ON THE MECHANISM OF THE $^{24}Mg(\alpha, p)^{27}Al$ AND $^{24}Mg(\alpha, \alpha)^{24}Mg$ REACTIONS*

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The excitation functions for the $^{24}Mg(\alpha, p)^{27}Al$ and $^{24}Mg(\alpha, \alpha)^{24}Mg$ reactions leading to several excited states of ^{27}Al and ^{24}Mg, respectively, were measured at $\theta_{lab} = 40°$, 80°32′, 144°19′, and 175° over an α-energy range of 23.05 — 28.55 MeV, in ~200 keV steps. Statistical analysis of these excitation functions was performed. The direct interaction contribution y_D to the reactions studied was obtained from auto-correlation coefficients. Cross-correlation coefficients calculated between different reaction channels did not indicate the existence of resonances common to all investigated channels. The final state spin dependence of the cross-sections for the $^{24}Mg(\alpha, p)^{27}Al$ reaction was also examined. It is in a good agreement with the predictions of the statistical model of compound nucleus reactions.

1. Introduction

One of the most interesting discoveries made in the earlier studies of the reactions initiated by alpha particles or by heavy ions was the observation of rapid variation of the cross-sections with bombarding energy [1–6]. The structure of the excitation functions was mainly attributed to the statistical fluctuations which occur in reactions proceeding entirely or in part through the formation of a highly excited compound system. However, some indications were also reported of the presence of non-statistical effects in the excitation functions [1, 7, 8]. In order to get some more information about the reactions mechanism and the possible intermediate resonances it is of considerable interest to measure excitation functions in many reaction channels, and to study the correlation among them.

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In the present work the excitation functions for the $^{24}Mg(\alpha, p)^{27}Al$ and $^{24}Mg(\alpha, \alpha)^{24}Mg$ reactions were studied in the excitation region where typical statistical fluctuations occur. The properties of the compound nucleus ^{28}Si are discussed with regard to both statistical and non-statistical effects. The final state spin dependence of the cross-section for the $^{24}Mg(\alpha, p)^{27}Al$ reaction was also examined.

2. Experimental results

The differential cross-sections for the $^{24}Mg(\alpha, p)^{27}Al$ and $^{24}Mg(\alpha, \alpha)^{24}Mg$ reactions were measured in the energy range $E_{lab} = 23.05 - 28.55$ MeV in ~ 200 keV steps. The measurements were performed at one forward angle $\theta_{lab} = 40°$, one backward angle $\theta_{lab} = 175°$, and at the angles $\theta_{lab} = 80°32'$ and $144°19'$ which correspond to zeros of Legendre polynomials of all odd orders and of order 10, respectively, for elastic scattering of alpha particle. The alpha particle beam from the 120 cm cyclotron of the Institute of Nuclear Physics in Cracow was used. The energy spread of the beam was about 200 keV and the accuracy of the beam energy measurement was about 50 keV. The self-supporting magnesium target was of natural abundance and its thickness was 0.3 mg/cm^2. The measurements were carried out using two telescopes of silicon detectors. The method of particle identification and the experimental arrangement have been described elsewhere [9, 10].

Five alpha particle groups and ten proton groups corresponding to low-lying states of ^{24}Mg and ^{27}Al were observed. Some of them correspond to two or three closely lying unresolved levels. The examples of the obtained excitation functions are presented in Figs 1 and 2. A rich structure having a fluctuation character was found in all excitation functions. The error bars in Figs 1 and 2 indicate the total error composed of the statistical and charge measurement error and those connected with the accuracy of the Gaussian fits to the energy spectra. All the experimental results were presented in the previous paper [10].

3. Statistical analysis

In the reaction under investigation the compound nucleus ^{28}Si is formed in the excitation energy range 29.7–34.4 MeV. At these excitations the average compound nuclear width $\langle \Gamma \rangle$ is considerably larger then the average level spacing $\langle D \rangle$ hence the observed cross-sections can be compared with the predictions of statistical theory [11, 12] in terms of the correlation function $C_{ab}(\varepsilon)$ defined as:

$$C_{ab}(\varepsilon) = \frac{\langle \sigma_a(E)\sigma_b(E+\varepsilon) \rangle}{\langle \sigma_a(E) \rangle \langle \sigma_b(E+\varepsilon) \rangle} - 1, \tag{1}$$

where σ_a and σ_b are the differential cross-sections for particular nuclear channels at the specific energy and angle. The averages are taken over the total energy range under investigation.

