COMPOUND NUCLEUS CONTRIBUTION TO THE ALPHA PARTICLE SCATTERING ON ^{28}Si NUCLEI

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Compound nucleus contribution to the elastic and inelastic scattering of alpha particles on ^{28}Si nuclei is estimated. The analysis is based on the Hauser-Feshbach theory of compound reactions. For two selected alpha particle energies the experimental energy averaged angular distributions are compared with those calculated as an incoherent sum of direct and compound nucleus (for ground and 1.78 MeV states) or pure compound nucleus (for 4.61 MeV state) cross-sections.

1. *Introduction*

In the past few years several attempts were made in order to obtain a consistent description of the angular distributions of elastically and inelastically scattered alpha particles in a broad range of angles. The commonly used models were as follows: optical model (standard or modified), distorted wave Born approximation, coupled channels and the compound nucleus. On the other hand the problem of a satisfactory description of alpha particle scattering was solved on the basis of an assumption, that there are two reaction mechanisms which contribute incoherently to the measured cross-sections. Numerically this was calculated by an incoherent addition of a compound nucleus cross-section and that calculated from one of the direct reaction models.

Wühr et al. [1] obtained a satisfactory description of the elastic and three low lying inelastic transitions observed for alpha particles of 15.7 MeV scattered on ^{28}Si nuclei. The theoretical angular distributions were calculated as an incoherent sum of the optical model (or DWBA) and the Hauser-Feshbach compound nucleus model cross-sections. Obst and Kemper [2] studied the elastic and inelastic scattering of alpha particles in the range of incident energies from 20 to 27 MeV. They searched the parameters of the optical

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model as well as compound nucleus one in order to fit the measured angular distributions in a broad range of angles. Their fits (for three selected averaged energies, i. e. 25.2, 26.2 and 27.2, of incident α's) corresponding to elastic and three low lying inelastic transitions cannot be treated as a satisfactory description of the experiment in a whole range of scattering angles. Jarczyk et al. [3] tried to estimate the compound nucleus contribution to the scattering of alpha particles with energies of 19.1 and 24.2 MeV through the analysis of an inelastic transition to the unnatural parity state ($J^\pi = 3^+$) in ^{28}Si. The compound nucleus parameters were next used for calculating the compound nucleus contribution to the cross-sections corresponding to 0^+, 2^+ and 4^+ transitions in ^{28}Si. Recently Budzanowski et al. [4] performed a very detailed statistical analysis of the Obst and Kemper data [2]. They concluded that the direct reaction mechanism dominates in the region of back angles.

We estimated the compound nucleus contribution to the elastic and inelastic scattering of alpha particles on ^{28}Si nuclei on the basis of a complex analysis of averaged cross--sections, assuming that direct (DI) and compound nucleus (CN) processes contribute to the cross-sections incoherently.

2. *Analysis*

Analysis is based on the Obst and Kemper data [2]. They measured the excitation functions for the elastically and inelastically scattered alpha particles from ^{28}Si nuclei. The reasons for choosing these data were as follows:

(*a*) broad range of the bombarding alpha particles energies ($E_\alpha = 21-28$ MeV) and small step of the energy interval ($\Delta E = 125$ keV),

(*b*) large angular region taken into account ($\Theta_{\rm lab} = 30^\circ - 170^\circ$),

(*c*) observation of the ground state, 1.78 MeV (2^+), and 4.61 MeV (4^+) state transitions to the residual nucleus.

