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STUDY OF THE Si^{28} (n, α) REACTION AND EXPERIMENTAL EVIDENCE OF THE ERICSON FLUCTUATIONS

by

L. COLLI, V. FACCHINI
I. IORI, M. G. MARCAZZAN
M. MILAZZO, E. SAETTA MENICHELLA
F. TONOLINI

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Study of the Si^{28} (n, α) reaction and experimental evidence of the Ericson fluctuations

L. Colli*+, U. Facchini*+, I. Iori*, M. G. Marcazzan*,
M. Milazzo+, E. Saetta Menichella*, F. Tonolini*

**Laboratori CISE - Segrate (Milano)*
+*Istituto di Fisica dell'Università - Milano*

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Study of the Si^{28} (n, α) reaction and experimental evidence of the Ericson fluctuations (*)

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M. Milazzo +, E. Saetta Menichella*, F. Tonolini*
* *Laboratori CISE - Segrate (Milano)*
\+ *Istituto di Fisica dell'Università - Milano*

1. INTRODUCTION

The study of n, α reactions for medium nuclei ($20 < A < 60$) is particularly interesting in connection with the understanding of the evaporative emission.

In some recent works [1, 2] it has been shown that a large group of reactions produced by ~ 14 MeV energy neutrons, such as n, n' and n, p can be fairly well framed into the model of statistical emission [3, 4].

The n, α reactions at 14 MeV have not been experimentally studied very much. A number of works by Kumabe and coworkers give the spectra and the angular distribution of α particles emitted, for few nuclei in the region from Al to Co [5].

More recently, Patzk and Vonach [6] and Bizzeti and co-workers [7] have studied Na, Al, and Co with various methods and have reported results in reasonable agreement with what may be expected from the evaporative model. There exist also a few measurements of n, α reactions cross sections but an accurate analysis of the situation is still lacking.

Recent results obtained by studying the n, α spectrum of Si with 14 MeV neutrons [8] by means of silicon semiconductor detectors have shown that it is possible, in the α spectrum, to separate a few groups of particles corresponding to transitions to the ground state and to the first excited levels of the residual nucleus.

Since the excitation energy of the compound nucleus is of the order of 22 MeV its levels are strongly overlapped. On the other hand, the levels of residual nucleus are selected individually.

This situation is of particular interest in order to test the properties of the evaporation mechanism, by means of a detailed study of the cross-sections, as has been recently shown by Ericson [3, 4]. In view of that we have undertaken an experimental study of the behaviour of these cross sections in function of the incident energy of the neutrons.

The main points of the Ericson's discussion in which we are interested here are reported in what follows.

We will consider the case of a compound nucleus in which the levels are of a width Γ much greater

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(*) This work has been done in cooperation with the Nuclear Physics group of the Physics Institute of the Milan University working under the CNEN-Euratom program.

than D (overlapping levels region). Ericson shows how in this case the basic statistical laws can still be verified if the measurements are averaged over an interval of incident energy $\Delta E \gg \Gamma$.

In this case we should expect a smoothly varying behaviour of the cross sections and symmetrical angular distribution with respect to 90 degrees. On the contrary when the resolution ΔE of the incident beam is less than or of the order of Γ we should expect deviations from the basic statistic laws and particularly:

1. strong fluctuations in the cross sections with spacings of the order of Γ,
2. angular distributions no longer symmetrical with respect to 90 degrees.

These effects are due to interference of the levels of the compound nucleus and are strong when few final states are involved, whereas they are gradually washed out in the case of many final states.

In section 5 we will discuss with greater details the characteristics of the Ericson fluctuations.

The possibility of demonstrating the validity of these conclusions in the case of Si^{28} (n, α) reaction lies in being able to dispose of a resolution of the incident neutron beam ΔE that is smaller than Γ; practically we can see whether, with the smallest ΔE at our disposal, it is possible to demonstrate the presence of effects of the type described by Ericson.

Particularly successful in this respect, were the conclusions obtained by Marcazzan et al. [10] in respect of the Si^{28} (n, α) spectra, of which fig. 1 gives an example.

These authors have shown how it is possible to obtain the energy of the neutrons beam and its resolution within 1%. In this sense, the measurement itself of reaction Si^{28} (n, α) supplies a way of checking the energy definition of the neutron beam used.

2. EXPERIMENTAL MEASUREMENTS

A first run of measurements was carried out using neutrons of energy varying between 12.5 and 18.5 MeV produced by means of CISE's Van de Graaff accelerator [11] using the $d + t$ reaction with a thin tritium target and 2.2 MeV deutcrons. The detector is a surface semiconductor silicon detector

TABLE 1

Reactions	Incident energy interval (MeV)	Reference		Residual nucleus	Exct. residual nucleus (MeV)	Spin j	$\overline{\sigma}$ arbitrary units	$\frac{\overline{\sigma}}{2j+1}$ normalized (first exct. state = 1)
Si^{28} (n, α)	12.5-18.5	Present measurement	*A*	Mg^{25}	0	5/2	6558	1.26
			B	Mg^{25*}	0.58	1/2	1726	1
			C	Mg^{25*}	0.98	3/2	3073	0.89
			D	Mg^{25*}	1.61	7/2	5468	0.79
			E	Mg^{25*}	1.96	5/2	4484	0.86
			F	Mg^{25*}	2.56; 2.74; 2.80	1/2; 7/2; 3/2	9624	0.79
			G	Mg^{25*}	3.40; 3.41	9/2; 3/2	9934	0.82
Si^{28} (d, α)	5.5- 7.5	Browne [14]		Al^{26}	0	5	196	0.57
				Al^{26*}	0.229	0	31	1
				Al^{26*}	0.418	3	197	0.90
Al^{27} (p, α) $\vartheta_{C.M.} = 48^\circ$	9.7-11	Fischer and co. [16]		Mg^{24}	0	0	33	1.21
				Mg^{21*}	1.37	2	136	1
Al^{27} (p, α)	10.5-14.5	Ogata and co. [17]		Mg^{24}	0	0	95	1.01
				Mg^{24*}	1.37	2	470	1

of the *n-p* type placed at 10 cm from the target in such a way as to obtain ΔE of the order of 150 keV (fig. 2).