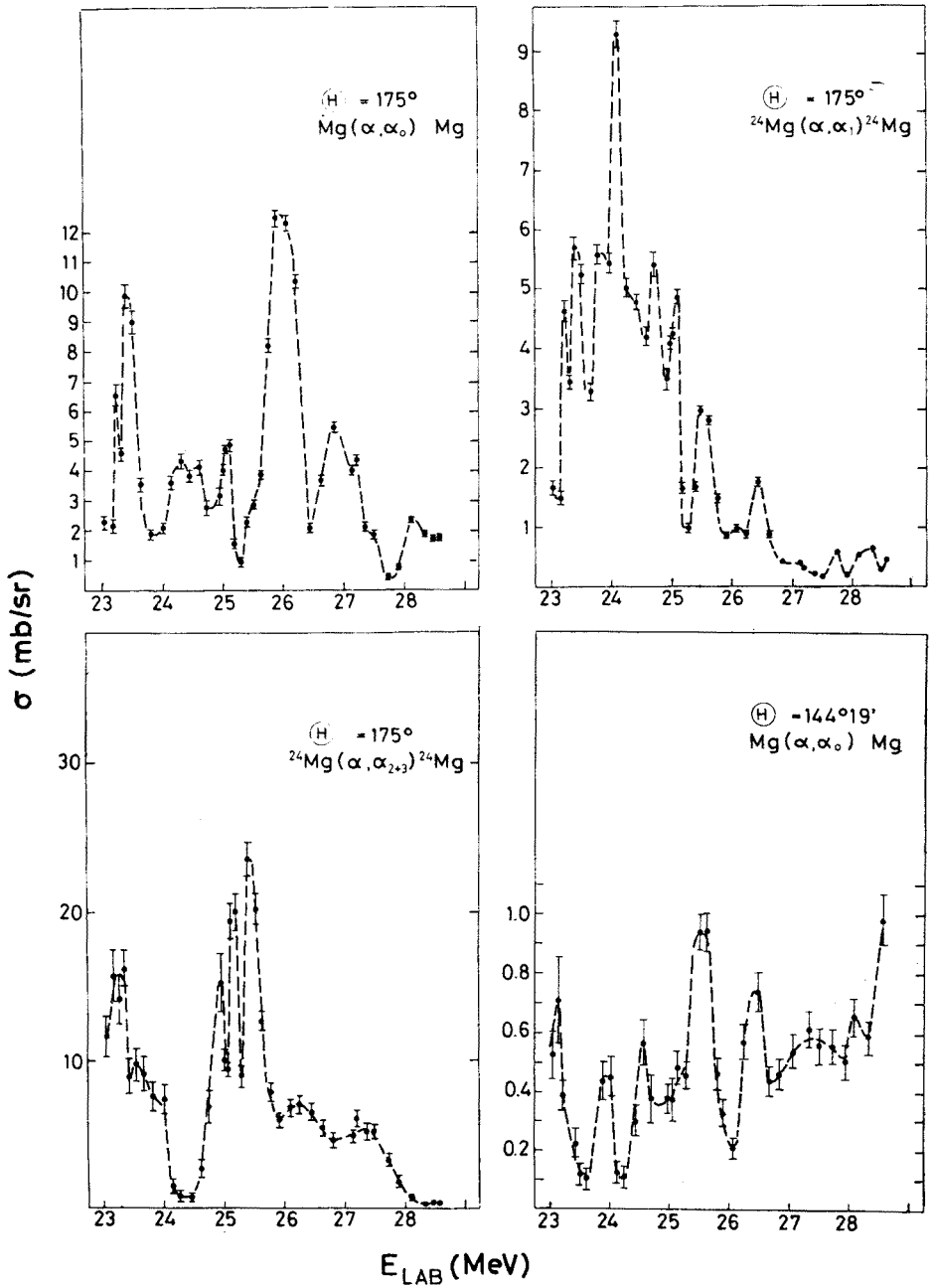

Fig. 1. Examples of measured excitation functions for the $^{24}Mg(\alpha, \alpha)^{24}Mg$ reaction