Our analysis consists of two parts. First we estimated the compound nucleus contribution to the elastic and inelastic scattering of alpha particles on ^{28}Si as it is discussed later. Next with these CN parameters we have performed the calculations based on the following assumptions:

(*i*) for elastic scattering

$$\sigma_{\alpha\alpha}^{\rm calc}(\Theta) = \sigma_{\alpha\alpha}^{\rm OM}(\Theta) + \sigma_{\alpha\alpha}^{\rm HF}(\Theta), \tag{1}$$

(*ii*) for inelastic scattering

$$\sigma_{\alpha\alpha'}^{\rm calc}(\Theta) = \sigma_{\alpha\alpha'}^{\rm DI}(\Theta) + \sigma_{\alpha\alpha'}^{\rm HF}(\Theta),$$

where $\sigma_{\alpha\alpha}^{\rm OM}(\Theta)$ is the optical model differential cross-section, $\sigma_{\alpha\alpha'}^{\rm DI}(\Theta)$ is the differential cross--section of inelastically scattered alpha particles, calculated in our case by the distorted wave Born approximation (DWBA). The second components in Eqs (1) and (2) were calculated by the compound nucleus Hauser-Feshbach formula.

2.1. Estimation of the compound nucleus parameters with the Hauser--Feshbach model

The energy averaged differential cross-section for compound nucleus reactions can be calculated following the Hauser and Feshbach theory [7] and the approximations introduced by Eberhard et al. [8] from the formula

$$\sigma_{\alpha\alpha'}^{\mathrm{HF}}(\Theta) = \frac{\lambda_\alpha^2}{4\varrho(2i+1)(2I+1)} \sum_{sls'l'J} W_{\alpha\alpha'} A_{\alpha\alpha'}^J(\Theta) \frac{T_\alpha^J T_{\alpha'}^J}{(2J+1)\exp\left[-J(J+1)/2\sigma^2\right]}, \tag{3}$$

where α and α' specify the initial and final states, λ_α is the Broglie wave length, i and I are the spins of the projectile and target nucleus, respectively. Summation is performed over the channel spin and angular momentum of the incoming (s, l) and outgoing (s', l') particles as well as over J which represents the spin of the compound nucleus. The quantity $A_{\alpha\alpha'}^J(\Theta)$ contains all geometrical factors as, e. g. Z-coefficients and Legendre polynomials; $W_{\alpha\alpha'}$ is the so called width correlation factor [9]; T_α^J and $T_{\alpha'}^J$, are transmission coefficients for the entrance and exit channel. According to Eberhard et al. [8] the parameters ϱ and σ are defined as follows:

$$\varrho = 2\pi \frac{\Gamma_0}{D_0}, \tag{4}$$

$$\sigma^2 = \sigma_{\mathrm{res}}^2(1+\omega_{\mathrm{res}}), \tag{5}$$

where Γ_0 and D_0 are the mean level width and the mean level spacing of compound nucleus states with spin $J = 0$, respectively; σ_{res} represents an average spin cut-off parameter for the various possible residual nuclei formed in the exit channel and ω_{res} is the correction factor [8]. The compound nucleus calculations were done with program CORA [13].

We analyzed the energy averaged angular distributions corresponding to the elastic scattering as well as to the 2^+ and 4^+ inelastic transitions. For each of the following averaged energy: 22.08, 23.08, 24.08, 25.08, 26.08 and 27.2 MeV we had a set of three mentioned above angular distributions averaged in the interval of ± 500 keV.

For each energy averaged experimental data set we calculated the CN angular distributions (according to Eq. (3)), so as the following conditions were fulfilled simultaneously:

$$\bar{\sigma}_{\alpha\alpha}^{\mathrm{exp}}(\Theta) \geqslant \sigma_{\alpha\alpha}^{\mathrm{HF}}(\Theta) \quad \text{(ground state transition)},$$

$$\bar{\sigma}_{\alpha\alpha'}^{\mathrm{exp}}(\Theta) \geqslant \sigma_{\alpha\alpha'}^{\mathrm{HF}}(\Theta) \quad \text{(1.78 MeV state transition)},$$

$$\bar{\sigma}_{\alpha\alpha''}^{\mathrm{exp}}(\Theta) \geqslant \sigma_{\alpha\alpha''}^{\mathrm{HF}}(\Theta) \quad \text{(4.61 MeV state transition)}.$$

