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Non-statistical structures in $^{12}C(^{15}N, ^{4}He)^{23}Na$ reaction

R SINGH
Physics Department, North-Eastern Hill University, Shillong 793003, India

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Abstract. The data on the $\theta_{lab} = 7^{\circ}$ excitation functions of $^{12}C(^{15}N, ^{4}He)^{23}Na$ reaction between $E_{cm} = 9{\cdot}42$ and 17·33 MeV for 28 states upto an excitation energy of 8·940 MeV in ^{23}Na have been subjected to statistical analysis. In addition to statistical fluctuations, the results of the analysis indicate the existence of non-statistical structures at $E_{cm} =$ 10·66, 10·93, 11·38, 12·62, 13·16, 15·32 and 16·18 MeV.

Keywords. Statistical analysis; Hauser-Feshbach cross-sections; probability distributions; deviation function; correlation function; coherence widths.

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1. Introduction

Pronounced resonant effects have been observed in many light heavy-ion reactions involving α-conjugate nuclei (see papers in Cindro 1978, 1981, for example). The resonant effects are particularly marked for $^{12}C + ^{12}C$ (Macgregor *et al* 1968; Cosman *et al* 1973; Van Bibber *et al* 1974; Voit *et al* 1974), $^{12}C + ^{16}O$ (Macgregor *et al* 1969; Viggars *et al* 1976; Brady *et al* 1977) and $^{16}O + ^{16}O$ (Siemssen *et al* 1967; Maher *et al* 1969; Shaw Jr *et al* 1969; Gay *et al* 1986) systems. The scattering and reactions involving combinations of non-α-conjugate even-even nuclei such as $^{14}C + ^{14}C$ (Konnerth *et al* 1980; Drake *et al* 1981), and other even-even nuclei like $^{14}C + ^{12}C$ (Freeman *et al* 1980, 1981; Konnerth *et al* 1985) and $^{14}C + ^{16}O$ (Bernhardt *et al* 1978; Kolata *et al* 1981) have also exhibited pronounced resonant and other non-statistical effects. In addition, the collisions involving combinations of non-α-conjugate (at least one partner) nuclei like $^{12}C + ^{9}Be$ (Mateja *et al* 1978; Dennis *et al* 1981), $^{12}C + ^{11}B$ (Frawly *et al* 1979), $^{10}B + ^{14}N$ (Ecuyer *et al* 1975; Marquardt *et al* 1977), $^{12}C + ^{13}C$ (Crozier and Legg 1974; Cordell *et al* 1979), $^{12}C + ^{14}N$ (Cordell *et al* 1978; Dennis and Thornton 1980), and $^{12}C + ^{15}N$ (Gomez del Campo *et al* 1977; Ortiz *et al* 1980) lead to scattering and/or reactions that also show resonant and correlated structures. Gomez del Campo *et al* (1977) reported 16 resonances in $^{12}C(^{15}N, ^{4}He)^{23}Na$ reaction over the energy range from $E_{cm} = 9{\cdot}5$ to 17·3 MeV, which were interpreted to be arising from the strong population of non-overlapping states near the yrast line in ^{27}Al compound nucleus. Further analyses of these data confirmed the existence of non-statistical structures at 10·1 and 15·4 MeV (Thornton 1980) and at 11·47, 12·4, 15·4 and 16·2 MeV (Dennis *et al* 1979). According to the most recent analysis (Ortiz *et al* 1980) of the $^{12}C(^{15}N, ^{4}He)^{23}Na$ excitation functions at $\theta_{lab} = 7^{\circ}$ there are large anomalies which are not compatible with the statistical model predictions. It was noted by these authors

that these anomalies manifest in the form of large fluctuations (resonances) having widths as large as twice or thrice the values of the coherence widths and through an abnormally large number of correlated structures (16 in number) among various excitation functions. As mentioned earlier, these resonant structures have been explained in terms of the population of high-spin states close to the yrast line in ^{27}Al compound nucleus. In view of the existing confused situation regarding the existence of resonances/non-statistical structures/anomalies (reported by Gomez del Campo *et al* (1977), Thornton (1980), Dennis *et al* (1979), and Ortiz *et al* (1980)), we have subjected a large body of experimental data (28 excitation functions) on ^{12}C(^{15}N, ^{4}He)^{23}Na reaction in the energy range from $E_{cm} = 9{\cdot}42$ to 17·33 MeV up to an excitation energy of 8·940 MeV in ^{23}Na to a detailed statistical analysis following the approach of Ericson (1963), and Brink and Stephen (1963) (for reviews see Ericson and Meyer-Kuckuk 1966; Braga Marcazzan and Milazzo Colli 1970; Richter 1974) in order to have a more definite idea of the structures observed in these excitation functions. The analysis consists of the calculations of the percentage deviations of the reduced data from unity, the Hauser-Feshbach cross-sections, the distribution of fluctuating cross-sections, energy-dependent correlation function and deviation function, and the coherence widths.