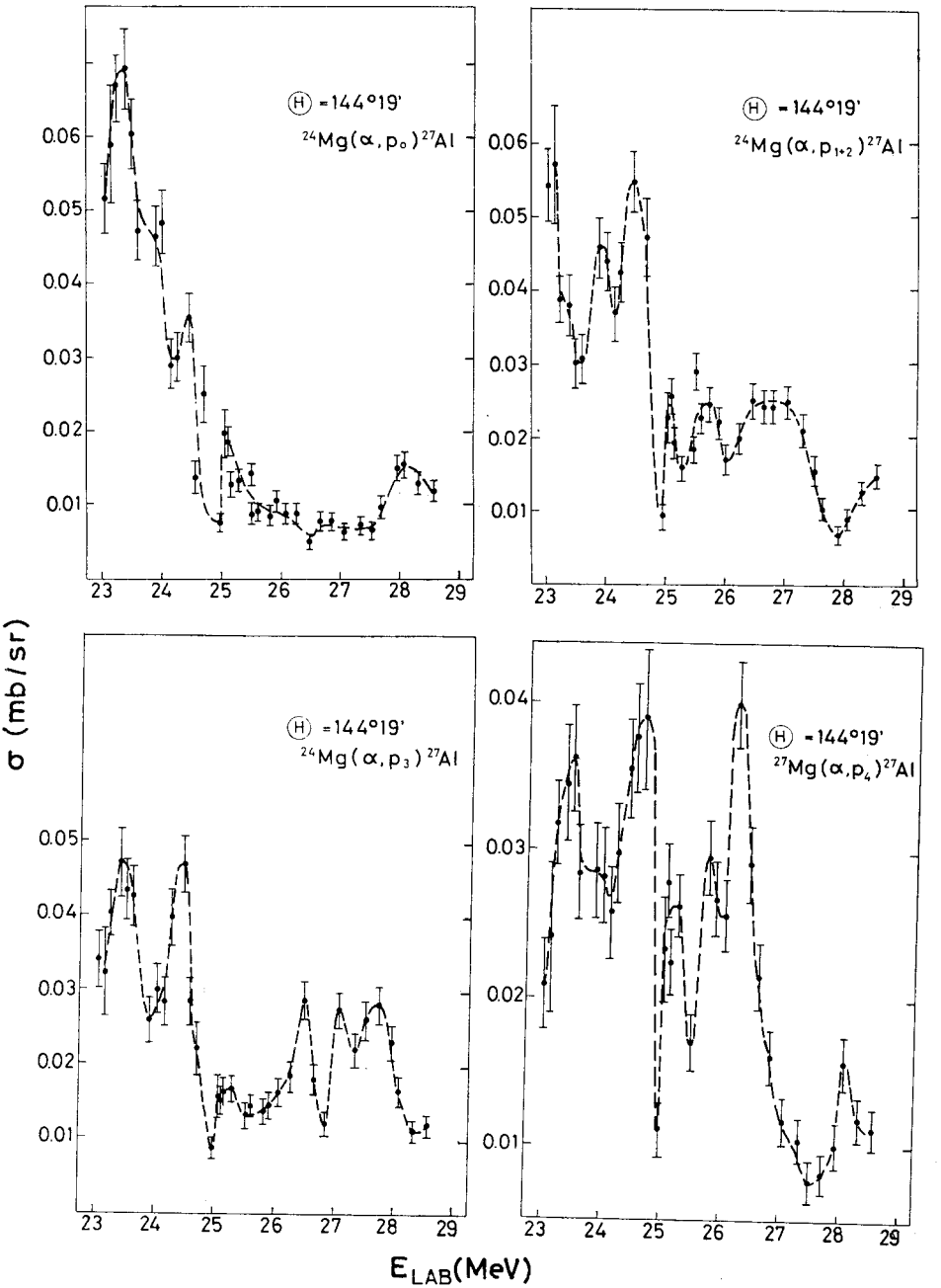

Fig. 2. Examples of measured excitation functions for the $^{24}Mg(\alpha, p)^{27}Al$ reaction

According to Ericson [11], the autocorrelation function is equal to:

$$C_{aa}(\varepsilon) = C_{aa}(0)\frac{\Gamma^2}{\Gamma^2+\varepsilon^2}, \tag{2}$$

$$C_{aa}(0) = \frac{1-y_D^2}{N_{\text{eff}}}, \tag{3}$$

where $y_D = \dfrac{\sigma_D}{\langle\sigma\rangle}$, and σ_D is the "direct interaction" component which includes all components of the cross-section varying smoothly with energy. It should be pointed out that this definition of σ_D, introduced by Ericson, is not always equivalent to the definition of the direct interaction cross-section as being connected with excitation of a few degrees of freedom. N_{eff} is the effective number of independent channels contributing to the observed cross-section and is equal to or less than the number of different positive spin projections given by:

$$N_{\max} = \begin{cases} \frac{1}{2}\,q & \text{for } q \text{ even}, \\ \frac{1}{2}\,(q+1) & \text{for } q \text{ odd}, \end{cases} \tag{4}$$

$$q = (2i+1)\,(2I+1)\,(2i'+1)\,(2I'+1),$$

where i, I, i', I' are the spins of the particles in the entrance and exit channels.

3.1. Determination of y_D

From the observed values of the autocorrelation coefficients $C_{aa}(0)$ and the relation (3) one can obtain the magnitude of the "direct interaction" contribution at each angle θ if N_{eff} is known. The number N_{eff} depends on the angle θ. For the reaction studied in this paper N_{eff} is unity at 0° and 180° and is equal to $N_{\max}$ over a wide angular range around 90°, i. e. from 40°–140° [12]. In the angular range 0°–40° and 180°–140° N_{eff} increases from unity to $N_{\max}$. Assuming that this increase can be approximated by a straight line we have determined values of N_{eff} for all angles of observation by an interpolation method.