α spectra from Si (n, α) reaction were detected, by varying the energy of neutrons at interval of 500 keV.

The spectra obtained were of the type of the one in fig. 1. The neutron flux was monitored continuously with a proton recoil detector and moreover, the flux of neutrons emitted at various angles was checked by means of a proton spectrometer.

The areas of the various peaks *A, B, C, D, E, F* (see table 1) in the spectra were therefore reported as a function of the energy of incident neutrons and are shown in fig. 3.

No corrections were performed for edge effects of the α particles in the detector. In operating conditions, such detector has a thickness about three times the range of the α particles and the corrections are not important as far as our discussion is concerned.

Fig. 3 shows how the relative cross sections for the various transitions are decreasing functions of the

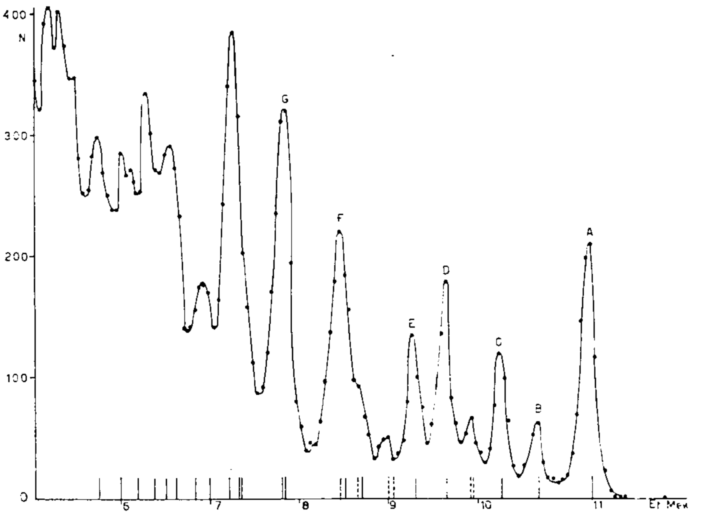

Fig. 1 - Energy spectrum of particles emitted bombarding the silicon detector with neutrons of 14 MeV. The peaks corresponding to the Si^{28} (n, α) Mg^{25} reactions and to the various levels of the residual nucleus are reported with the continuous line and are labelled with A, B, C, D, E, F, G (see table 1). Dotted lines represent peaks due to the Si^{28} (n, p) Al^{28} reaction.

Compound nucleus	Average excitation energy compound nucleus (MeV)	$\overline{\Gamma}$ experim. keV	τ experim. (average) sec	τ theor. sec
Si^{29}	20.5	150 155 195 195 210 190 155 150	$0.4 \cdot 10^{-20}$	$2 \cdot 10^{-20}$
P^{30}	18.3	75 180 120	$0.55 \cdot 10^{-20}$	$4 \cdot 10^{-20}$
Si^{28}	18	120 200	$0.4 \cdot 10^{-20}$	$16 \cdot 10^{-20}$

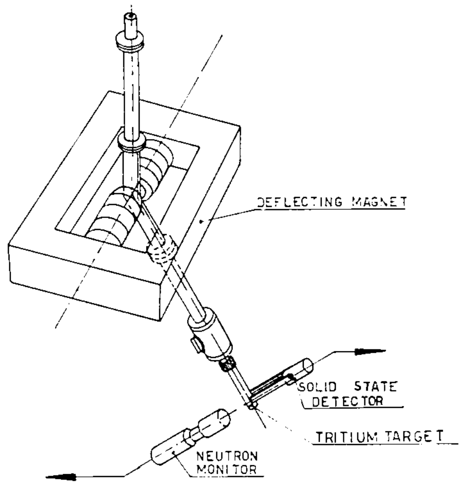

Fig. 2 - Experimental arrangement for the measurement of Si^{28} (n, α) Mg^{25} cross section as a function of neutron energy from 12.5 to 18.5 MeV.

neutrons energy and have large oscillations. These oscillations do not have a precise meaning on account of the lack of detail of the experiment. Then we have taken a more accurate measurement in a more limited energy interval. The measurement was carried out using a low energy accelerator: 80 keV and reaction $d + t$, with a thick tritium target.

Also in this case it was obtained a beam of neutrons defined by $\Delta E \sim 100$ keV (fig. 1 refers to a measurement obtained with this technique) and an energy varying between 13.5 and 14.7 MeV in the various direction of neutron emission.

The measurement was made with an experimental device similar to the previous one; much more favourable conditions of intensity are obtained than in the measurement done with the Van de Graaff accelerator.

The results of this second group of measurements are shown in fig. 4 in which appear the cross sections of the first seven groups *A*, *B*, *C*, *D*, *E*, *F*, *G* of α particles together with the sum of the seven cross sections.

It seems evident here that very marked fluctuations are present and that their spacing in energy is of the order of 150-250 keV.

Since these values are larger than the ΔE of the neutron beam, it turns out that these fluctuations have a physical meaning. A more complete measurement on all the energy range from 12 to 18.5 MeV and with better resolution is now planned.

3. OTHER RESULTS REGARDING α EMISSION

Before proceeding on a comparison of the results of figs. 3-4 with the statistical model, it seems interesting to note that in other reactions studied by different authors, fluctuations of this type were indeed observed but without any satisfactory explanation having been made for them.

