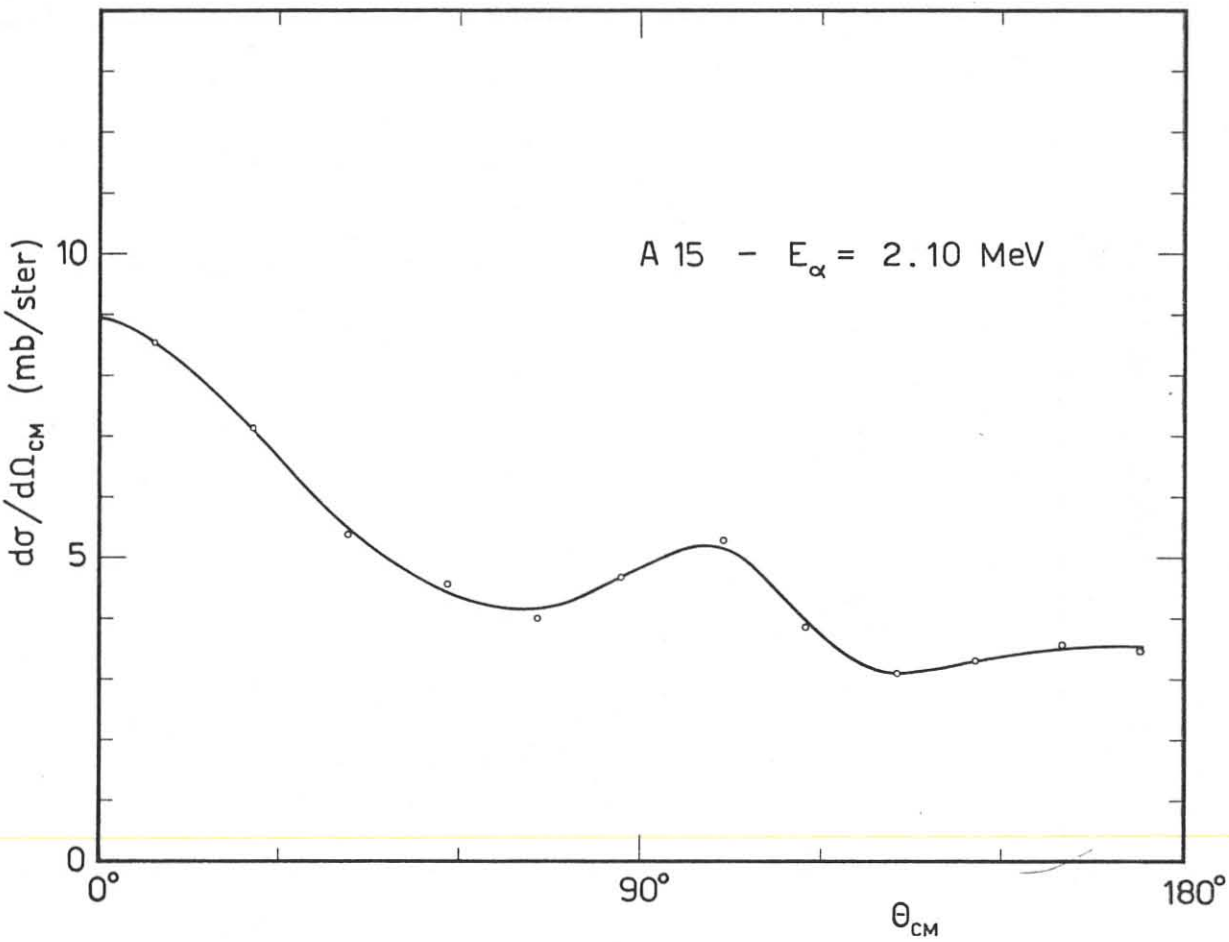

A 11 - E_α = 1.70 MeV
dσ/dΩ$_{CM}$ (mb/ster)
0
1
2
0°
90°
180°
θ$_{CM}$

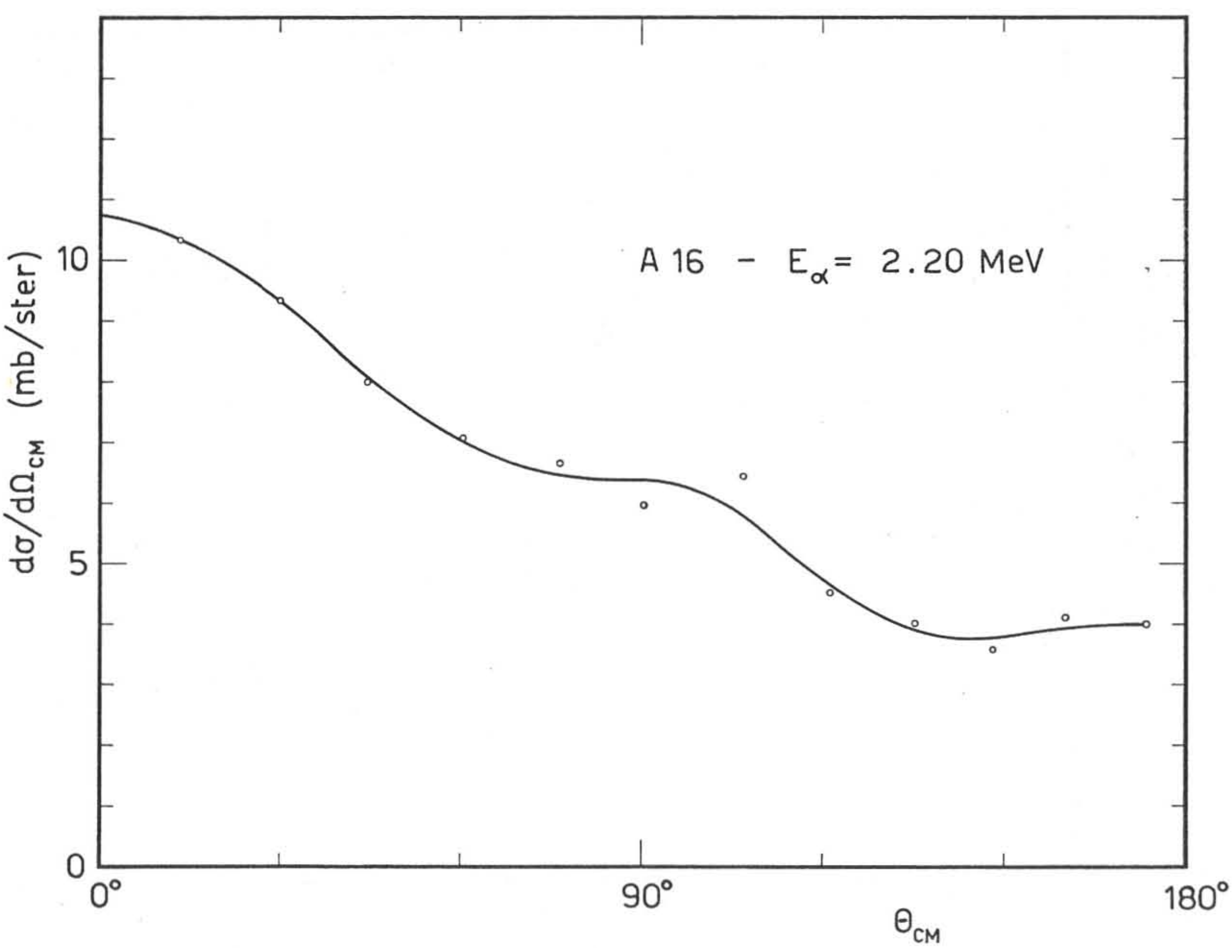

A 12 – E_α = 1.80 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ_{CM}

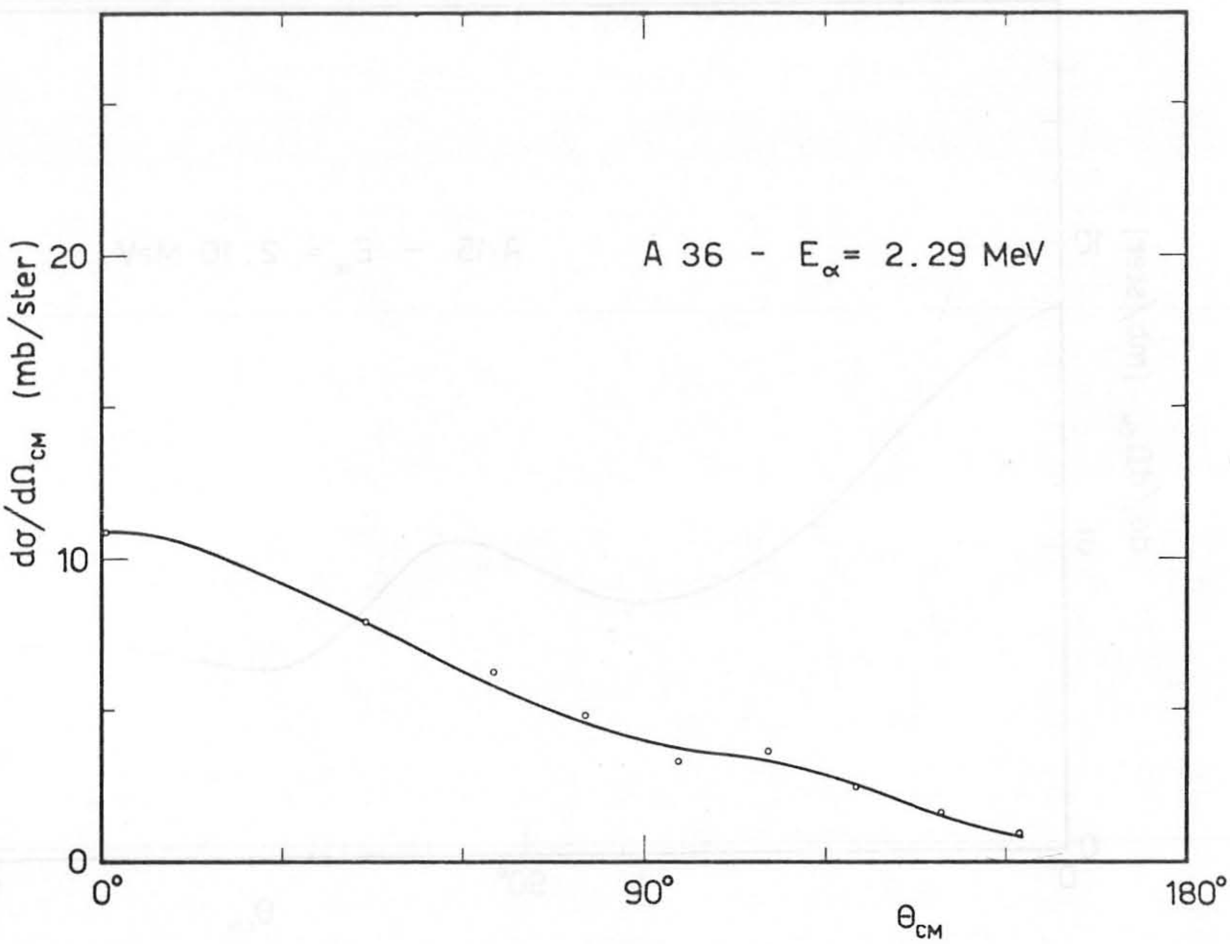

A 13 – E_α = 1.90 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ_{CM}


A 14 - E_α = 2.00 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

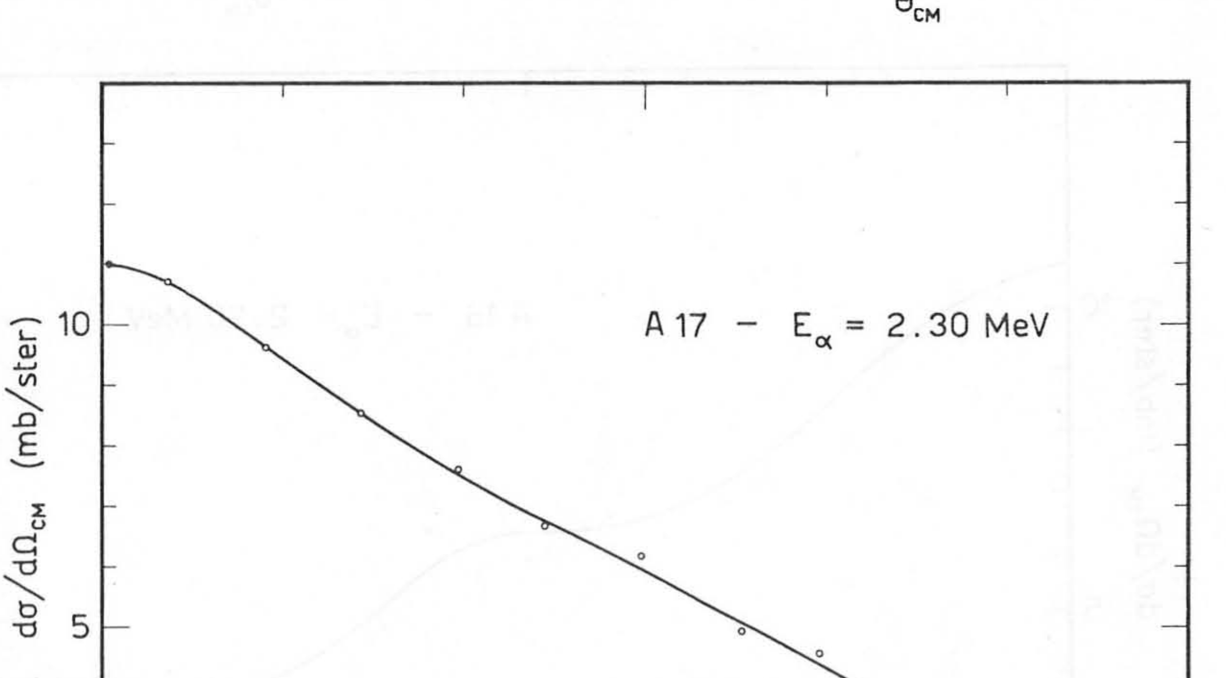

A 35 - E_α = 2.02 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
20
10
0
0°
90°
180°
Θ_{CM}


A 15 - E_α = 2.10 MeV
dσ/dΩ$_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ$_{CM}$

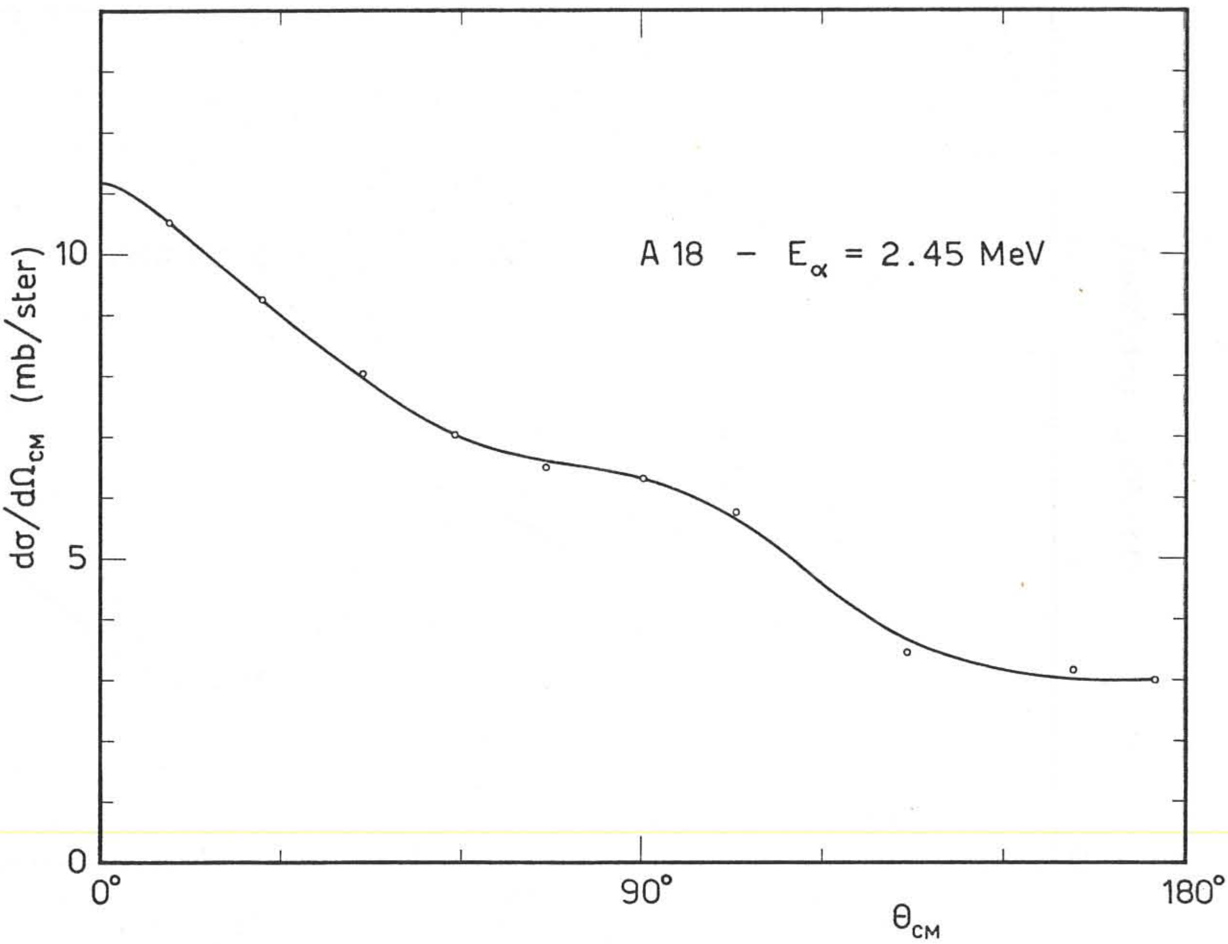

A 16 - E_α = 2.20 MeV
dσ/dΩ$_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ$_{CM}$

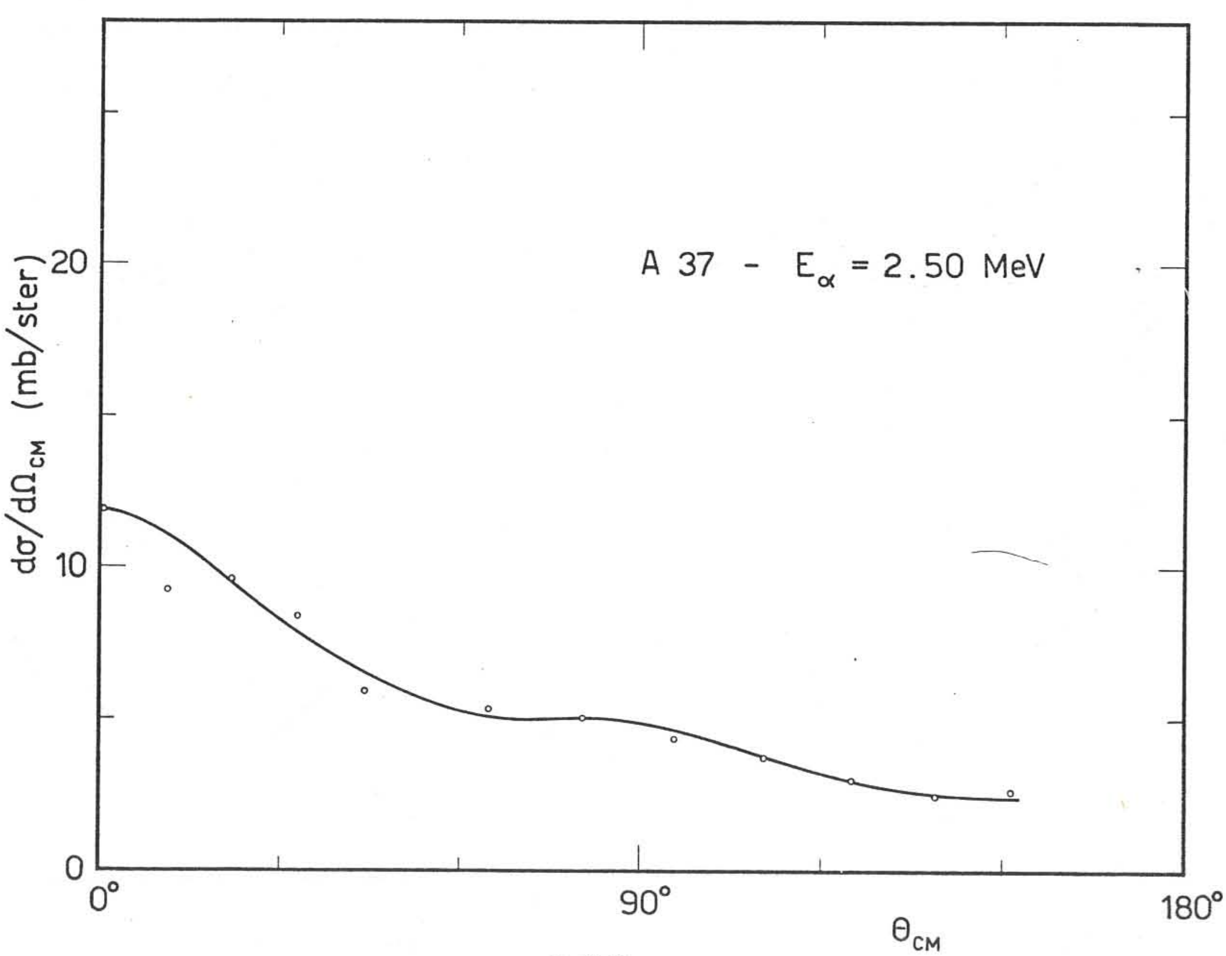


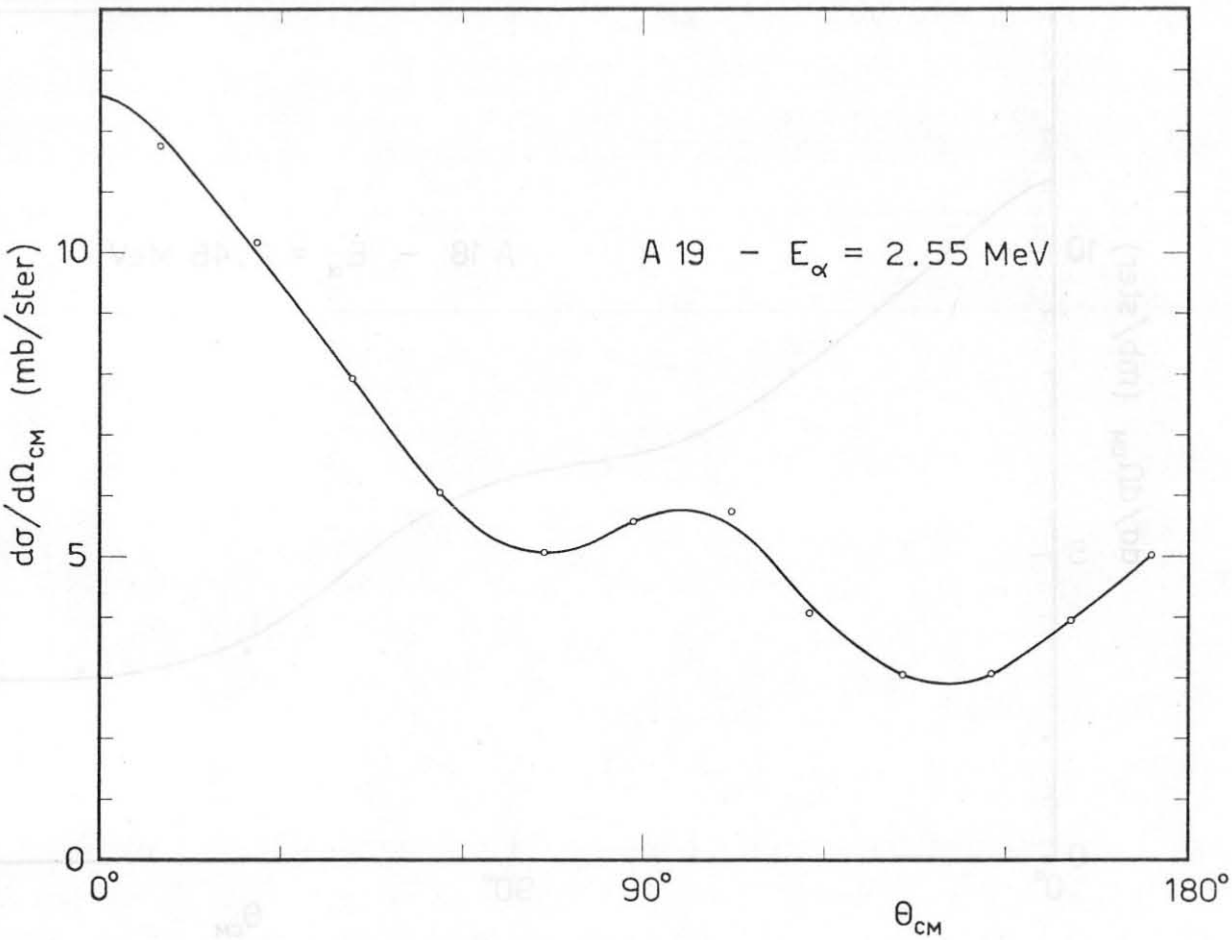
A 36 - E_α = 2.29 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
20
10
0
0°
90°
180°
Θ_{CM}