This procedure allowed us to estimate the *upper limit* of the CN contribution to the cross--sections. The spin cut-off parameters which entered the calculations were determined assuming a rigid body moment of inertia for the nucleus. Parameters required for these calculations were taken from Vonach and Hille [10] (level density parameter $a = 3.0$ MeV^{-1}, energy shift $\Delta = 2.0$ MeV). All calculations were done with the width correlation factor

TABLE I

Compound nucleus parameters σ and ϱ estimated by the analysis of elastic and inelastic scattering of alpha particles on ^{28}Si nuclei for various energies of incident alpha particles

E^{α}_{lab} [MeV]	σ	ϱ	Ref.
15.6	2.7	243	[11]
	2.9	133	[11]
	3.3	65	[11]
	3.4	59	[11]
15.7	$3.4^{+0.3}_{-0.4}$	39 ± 15	[1]
19.1	2.86	240	[3]
22.08	2.964	1000	present work
23.08	3.016	2250	present work
24.08	3.066	4250	present work
24.2	3.10	1750	[3]
25.08	3.115	6900	present work
25.2	3.21	3958	[2]
26.08	3.158	6700	present work
26.2	3.24	5404	[2]
27.2	3.202	8420	present work
27.2	3.27	7351	[2]

$W_{\alpha\alpha'}$ equal to unity, so the only quantity searched for was the level density parameter ϱ. The above assumption (i. e. $W_{\alpha\alpha'} = 1$) is exact for inelastic transitions. In the case of elastic scattering it can be different from unity and in our calculations is contained in ϱ.

Table I contains the compound nucleus parameters σ and ϱ found by our method completed by those taken from other papers [1, 2, 3] for similar or lower energies. The