2. Analysis

2.1 *Data reduction*

The data on this reaction consist of 28 excitation functions measured at $\theta_{lab} = 7°$ in steps of 88·89 keV(c.m.) between $E_{cm} = 9{\cdot}42$ and 17·33 MeV for ^{23}Na excited states up to an excitation energy of 8·940 MeV. Self-supporting carbon foils of 5 to 11 μg/cm^2 thickness, were used for these measurements. The present data have been taken from Gomez del Campo *et al* (1978). The overall uncertainties in the cross-sections ranged from about 7–15%. Before subjecting the data to statistical analysis the variation of the mean cross-section about which the cross-section fluctuates has to be removed. This energy-dependent structure of cross-sections has been removed by taking running average $\langle d\sigma(E) \rangle$ of $d\sigma(E)$ over an energy interval of $\Delta E = 2{\cdot}13$ MeV and by dividing the individual data points by this average. In choosing this size of averaging energy interval the usual criterion of $\Gamma_{fine} \ll \Delta E \ll \Gamma_{gross}$ has been followed (Shapira *et al* 1974). Here Γ_{fine} and Γ_{gross} denote the characteristic widths of the fine and gross structures respectively in the excitation functions. It might be mentioned that averaging intervals of 2–3 MeV have been employed for such reactions (Thornton 1980). The percentage deviations of this reduced data, $x = d\sigma(E)/\langle d\sigma(E) \rangle$, from unity were then calculated for obtaining the distributions of the fluctuating experimental cross-sections (to be compared with the corresponding theoretical distributions). It is this reduced data that has been subjected to a statistical analysis.

2.2 *Hauser-Feshbach cross-sections and the distribution of cross-sections*

The theoretical cross-sections for ^{12}C(^{15}N, ^{4}He)^{23}Na reaction were calculated by the statistical model code STATIS (Stokstad 1972) which employs Hauser and Feshbach (1952) expression for evaluating energy-averaged differential cross-sections for popula-

ting the specific final states. The $n + {}^{26}Al, p + {}^{26}Mg, d + {}^{25}Mg, {}^{3}H + {}^{24}Mg$ and $^{4}He + {}^{23}Na$ exit channels were considered for calculating these cross-sections. The transmission coefficients used in these calculations were obtained by the optical model code HOP2 (Cramer 1974). The optical model and level density parameters were taken from the literature (Gomez del Campo *et al* 1975). A typical comparison of the experimental and theoretical cross-sections is given in figure 1. From this figure it can be noted that for $^{12}C(^{15}N, ^{4}He)^{23}Na(3{\cdot}848, 5/2^{-})$ and $^{12}C(^{15}N, ^{4}He)^{23}Na(3{\cdot}673, 3/2^{-})$ excitation functions there are significant "non-compound" (direct) reaction contributions.

The code STATIS (Stokstad 1972) also calculates the number of effective channels N, the quantity that determines the statistically-independent cross-sections which contribute to the total cross-section that has to be compared with the measured cross-section. The details of the evaluation of this quantity have been described by Stokstad (1972) and by Dayras *et al* (1976). We calculated the values of N for obtaining the theoretical distributions of the cross-sections.

The distribution of the fluctuating cross-sections in the absence of direct reactions is given by (Brink and Stephen 1963; Ericson and Meyer-Kuckuck 1966)

$$P(x) = N(Nx)^{N-1} \exp(-Nx)/(N-1)!, \tag{1}$$

where $x \equiv d\sigma(E)/\langle d\sigma(E)\rangle$ and N is the number of effective channels mentioned above. In the presence of the direct reaction contributions the corresponding distribution is given by (Brink and Stephen 1963)

$$P(x) = \left(\frac{N}{1-Y_d}\right)^{N} x^{N-1} \exp\left(-N\frac{x+y_d}{1-y_d}\right) \frac{I_{N-1}[2N(xy_d)^{1/2}/(1-y_d)]}{[N(xy_d)^{1/2}/(1-y_d)]^{N-1}}, \tag{2}$$