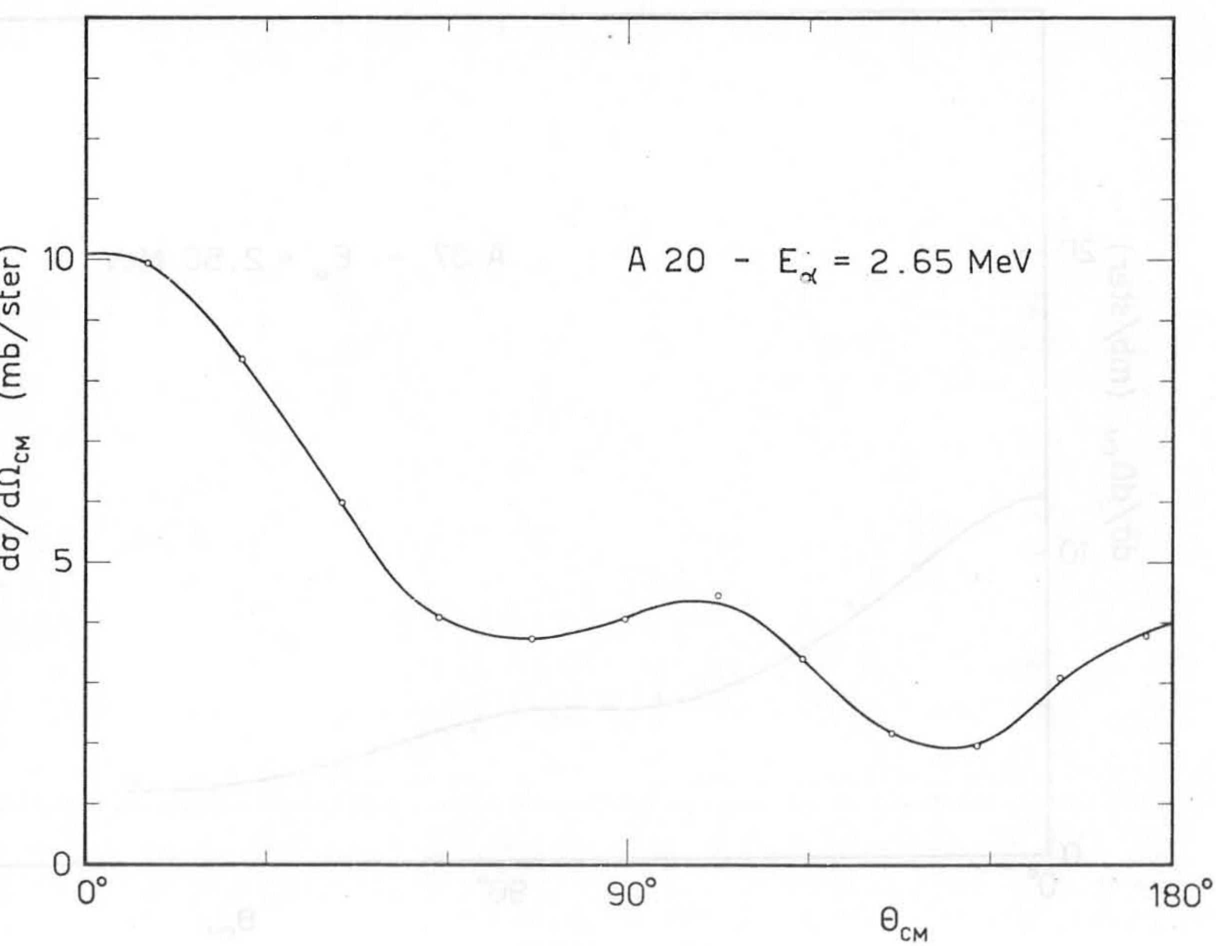
A 17 — E_α = 2.30 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}


A 18 - E_α = 2.45 MeV
dσ/dΩ$_{CM}$ (mb/ster)
0
5
10
0°
90°
180°
θ$_{CM}$

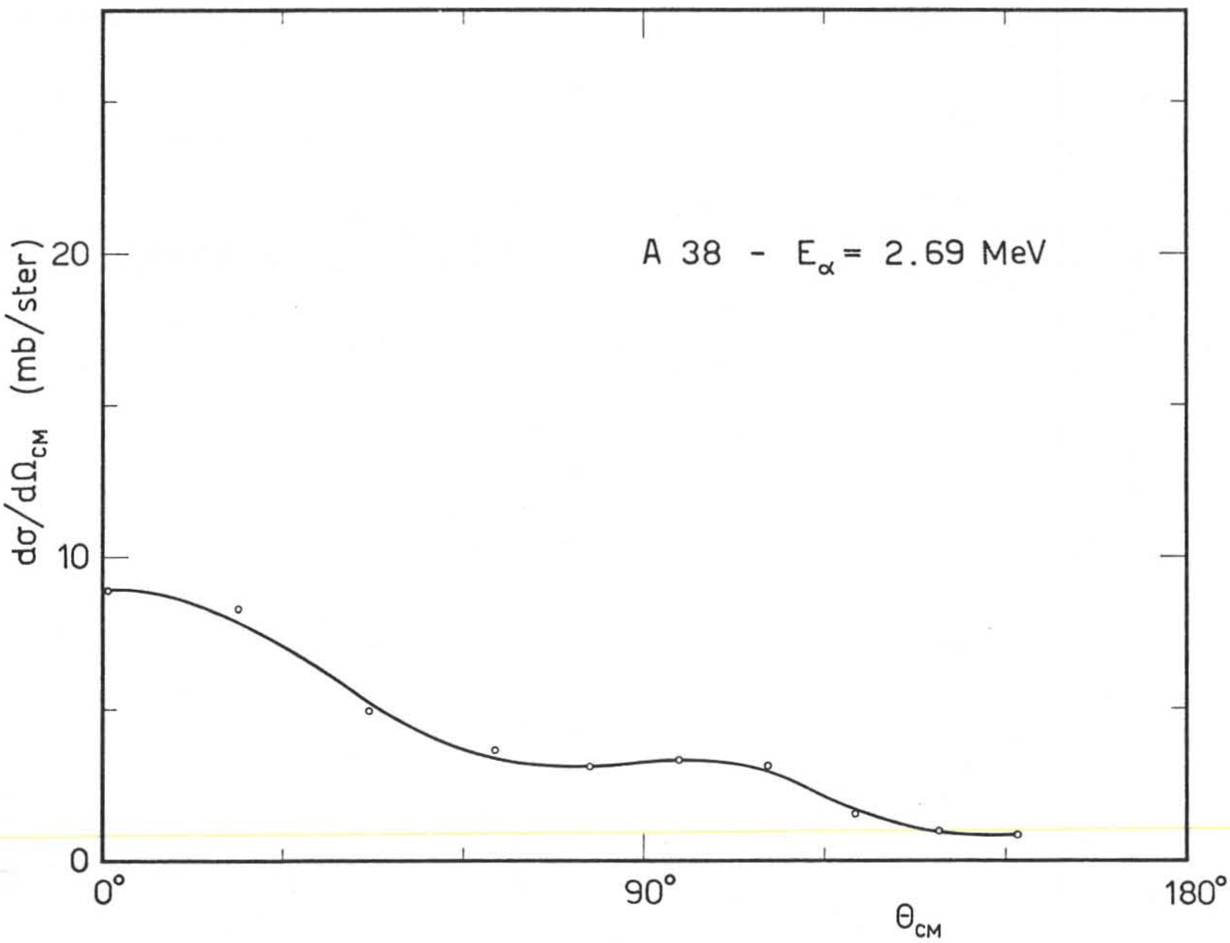

A 37 - E_α = 2.50 MeV
dσ/dΩ$_{CM}$ (mb/ster)
0
10
20
0°
90°
180°
θ$_{CM}$



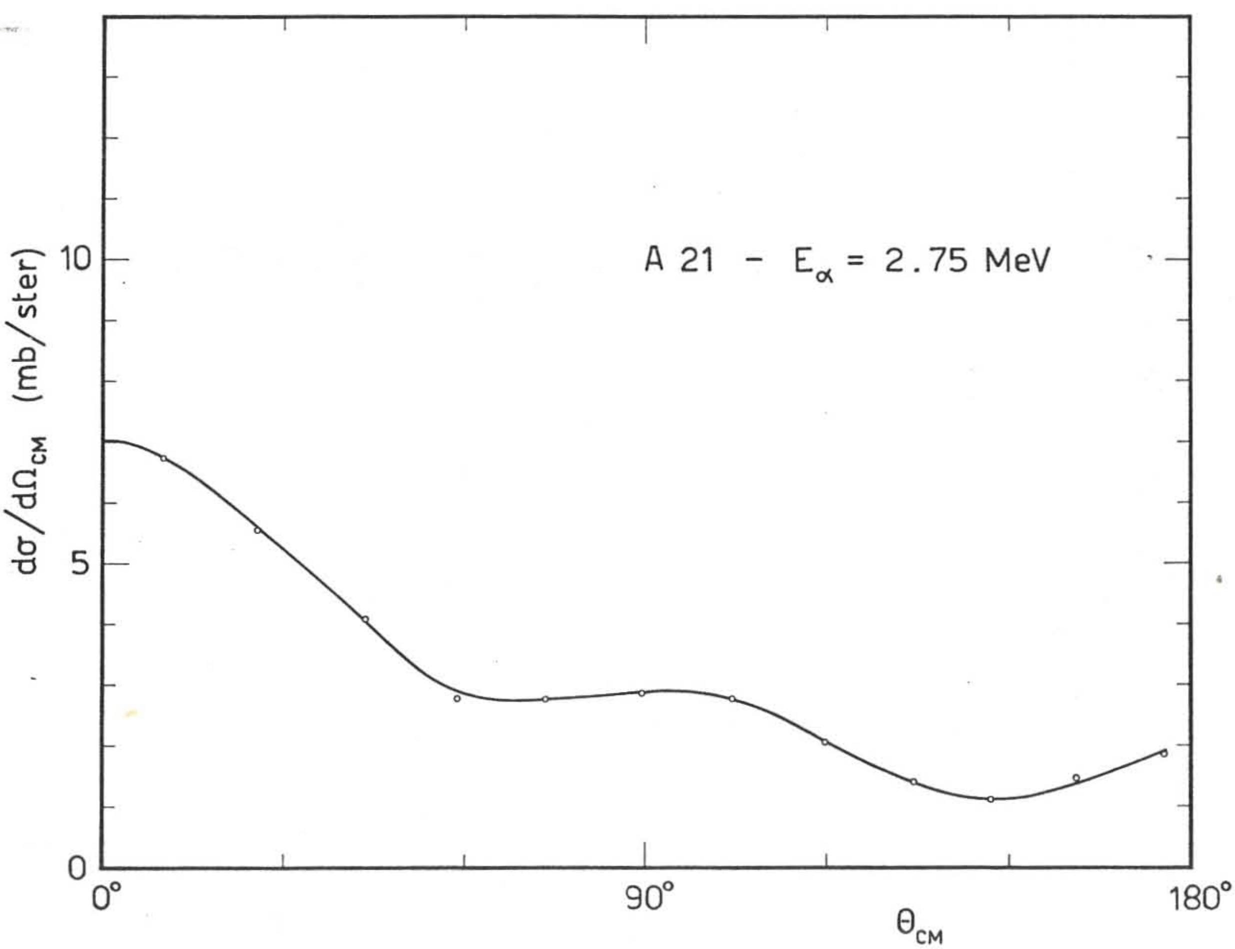
A 19 - E_α = 2.55 MeV
dσ/dΩ$_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ$_{CM}$



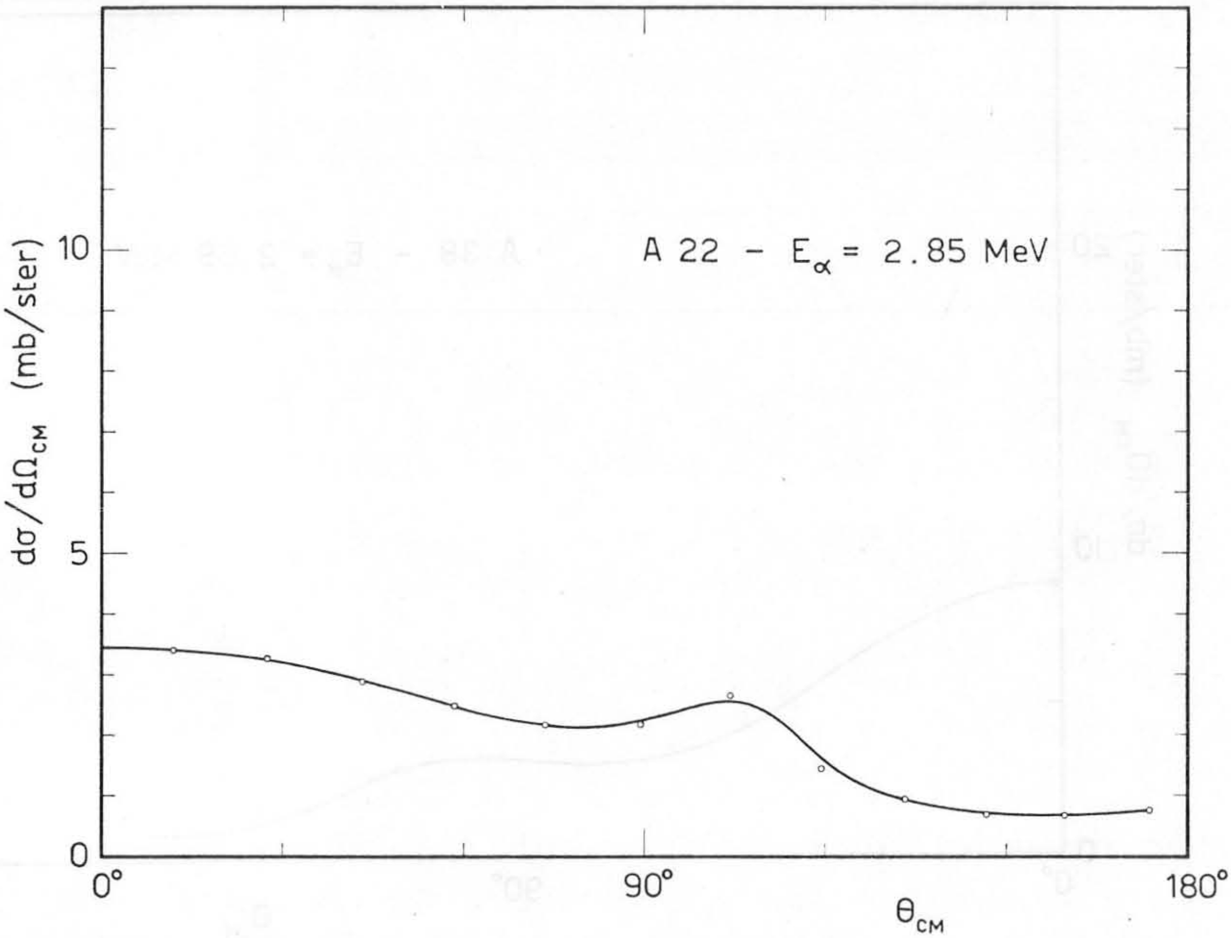
A 20 - E_α = 2.65 MeV
dσ/dΩ$_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ$_{CM}$

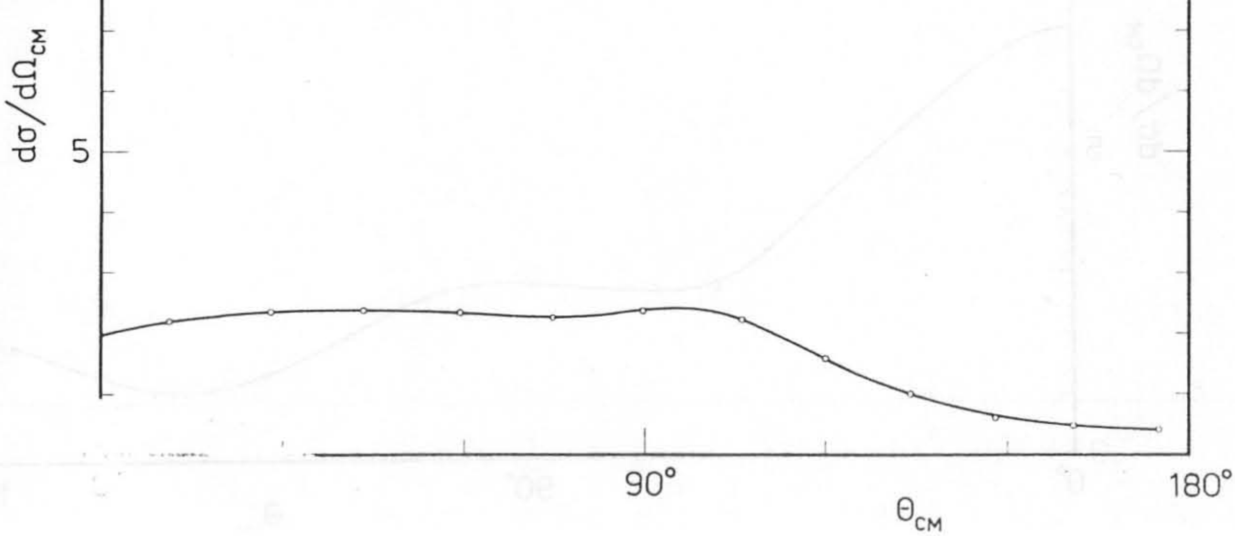


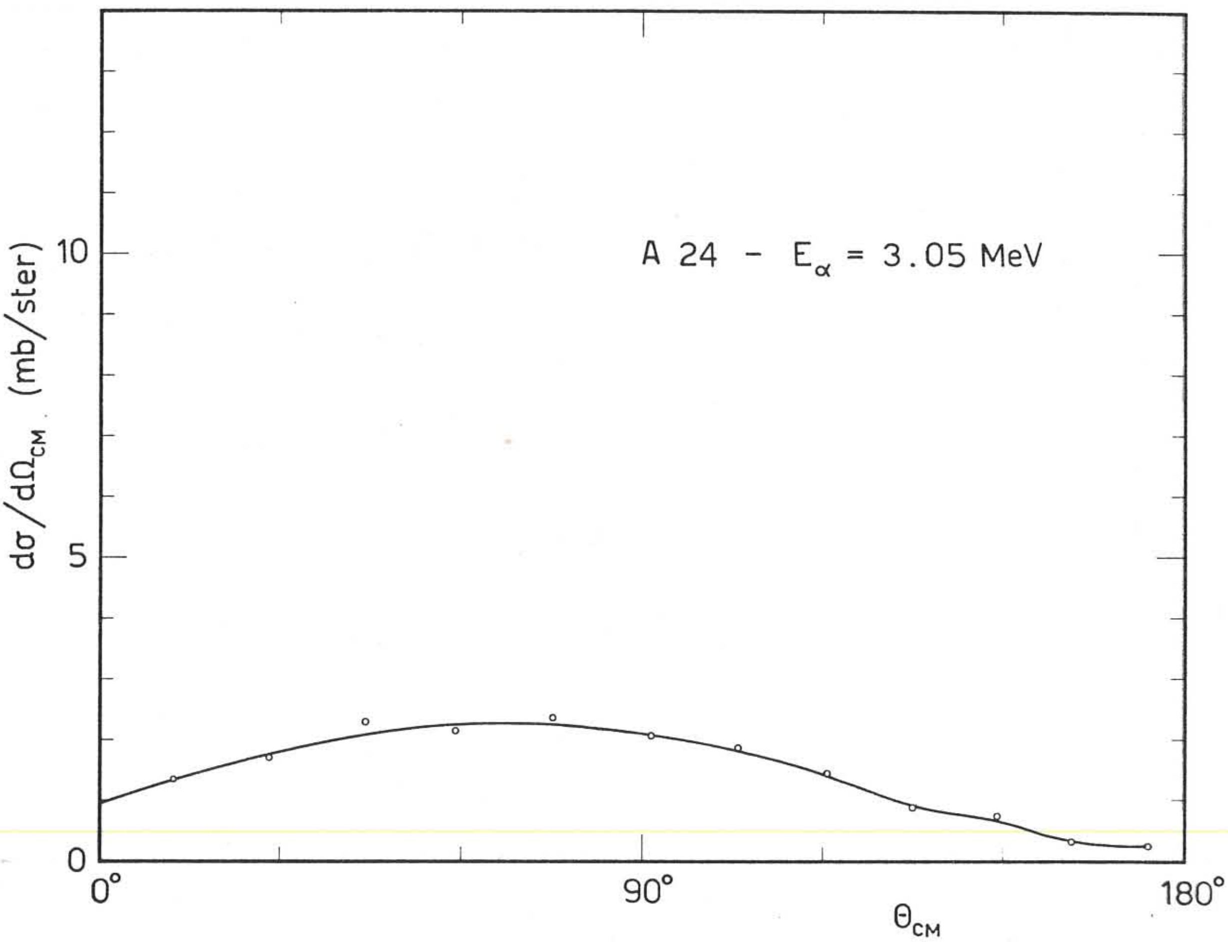
A 38 - E_α = 2.69 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
20
10
0
0°
90°
180°
Θ_{CM}

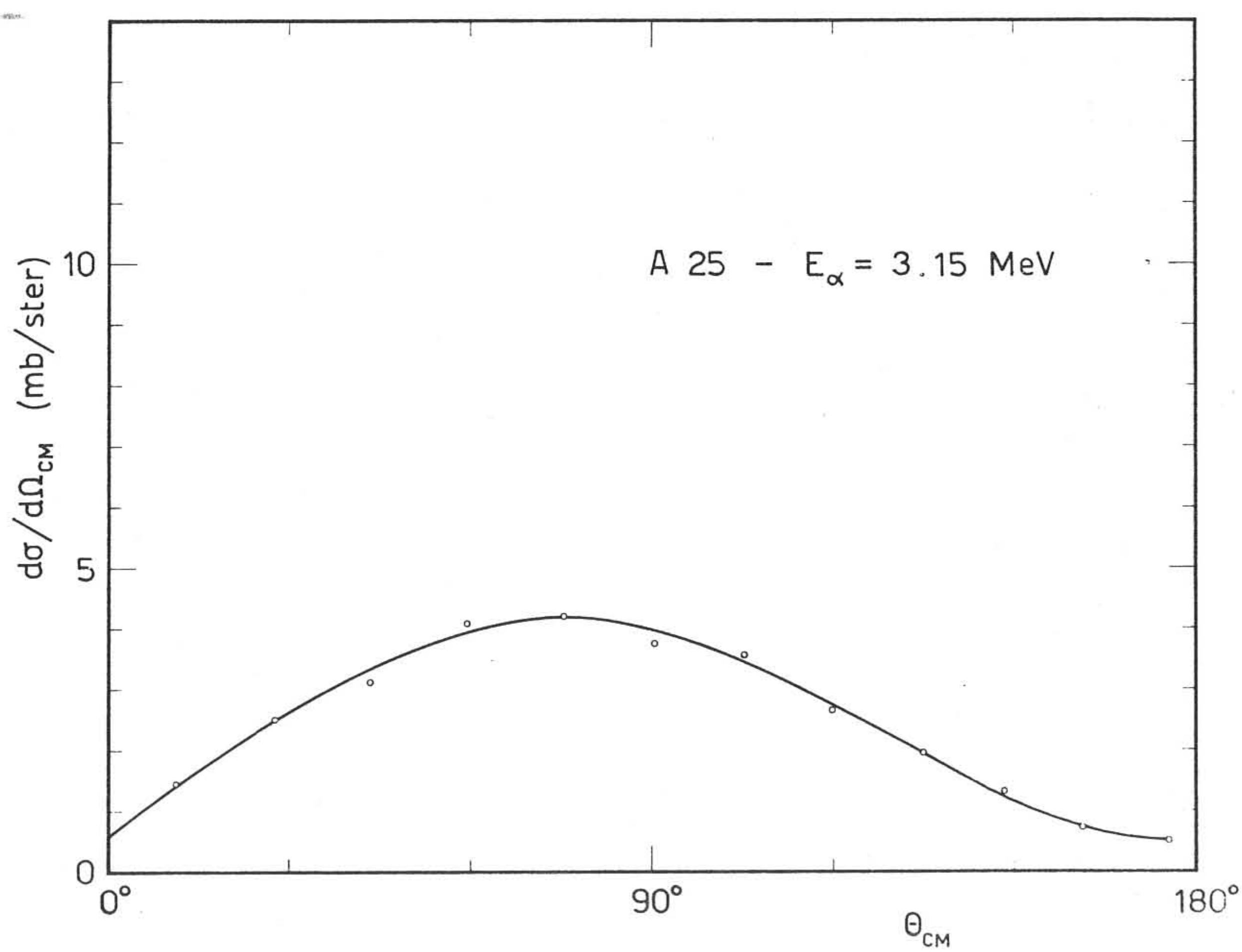


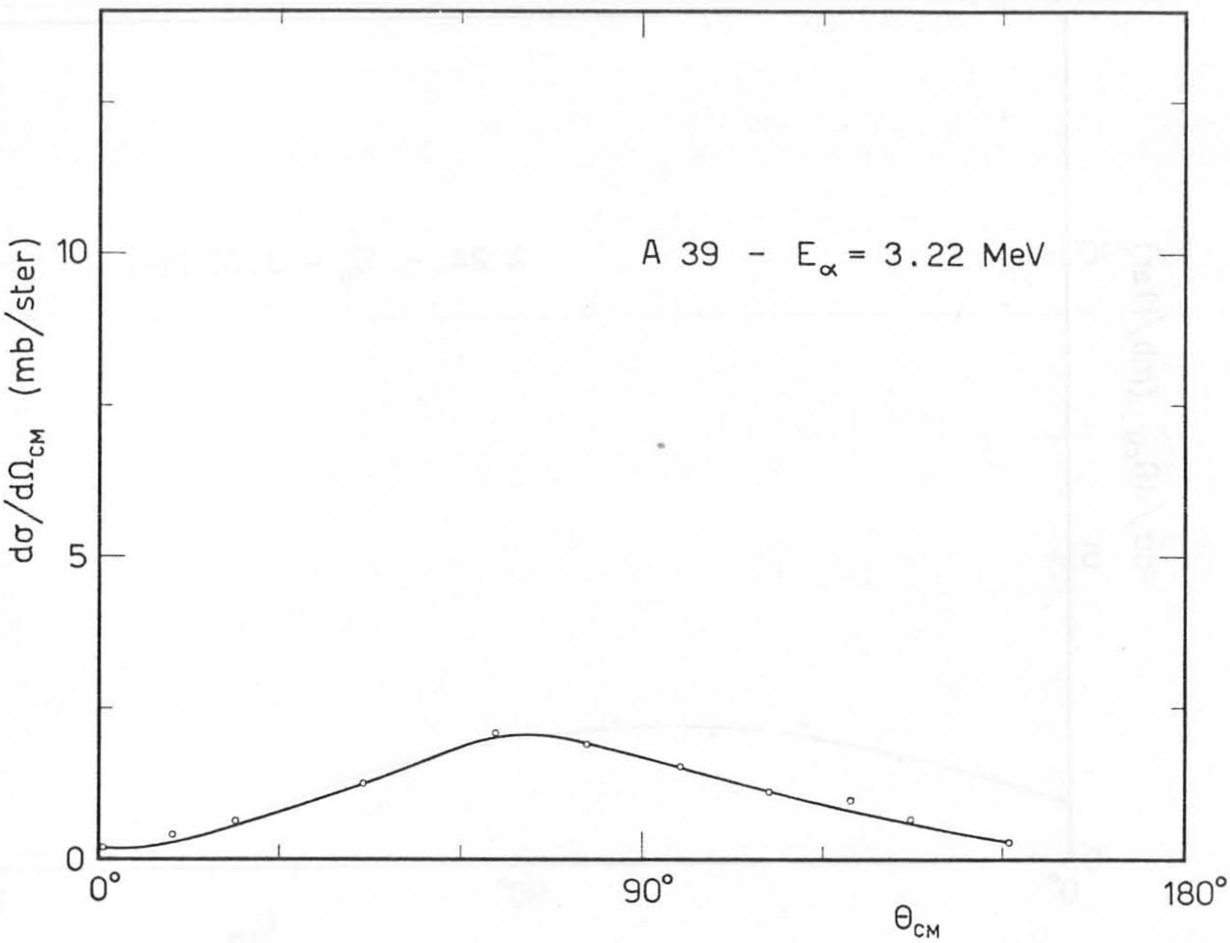
A 21 - E_α = 2.75 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