A short bibliographic research has enabled us in fact to collect some results as described below, and it is interesting to proceed on a study of few of these data within the framework of the statistical model.

Reaction Al^{27} (d, α) Mg^{25}.

Sheline and coworkers [12] analysed the intensities of α groups emitted at backward angles from

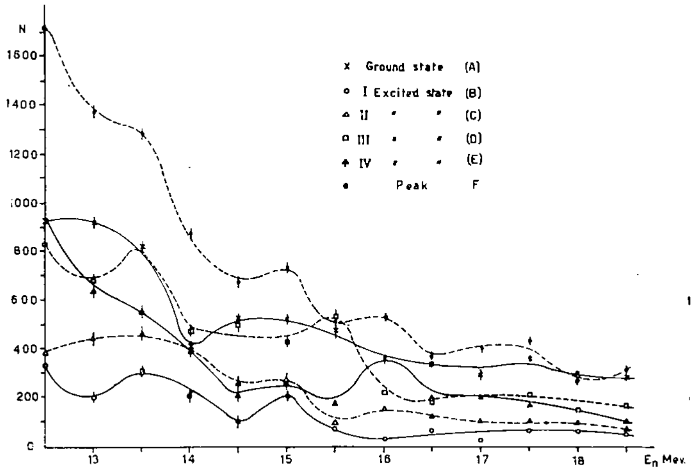

Fig. 3 - Cross sections in arbitrary units vs. neutron energy from 12.5 to 18.5 MeV for Si^{28} (n, α) Mg^{25} for the first six peaks. The peaks are labelled A, B, C, D, E, F.

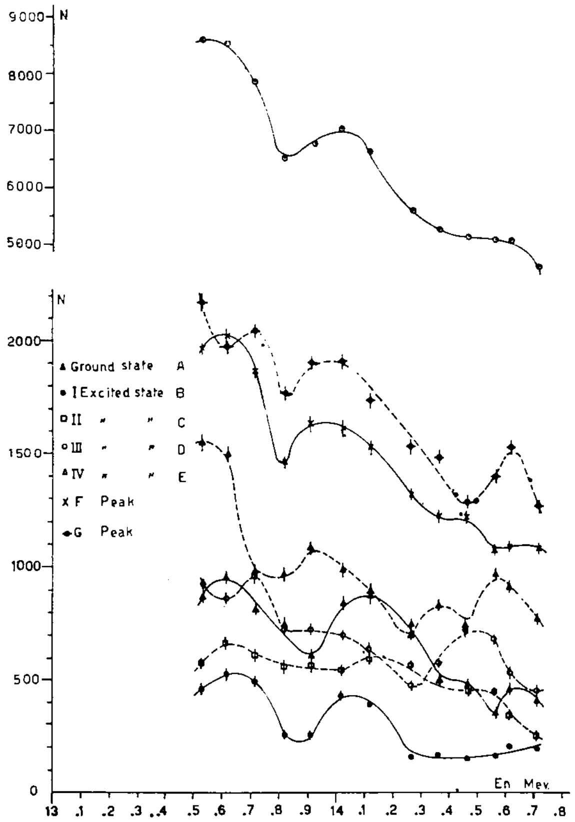

Fig. 4 - Cross sections in arbitrary units vs. neutron energy from 13.5 to 14.7 MeV for Si^{28} (n, α) Mg^{25} for seven peaks labelled A, B, C, D, E, F, G. The upper curve shows the cross sections vs. neutron energy for the A, B, C, D, E, F, G together. Statistical errors are indicated only where they are larger than the size of the points.

Al^{27} (d, α) Mg^{25} reactions for the first 12 excited levels; the intensities of these groups, corrected for the penetration factors, turn out to be proportional, within 30%, to the number of final states $2j + 1$, j being the spin of the corresponding level of Mg^{25}. The same reaction was studied by Hinds et al.[13] confirming the rule.

Reaction Si^{28} (d, α) Al^{26}.

Reference is made to the results obtained by Browne[14] for the reaction d, α on Si^{28}.

In this paper we are reporting in fig. 5 one of the figures of the Browne paper where are shown the cross sections as a function of the energy of incident deuterons from 5.5 to 7.5 MeV for transitions to the ground state and the first and second excited states. As it can be seen from fig. 5, these cross sections present strong fluctuations as a function of energy.

Reaction Ca^{40} (d, α) K^{38}.

The measurement obtained by Hashimoto and Alford[15] shows how the cross section for transitions to the ground state and to the first excited state of the K^{38} at angle $\vartheta = 30°$ presents fluctuations as a function of the deuteron energy; in this case however the fluctuations were not measured with detail and so these results have not been taken into consideration in our analysis.

Reaction Al^{27} (p, α) Mg^{24}.

The measurement obtained by G. E. Fischer and coworkers[16] is reported in fig. 6. In this case, fluctuations of the cross section as a function of the protons energy are present for the ground state and for the first excited level. The measurement has been made at an angle ϑ_{CM} of 48° and with an energy of protons varying between 9.7 and 11 MeV.

Reaction Al^{27} (p, α) Mg^{24}.

Again, for reaction p, α on aluminium, Ogata et al.[17] give the cross sections for the ground state and the first excited level of Mg^{24} as a function of energy, measuring every 100 keV and with an energy resolution of the incident protons of the order of 50 keV in the interval 10.5 to 14.5 MeV.

Ogata and coworkers report 37 angular distributions of the emitted α particles, taken at each 100 keV both for the ground state and for the first excited level. In figs. 7, 8, 9 and 10 we give these results taken from the paper of Ogata and coworkers.