Before evaluating y_D from the relation (3) some corrections have to be made because the Ericson theory was developed under some simplifying assumptions. This theory takes into consideration excitation curves in an infinite energy range measured with perfect energy resolution, with no energy dependence of the local average cross-section.

It is clear that our experimental data do not satisfy these conditions. In particular the local average cross-section is energy dependent. This can be seen from the excitation functions and also from Fig. 4, showing the autocorrelation function $C_{aa}(\varepsilon)$ for one of the excitation curves. The shift upwards of the autocorrelation function for the non-reduced data can be attributed to the slow energy dependence of the local average cross-section [13]. The energy dependence of the local average cross-section has to be eliminated from

the excitation functions. It can be achieved by transforming the experimental cross-section $\sigma(E)$ into the reduced cross-section $\sigma_r(E)$ by the formula:

$$\sigma_r(E) = \frac{\sigma(E)}{\sigma_A(E)}, \tag{5}$$

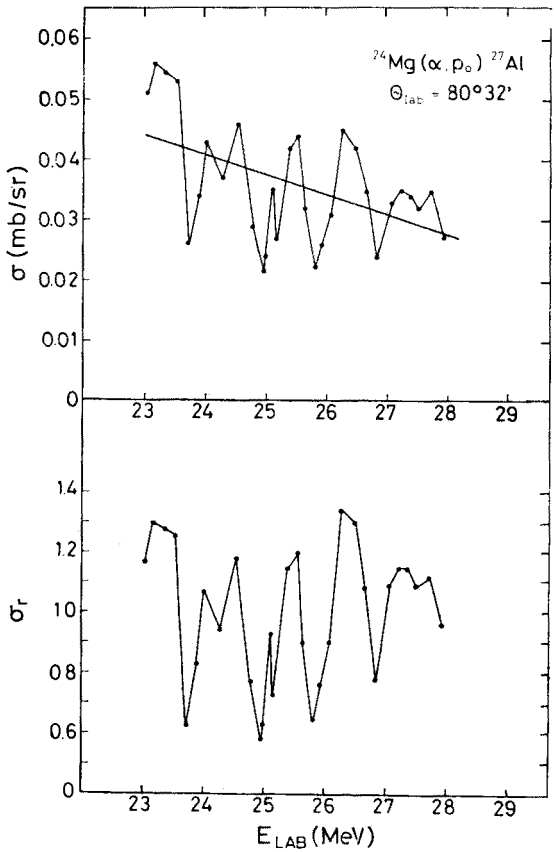

Fig. 3. Experimental (upper curve) and reduced (lower curve) excitation functions for the ^{24}Mg(α, p)^{27}Al reaction. The straight line in the upper part represents the energy dependence of the local average cross-section used for reduction of data

where $\sigma_A(E)$ is the local average cross-section. It can be obtained by fitting a polynomial of the form:

$$\sigma_A(E) = \sum_{i=0}^{n} a_i E^i \tag{6}$$

to the data points. It was found that in most cases it was sufficient to use the linear dependence of (6) i. e. with $n = 1$, while in very few cases it was necessary to apply $n = 2$. Fig. 3 shows an example of the average cross-section fitted to the experimental points for the ^{24}Mg(α, p$_0$) ^{27}Al reaction (upper part) and the reduced cross-section (lower part).

In Fig. 4 the autocorrelation functions $C_{aa}(\varepsilon)$ are presented for the reaction $^{24}Mg(\alpha, p_7)^{27}Al$ at $\theta_{lab} = 144°19'$. The upper curve is that obtained from the non-reduced data and the lover ones are obtained from the data reduced by polynomials of order $n = 1,2$, and 3.

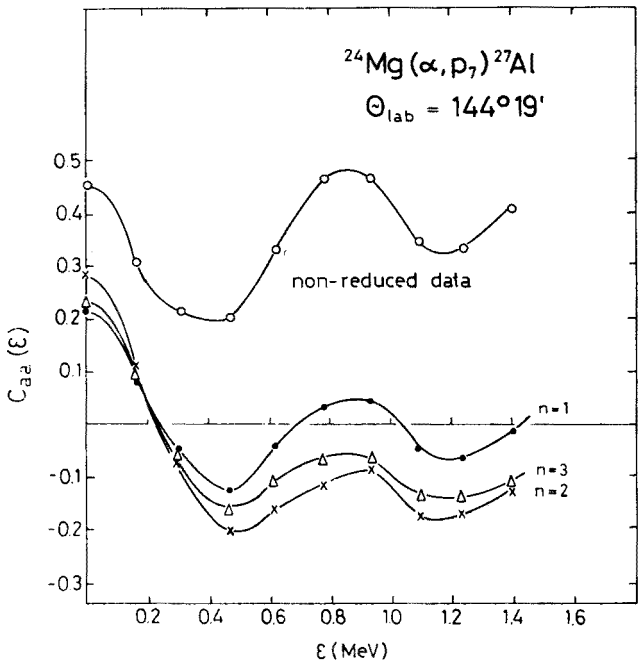

Fig. 4. The autocorrelation function $C_{aa}(\varepsilon)$ for the $^{24}Mg(\alpha, p_7)^{27}Al$ reaction calculated for non-reduced data (upper curve) and for the data reduced with polynomials of the order 1, 2, and 3 (lower curves)