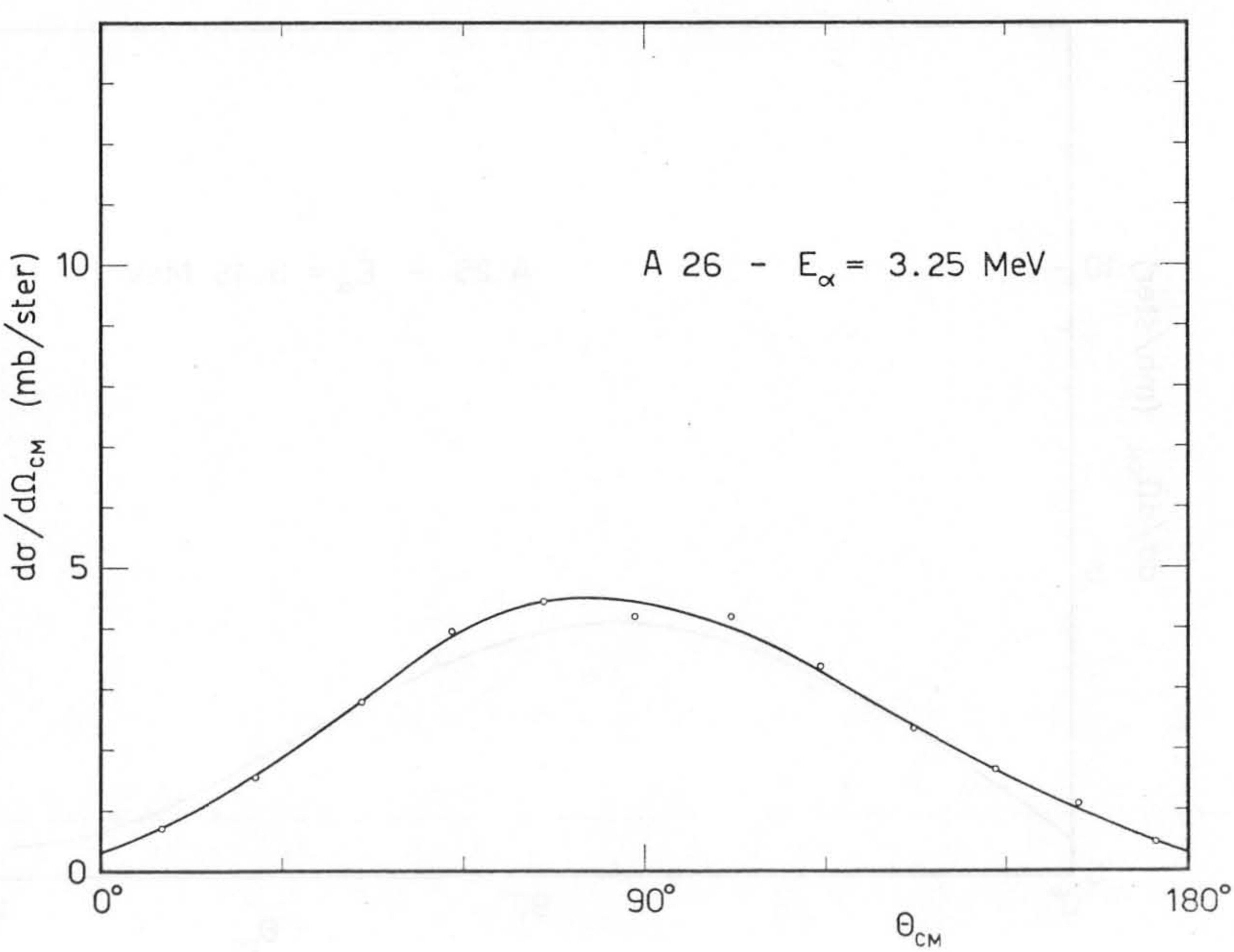

A 22 - E_α = 2.85 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ_{CM}

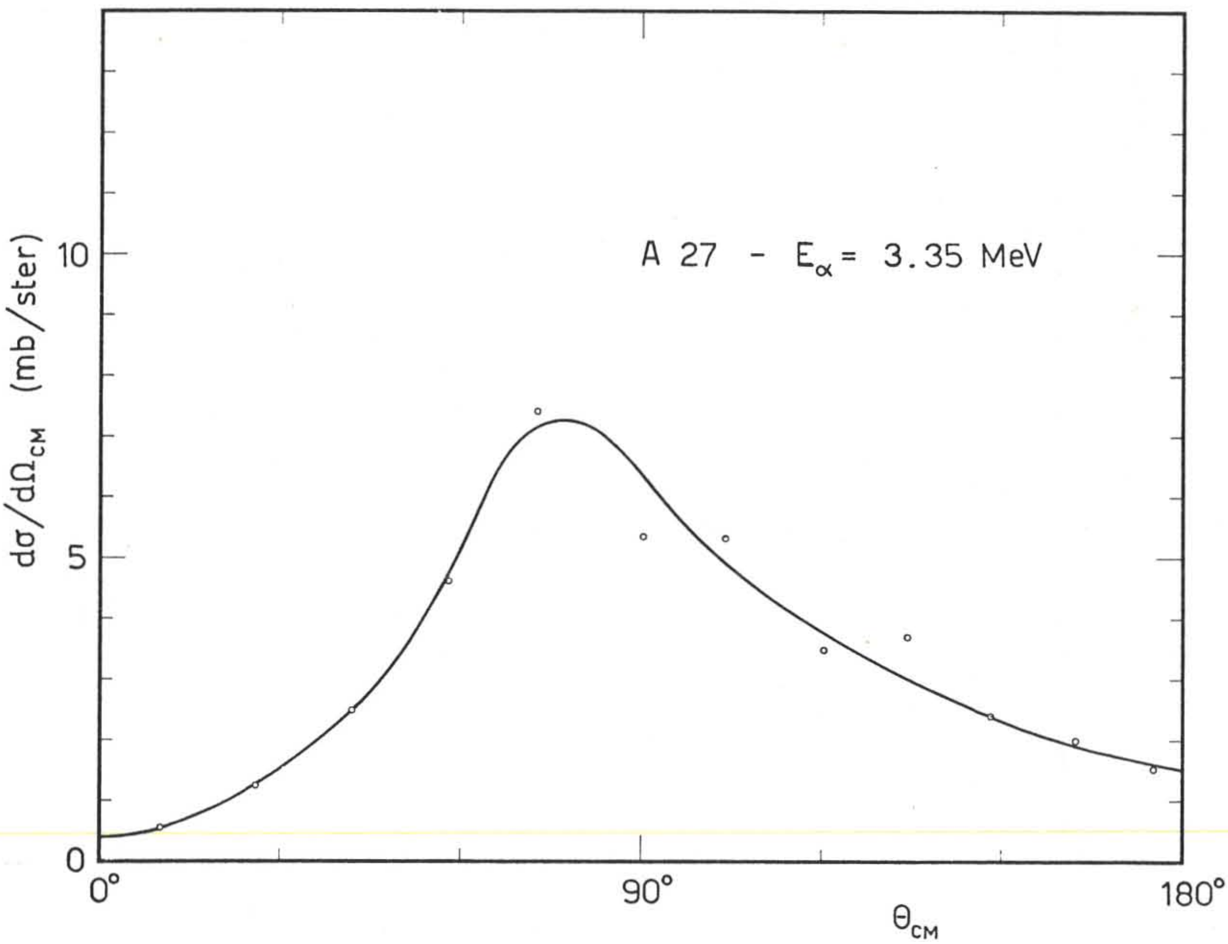

A 23 - E_α = 2.95 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
90°
180°
θ_{CM}

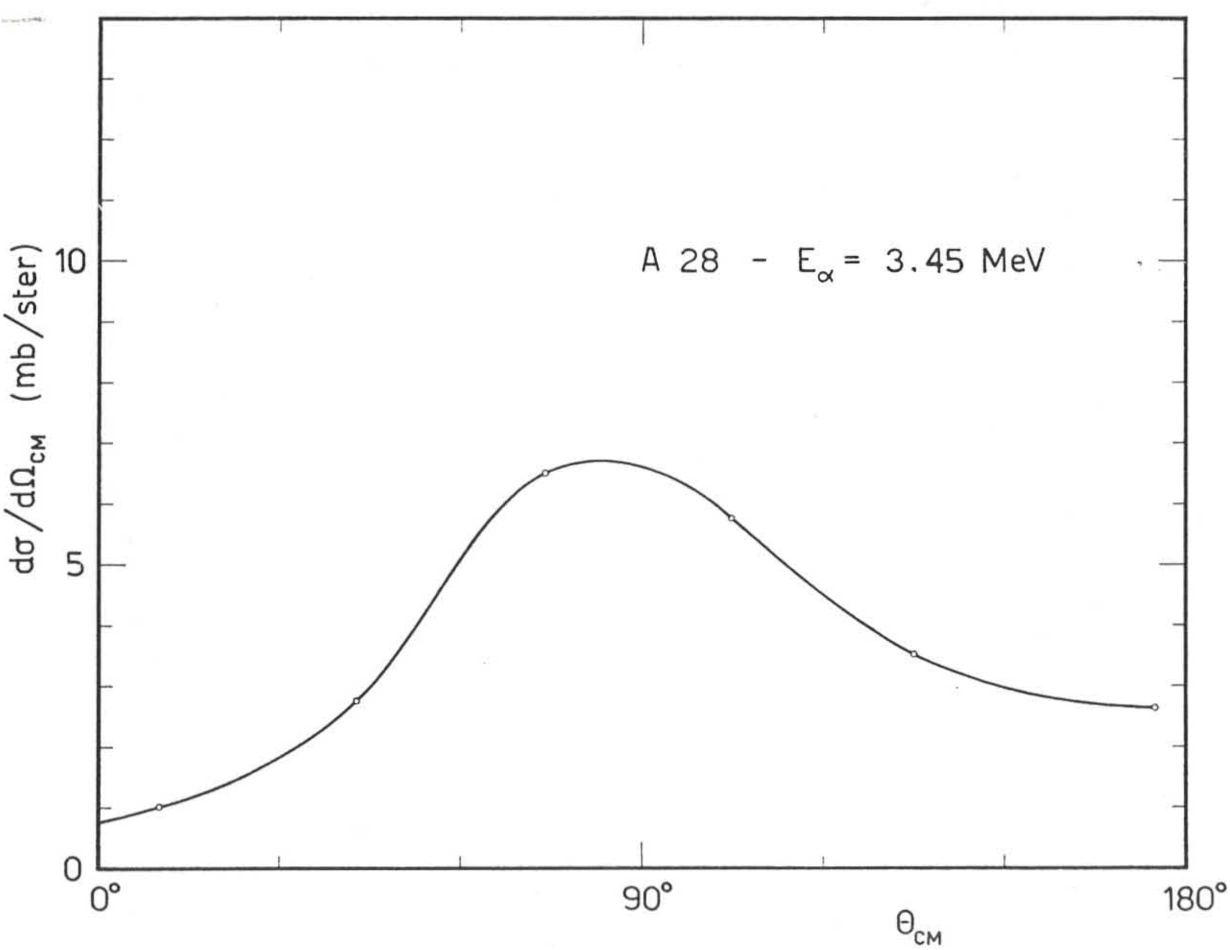

A 24 - E_α = 3.05 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

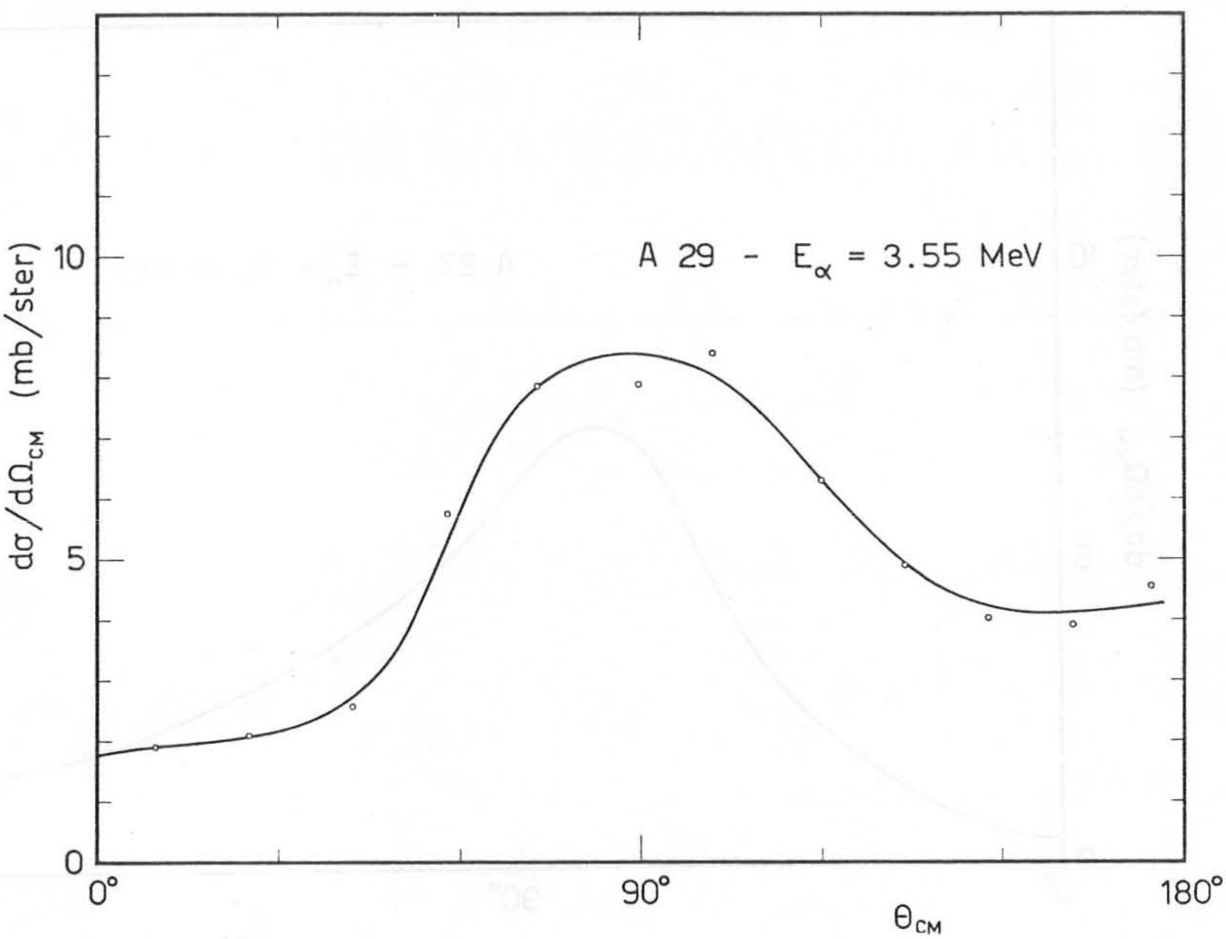

A 25 - E_α = 3.15 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}


A 39 - E_α = 3.22 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

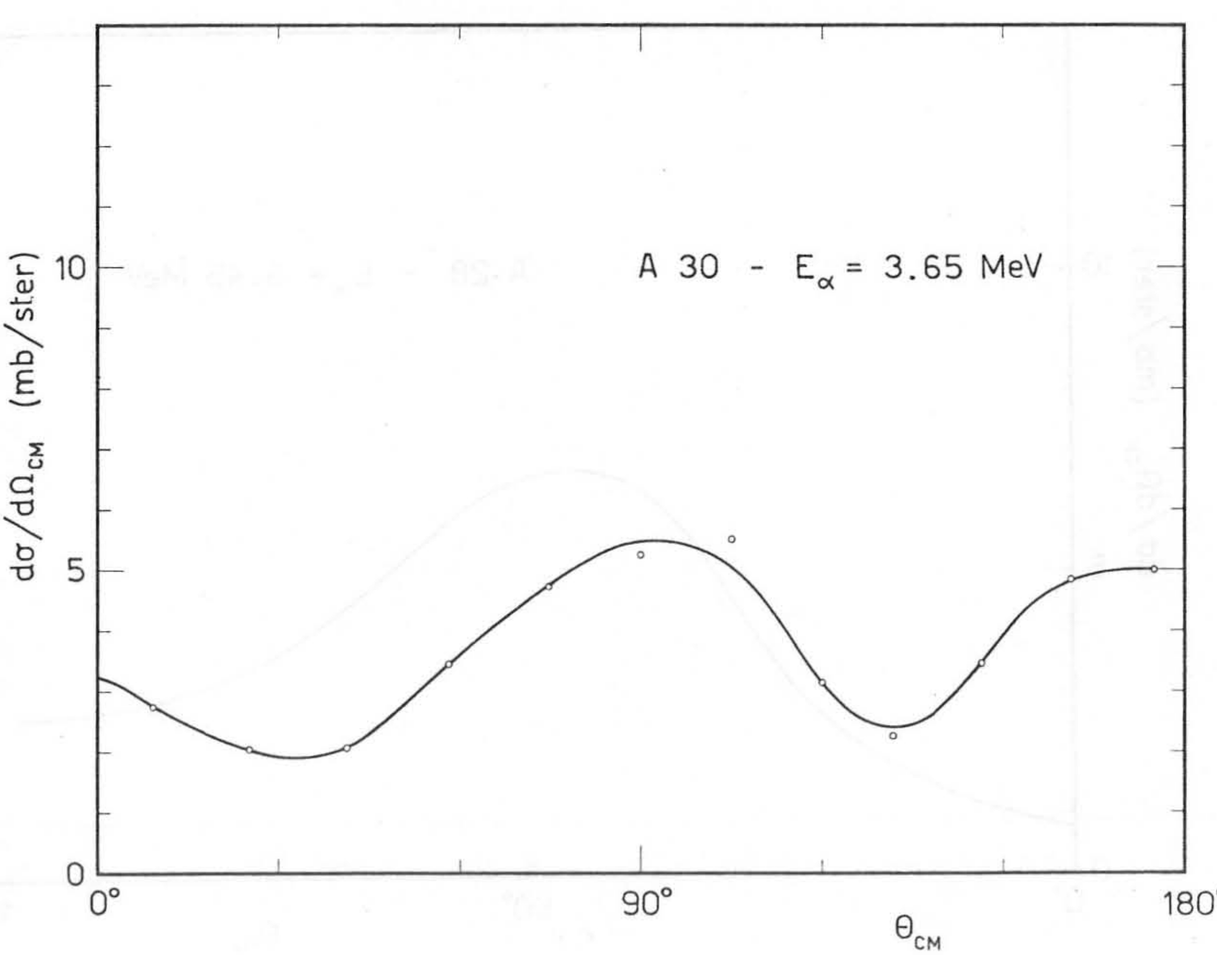

A 26 - E_α = 3.25 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}


A 27 - E_α = 3.35 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

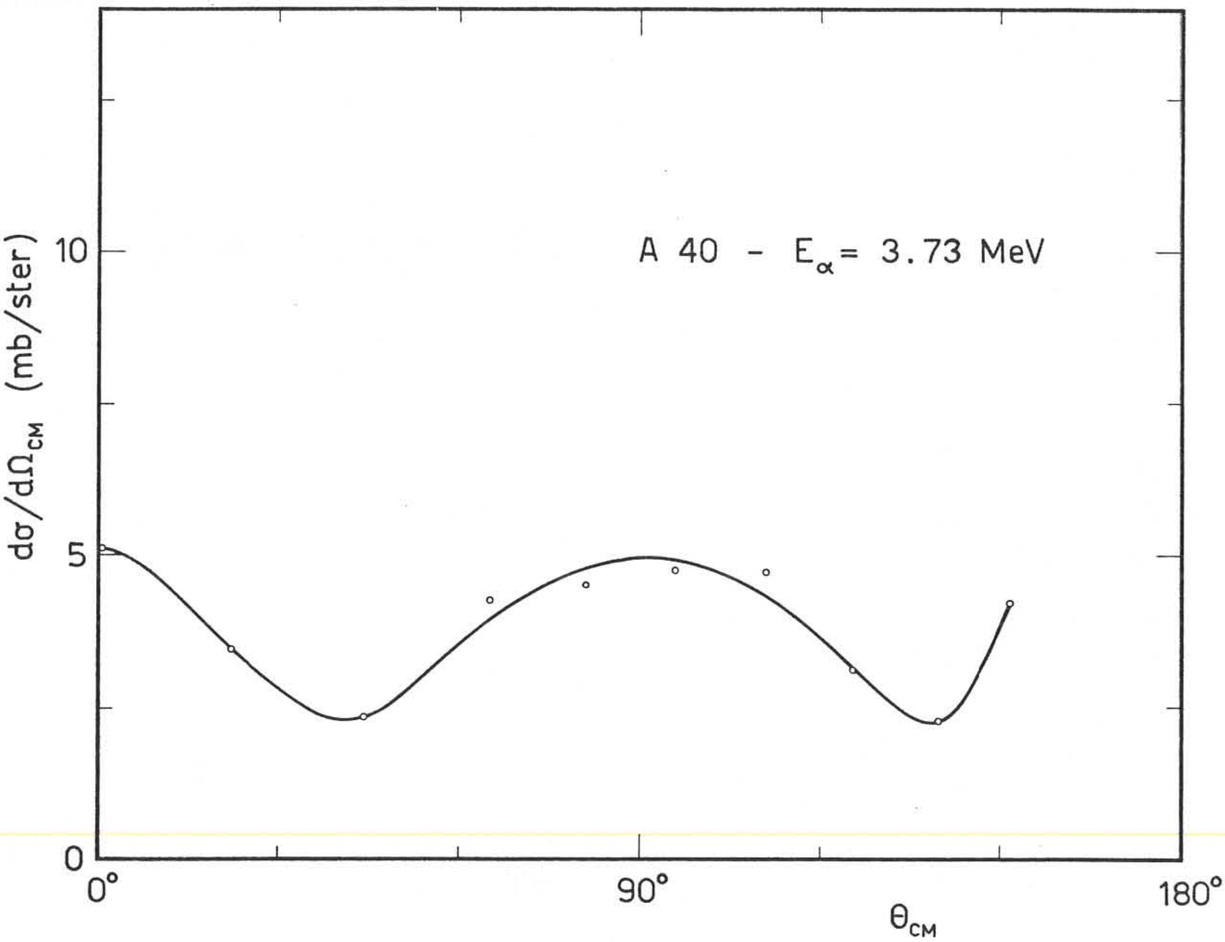

A 28 - E_α = 3.45 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}



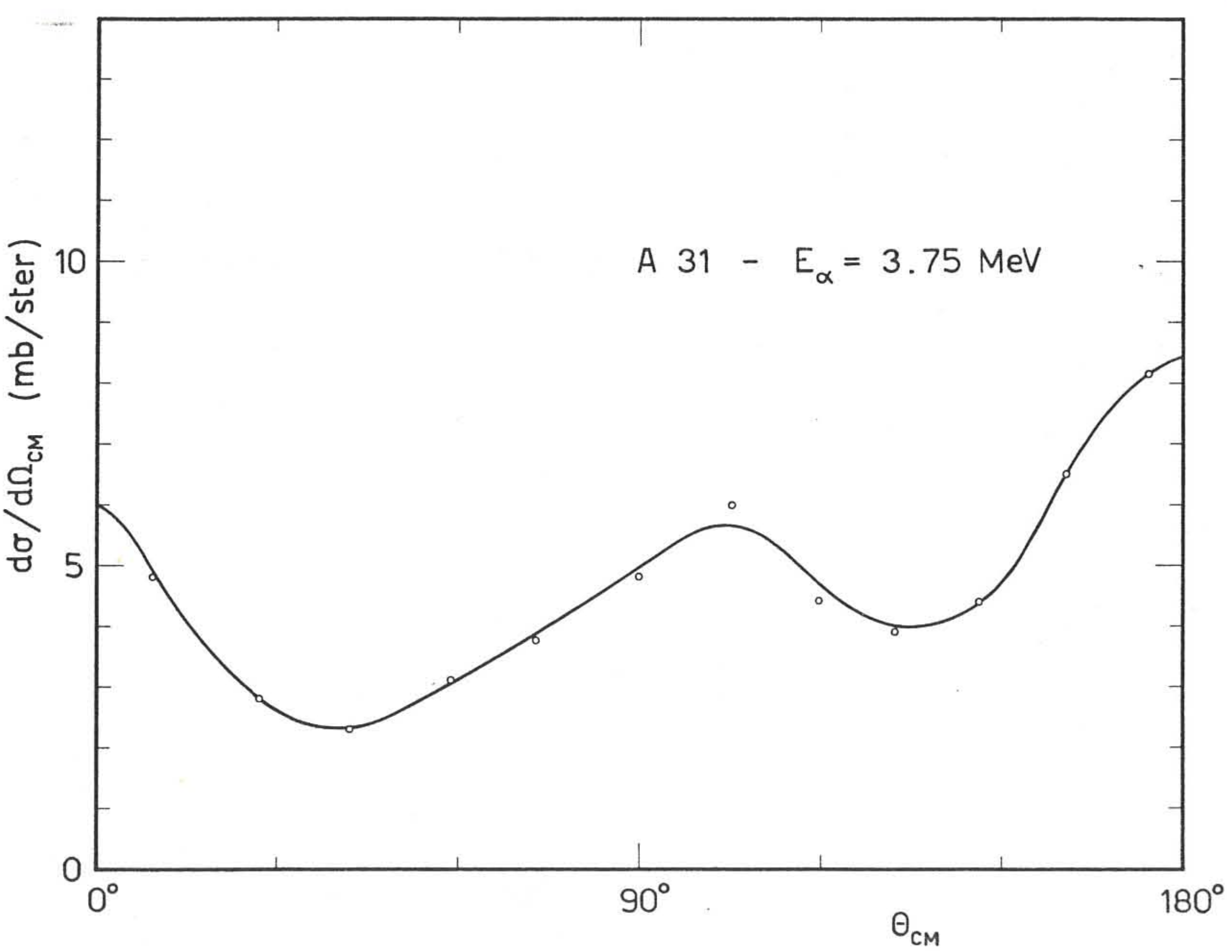
A 29 - E_α = 3.55 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}