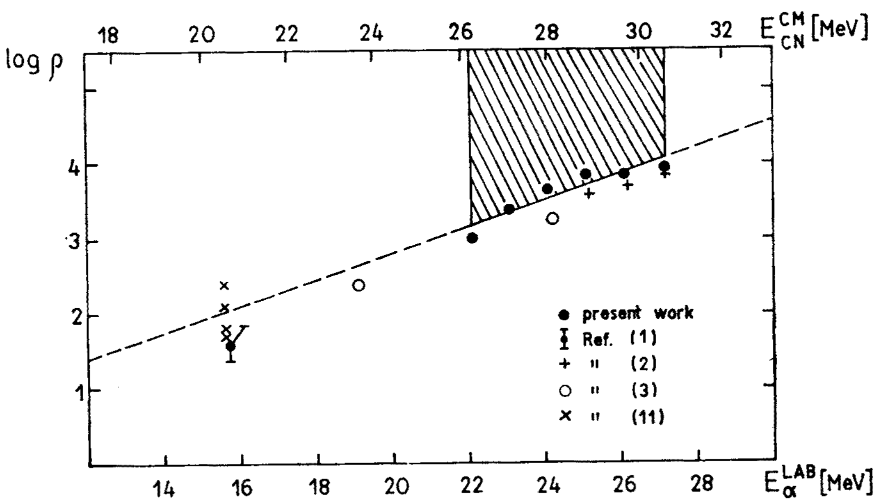
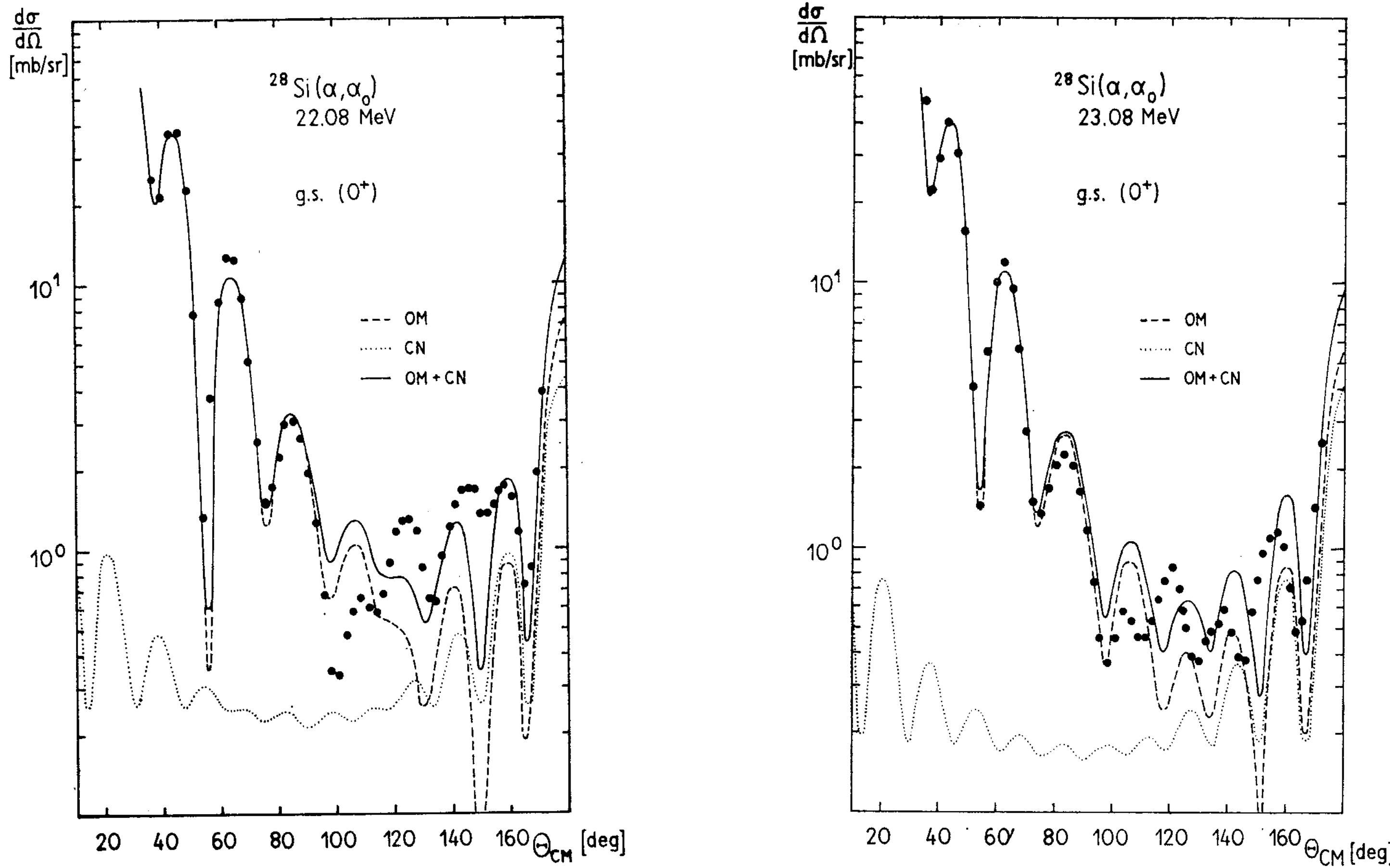


Fig. 1. Energy dependence of the level density parameter ϱ. Full line — linear approximation of points found in the present work (Eq. (6)). Dashed line — extrapolation beyond the energy region investigated



a b

Fig. 2a. Experimental and calculated cross-sections for the elastic scattering of 22.08 MeV α-particles by ^{28}Si. The curves represent: OM — optical model, CN — compound nucleus and the incoherent sum of OM and CN results of calculations