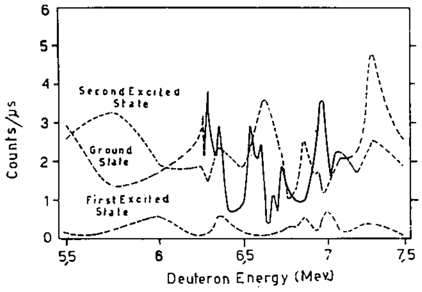

Fig. 5 - Yield curves for the Si^{28} (d, α) Al^{26} reaction. The curves are dashed in the regions where it is expected a more complex structure than that revealed by the widely spaced experimental points. Measurement of C. P. Browne[15].

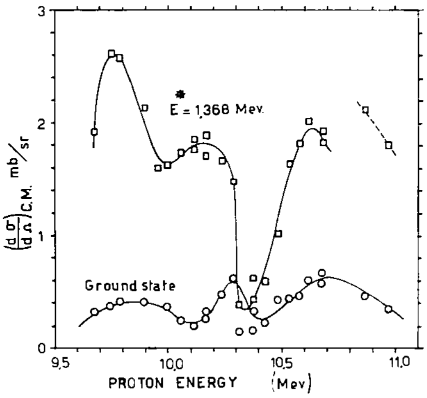

Fig. 6 - Differential cross sections for Al^{27} (p, α) Mg^{24} and Al^{27} (p, α) Mg^{24*} at $\vartheta_{CM} = 48°$ as a function of proton energy. Measurements of G. E. Fischer et al.[16].

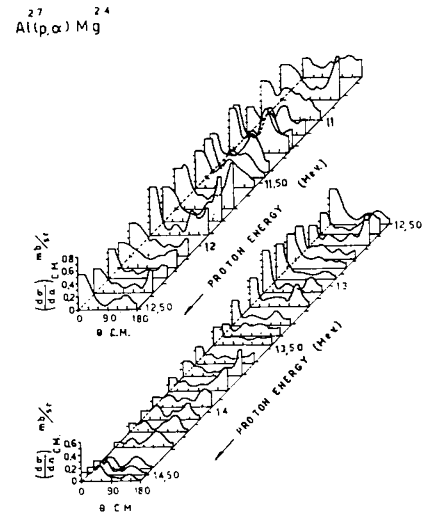

Fig. 7 - Three-dimensional view of the angular distributions for reaction Al^{27} (p, α) Mg^{24} (ground state) as a function of the incident proton energy and the C. M. angle. Measurements o H. Ogata et al.[17].

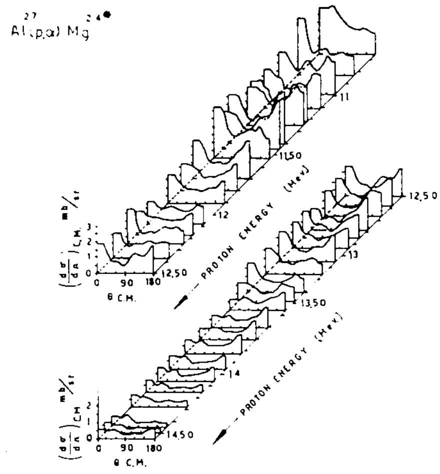

Fig 8 - Three-dimensional view of the angular distribution for the reaction Al^{27}(p, α) Mg^{24*} (first excited state) as a function of the incident protons energy and the C. M. angle. Measurements of H. Ogata et al. [17].

Other authors report various « irregularities » in reactions in which occur emissions of protons and, in particular, fluctuations in the shape of angular distributions in reaction p, p' on nuclei of Mg, Si, S, A, Ni^{58}, Ni^{60} and fluctuations in the cross section in reaction p, p' on Si, Ni and in Ca (d, p) reaction [18, 19, 20, 21, 22, 23].

We have not analysed these data because they are often presented with insufficient detail for our purposes, for example at intervals of 500 keV or greater. Moreover, in these reactions the presence of possible intense direct effects complicates the description of the phenomenon because of interference between these effects and the statistical effects.

4. ANALYSIS OF THE (n, α) (p, α) and (d, α) REACTIONS FOR $\Delta E \gg \Gamma$

a) In all the reactions shown in table 1 the excitation

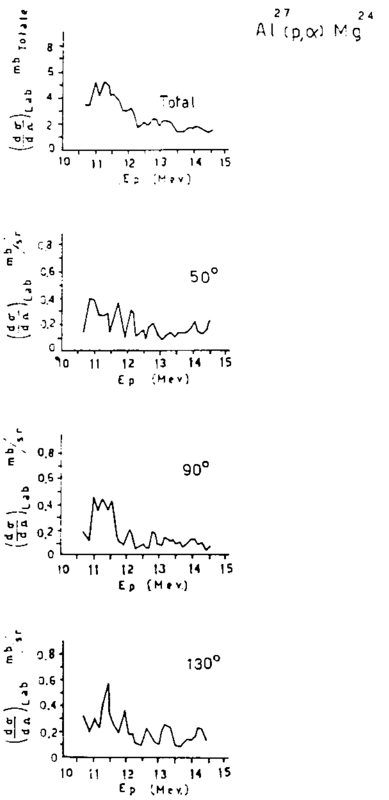

Fig. 9 - Differential cross sections at laboratory angles of 50°, 90° and 130° and the total cross sections for the ground state from Al^{27}(p, α) Mg^{24} of Ogata and coworkers [17], as a function of the incident protons energy.