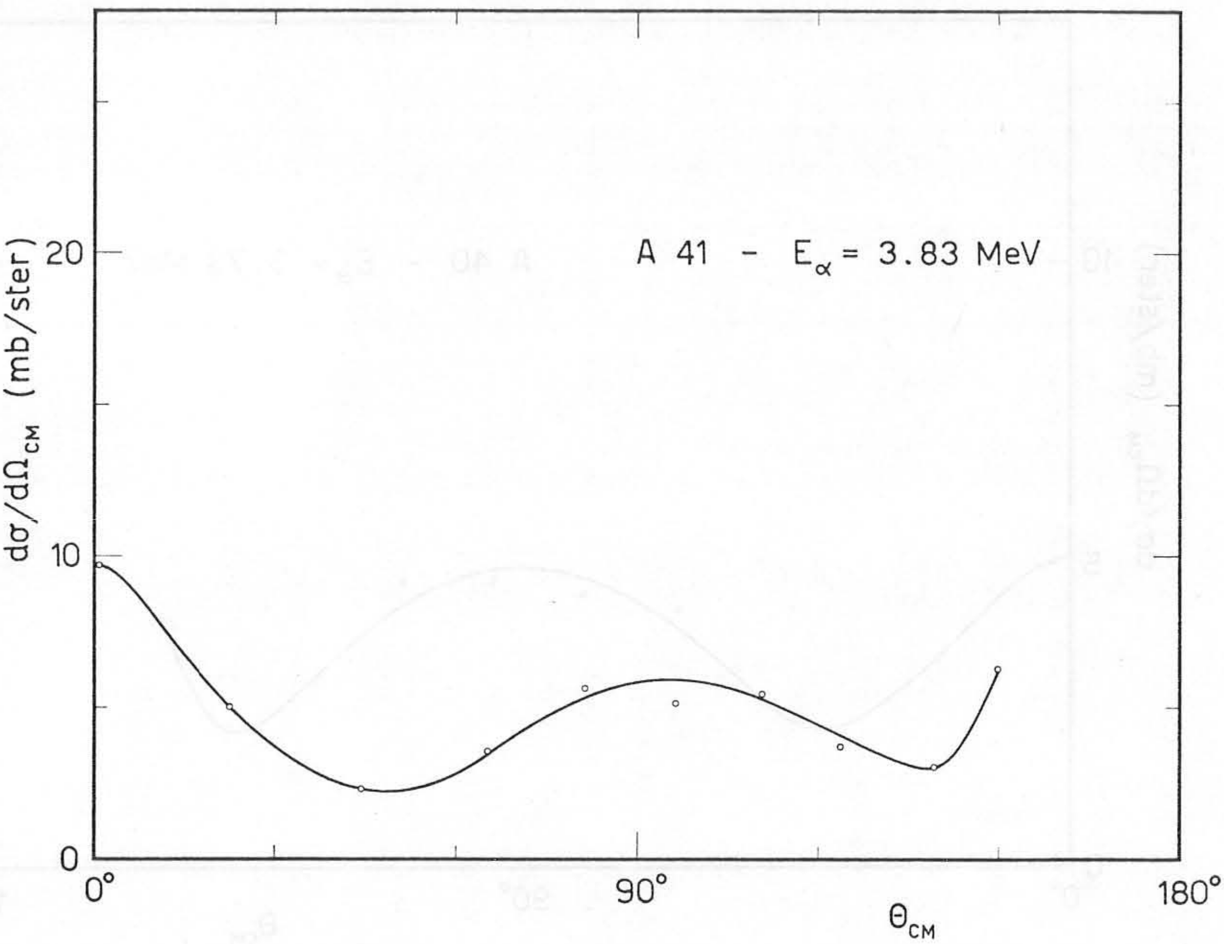
A 30 - E_α = 3.65 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}



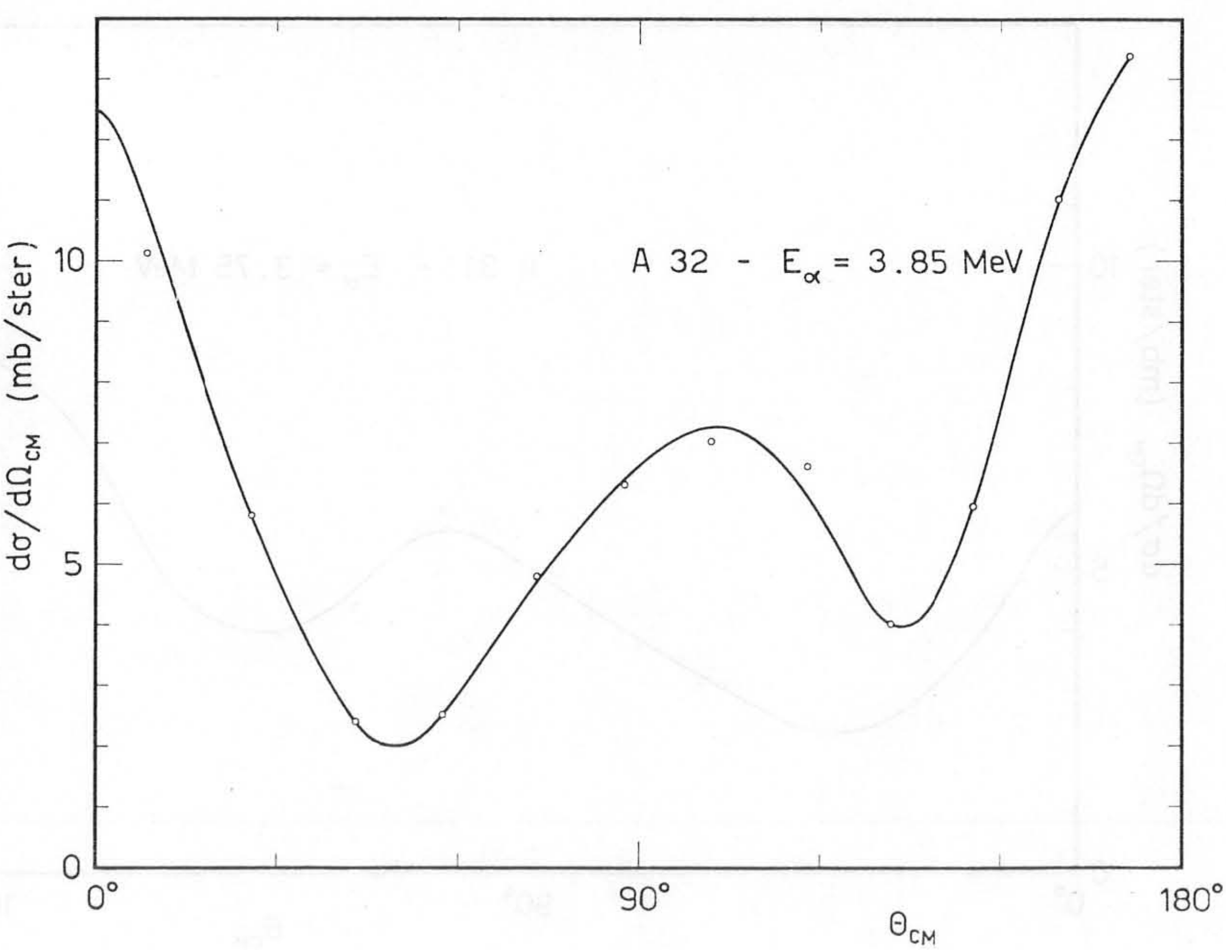
A 40 - E_α = 3.73 MeV
dσ/dΩ$_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ$_{CM}$



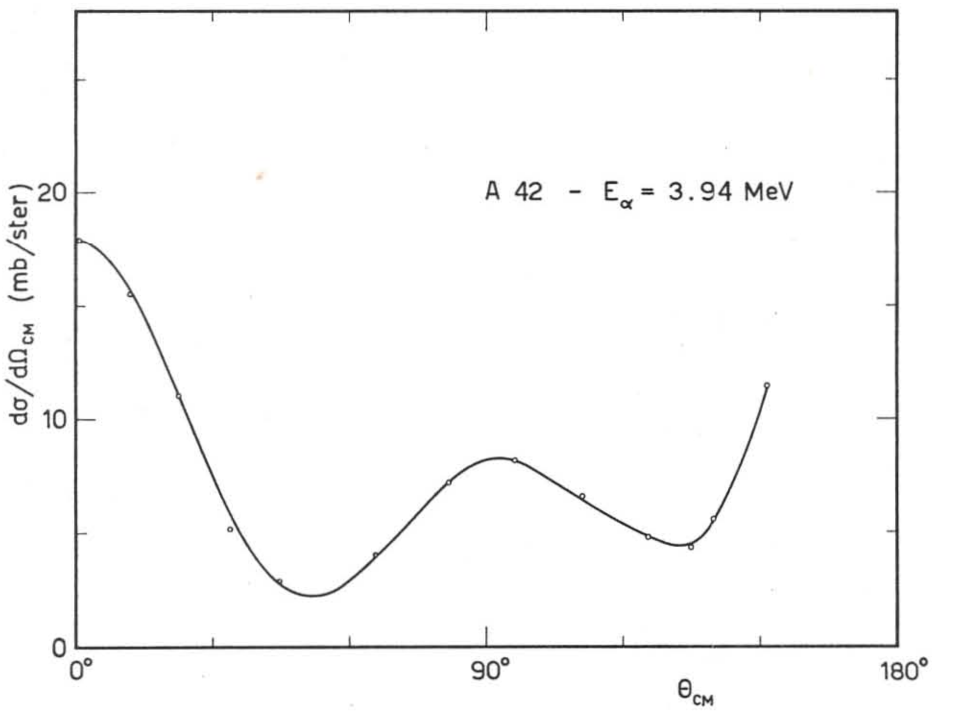
A 31 - E_α = 3.75 MeV
dσ/dΩ$_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ$_{CM}$

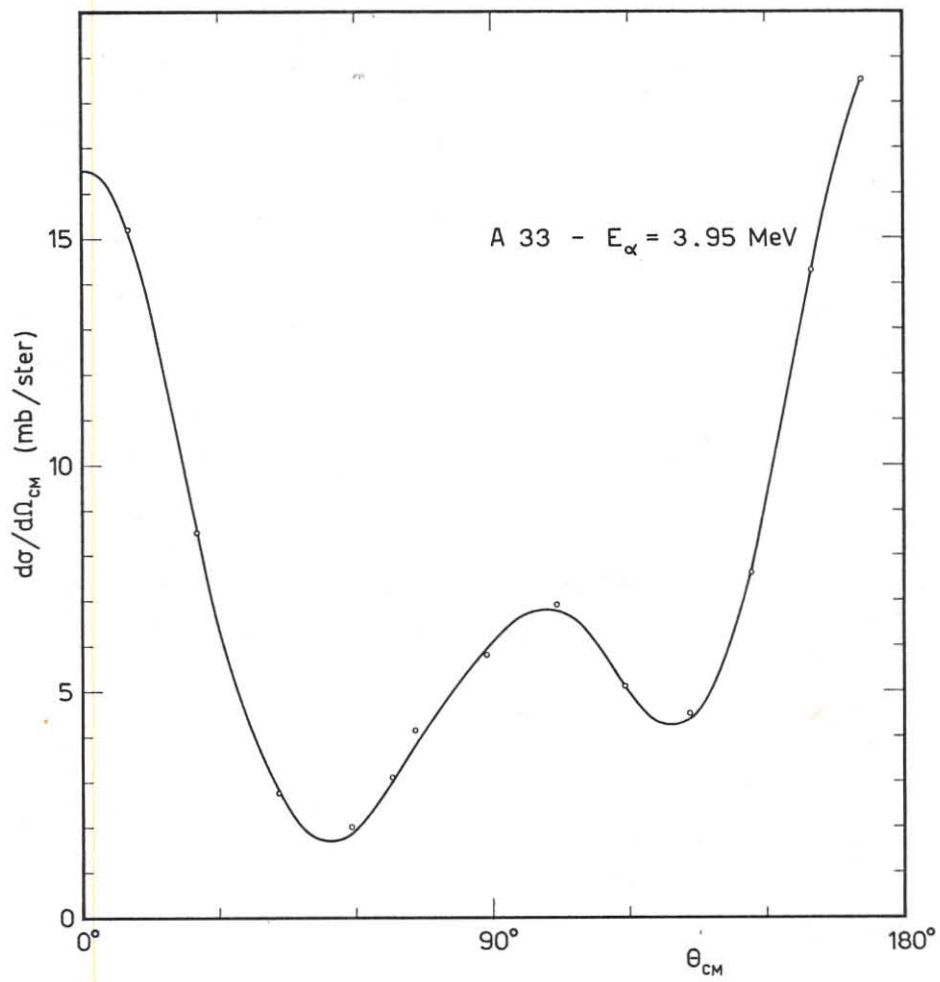


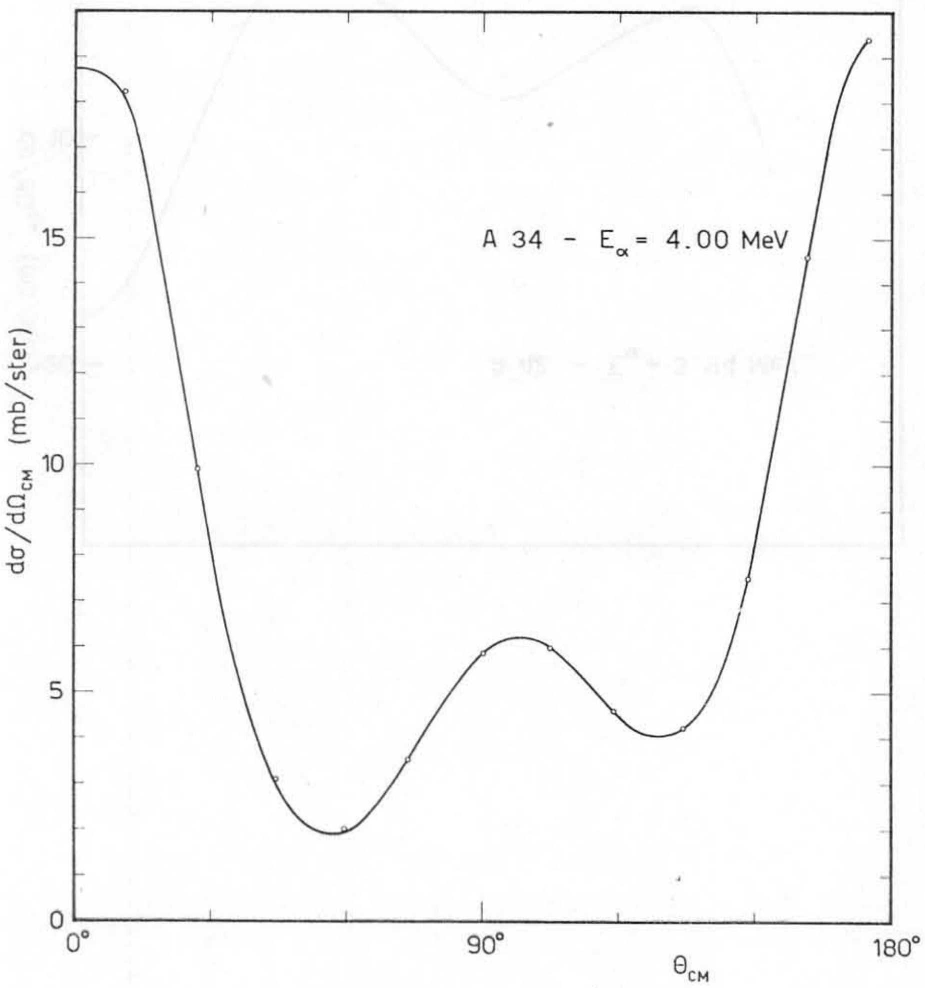
A 41 - E_α = 3.83 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
20
10
0
0°
90°
180°
Θ_{CM}

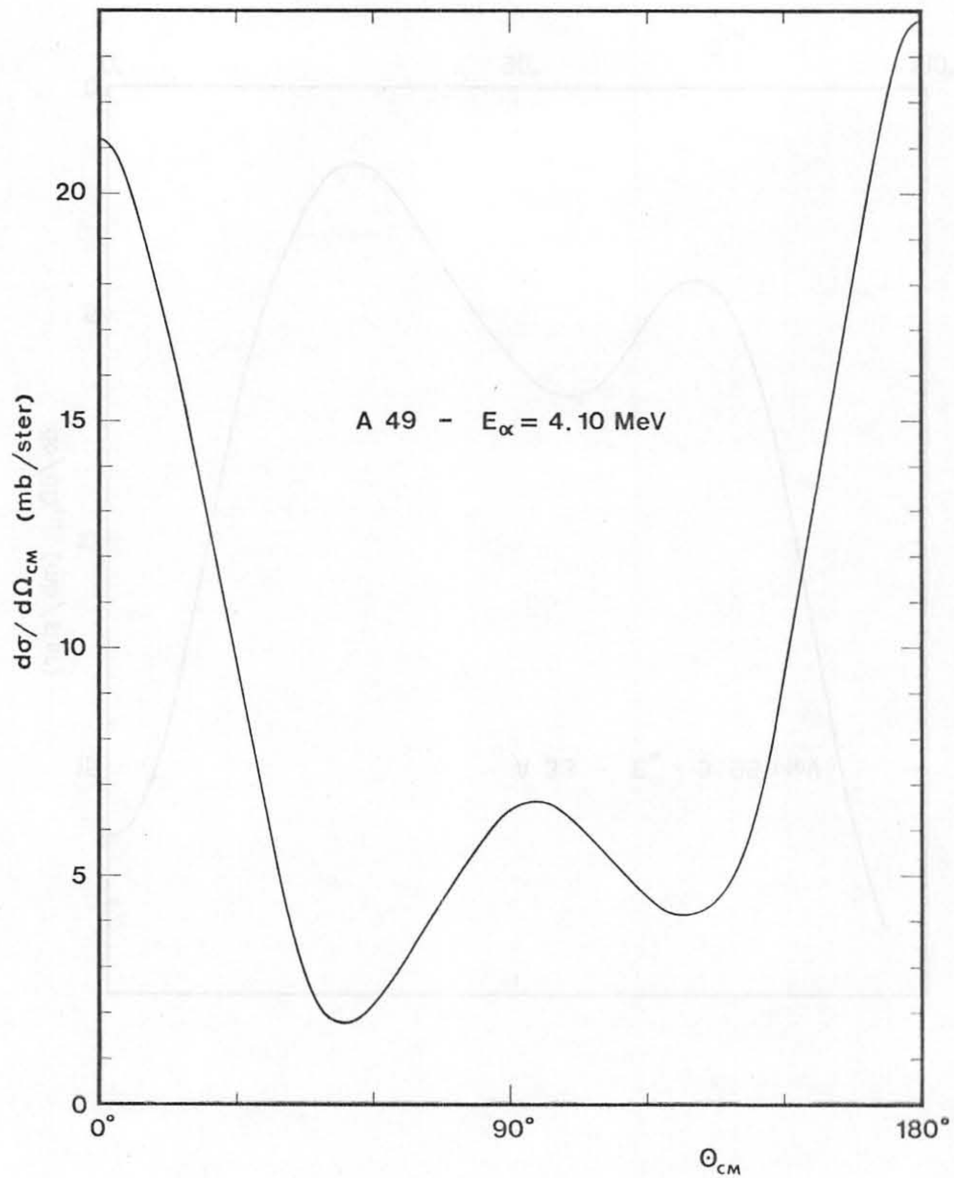


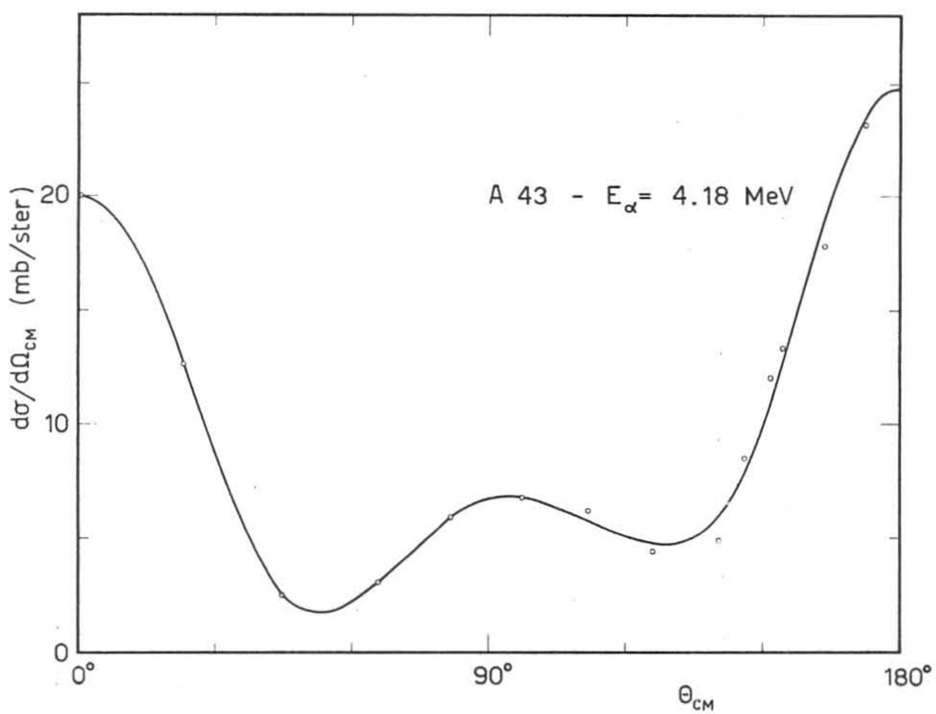
A 32 - E_α = 3.85 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

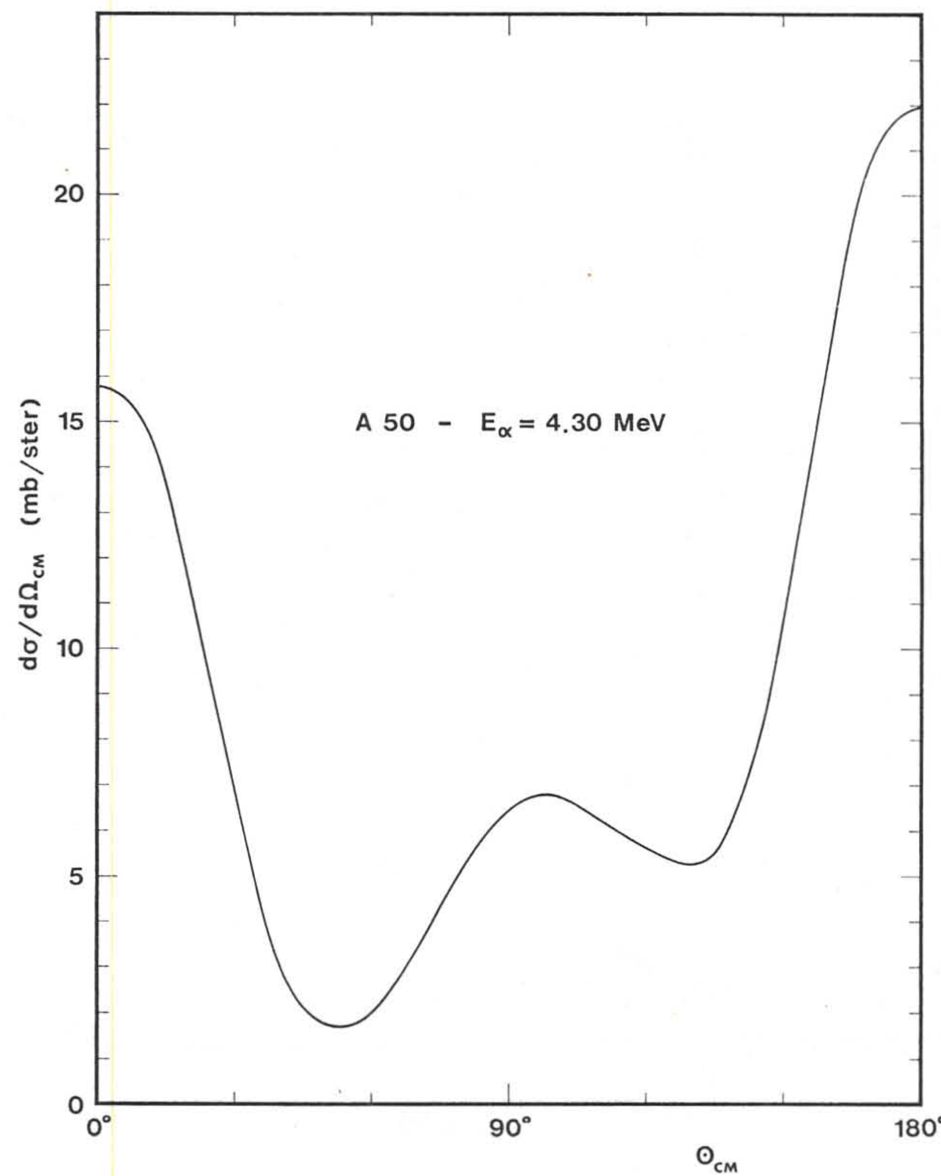

A 42 - E_α = 3.94 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
0
10
20
0°
90°
180°
θ_{CM}