where y_d is the ratio of direct to total cross-section and I_{N-1} is the modified Bessel function of order $N-1$. The average direct reaction contribution, y_d, was estimated as follows:

$$Y_d = \left\langle \frac{\langle d\sigma(E)\rangle - d\sigma_{HF}}{\langle d\sigma(E)\rangle} \right\rangle \tag{3}$$

where $d\sigma_{HF}$ is the calculated Hauser-Feshbach cross-section, and $\langle\ \rangle$ denotes the average over the entire energy range. These values of y_d (which range between 0 and 0·60) agreed well with the ones obtained by using the normalized variances of the data and calculated number of effective channels as described by Singh *et al* (1980). A comparison of two typical experimental and theoretical distributions is shown in figure 2. From this figure it can be noted that the agreement between the experimental and theoretical distributions is not good. Similar distributions of cross-sections (not shown here) were obtained for other excitation functions. This disagreement indicates the presence of non-statistical structures in the excitation functions. Here it may be remarked that since N and Y_d are inter-related (see Sarma and Singh 1988), if N is known it is possible to determine Y_d by using equation (2) and the experimental distributions of the cross-sections (see Temmer 1964; Weidinger *et al* 1976).

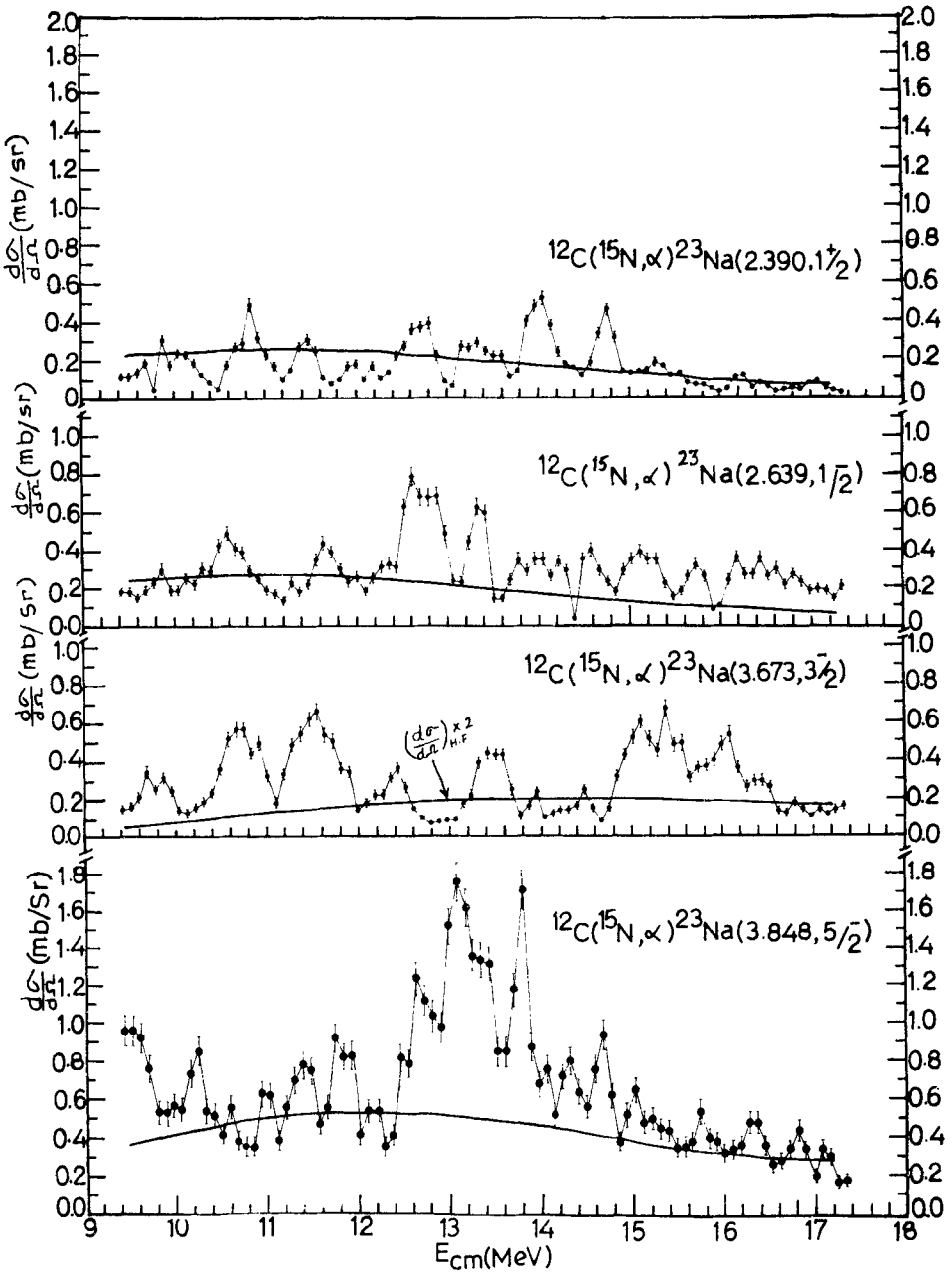

Figure 1. Experimental and theoretical (Hauser-Feshbach) cross-sections for $^{12}C(^{15}N,^{4}He)^{23}Na$ reaction for the indicated excitation functions. The theoretical cross-sections are shown by continuous lines. For the 3·673 MeV, $3/2^-$ state of ^{23}Na the calculated cross-sections have been multiplied by a factor of two for the convenience of plotting (as indicated).