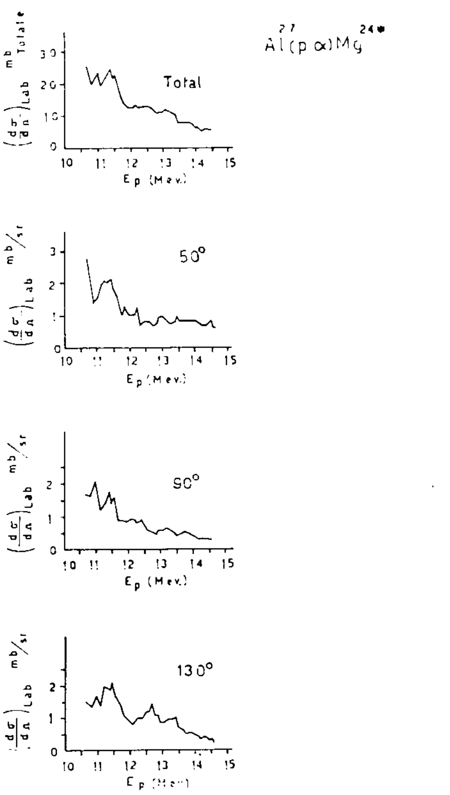

Fig. 10 - Differential cross sections at laboratory angles of 50° 90° and 130° and the total cross sections for the first excited level for the reaction Al^{27}(p, α) Mg^{24*} (first excited state) of Ogata and coworkers [17] as a function of the incident protons energy.

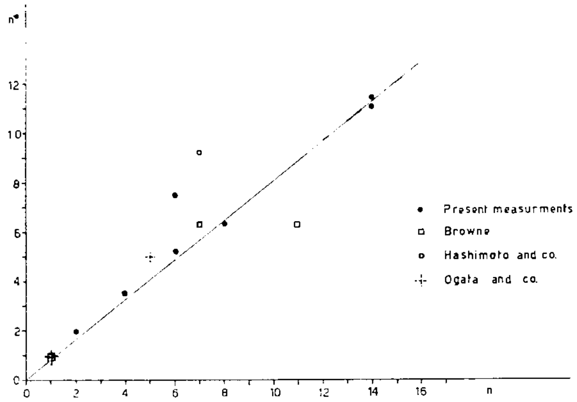

Fig. 11 - Averaged cross sections for various reactions divided by 2j + 1 and normalized for the transitions to the first excited states versus 2j + 1.

energy of the compound nucleus is such that overlapping levels condition exist. It is interesting to check, following Ericson, the validity of the statistical model studying the behaviour for very large ΔE intervals. At this aim, we have considered values of ΔE generally above 1 MeV, which will be specified further on.

The most interesting fact that came out of the study of averaged σ is the validity for all these reactions of the law, according to which, once a particular reaction has been fixed, and varying the final states of the residual nucleus, $\overline{\sigma}$ turns out to be proportional to $2j + 1$ where j is the spin of the residual nucleus itself.

It is interesting to note that this law is better fitted when ΔE is large. For this purpose one may well compare in table 1 the particularly good agreement existing, for example, in the case of reaction Si^{28} (n, α) of fig. 3, ΔE being $\sim$ 6 MeV from 12.5 to 18.5 MeV, and in the case of reaction Al^{27} (p, α) of Ogata and coworkers, ΔE being 4 MeV from 10.5 to 14.5 MeV.

Fig. 11 gathers all the data referring to the various reactions of table 1 each normalized at the first excited level. We have chosen this normalization because often the ground state could be affected to a greater extent by direct effects.

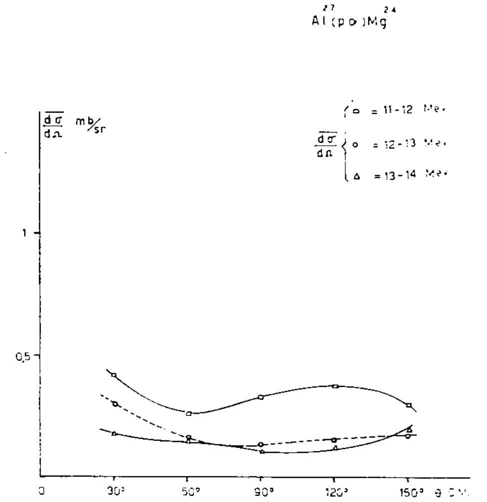

Fig. 12 - Angular distribution in C. M. system from fig. 7 averaged over 1 MeV interval for Al^{27} (p, α) Mg^{24} reaction (ground state) in three intervals between 11 and 14 MeV.

b) The proportionality of $\overline{\sigma}$ to $2j + 1$ is connected with the validity of the statistical model.

An interesting fact is that the law holds better the greater ΔE is, that is when we average on more and more states of the compound nucleus.

We can moreover recall Sheline and coworkers' [12] observation that the law does not apply in forward angles for reaction Al^{27} (d, α) and conclude that

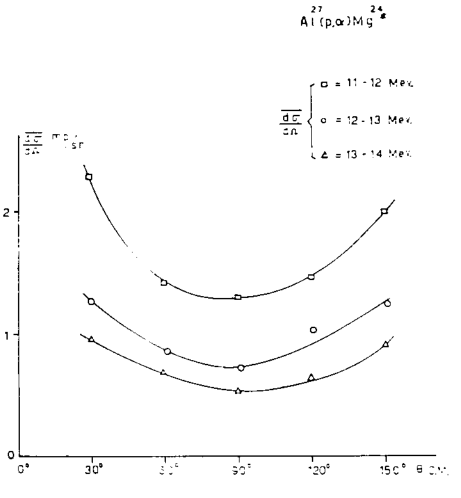

Fig. 13 - Angular distribution in C. M. system from fig. 8 averaged from 1 MeV for Al^{27} (p, α) Mg^{24} (first excited state) in three intervals between 11 and 14 MeV.