Fig. 2b. Same as in Fig. 2a but for 23.08 MeV α-particles

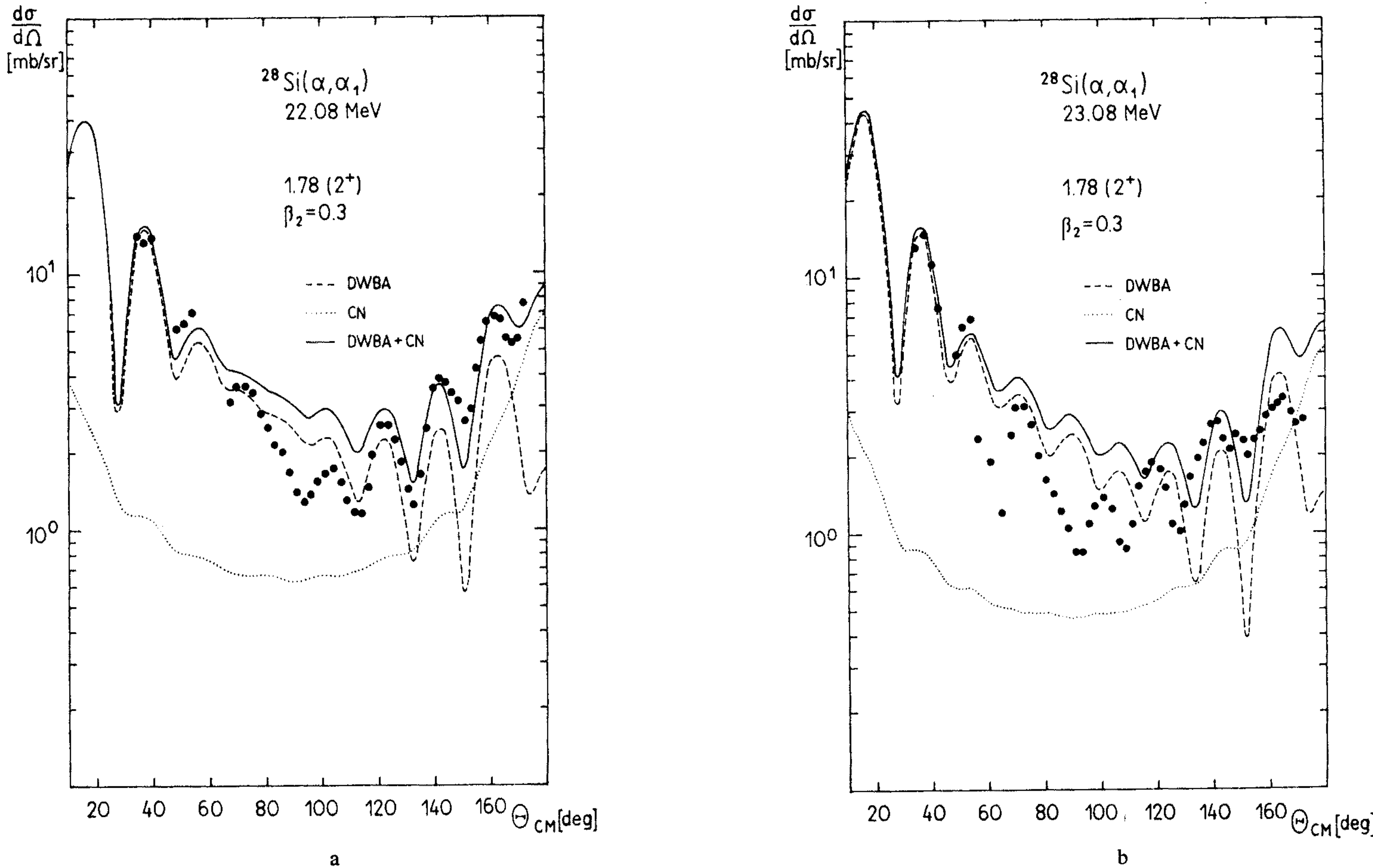


Fig. 3a. Experimental and calculated cross-sections for the inelastic scattering of 22.08 MeV α-particles by ^{28}Si to the 1.78 MeV(2^+) state. The curves represent: DWBA — distorted wave Born approximation, CN — compound nucleus and the incoherent sum of DWBA and CN results of calculations