It can be seen that the shape of these functions, especially for the small ε values, does not much depend on the order of the polynomial.

The values of $C_{aa}(0)$ are affected by the finite experimental energy resolution Δ in the measurements of excitation functions. Gibbs has shown [14, 15] using the rectangular resolution function, that in the case of $\Delta > \Gamma$ the corrected formula for the autocorrelation coefficient has the form:

$$C_{aa}^{\Delta}(0) = \frac{1 - y_D^2}{a N_{eff}}, \tag{7}$$

where

$$\frac{1}{a} = \left\{ 2 \frac{\Gamma}{D} \operatorname{arc\,tg} \frac{\Delta}{\Gamma} - \left(\frac{\Gamma}{\Delta}\right)^2 \ln\left[1 + \left(\frac{\Delta}{\Gamma}\right)^2\right] \right\}. \tag{8}$$

Fig. 5, taken from the work of Gibbs [14], illustrates the influence of Δ expressed in units of Γ on the autocorrelation coefficient in the case of $N_{eff} = 1$ and $y_D = 0$.

The next correction which must be introduced is that caused by the finite range of data (f. r. d.). It arises from the fact that the measurements cover a finite energy interval. The f. r. d. bias and f. r. d. error have been calculated by Dallimore and Hall [16], Böhn-

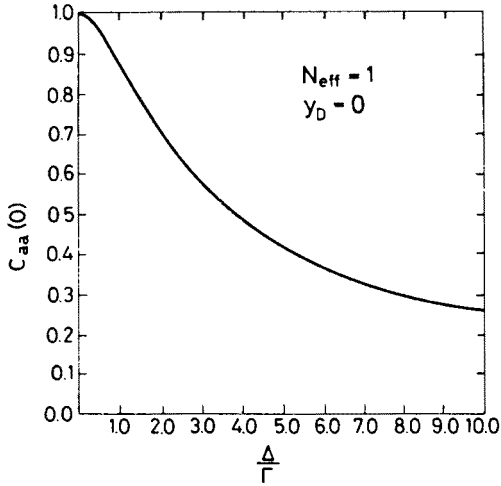

Fig. 5. The effect of energy resolution Δ on the autocorrelation coefficient in the case $N_{\text{eff}} = 1$ and $y_D = 0$, according to Gibbs [14]

ing [17], and Roeders [3], for the f. r. d. effect we have applied formulas found by Roeders with the aid of synthetic excitation functions [3]:

$$C_{aa}^{\text{exp}}(0) = C_{aa}^{\Delta}(0) - \gamma(0) \pm \beta, \tag{9}$$

where $\gamma(0)$ is the f. r. d. bias, β is the f. r. d. error:

$$\gamma(0) = \tfrac{1}{3}\, C_{aa}^{\Delta}(0) \left(1 - \frac{1 - y_D^2}{N_{\text{eff}}}\right) \sqrt{\frac{\pi}{p}}, \tag{10}$$

$$\beta = [C_{aa}^{\Delta}(0) - \gamma(0)] \sqrt{\frac{\pi}{2p} \left(1 + \frac{1 - y_D^2}{N_{\text{eff}}}\right)}, \tag{11}$$

$$p = \frac{\Delta E}{\Gamma}$$

and ΔE is the experimental energy interval.

From the experimental autocorrelation coefficients $C_{aa}(0)$ obtained on the basis of experimental excitation curves, for all resolved levels, we determined the values of y_D using formula (9). The value of $\Gamma = 116$ keV recently found by Roeders et al. [18] for the same energy interval of the compound nucleus ^{28}Si was used in these calculations.