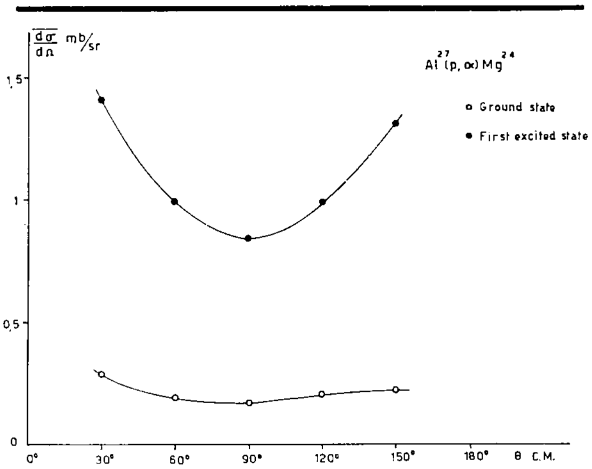

Fig. 14 - Angular distributions for ground state and first excited level of Al^{27} (p, α) Mg^{24} reaction from figs. 7 and 8 averaged over 11-14.5 MeV interval.

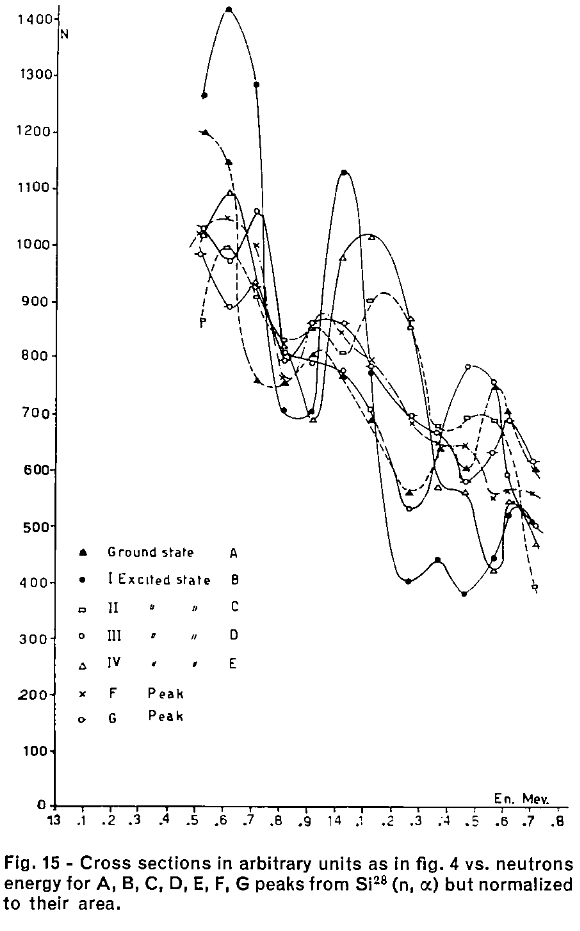

Fig. 15 - Cross sections in arbitrary units as in fig. 4 vs. neutrons energy for A, B, C, D, E, F, G peaks from Si^{28} (n, α) but normalized to their area.

there is a general evidence of the validity of the statistical emission in these reactions.

As far as concerns reactions Si^{28} (n, α) studied in this paper, we can recall in support of the statistical emission what has been said in the introduction, i. e. that reactions n, p and n, n' in medium weight nuclei proceed at ~ 14 MeV by a statistical way. According to the data of P. G. Bizzeti and coworkers [7] and Patzk and Vonach [6] even reactions n, α on medium nuclei proceed in accordance with this mechanism.

Furthermore, the fact illustrated in fig. 3 that the $\overline{\sigma}$ of the particular levels decrease with increasing incident energy, is in agreement with predictions of the statistical model inasmuch as the increase in energy opens other outgoing channels which enter in competition with the α emission.

A similar behaviour corresponding to evaporation emission was observed by Kumabe for reaction Cr^{54} (p, α) [24].

Another interesting proof of the statistical emission is offered by a study of Ogata and coworkers' paper [17].

As mentioned in section 3, Ogata has obtained a series of angular distributions in reaction Al (p, α) which are shown in figs. 7 and 8.

Having a shape variable with energy, each of these angular distributions is not symmetrical with respect to 90° but present maxima now at forward angles or at other angles.

We have considered the angular distributions averaged over intervals of 1 MeV both for the ground state and the first excited level and they are reported in figs. 12 and 13. Fig. 14 then shows the average over all the interval studied from 11 to 14.5 MeV.

It turns out that the angular distributions are practically symmetrical for the first excited level and nearly isotropical for the ground state transitions.

5. THE ERICSON FLUCTUATIONS

Since the reactions studied here can be adequately explained with the statistical emission, it is interesting to study them with respect to Ericson's theory when $\Delta E < \Gamma$. For this purpose, we will consider the experimental measurements represented in fig. 4 for Si^{28} (n, α) and in figs. 5, 6 for reactions Si^{28} (d, α) and Al^{27} (p, α), which have been obtained with an energy resolution of the incident beams of the order of 20-100 keV.

Ericson's fundamental observation is that the cross sections of the various transitions to final states should present strong fluctuations whenever the number of final states is small.

Figs. 4 for Si^{28} (n, α), 5 for Si^{28} (d, α), 6 for Al^{27} (p, α) and 9 and 10 for Al^{27} (p, α) show clearly, as it has already been said, the existence of these fluctuations.

We shall now see how their properties are in agreement with Ericson's predictions.

First of all, these fluctuations should not be correlated among themselves when compared as a function of the incident energy.

This fact is illustrated in fig. 4 for Si^{28} (n, α); fig. 15 shows the same curves of fig. 4 normalized to their area, for higher evidence. For the other measurements, figs. 5, 6 show, by themselves, the non-correlation between the maxima and minima of the fluctuations for the various final states.