Fig. 3b. Same as in Fig. 3a but for 23.08 MeV α-particles

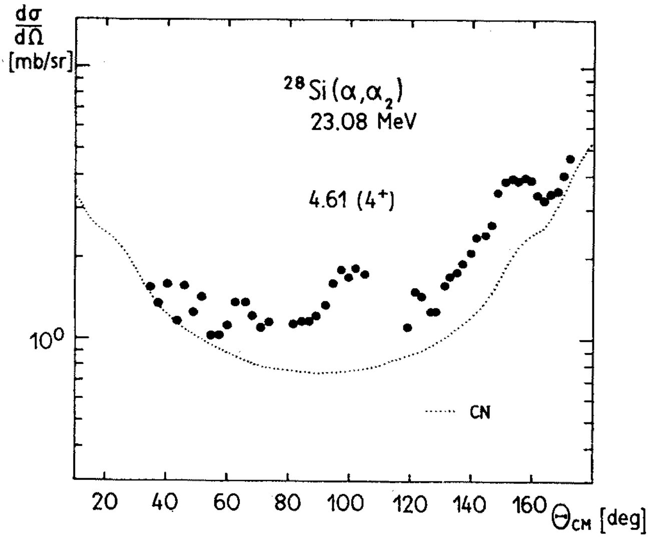


Fig. 4a. Experimental and calculated cross-sections for the inelastic scattering of 22.08 MeV α-particles by ^{28}Si to the 4.61 MeV(4^+) state. The curve labelled CN represents the compound nucleus result of calculations

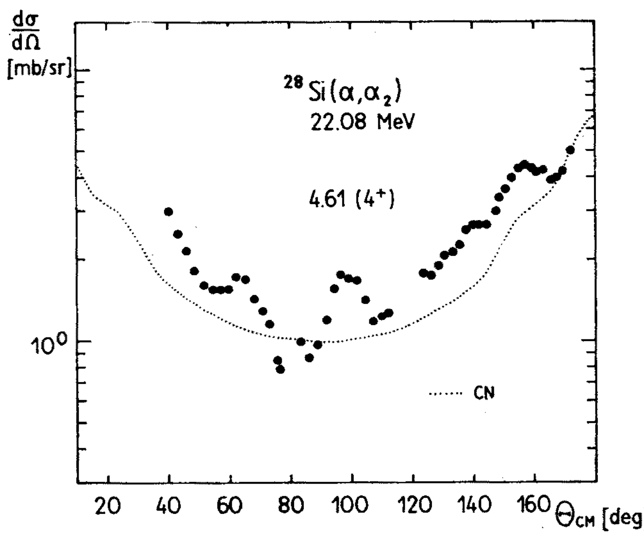


Fig. 4b. Same as in Fig. 4a but for 23.08 MeV α-particles

level density parameters ϱ for corresponding energies are shown in Fig. 1. For convenience a decimal logarithm of ϱ is taken. In the range of energies investigated in our work we made a least squares linear approximation for the level density parameters. One obtains the following formula:

$$\lg \varrho = 0.175\, E^{\alpha}_{\text{lab}} - 0.709, \tag{6}$$

where E^{α}_{lab} is the alpha particle laboratory energy in MeV. Assuming that the experimental error is 10%, the uncertainties of the above parameters are: $\Delta a = \pm 0.010$ (for slope) and $\Delta b = \pm 0.239$.

2.2. Optical model and DWBA calculations

In these calculations we applied the standard (Woods-Saxon geometrical form factor and valume absorption) four parameter optical model. The parameters used were those found by Kamys [5]. The optical model with these parameters describes very well the forward angles ($\Theta_{CM} \lesssim 60°$) energy averaged experimental elastic data of Obst and Kemper [2].