TABLE I

Values of "direct interaction" contribution

Reaction	Excitation energy of the residual nucleus (MeV)	y_D			
		40°_{lab}	$80°32'_{lab}$	$144°19'_{lab}$	175°_{lab}
(α, α_0)	0.000	$0.99^{+0.01}_{-0.01}$	$0.89^{+0.03}_{-0.03}$	$0.81^{+0.07}_{-0.05}$	$0.35^{+0.27}_{-0.35}$
(α, α_1)	1.369	$0.73^{+0.08}_{-0.09}$	$0.62^{+0.12}_{-0.14}$	$0.83^{+0.05}_{-0.05}$	$0.00^{+0.40}_{-0.00}$
(α, α_4)	5.236	$0.00^{+0.44}_{-0.00}$			
(α, α_5)	6.010		$0.42^{+0.21}_{-0.42}$		
(α, p_0)	0.000		$0.78^{+0.06}_{-0.06}$	$0.71^{+0.08}_{-0.10}$	$0.89^{+0.02}_{-0.03}$
(α, p_3)	2.211		$0.00^{+0.00}_{-0.00}$	$0.00^{+0.30}_{-0.00}$	$0.64^{+0.12}_{-0.16}$
(α, p_4)	2.734			$0.67^{+0.10}_{-0.12}$	$0.82^{+0.05}_{-0.05}$
(α, p_7)	3.678			$0.61^{+0.13}_{-0.16}$	$0.00^{+0.52}_{-0.00}$
(α, p_{13})	4.812		$0.73^{+0.08}_{-0.09}$	$0.28^{+0.29}_{-0.28}$	$0.83^{+0.05}_{-0.05}$

The values of y_D obtained from this analysis are given in Table I and are presented in Fig. 6.

3.2. Cross-correlations; search for an intermediate structure

Generally, the term "intermediate structure" is used to denote structure of a non-statistical origin, e. g. caused by the presence of doorway states or some configurations representing a simple structure in the continuum [19]. There exists some experimental evidence that such a structure could be present in our range of excitation in compound nucleus ^{28}Si [7, 8, 20].

One way of tracing intermediate structure in excitation functions is to look for correlations between different reaction channels, which should be evident if an intermediate structure is present. In our experiment we measured the excitation functions for 40 reaction channels, which should be independent in the meaning of Ericson's theory. For

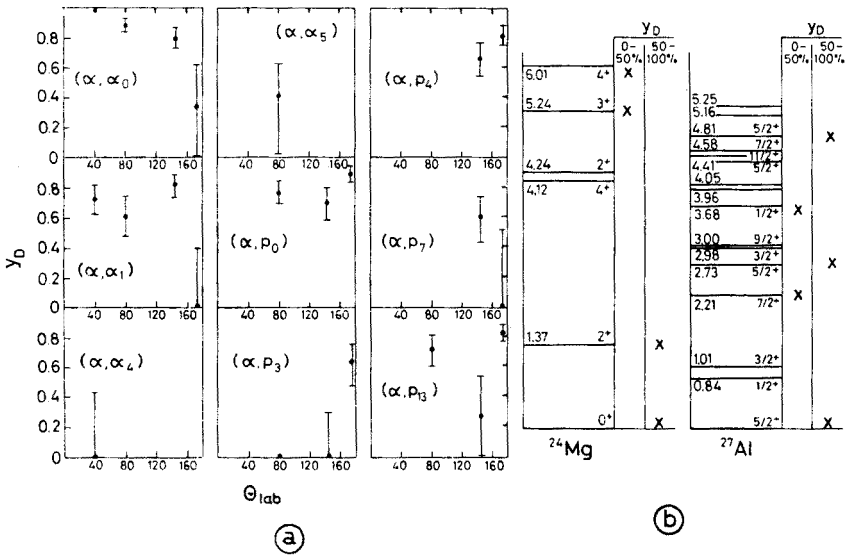

Fig. 6. Values of "direct interaction" contribution for different reaction channels in function of θ_{lab} (a), and schematic representation of the results (b)