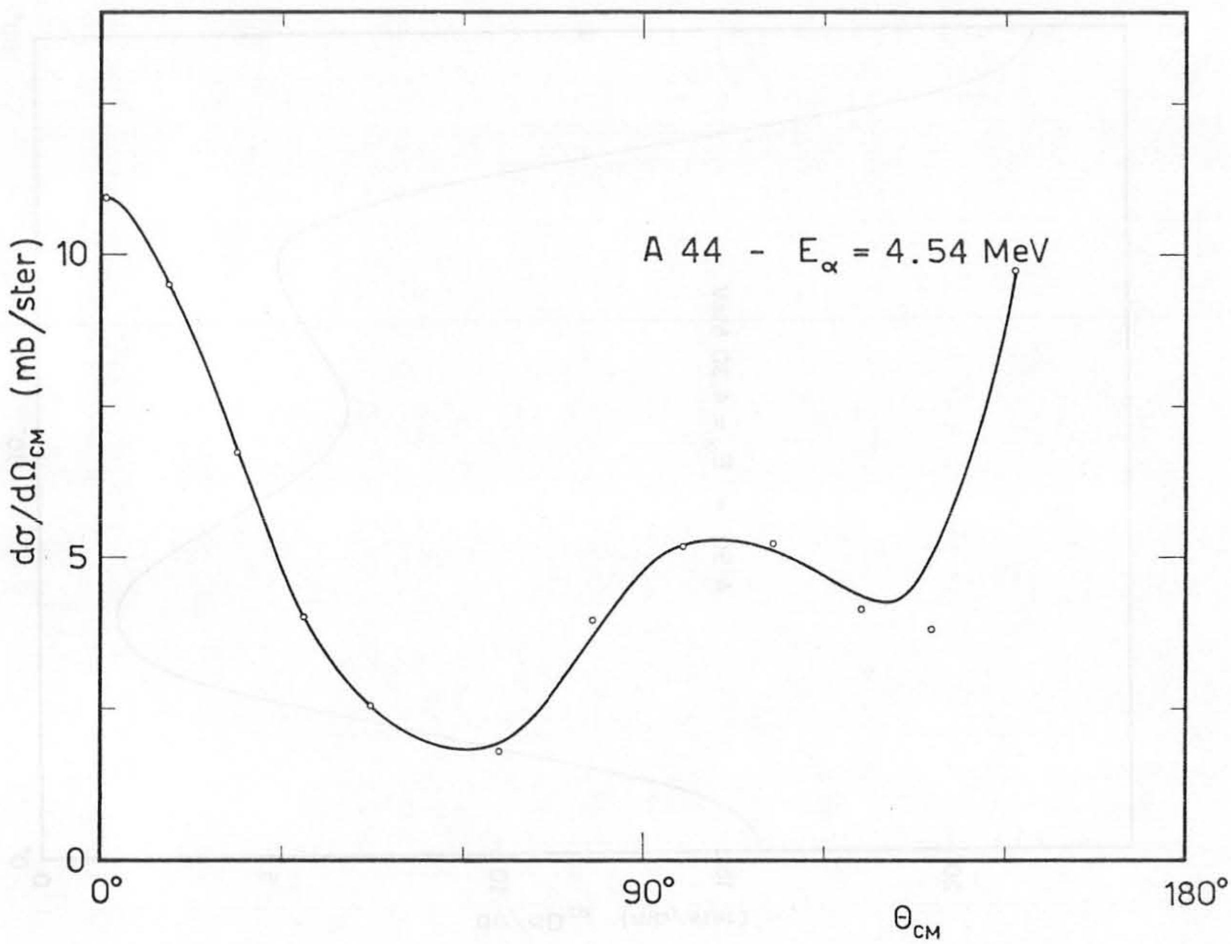

A 33 - E_α = 3.95 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
0
5
10
15
0°
90°
180°
θ_{CM}

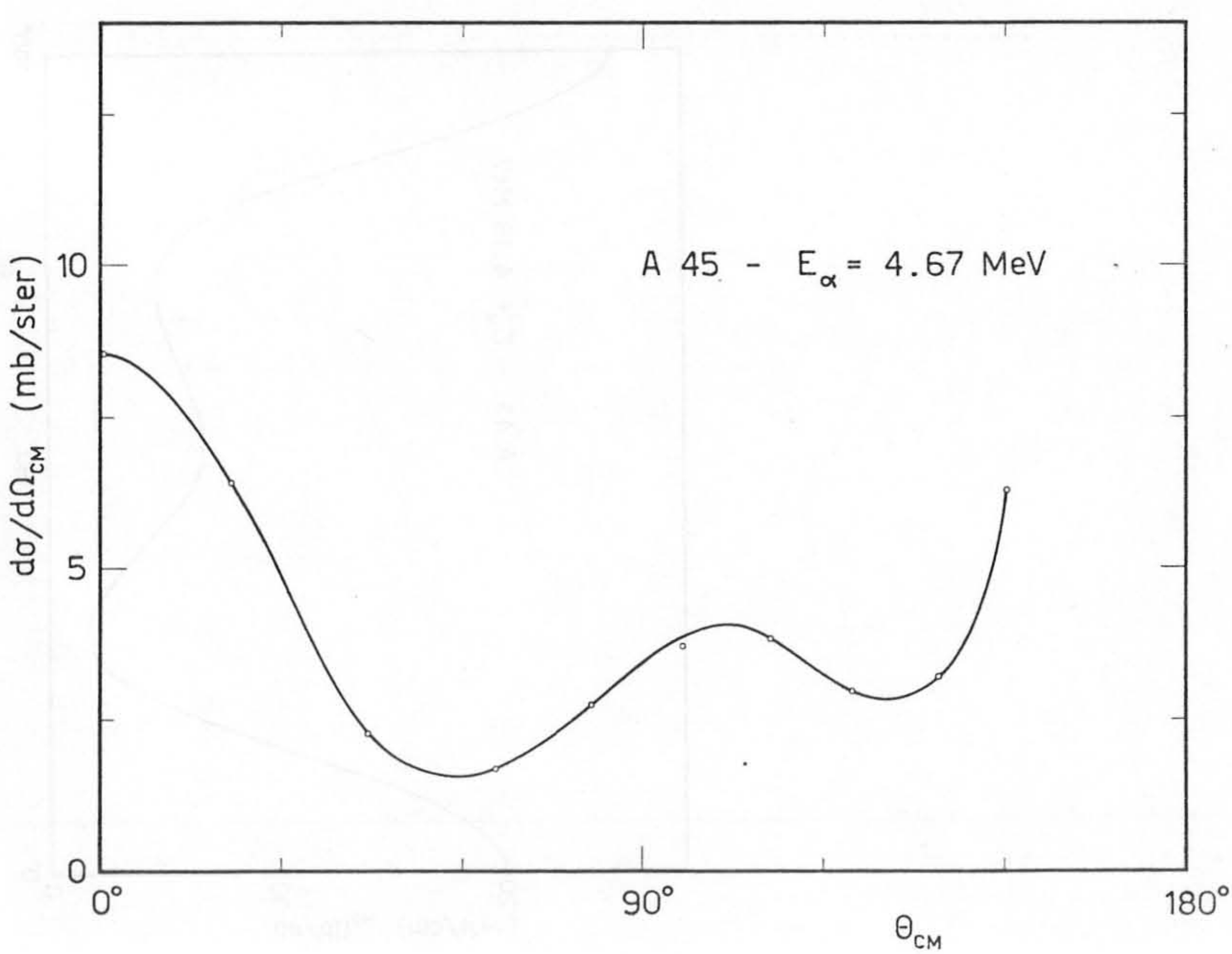

A 34 - E_α = 4.00 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
θ_{CM}
0°
90°
180°
0
5
10
15


A 49 - E_α = 4.10 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
Θ_{CM}
0°
90°
180°
0
5
10
15
20

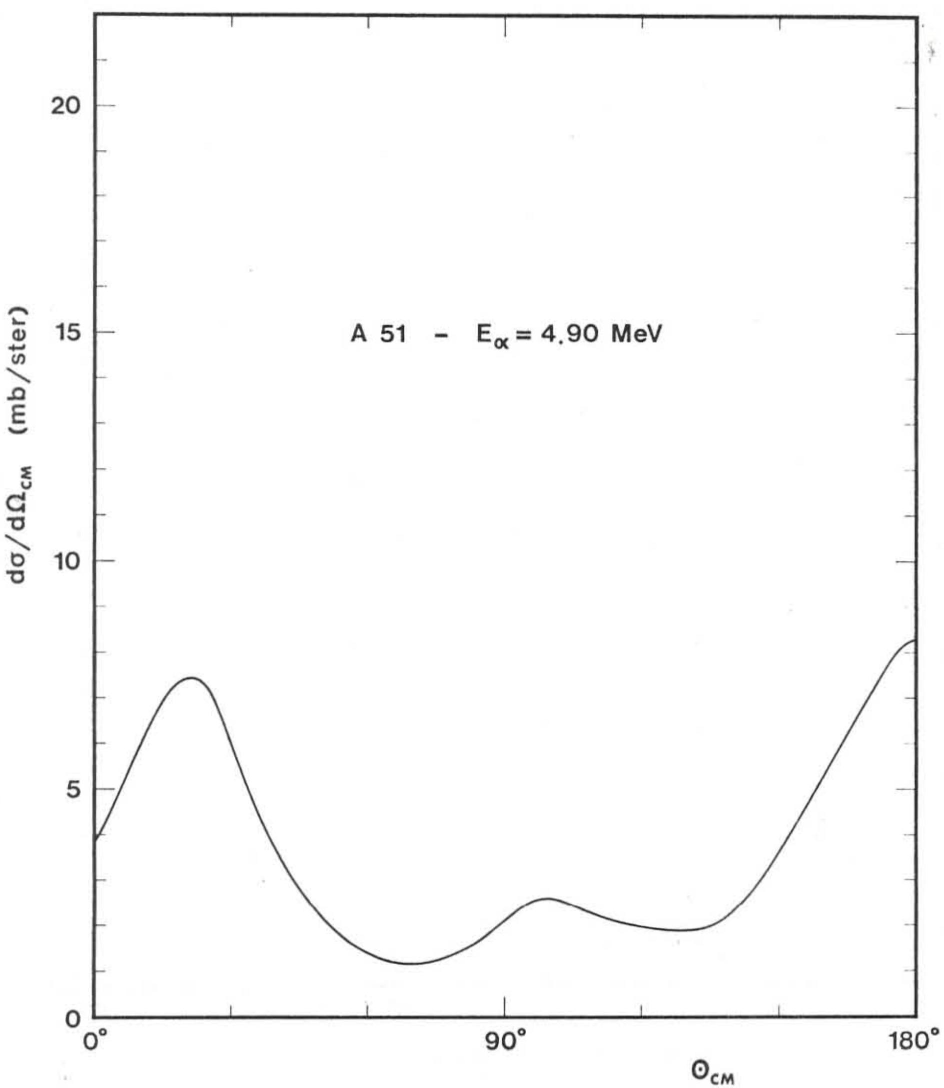

A 43 - E_α= 4.18 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
0
10
20
0°
90°
180°
Θ_{CM}


A 50 - E_α = 4.30 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
0
5
10
15
20
0°
90°
180°
Θ_{CM}

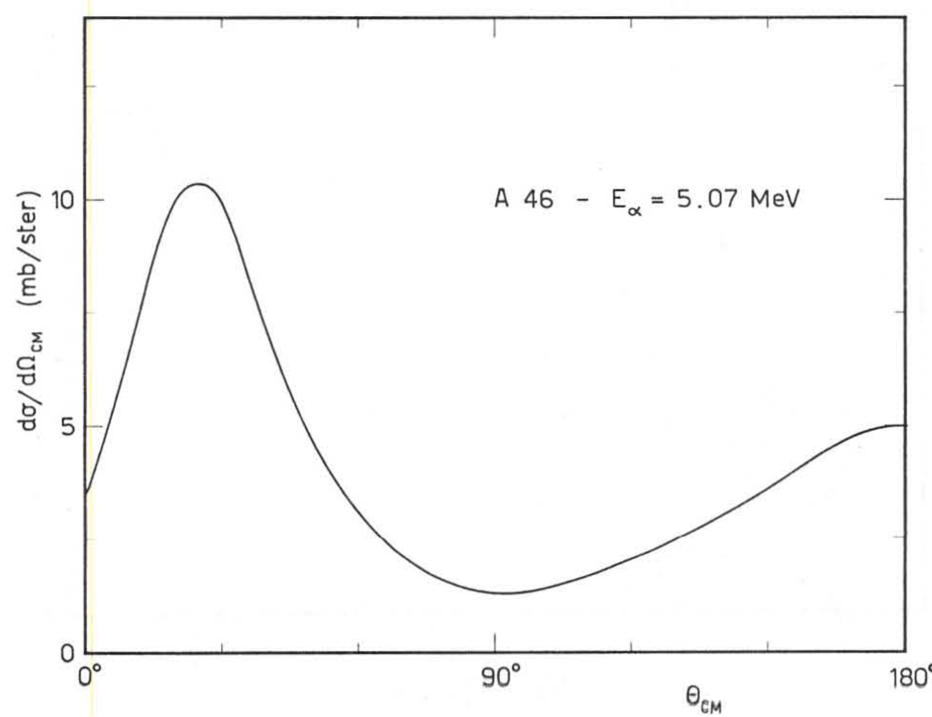

A 44 - E_α = 4.54 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}


A 45 - E_α = 4.67 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
Θ_{CM}

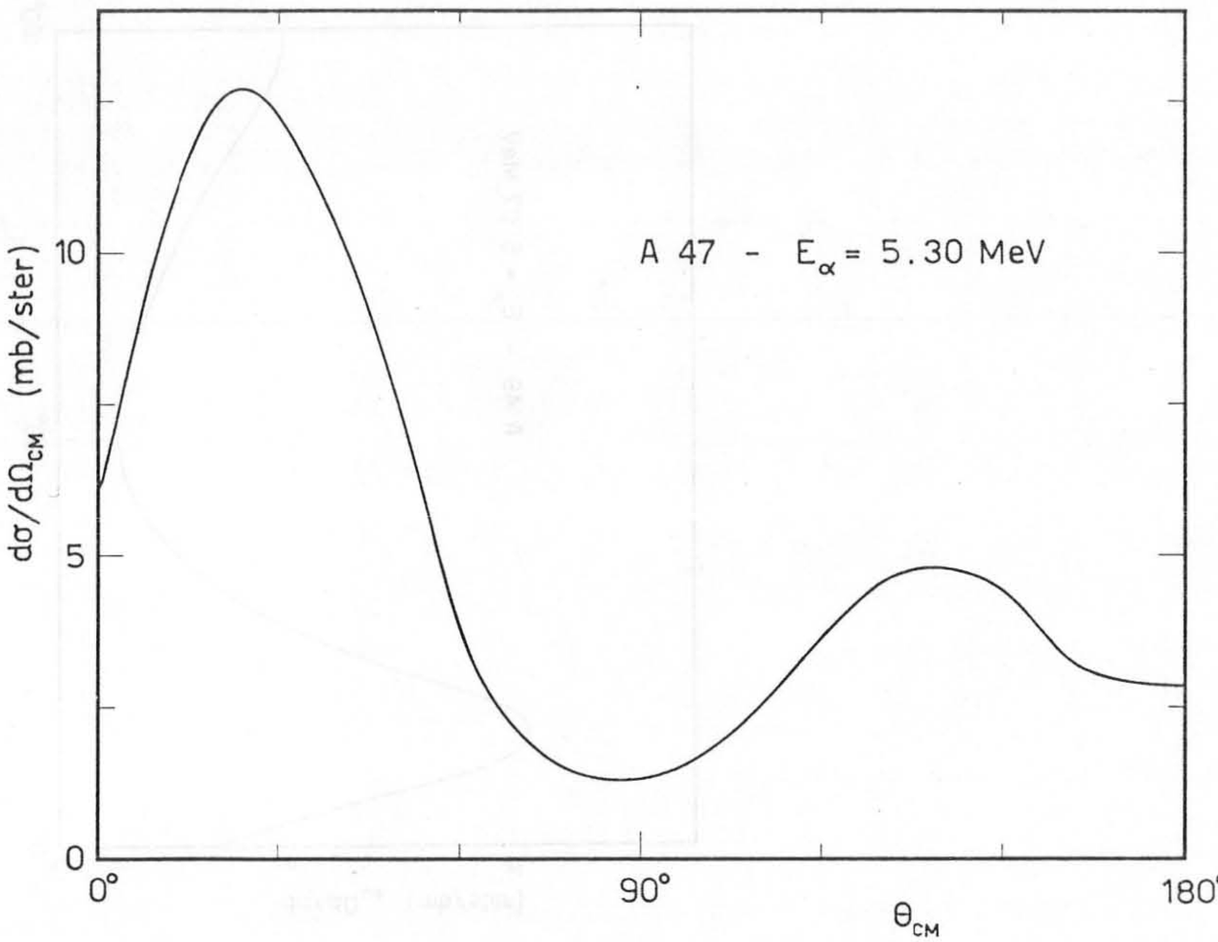
371

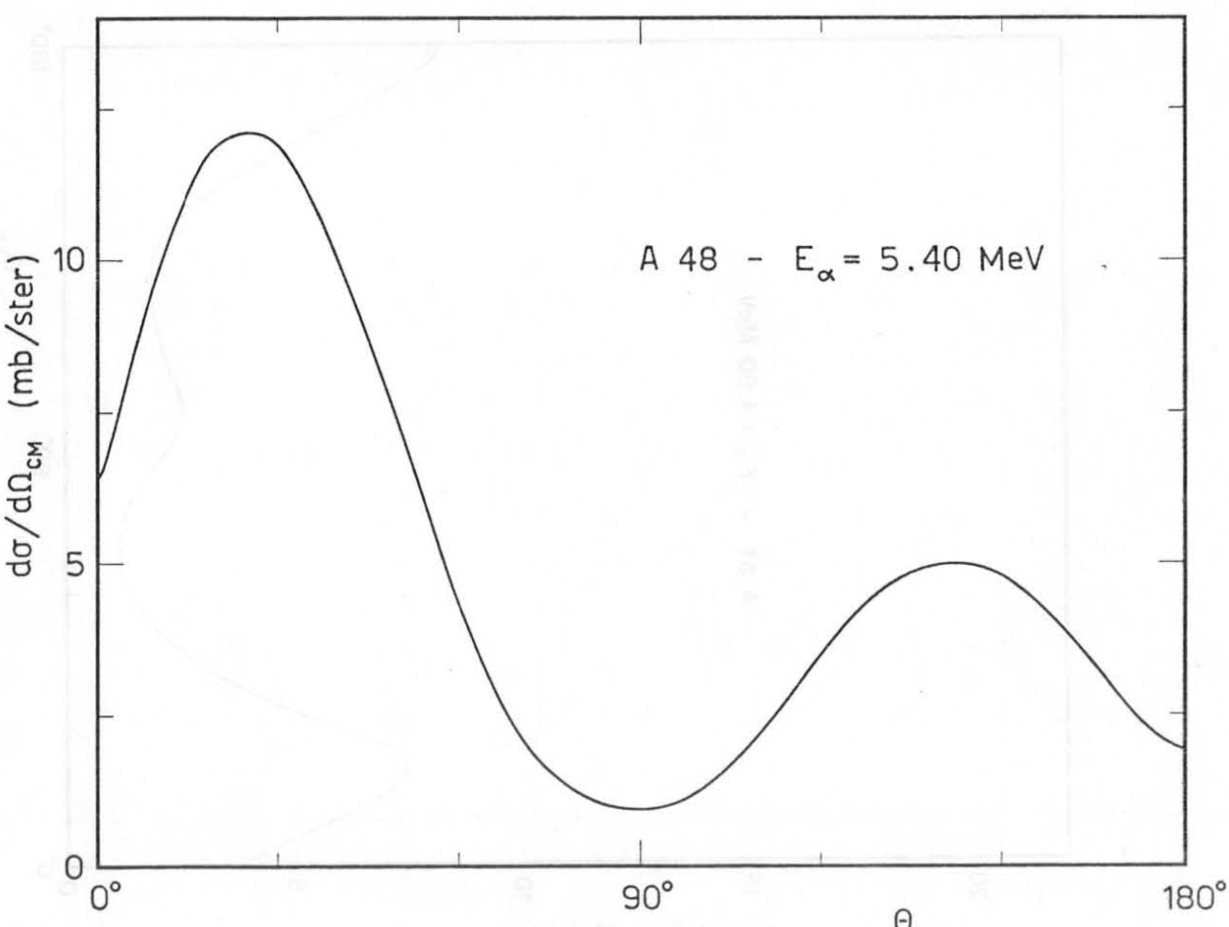


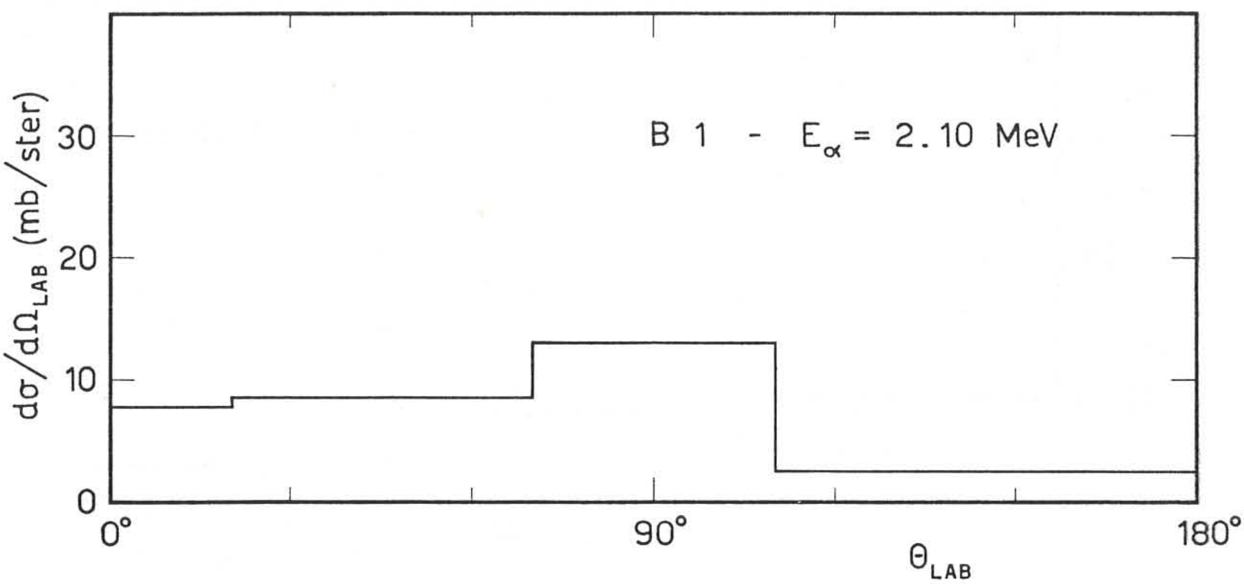
A 51 - E_α = 4.90 MeV
dσ/dΩcm (mb/ster)
20
15
10
5
0
0°
90°
180°
Θcm