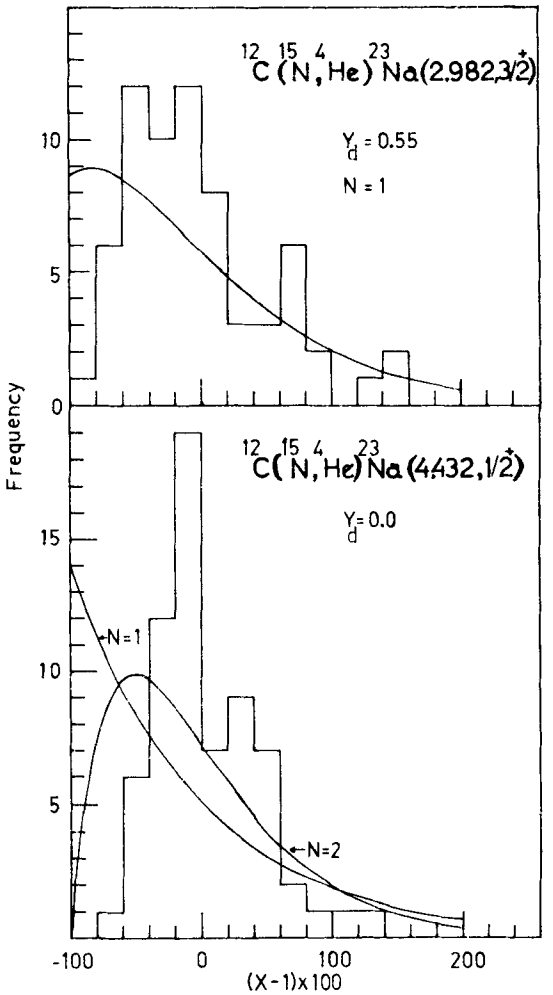

Figure 2. Experimental (histogram) and theoretical (continuous curve) distributions of the cross-sections for the indicated excitation functions of $^{12}C(^{15}N, ^{4}He)^{23}Na$ reaction. The values of Y_d and N have been indicated (see text). For 2·982, $3/2^+$ state $N = 1{\cdot}0$ and for 4·432, $1/2^+$ state N varied between 1·0 and 1·6.

2.3 *Deviation function and energy-dependent correlation function*

In order to figure out the location of non-statistical structures in a set of excitation functions it is useful to calculate the deviation function and energy-dependent correlation function as defined by Dennis *et al* (1979)

$$D(E) = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{d\sigma_i(E)}{\langle d\sigma_i(E)\rangle} - 1\right), \tag{4}$$

$$C(E) = \frac{2}{N(N-1)}\sum_{i>j=1}^{N}\left(\frac{d\sigma_i(E)}{\langle d\sigma_i(E)\rangle} - 1\right)\left(\frac{d\sigma_j(E)}{\langle d\sigma_j(E)\rangle} - 1\right)[R_i(0)R_j(0)]^{-(1/2)}, \tag{5}$$

where $d\sigma_i(E)$ is the differential cross-section at a given angle for the ith excitation at bombarding energy E and $\langle\ \rangle$ denotes an average value over energy (taken over the same ΔE as mentioned in § 2·1). The $R_i(0)$ and $R_j(0)$ are the variances of the ith and jth excitation functions. These calculations were done for all $N = 28$ excitation functions. The deviation function and the correlation function are shown in figure 3. In the same figure we also show the summed excitation function. A closer inspection of this figure reveals the existence of correlated structures at 10·66, 10·93, 11·38, 12·62, 13·16, 15·32 and 16·18 MeV which stand out quite prominently in all the three functions.