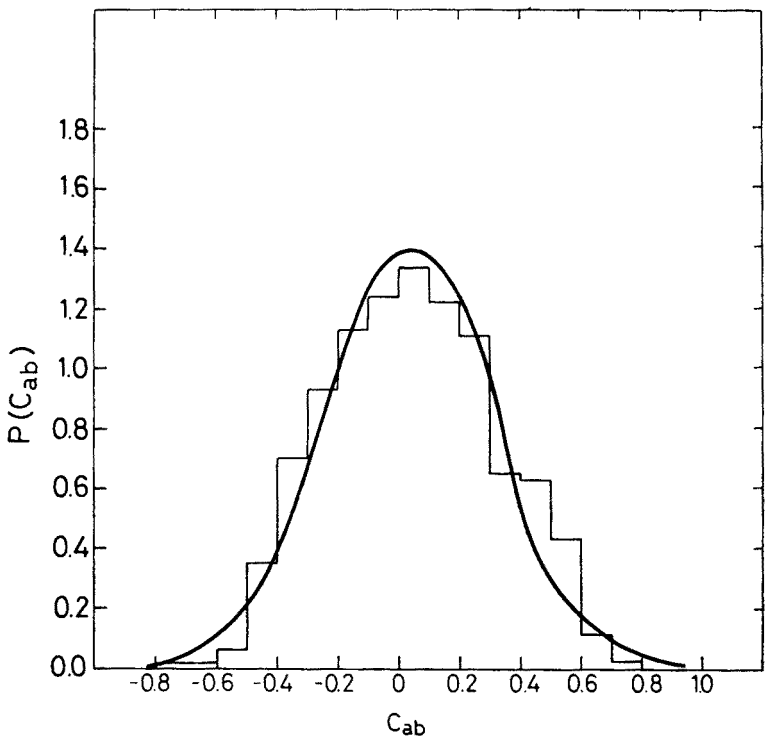

Fig. 7. Histogram of cross-correlation coefficients together with the least square fit with the Gaussian curve (solid line)

all possible pairs of reduced excitation functions the cross-correlation coefficients were calculated:

$$C_{ab}(0) = \frac{1}{\sqrt{C_{aa}(0)C_{bb}(0)}} \left\{ \frac{\langle \sigma_a(E)\sigma_b(E) \rangle}{\langle \sigma_a(E) \rangle \langle \sigma_b(E) \rangle} - 1 \right\}. \tag{12}$$

The $C_{ab}(0)$ coefficients are shown in Fig. 7.

It should be pointed out that the reduction of excitation functions by the local average cross-section described by the polynomial of the order 1 (the straight line) does remove from excitation curves the monotonic energy dependence of the local average cross-section and/or structures of the half width much greater than the energy interval studied.

According to the statistical theory, the distribution of cross-correlation coefficients should be normal and symmetric with respect to the value $C_{ab}(0) = 0$ [3]. The standard deviations of the cross-correlation coefficients should not exceed the f. r. d. error given for these coefficients by the following formula [16]:

$$\text{f.r.d.} \{C_{ab}(0)\} = \pm \sqrt{\frac{1}{2mN_aN_b}}, \tag{13}$$

where N_a and N_b represent the effective numbers of independent channels for the reactions a and b, respectively, and m is the number of independent points in the excitation curve given by:

$$m = \frac{\Delta E}{\pi \sqrt{\Gamma^2 + \Delta^2}}. \tag{14}$$

The least square fit of the Gaussian curve to the experimental histogram is shown in Fig. 7. The mean value of cross-correlation coefficients does not differ significantly from zero, being equal 0.04 ∓ 0.03. The standard deviation of the coefficients is equal to 0.27 and it is close to the maximum value of the f. r. d. error equal to 0.28 in our case. Two other histograms obtained for alpha particle and proton channels separately showed no difference in the shape and in the mean value of $C_{ab}(0)$.

All the features of distributions of the cross-correlation coefficients indicate that there is very small probability that the correlated structures exist in the investigated energy range.

4. The $(2I+1)$ cross-section dependence for the $^{24}Mg(\alpha, p)\,^{27}Al$ reaction

It was shown by Takeuchi and Samada [21] that in the reaction going through the compound nucleus formation in the region of overlapping states, the cross-section integrated over angles and averaged over energy is proportional to $(2I+1)$, where I is the spin of the residual nucleus, i. e.:

$$\langle \sigma(I) \rangle = G(2I+1)+C, \tag{15}$$

where G and C are constants.

In the reactions studied here the averaged data were obtained using the expression:

$$\langle\sigma(I)\rangle = \frac{1}{c}\sum_{E=23.05}^{28.55}\sum_{\substack{\theta=144°19'\\175°}}\frac{d\sigma}{d\Omega}(E,\theta)\sin\theta, \tag{16}$$

where $c = 41$ is the number of experimental points in the excitation functions.

In Table II the experimental values of $\langle\sigma(I)\rangle$ for particular levels or groups of levels are shown. In spite of the fact that our calculations were based on measurements at two

TABLE II

$^{24}Mg(\alpha, p)^{27}Al$

Residual nucleus level number	E_{exc} (MeV)	J^{π}	$\langle\sigma(I)\rangle$ (mb)
0	0.000	5/2+	1.319±0.210
1	0.844	1/2+	1.793±0.176
2	1.014	3/2+	
3	2.211	7/2+	1.458±0.120
4	2.734	5/2+	1.288±0.093
5	2.981	3/2+	4.806±0.493
6	3.004	9/2+	
7	3.678	1/2+	0.633±0.083
8	3.956	3/2 or 5/2	1.286±0.090
9	4.054	1/2 or 3/2	
10	4.409	5/2+	6.750±0.604
11	4.510	11/2+	
12	4.580	7/2+	
13	4.812	5/2+	1.272±0.140
14	5.155	1/2 or 3/2	1.269±0.167
15	5.246	3/2 or 5/2	

angles only, the spin dependence presented in Fig. 8 shows qualitative agreement with the $(2I+1)$ rule except for two points which lie distinctly above the $(2I+1)$ lines. For unresolved states (for doublets and one triplet) the mean value of $(2I+1)$ was obtained using the formula:

$$(2I+1) = \frac{1}{k}\sum_{i=1}^{k}(2I_i+1) \tag{17}$$

where k is the number of states in the group and I_i is the spin of the particular state. As the spins of the levels 8th, 9th, 14th, and 15th of ^{27}Al are not uniquely determined [22], three possible values of $(2I+1)$ are shown for these states. The spin values 3/2 and 1/2 for the 8th and 9th levels and 1/2 and 3/2 for the 14th and 15th levels, respectively, are in