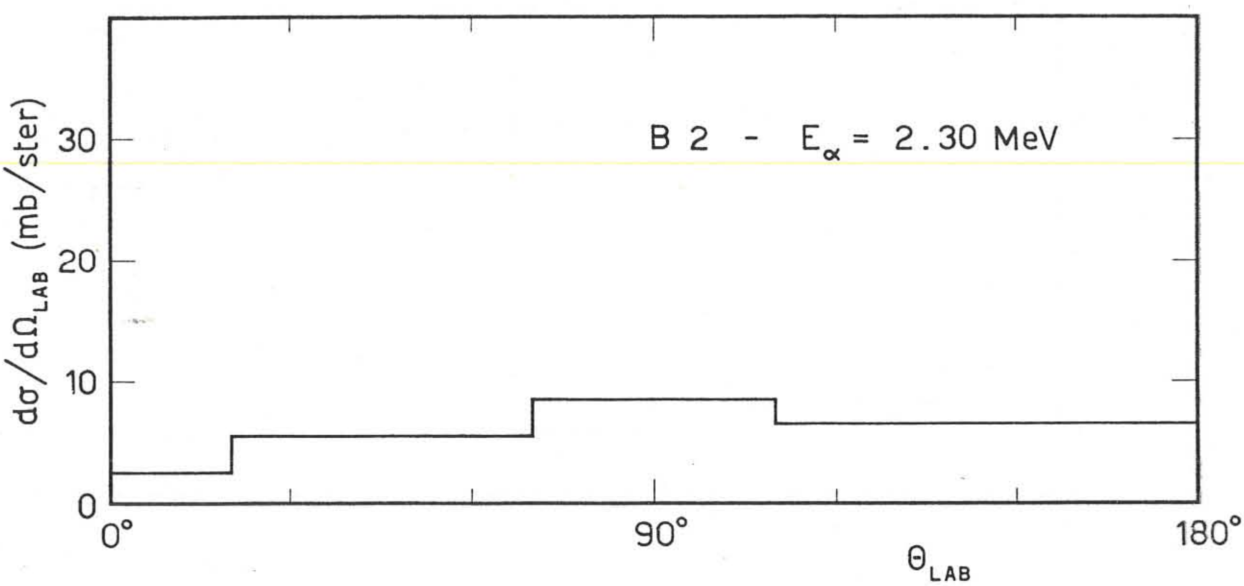


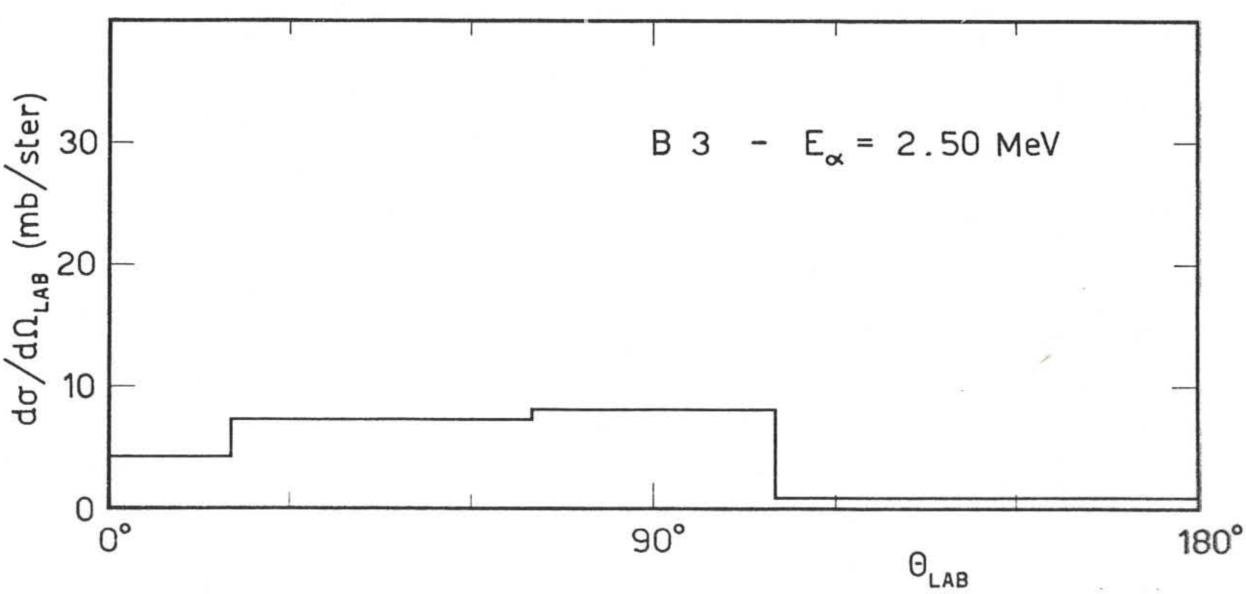
A 46 - E_α = 5.07 MeV
dσ/dΩcm (mb/ster)
10
5
0
0°
90°
180°
Θcm

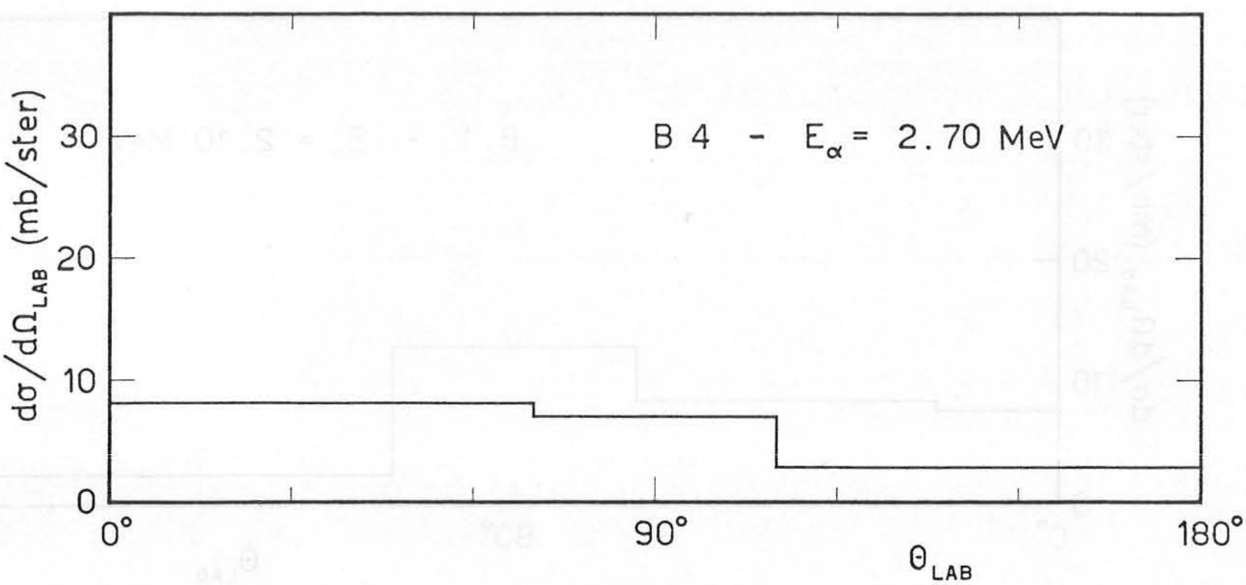

A 47 - E_α = 5.30 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ_{CM}

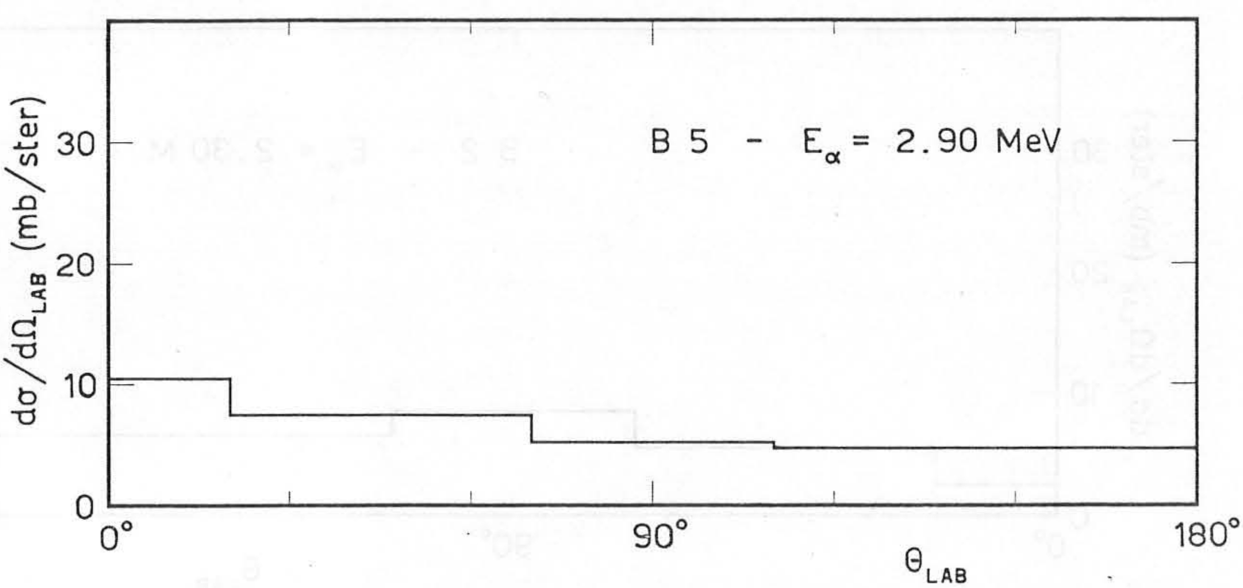

A 48 - E_α = 5.40 MeV
$d\sigma/d\Omega_{CM}$ (mb/ster)
10
5
0
0°
90°
180°
θ_{CM}

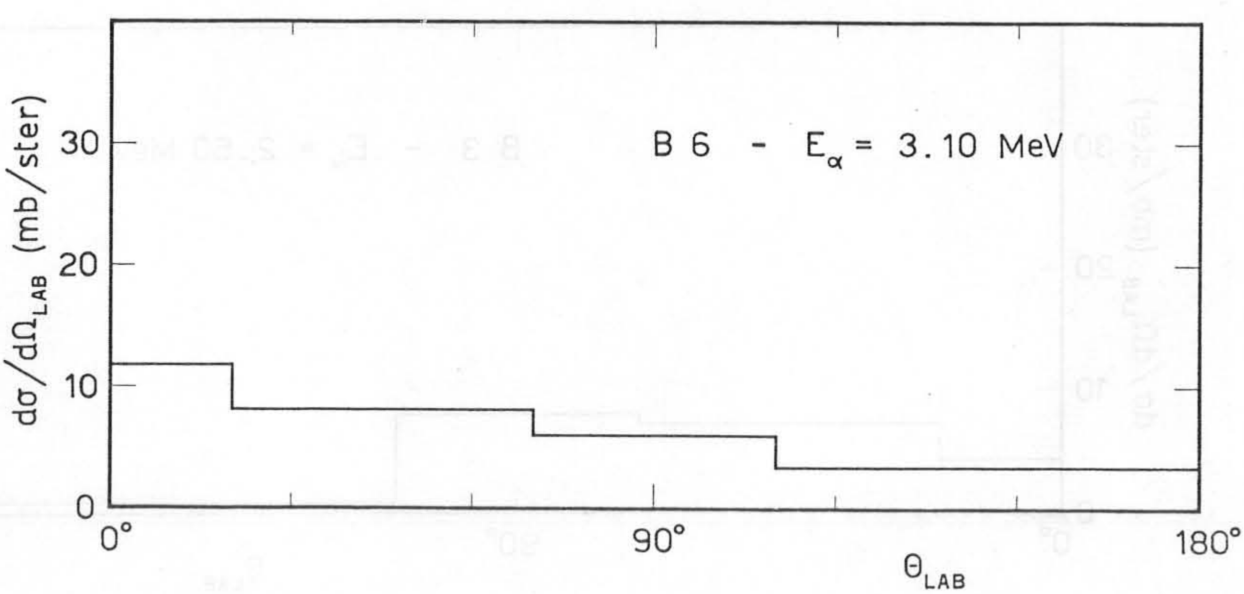

B 1 - E_α = 2.10 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

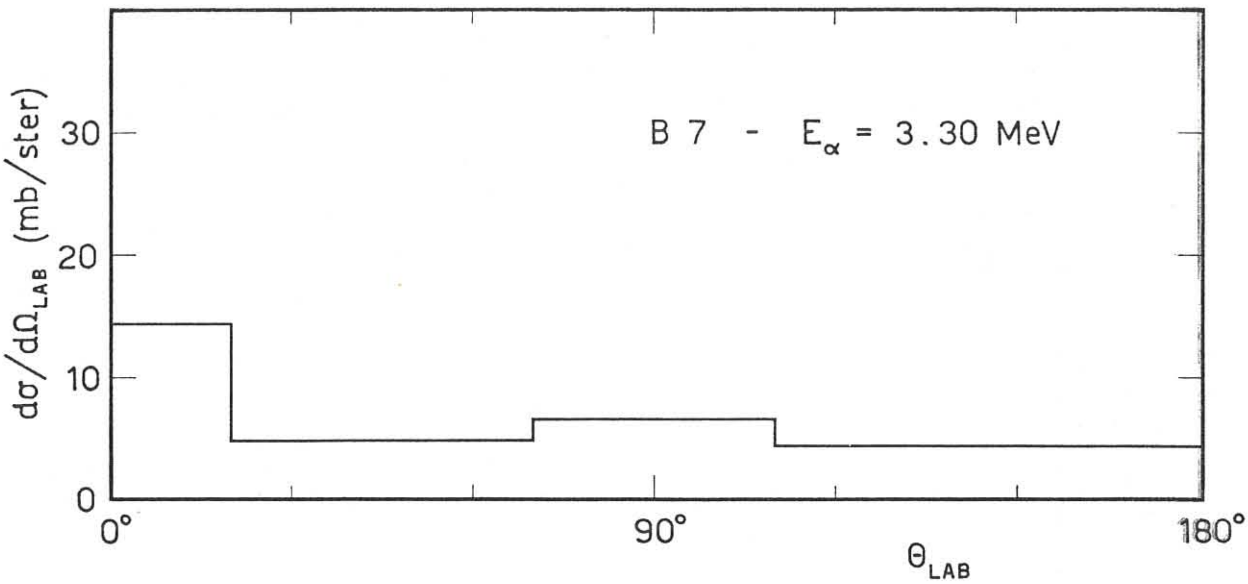

B 2 - E_α = 2.30 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

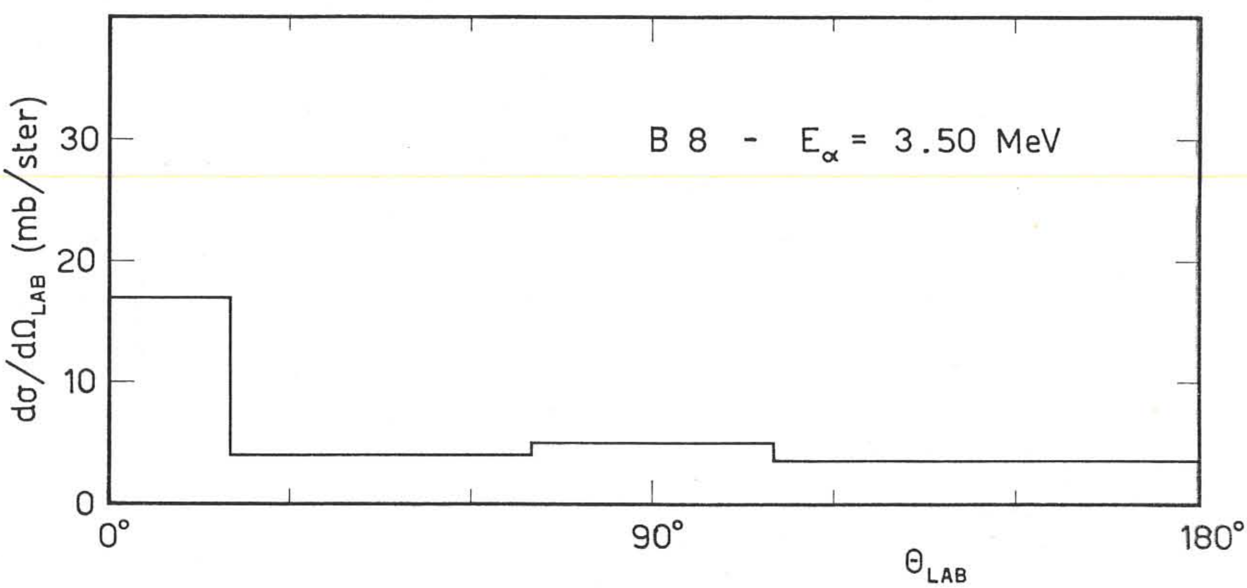

B 3 - E_α = 2.50 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

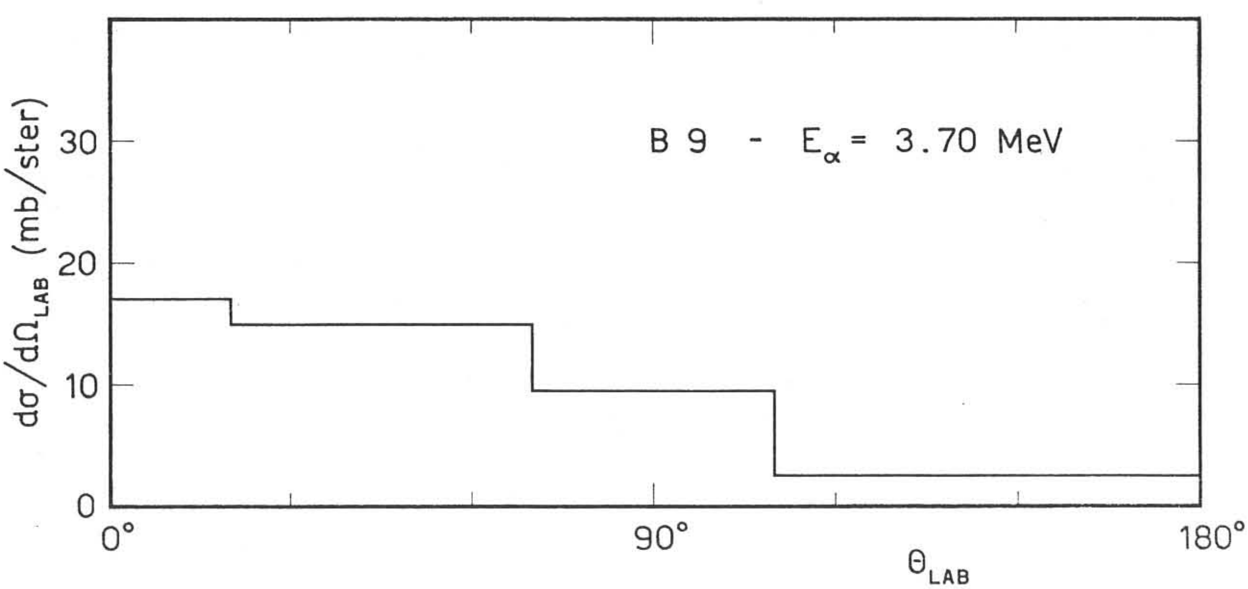

B 4 - E_α = 2.70 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
30
20
10
0
0°
90°
180°
Θ_{LAB}

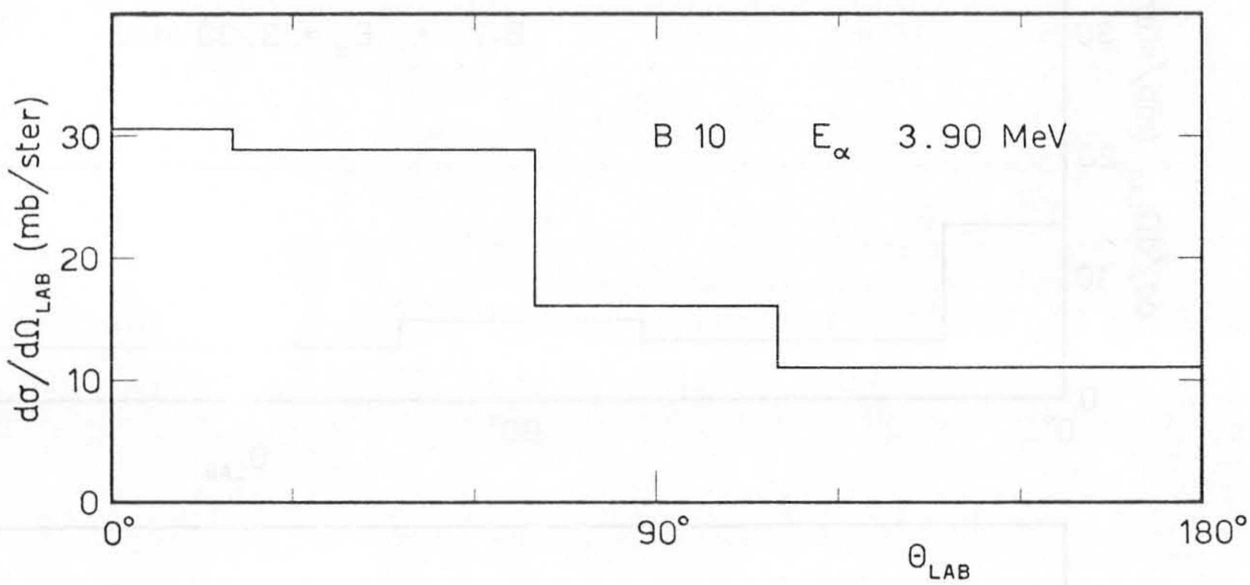

B 5 - E_α = 2.90 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
30
20
10
0
0°
90°
180°
Θ_{LAB}


B 6 - E_α = 3.10 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
30
20
10
0
0°
90°
180°
Θ_{LAB}