The width of these fluctuations should correspond to the width of the compound nucleus levels. This width depends on the particular condition of excitation in which the compound nucleus is formed: excitation energy and angular momenta, but is independent from the particular outgoing channel. An accurate experimental measurement of Γ is not possible in view of the insufficience of the experimental data.

The mean values of Γ for the various cases, derived empirically taking the half width of the more salient fluctuations gathered in table 1, turn out to be in good agreement for the various outgoing channels in the various reactions.

We have to recall that these values are in fact not much greater than the energy resolution ΔE of the incident particles. In this respect more accurate experiments are needed.

The amplitude of fluctuations should be, according to Ericson, inversely proportional to the square root of the number n of final states.

For the fluctuations amplitude Ericson[9] gives a formula according to which

$$\overline{(\sigma - \bar{\sigma})^2} = \frac{2\,\bar{\sigma}^2}{n} \qquad (1)$$

$\bar{\sigma}$ being the mean value of the cross section on a large energy interval, $\sqrt{\overline{(\sigma - \bar{\sigma})^2}}$ is the root mean square deviation of the cross section, and n the number of the final states.

TABLE 2

Reactions	Incident energy	Reference	Residual nucleus	n	$\frac{1}{\sqrt{n}}$	$\sqrt{\frac{\overline{(\sigma - \bar{\sigma})^2}}{2\,\bar{\sigma}^2}}$
Si^{28} (n, α)	13.5-14.7	Present measurements	Mg^{25}	6	0.41	0.17 (*)
		fig. 4		2	0.70	0.33
				4	0.50	0.15
				8	0.35	0.16
				8	0.41	0.21
				14	0.26	0.16
				14	0.26	0.11
Si^{28} (d, α)	5.5- 7.5	Browne[14]	Al^{26}	11	0.3	0.34
		fig. 5		1	1	0.45
				7	0.38	0.26
Al^{27} (p, α)	9.7-11	Fischer and co.[16]	Mg^{24}	1	1	0.24
		fig. 6		5	0.45	0.26

(*) These values have been obtained assuming $\bar{\sigma}$ constant between 13.5 and 14.7 MeV. Because $\bar{\sigma}$ is a decreasing function of the neutron energy these values are overestimated.

A more involved discussion, conducted by Ericson himself (see ref. 4, § 11.2), leads one to expect the fluctuations of σ to be lower than $\pm \sqrt{\frac{2}{n}}$ when many values of angular momenta are involved both in the ingoing and outgoing channels.

Due to these effects the amplitude of the fluctuations should depend both on the entrance channel (energy of the incoming particle and spin of the target nucleus) and on the outgoing channel which contains the final states. In table 2 we report the experimental values of $\sqrt{\frac{\overline{(\sigma-\bar{\sigma})^2}}{2\bar{\sigma}^2}}$ and compare it with $\frac{1}{\sqrt{n}}$.

In absence of a more exact description we have, as a first approximation, assumed $n = 2j + 1$ where j is the spin of the residual nucleus ($n = \sum_k (2j_K + 1)$ when many levels are measured together).

The orders of magnitude of the two quantities are in agreement; let us recall that $\frac{1}{\sqrt{n}}$ represent a maximum possible value of the fluctuations.

It is interesting to recall the conclusions obtained by Ericson with regard to the angular distributions and their behaviour. Using the formulation developed by Blatt and Biedenharn [25], Ericson expresses $\sigma(\vartheta)$ by means of the formula

$$\frac{d\sigma_{\alpha\alpha'}}{d\Omega} \sim \Sigma_L B_L(\alpha' s';\ \alpha s)\, P_L(\cos\vartheta), \qquad (2)$$

where B_L are suitable coefficients that contain, among others, the reaction matrix elements and $P_L(\cos\vartheta)$ are Legendre polynomials. He shows that B_L should present fluctuations according to the formulae:

$$\begin{aligned} B_L &= \bar{B}_L \left(1 \pm \frac{1}{\sqrt{n}}\right) && \text{for } L \text{ even} \\ B_L &= \pm \bar{B}_{L\pm1} \frac{1}{\sqrt{n}} && \text{for } L \text{ odd} \end{aligned} \qquad (3)$$

The coefficients B_L for even L and odd L should be considered not correlated among themselves as a function of the incident energy; however, coefficients B_L of the same parity but with different L can be, at least in part, correlated.

The contribute in $\sigma(\vartheta)$ of an increasing number of B_L terms of different parities reduces the $\sigma(\vartheta)$ fluctuations. On the other hand, if few B_L terms intervene and are correlated among themselves, the fluctuations of the $\sigma(\vartheta)$ approach the ones given by the formula (1).

Conjointly with these behaviours we should expect angular distribution shape changing with incident energies.

It is interesting to compare qualitatively these predictions with the results of Ogata and coworkers [17] who give the angular distributions at various energies of the incident protons (figs. 7 and 8) and correspondently the cross sections at given angles as a function of the energy of incident protons (figs. 9 and 10).

What appears qualitatively is that the angular distributions vary in shape but not-always abruptly with varying E_p.

On the whole, it may be concluded that these behaviours are in qualitative agreement with Ericson's conclusions and that a more detailed analysis of these may give interesting results.

Particularly a complete analysis of these results could be made, obtaining the B_L coefficients from the various curves and studying their properties.

6. THE COMPOUND NUCLEUS LIFE TIME

According to the conclusion illustrated in the preceding paragraphs, on the basis of which the statistical model may explain on the whole the reactions (n, α), (p, α) and (d, α) illustrated, the width Γ in table 1 turns out to be the level widths of the compound nuclei involved in the various reactions.

These Γ correspond to a mean life time τ of the compound nuclei of the order of $0.4\text{-}1 \cdot 10^{-20}$ s.

It is interesting now to compare these experimental τ values with what foreseen by statistical evaporation theory.