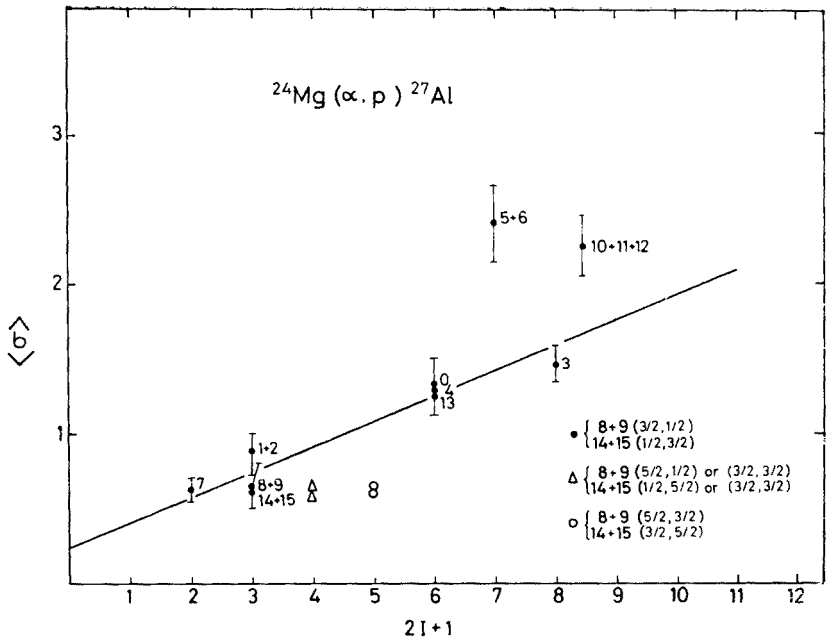

Fig. 8. Averaged cross-section for the ^{24}Mg(α, p)^{27}Al reaction in function of $(2I+1)$. Numbers indicate different residual nucleus levels according to Table II

agreement with the $(2I+1)$ rule. The pronounced disagreement with the $(2I+1)$ rule observed for the groups of levels $5+6$ and $10+11+12$ may be caused by a possible large contribution of a mechanism other than the compound nucleus formation. It should be pointed out that the levels 6th and 11th have the largest spins of the levels of interest.

5. *Discussion and conclusions*

The purpose of our work was to investigate the statistical and non-statistical effects in the reactions ^{24}Mg(α, α) ^{24}Mg and ^{24}Mg(α, p) ^{27}Al in the energy range of alpha particles from 23.05 MeV to 28.55 MeV. The measured excitation functions exhibit a fluctuating character of the cross-section data.

The "direct interaction" contribution to the investigated reactions was calculated for all resolved levels of the ^{24}Mg and ^{27}Al residual nuclei on the basis of the Ericson theory. In the investigated energy range the values of y_D obtained for the ^{24}Mg(α, α) ^{24}Mg reaction are consistent with other results [2, 3]. The "direct interaction" dominates in the alpha particle scattering to the ground and first excited state of ^{24}Mg. The compound nucleus formation plays a significant role only at backward angles. Scattering to the 5.24 MeV and 6.01 MeV states proceeds mainly through the compound nucleus formation. The "direct interaction" contribution to the ^{24}Mg(α, p) ^{27}Al reaction strongly depends on the scattering angle.

The large y_D values indicate that the effects slowly varying with energy, which damp fluctuations in the excitation functions, dominate in the reaction studied. These effects

may be caused not only by direct interaction but also by other processes slowly varying with energy.

The observed final state spin dependence of the cross-section averaged over the whole energy range and summed over two backward angles is in fairly good agreement with the predictions of the statistical model of the compound nucleus reactions.

Cross-correlation coefficients calculated for all possible pairs of excitation curves do not indicate the existence of the isolated resonances common to all investigated channels. There are, however, other possible explanations of the lack of correlation, e. g. the existence of doorway states with $\frac{\Gamma_d^{\uparrow}+\Gamma_d^{\downarrow}}{D_d} \geqslant 1$ [23] in the energy region under investigation or a strong channel dependence of the intermediate resonances.

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