The DWBA calculations with the above optical model parameters were performed assuming the rotational excitation of the 1.78 MeV residual nucleus state and taking the β_2 deformation parameter equal to 0.3 [6]. The calculations were performed for two averaged energies, i. e. 22.08 and 23.08 MeV, previously no analyzed. In the case of elastic and 2^+ inelastic transitions, we summed incoherently the optical model and DWBA angular distributions with the compound nucleus contributions. The level density parameters ϱ used in the compound nucleus calculations were those predicted from the linear formula found in our work. Thus these contributions have to be treated as maximum ones. The 4^+ inelastic transitions were calculated only with the Hauser-Feshbach theory. All DWBA calculations were done with the VENUS code [12]. Figs 2–4 show a comparison of the calculated and experimental angular distributions.

3. Discussion and conclusions

By the complex analysis of the elastic and inelastic alpha particle scattering on the basis of the Hauser–Feshbach theory of compound nucleus reactions an estimation of the contribution of this reaction mechanism has been made. An energy dependence of the level density parameter found in our analysis extended beyond the region investigated corresponds closely to the values found in other works.

An incoherent addition of the angular distributions in the case of elastic and first inelastic transitions give a slightly better description of the experimental data for backward angles (excluding the case shown in Fig. 3b). It should be stressed, that we did not try to improve fits in the region of backward angles by decreasing the compound nucleus contribution, which in general cannot be excluded. Addition of the CN contribution in the region of forward angles does not change the situation too much, because in this region the DI process dominates. On the other hand the description of the experimental points in the region of middle angles is very bad. This fact could be evidence, that some interference phenomena exist, which are of course not included in our summation of DI and CN cross-sections. Another possibility is that the strong coupling between elastic and the first inelastic transition occurs which requires the coupled channel calculations. Such calculations are in progress [14]. The situation is similar for both energies investigated.

In the case of the 4^+ state transition the calculated compound nucleus distributions cannot describe a well pronounced structure of the observed cross-sections. However, the symmetric shape of the angular distributions is reproduced by the CN calculations.

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REFERENCES

[1] W. Wühr, A. Hofman, G. Philipp, *Z. Phys.* **269**, 365 (1974).
[2] A. W. Obst, K. W. Kemper, *Phys. Rev.* **C6**, 1705 (1972).
[3] L. Jarczyk, M. Siemaszko, W. Zipper, Proc. 1st Louvain-Cracow Seminar on the Alpha-Nucleus Interaction, Cracow 1974, Report INP No. 870/PL, p. 154.
[4] A. Budzanowski, L. Jarczyk, B. Kamys, A. Kapuścik, *Nucl. Phys.* **A265**, 461 (1976).
[5] B. Kamys, L. Jarczyk, Proc. 1st Louvain-Cracow Seminar on the Alpha-Nucleus Interaction, Cracow 1974, Report INP No. 870/PL, p. 180.
[6] L. Jarczyk, B. Maciuk, M. Siemaszko, W. Zipper, *Acta Phys. Pol.* **B7**, 531 (1976).
[7] W. Hauser, H. Feshbach, *Phys. Rev.* **87**, 366 (1952).
[8] K. A. Eberhard, P. von Brentano, M. Böhning, R. O. Stephen, *Nucl. Phys.* **A125**, 673 (1969).
[9] P. A. Moldauer, *Phys. Rev.* **123**, 968 (1961); *Phys. Lett.* **8**, 249 (1964); **19**, 1047 (1967); *Phys. Rev.* **157**, 907 (1967); **171**, 1164 (1968); **177** 1841 (1969).
[10] H. K. Vonach, M. Hille, *Nucl. Phys.* **A127**, 189 (1969).
[11] R. Prasad, A. Hofman, F. Vogler, *Nucl. Phys.* **A225**, 64 (1975).
[12] T. Tamura, W. R. Coker, F. Rybicki, *Comput. Phys. Commun.* **2**, 94 (1971).
[13] A. Hartman, M. Siemaszko, W. Zipper, IFJ Report No. 865/PL, Cracow 1974 unpublished.
[14] M. Siemaszko, to be published.