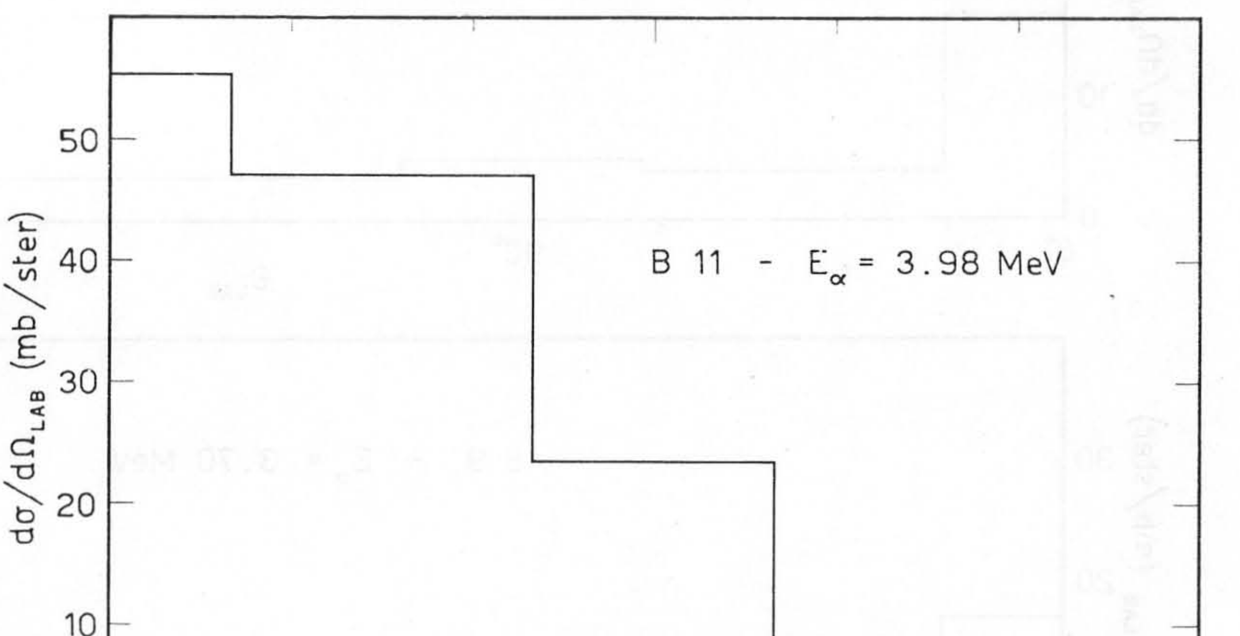

B 7 - E_α = 3.30 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}


B 8 - E_α = 3.50 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

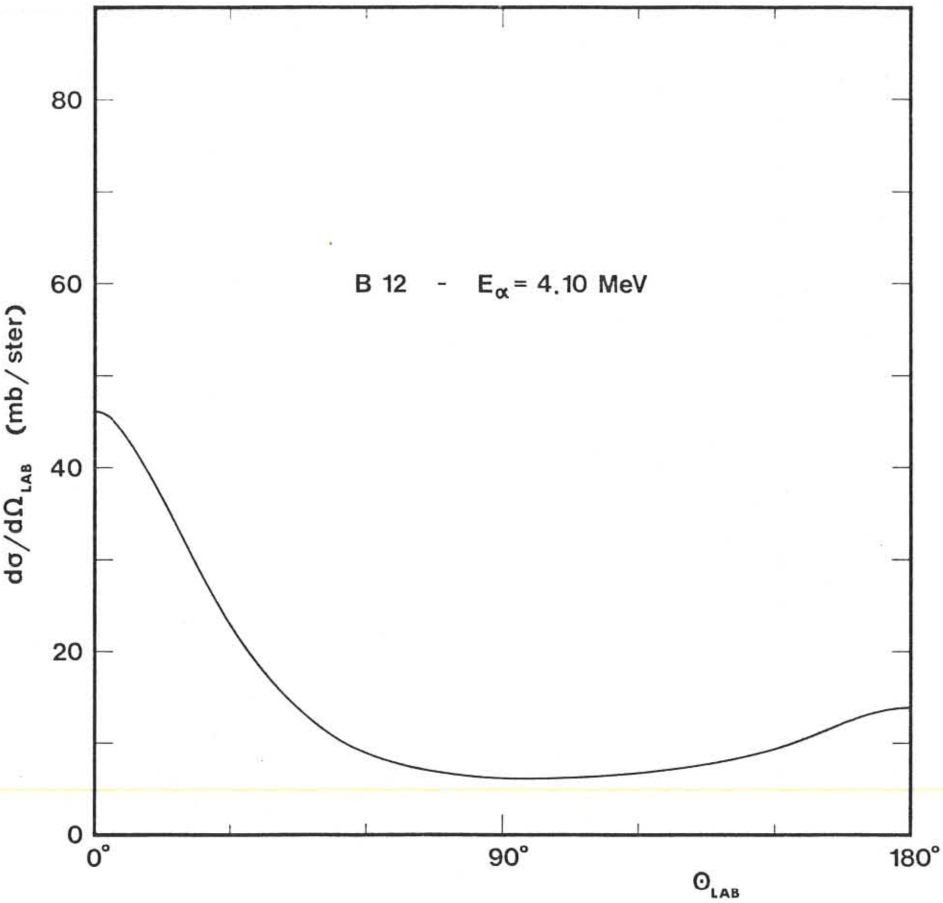

B 9 - E_α = 3.70 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

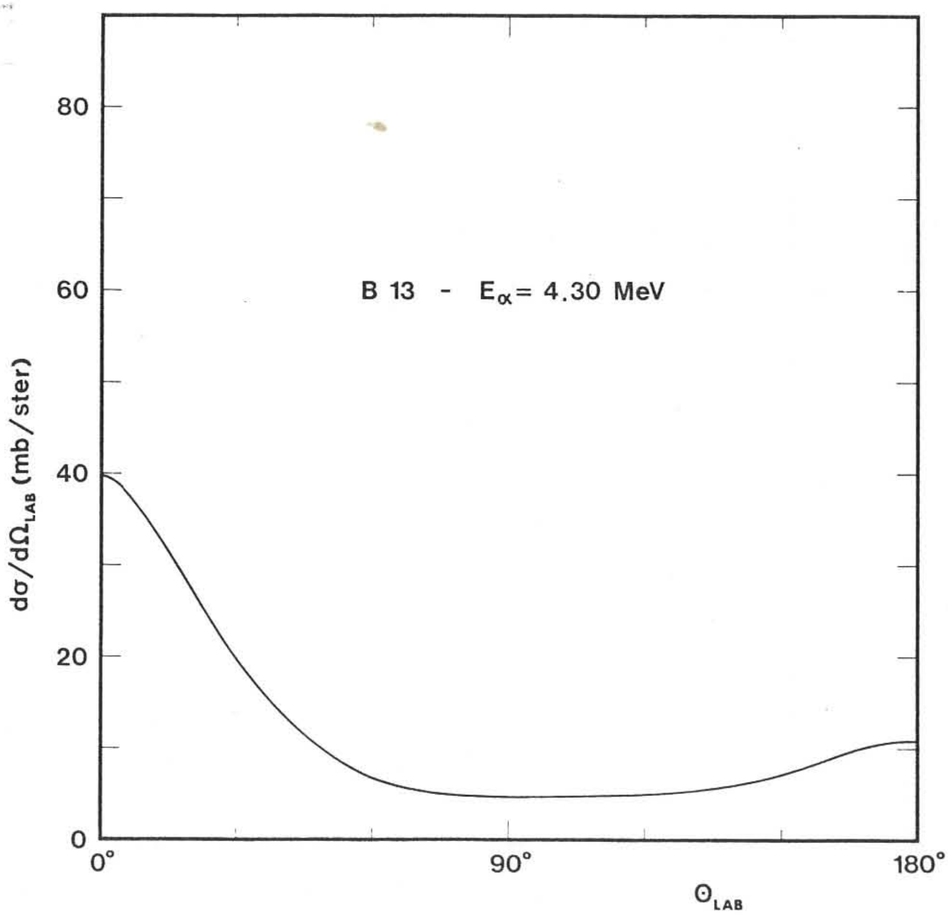


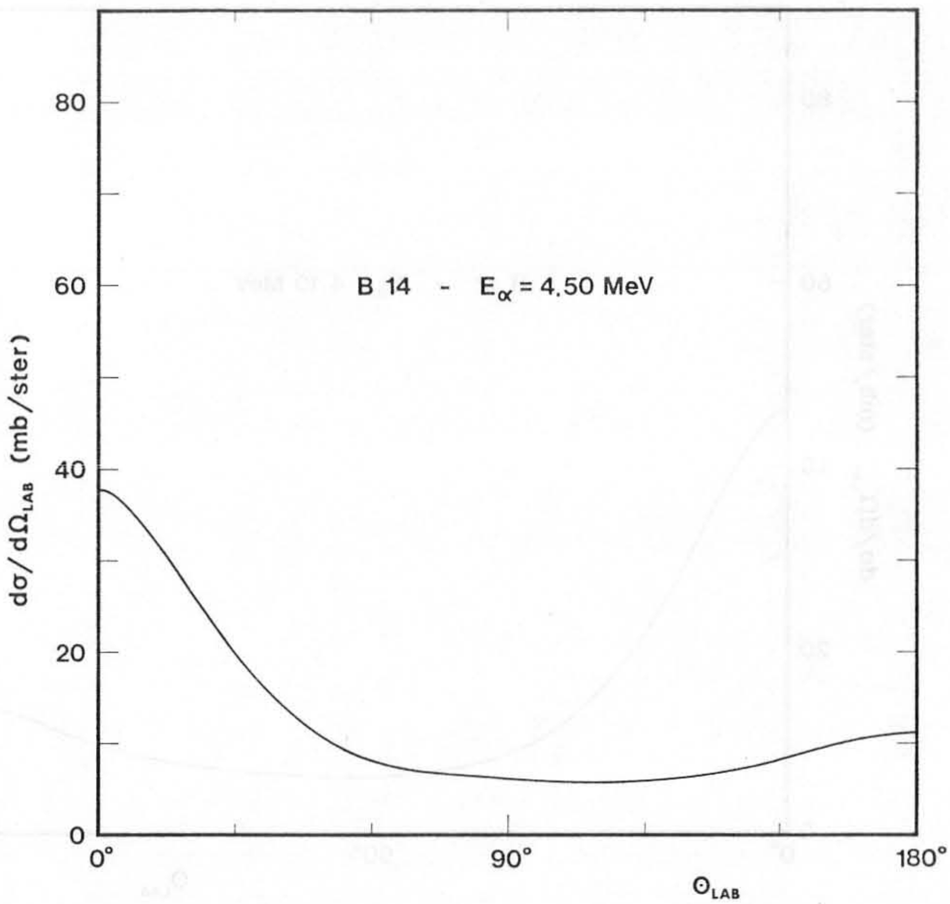
B 10 E$_\alpha$ 3.90 MeV
dσ/dΩ$_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ$_{LAB}$

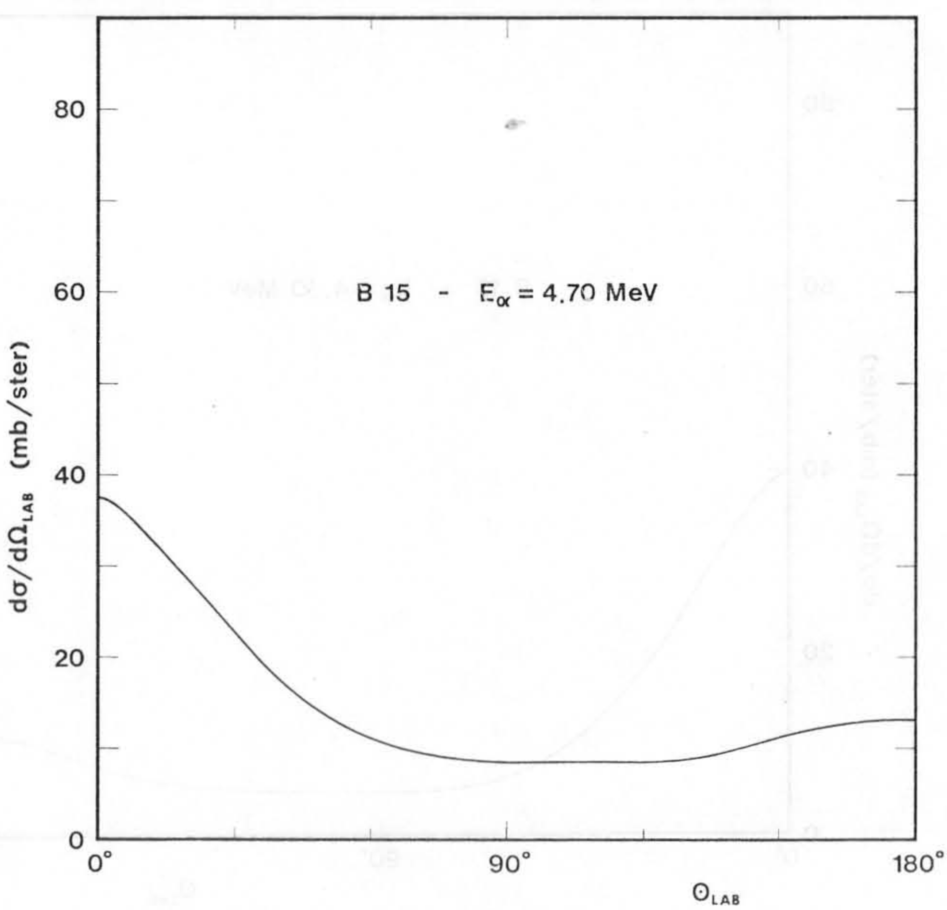


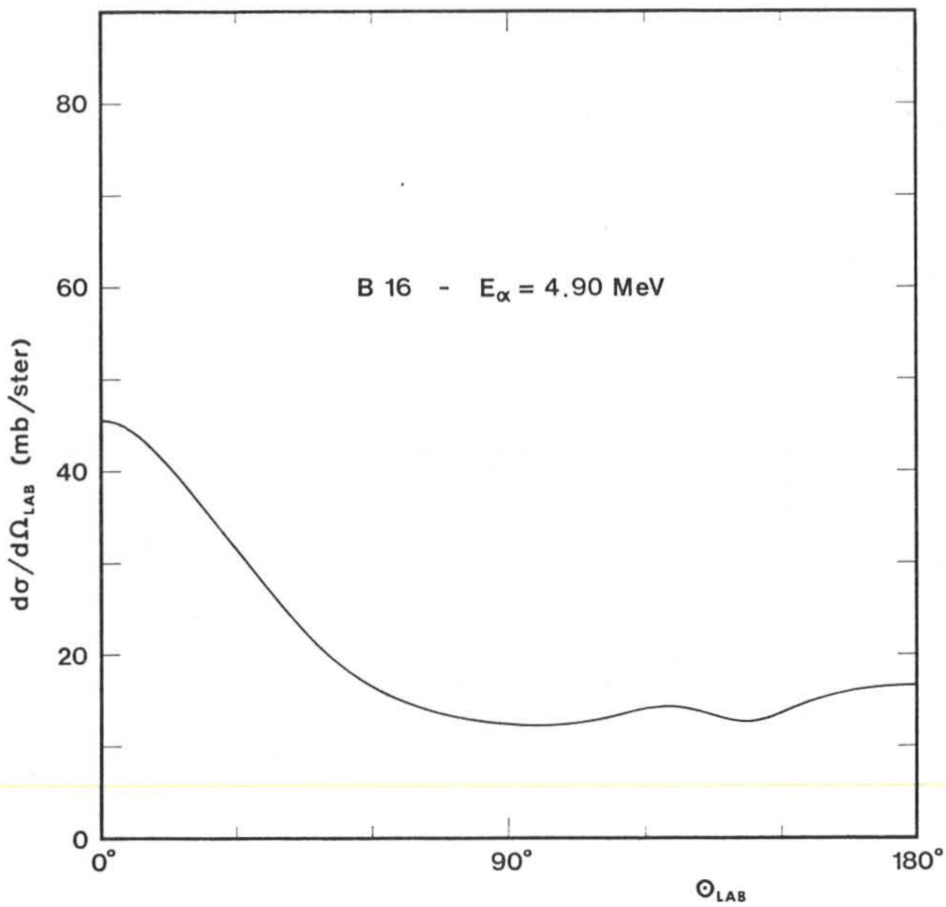
B 11 - E$_\alpha$ = 3.98 MeV
dσ/dΩ$_{LAB}$ (mb/ster)
0
10
20
30
40
50
0°
90°
180°
Θ$_{LAB}$


B 12 - E_α = 4.10 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
80
60
40
20
0
0°
90°
180°
Θ_{LAB}

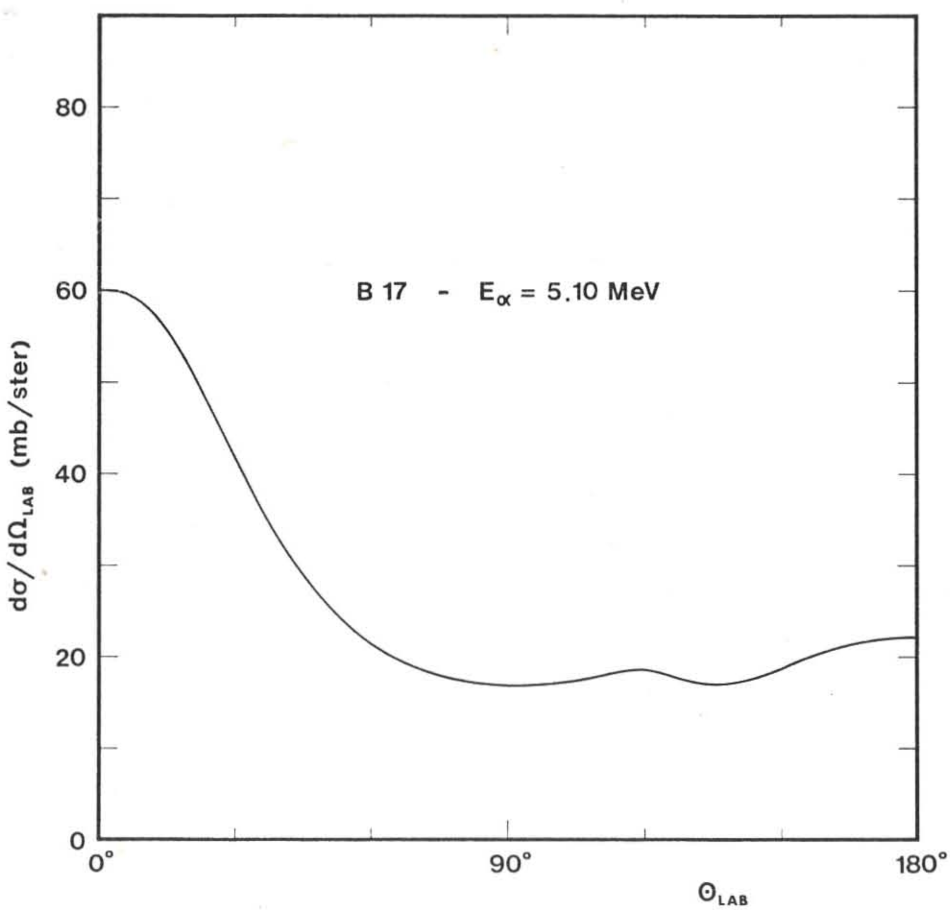

B 13 - E_α = 4.30 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
80
60
40
20
0
0°
90°
180°
Θ_{LAB}


80
60
40
20
0
dσ/dΩ_LAB (mb/ster)
B 14 - Eα = 4.50 MeV
0°
90°
180°
Θ_LAB

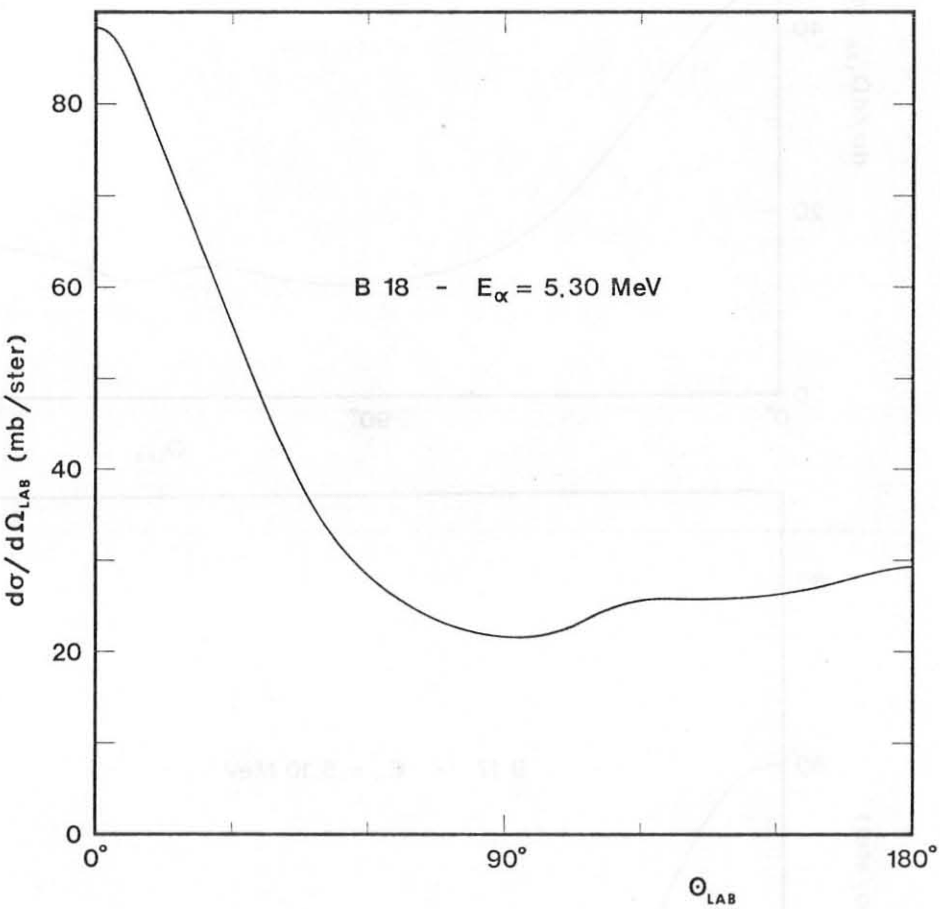

80
60
40
20
0
dσ/dΩ_LAB (mb/ster)
B 15 - Eα = 4.70 MeV
0°
90°
180°
Θ_LAB

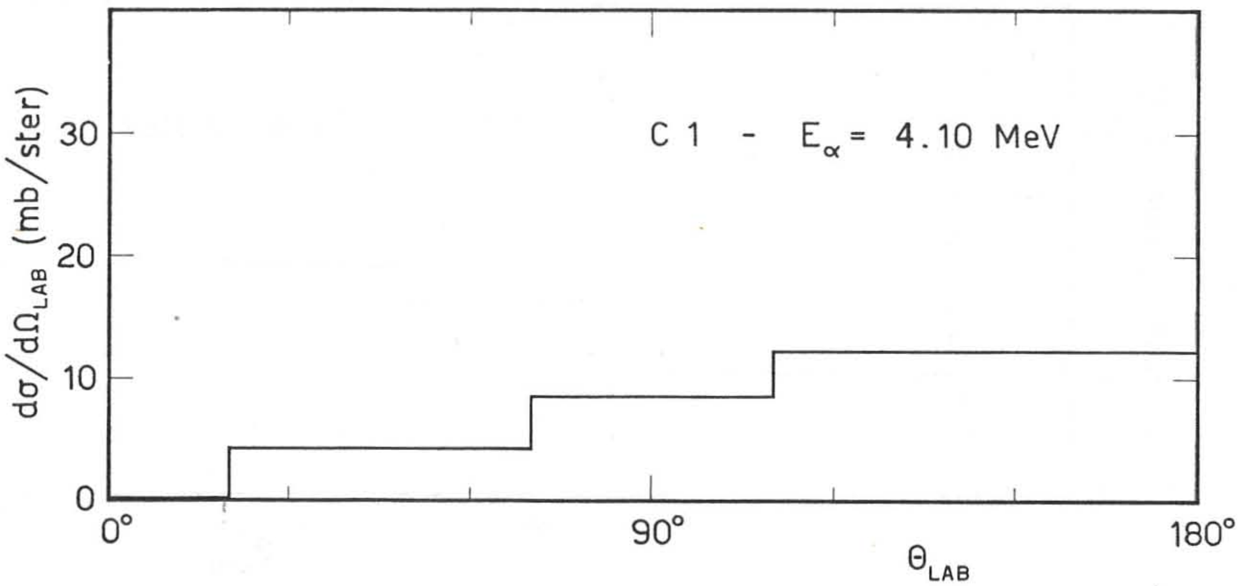


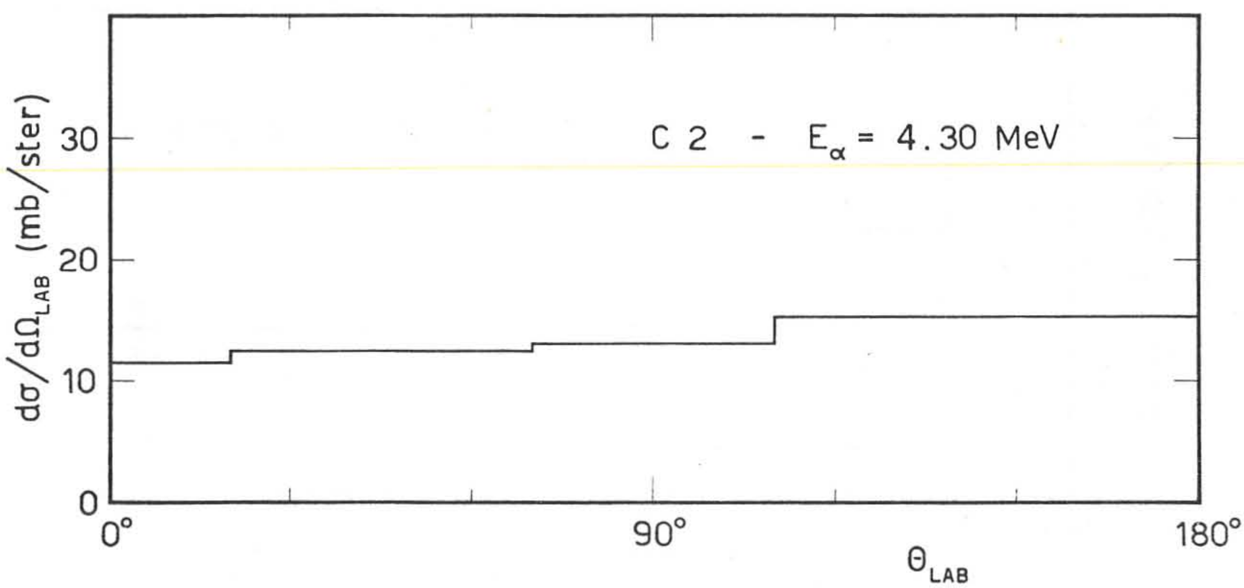
B 16 - E_α = 4.90 MeV
80
60
40
20
0
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0°
90°
180°
Θ_{LAB}

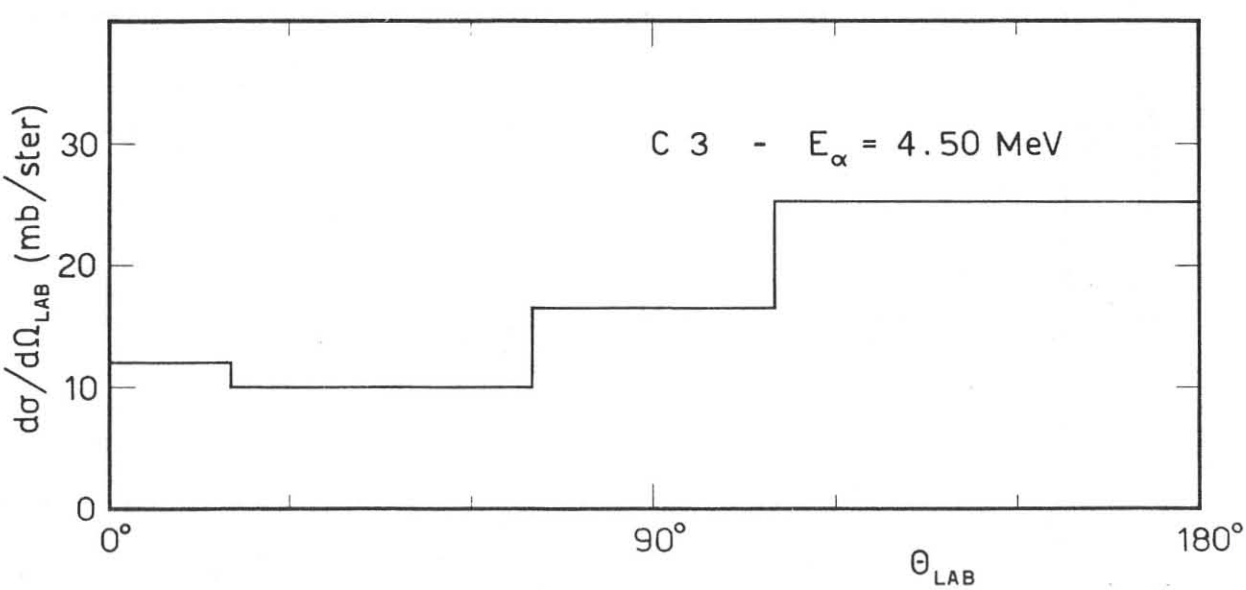


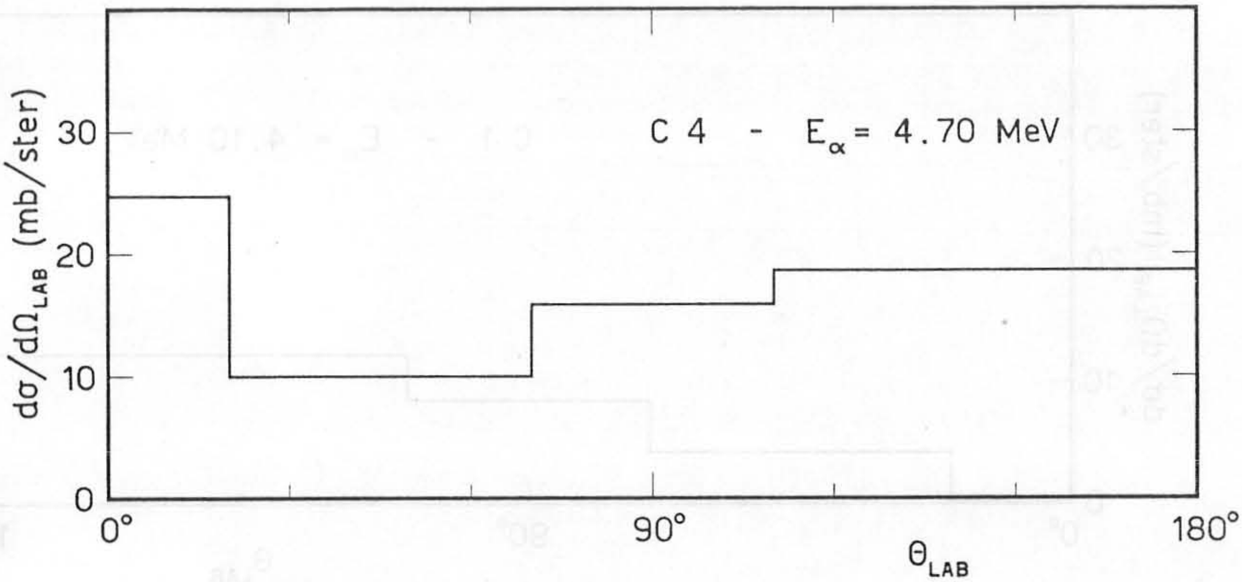
B 17 - E_α = 5.10 MeV
80
60
40
20
0
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0°
90°
180°
Θ_{LAB}