The statistical model enables us to calculate the mean life time of the compound nucleus by means of the formula of the detailed balance given as follows:

$$\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_p}$$

$$\frac{1}{\tau} = \frac{4\pi}{h^3} g\, 2\, M \,.$$

$$\cdot \left[\frac{\int_0^{\varepsilon_{n\,max}} \sigma_{in}\, \varepsilon_n\, \varrho_n (E - \varepsilon_n)\, \mathrm{d}\varepsilon_n}{\varrho_c (E)} + \right.$$

$$\left. + \frac{\int_0^{\varepsilon_{p\,max}} \sigma_{ip}\, \varepsilon_p\, \varrho_p (E - \varepsilon_p)\, \mathrm{d}\varepsilon_p}{\varrho_c (E)} \right]$$

In this formula ϱ_n and ϱ_p represent the level densities of residual nuclei respectively when neutrons or protons are emitted, $\varrho_c(E)$ is the level density of the compound nucleus, E is the excitation energy and ε_n and ε_p the emission energies. σ_{in} and σ_{ip} are the inverse cross sections, g and M the spin and the mass factors [4].

It is possible to see easily how in the nucleus of Si^{29} the term relative to the emission of neutrons is about twice the one relative to the emission of protons [2], while in the nuclei of P^{30} and Si^{28} the emission of neutrons is much reduced on account of the high binding energy of the neutron itself, while the emission of protons is dominant by a factor of ~ 10. In all these cases the emission of α is not appreciable. We can therefore approximate, considering:

For Si^{29} $\tau = 2/3\ \tau_n$
P^{30} $\tau = \tau_p$
Si^{28} $\tau = \tau_p$

The calculation of these mean life times requires knowledge of the values of the level density $\varrho_c(E)$ of the compound nucleus at 18-22 MeV excitation and for the various residual nuclei at up to 10 MeV excitations. A correct calculation should take into account the various values of the spin I at which it is possible to excite the compound nucleus and the various values of j which the residual nuclei can assume.

The terms $\sigma_i\, \varrho (E - \varepsilon)$ and $\varrho_c(E)$ should be represented by more complicated sums containing terms corresponding to the various angular momenta.

Due to these considerations the values of τ at a given excitation energy should depend on the entrance channel: energy of the incoming particle and spin of the target nucleus.

Different values of τ will be obtained for a given compound nucleus when (d, α) or (n, α) reactions are considered.

We have not taken into consideration the problem of angular momenta and in a first rough approximation we have assumed that the level densities are expressed simply by the term

$$\frac{e^{2\sqrt{aU}}}{U^2}$$

respectively for the compound and residual nuclei. The values of the parameters a are given in ref. 2 and U are the effective excitation energies.

The extrapolation of the level density of the compound nucleus up to 18-22 MeV is very uncertain. In fact, the work of Erba, Facchini and Saetta Menichella [2] gives ϱ values up to excitations of 10-12 MeV. It should be noted that the value of τ is very sensitive to the particular values of parameter a. For instance changing one of the a values appearing in formula (2) either in the ϱ_n, ϱ_p or in the ϱ_c, from 4 to 4.5 affects the values of τ by a factor of 3.

The a values given by Erba, Facchini and Saetta Menichella [2] for nuclei with $A \sim 30$ vary between 4 and 5.5 MeV^{-1} differing from one nucleus to another.

We have selected the value of $a = 4.5$ MeV^{-1} which turned out to be a good average of these values.

The values of τ so obtained are reported in table 1 and turn out to be somewhat greater than the experimental ones.

The agreement is however satisfactory, taking into account all the uncertainties of these calculations. It is noted that the measurements of the cross sections with slow neutrons in the study of resonances give direct values of the widths Γ of nuclei of $A \sim 30$ at excitation energies of the order of 7-8 MeV. These widths turn out to be of the order of a few keV [29].

7. CONCLUSIONS

The reaction Si^{28} (n, α) studied by us and the reactions Si^{28} (d, α) and Al^{27} (p, α) analysed when individual final states are considered, can be adequately explained by the statistical model and particularly:
— their behaviour averaged over intervals $\Delta E > \Gamma$ follows with good approximation basic laws given by this model; individual transition follow the $2j + 1$ rule and averaged angular distributions are symmetrical in respect to 90° degrees;
— their behaviour when ΔE is 20-100 keV presents properties that are well explained within the framework given by Ericson, and in particular the cross sections present strong fluctuations with the predicted properties.
— the mean life time of the compound nucleus at 18-22 MeV excitation is experimentally determined, from the three reactions studied, being of the order of $0.4\text{-}1 \cdot 10^{-20}$ s. ■

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riassunto

STUDIO DELLA REAZIONE Si^{28} (n, α) Mg^{25} ED EVIDENZA SPERIMENTALE DELLE FLUTTUAZIONI « ERICSON »

Sono state misurate le sezioni d'urto della reazione Si^{28} (n, α) Mg^{25} per le transizioni allo stato fondamentale ed ai primi stati eccitati del nucleo residuo in funzione dell'energia dei neutroni incidenti.
La misura è stata condotta con l'acceleratore Van de Graaff del CISE e con un acceleratore di 80 keV per energie di neutroni incidenti comprese fra 12,5 e 18,5 MeV con risoluzione energetica del fascio incidente di ~ 100 keV; le reazioni n, α erano prodotte in un rivelatore a semiconduttore al silicio usato come bersaglio e rivelatore.
Le misure così ottenute sono state analizzate in termini della teoria del nucleo composto recentemente sviluppata da T. Ericson.
L'analisi è stata condotta anche sulle reazioni Al^{27} (p, α) e Si^{28} (d, α) per le quali l'energia di eccitazione del nucleo composto sia tale da interessare la regione dei « livelli sovrapposti ».