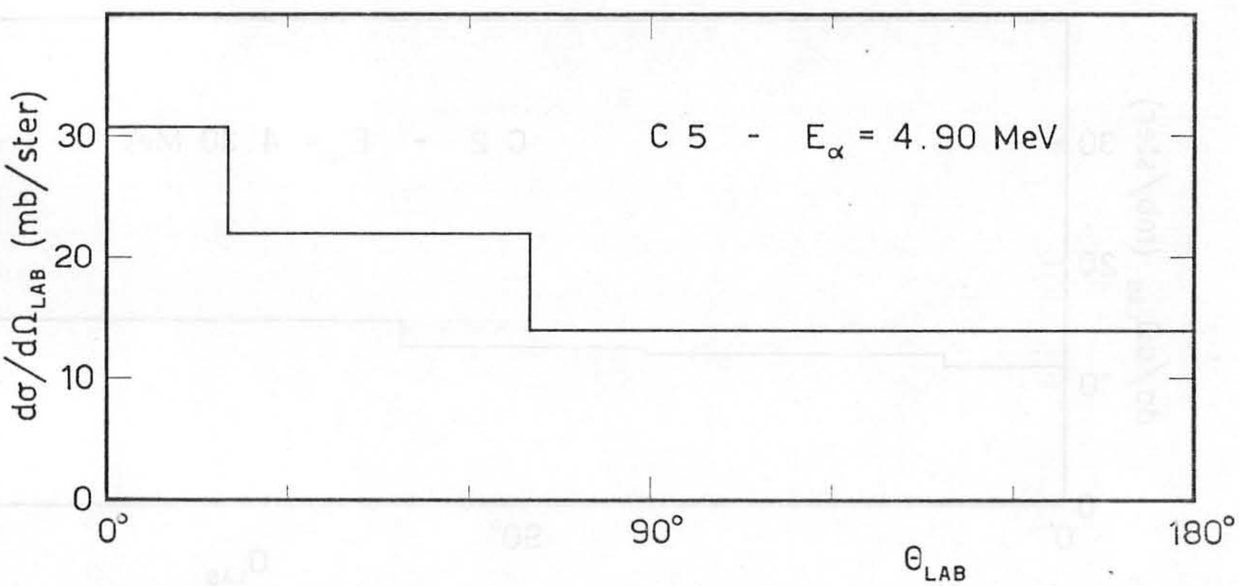

80
60
40
20
0
0°
90°
180°
Θ_{LAB}
$d\sigma/d\Omega_{LAB}$ (mb/ster)
B 18 - E_α = 5.30 MeV

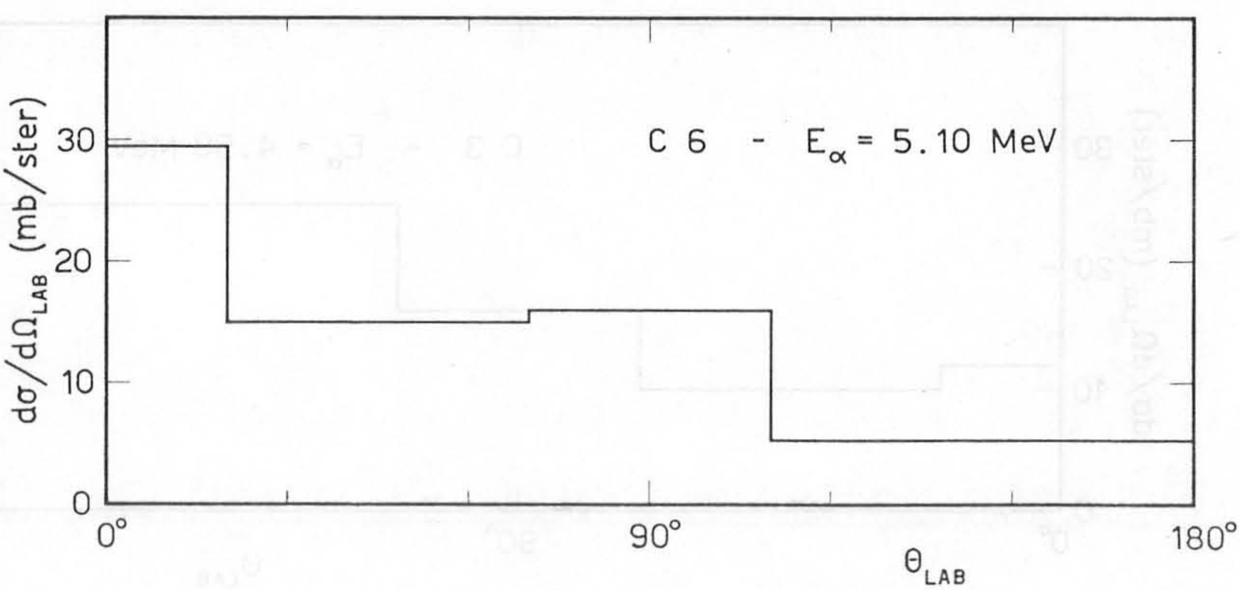

C 1 - E_α = 4.10 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

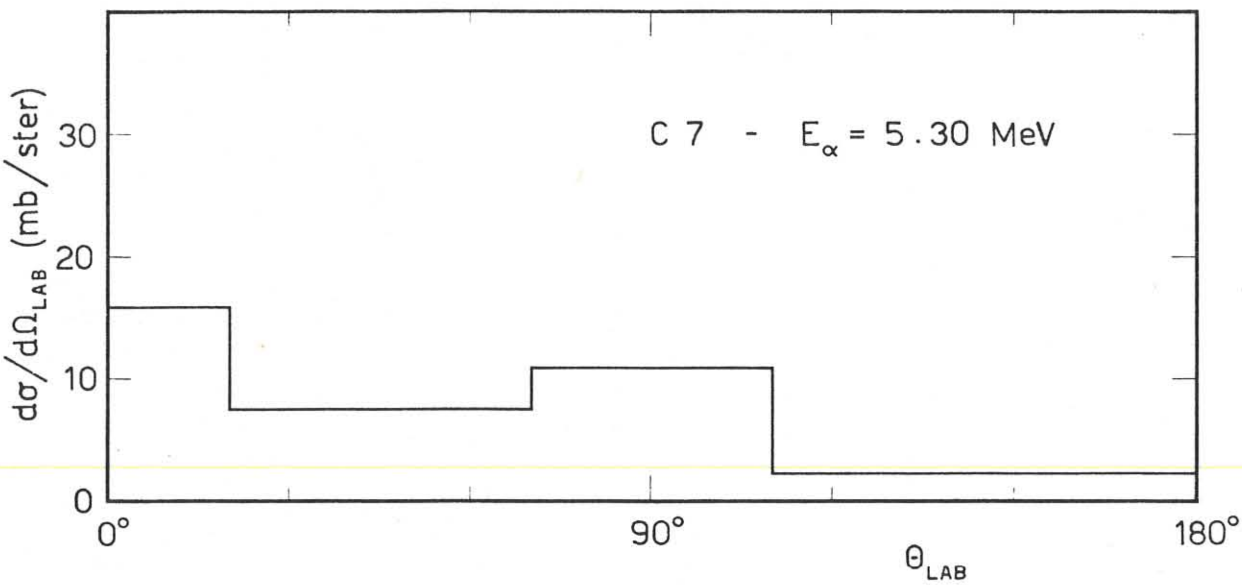

C 2 - E_α = 4.30 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

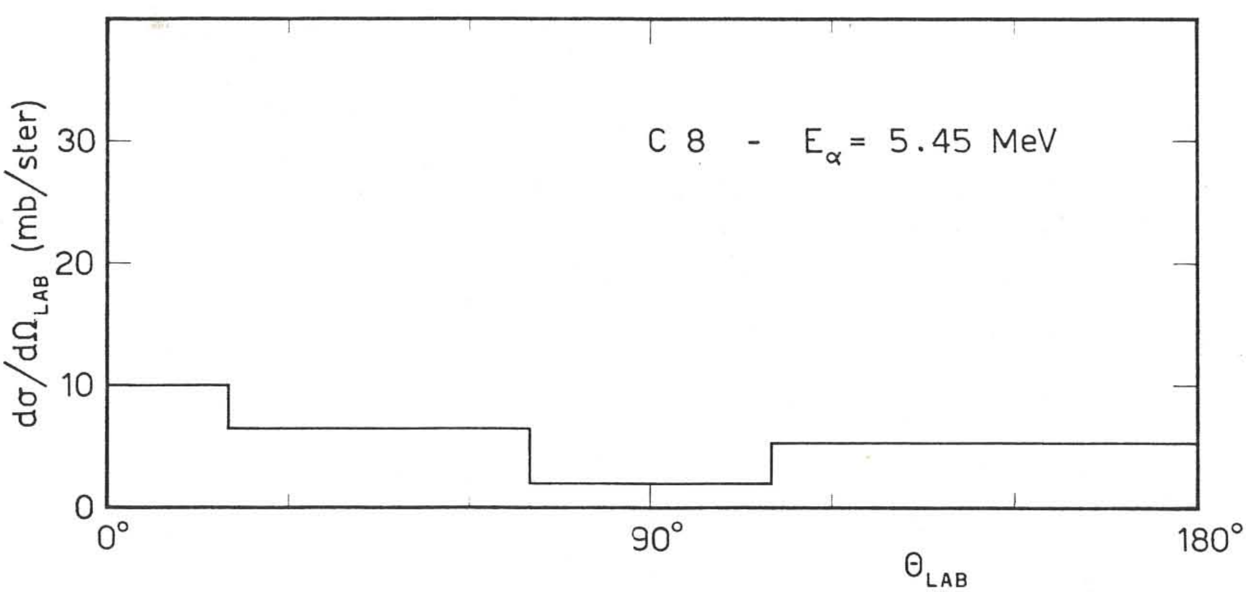

C 3 - E_α = 4.50 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

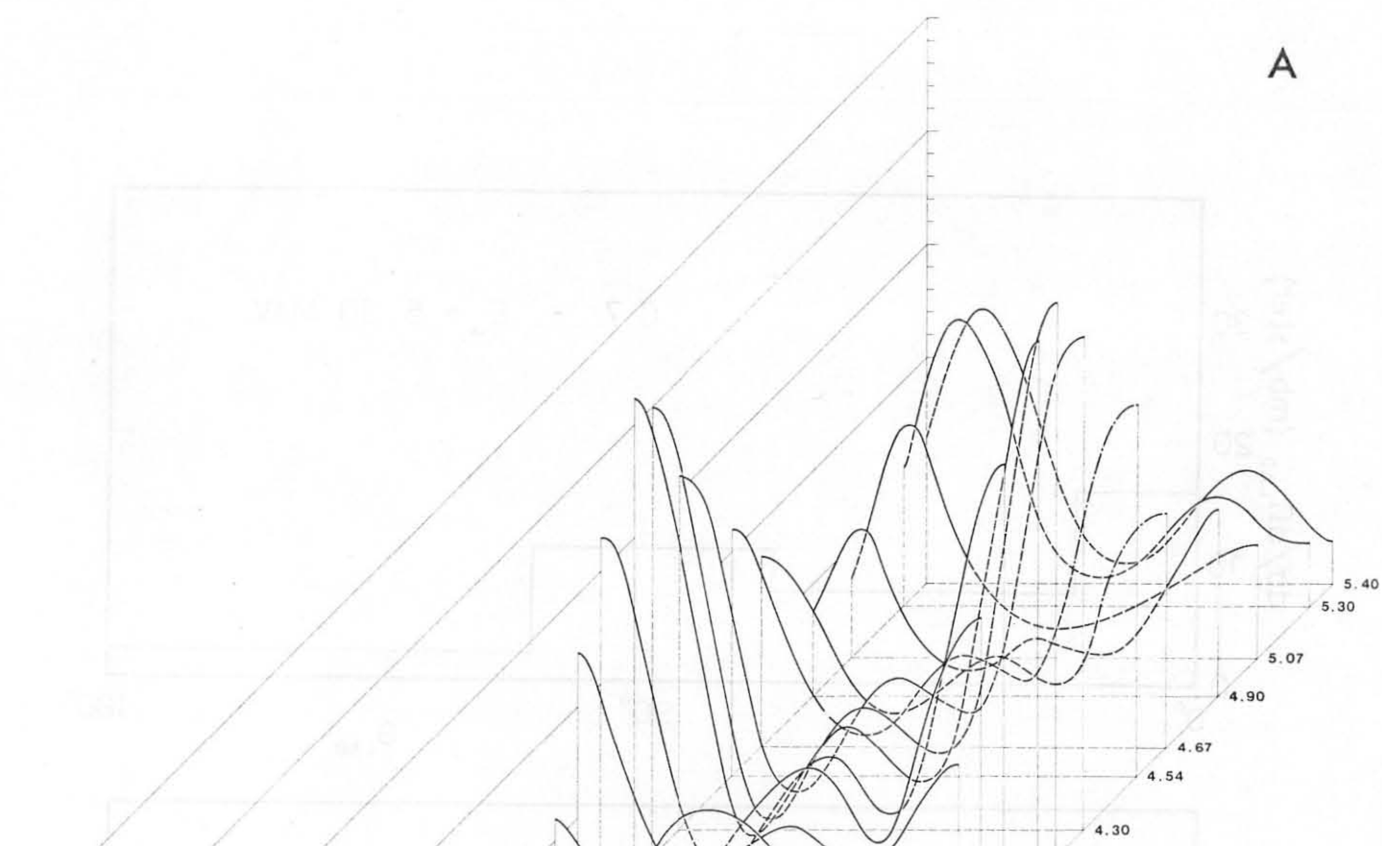

C 4 - E_α = 4.70 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

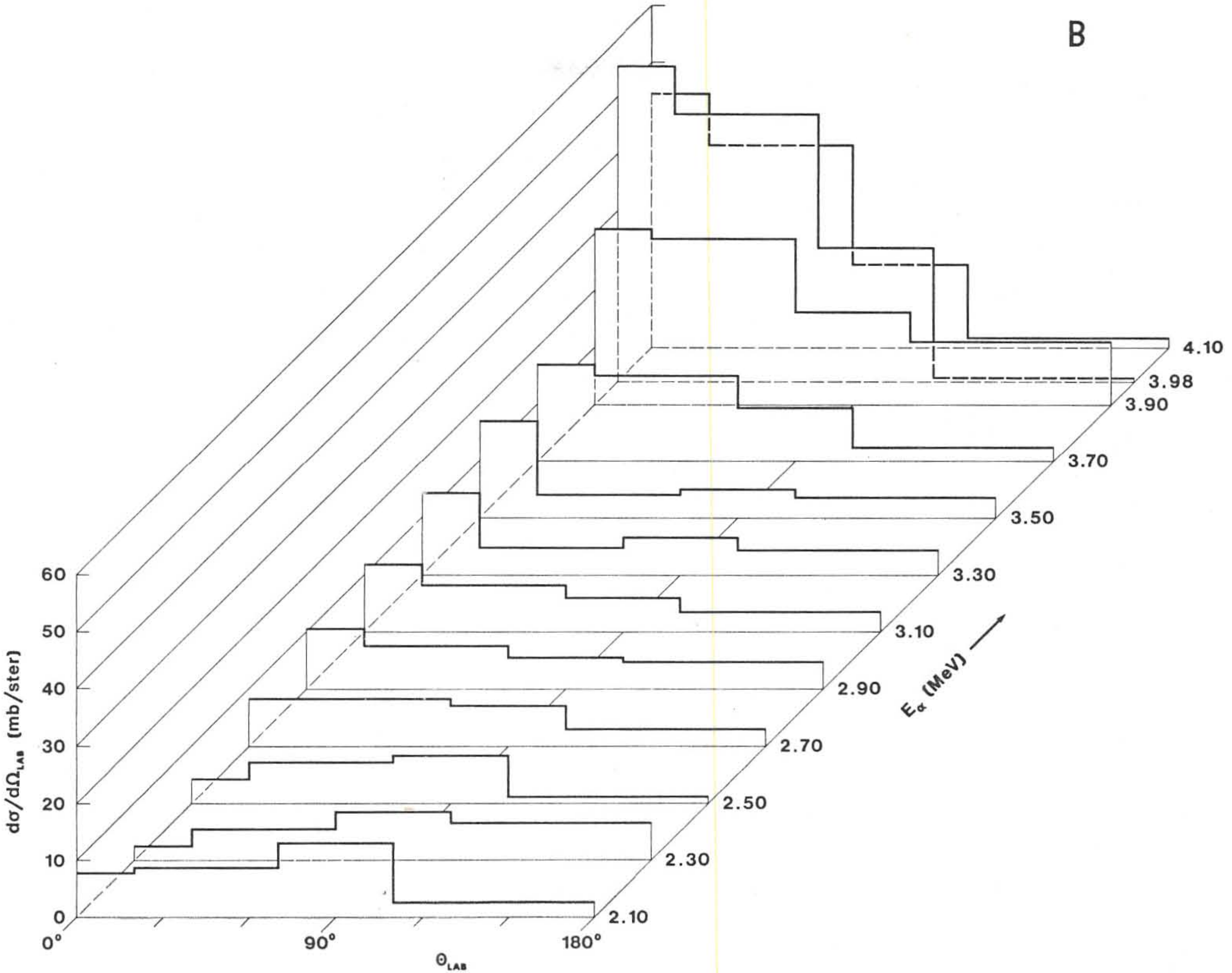

C 5 - E_α = 4.90 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}

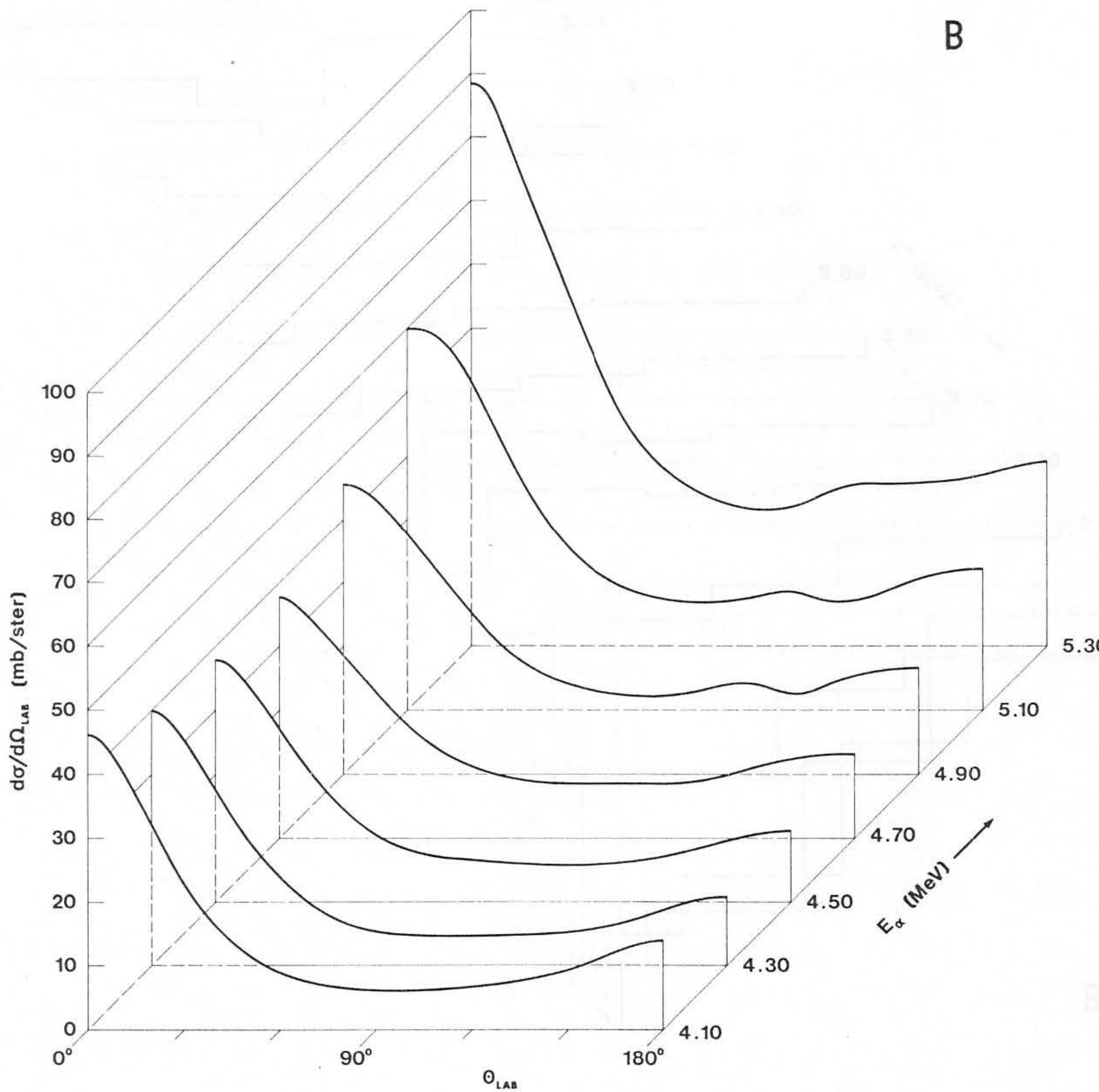

C 6 - E_α = 5.10 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
0
10
20
30
0°
90°
180°
Θ_{LAB}


C 7 - E_α = 5.30 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
30
20
10
0
0°
90°
180°
Θ_{LAB}

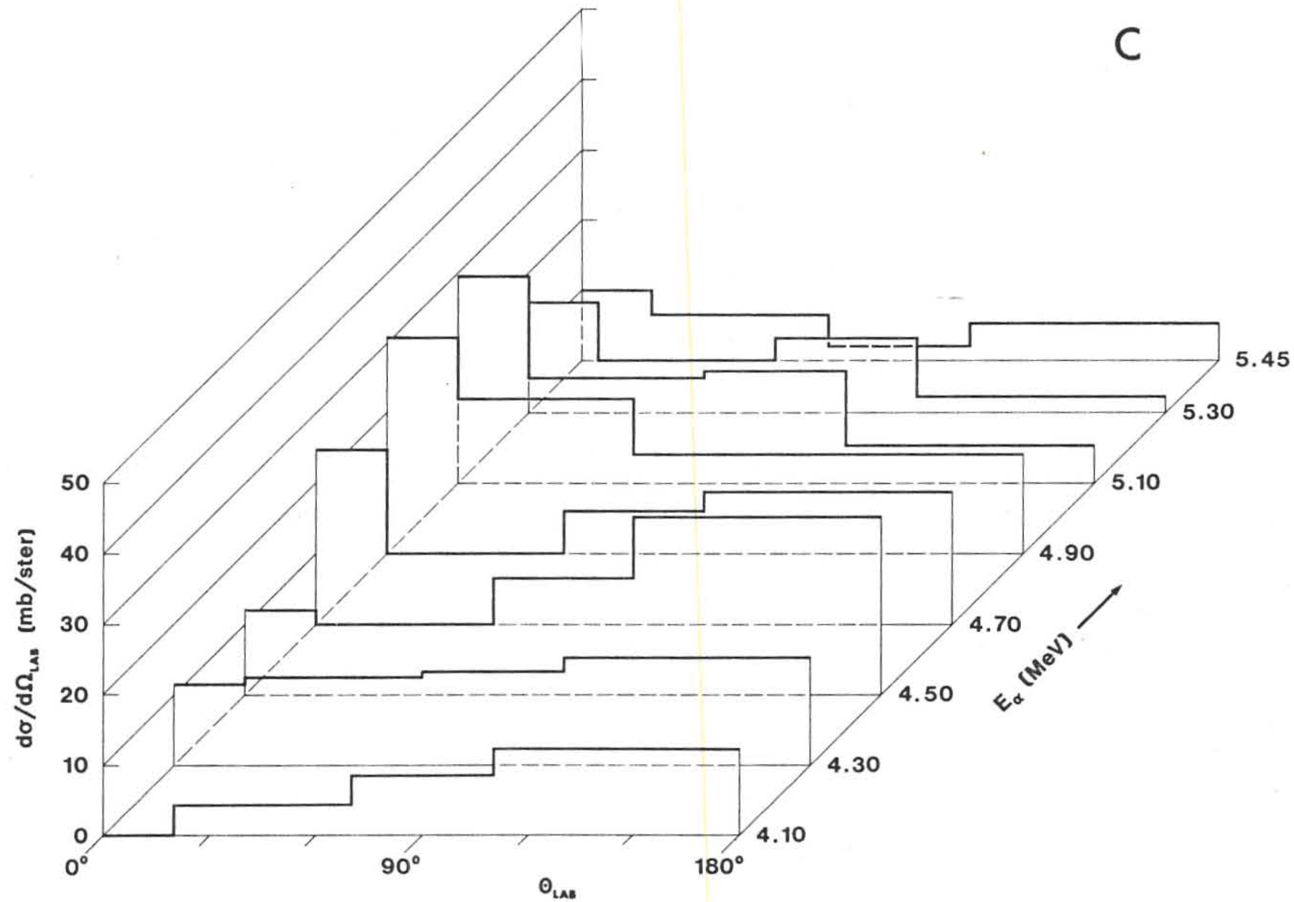

C 8 - E_α = 5.45 MeV
$d\sigma/d\Omega_{LAB}$ (mb/ster)
30
20
10
0
0°
90°
180°
Θ_{LAB}


A
dσ/dΩcm (mb/ster)
θcm
Eα (MeV)
0°
90°
180°
1.55
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.45
2.55
2.65
2.75
2.85
2.95
3.05
3.15
3.25
3.35
3.45
3.55
3.65
3.75
3.85
3.95
4.10
4.18
4.30
4.54
4.67
4.90
5.07
5.30
5.40


B
dσ/dΩ_LAB (mb/ster)
60
50
40
30
20
10
0
0°
90°
180°
Θ_LAB
E_α (MeV)
4.10
3.98
3.90
3.70
3.50
3.30
3.10
2.90
2.70
2.50
2.30
2.10


B
dσ/dΩ_LAB (mb/ster)
100
90
80
70
60
50
40
30
20
10
0
0°
90°
180°
Θ_LAB
4.10
4.30
4.50
4.70
4.90
5.10
5.30
E_α (MeV)

C



50
40
30
20
10
0
dσ/dΩ_LAB (mb/ster)
0°
90°
180°
Θ_LAB
5.45
5.30
5.10
4.90
4.70
4.50
4.30
4.10
E_α (MeV)