The standard deviation for $C(E)$ due to the finite range of data is given by (Pocanic *et al* 1985)

$$\sigma_c = \left(\frac{2}{N(N-1)(n-1)}\right)^{1/2}, \tag{6}$$

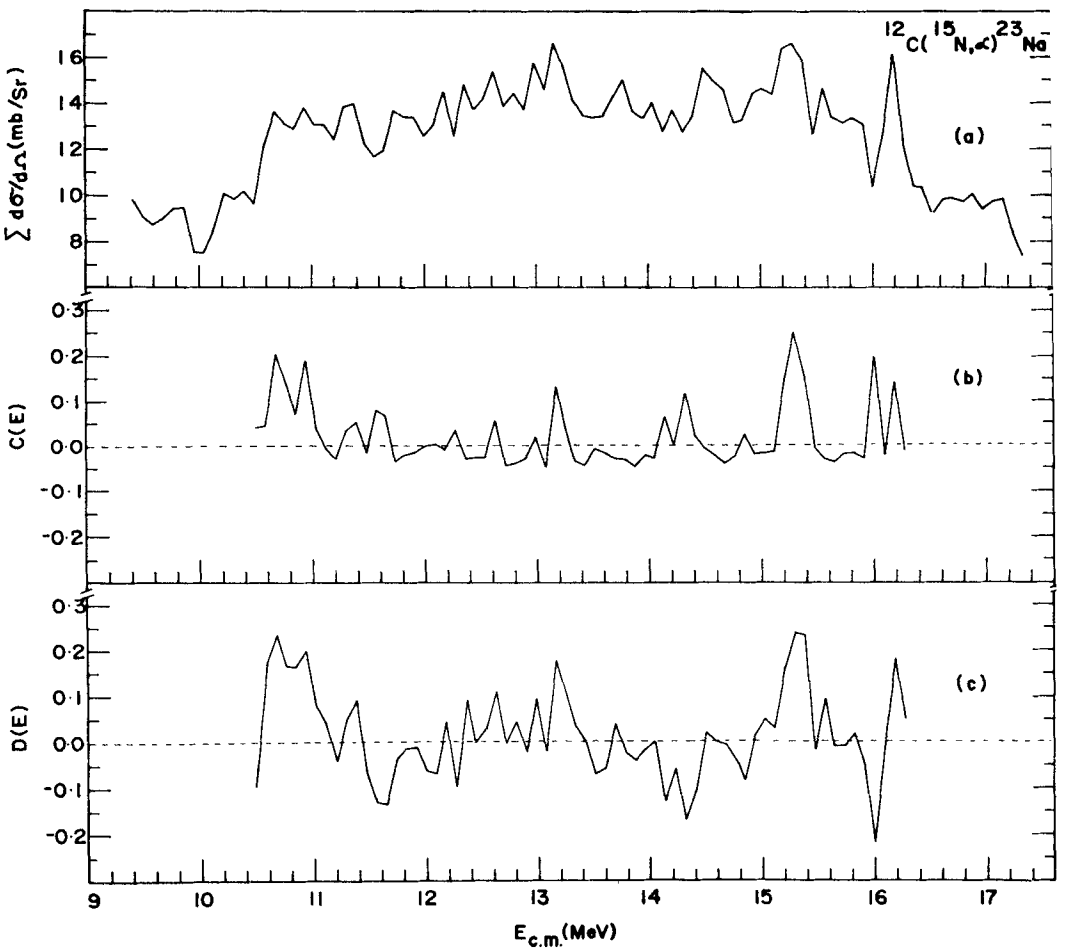

Figure 3. Deviation function, $D(E)$ (lower pannel), energy-dependent correlation function, $C(E)$ (middle pannel), and the summed excitation function (upper pannel) for $^{12}C(^{15}N, ^{4}He)^{23}Na$ reaction.

where N is the number of excitation functions and n is the number of data points in the averaging interval (used for data reduction). For the present data we have $\sigma_c = 0{\cdot}0105$. For an uncorrelated statistical ensemble, the values of $C(E)$ are expected to lie within $3\sigma_c = 0{\cdot}0315$ (Vourvopoulos *et al* 1986). Thus, as can be noted from this figure the maxima at 10·66, 10·93, 11·38, 12·62, 13·16, 15·32 and 16·18 MeV lie very well outside the statistical limit and are, therefore, of the non-statistical origin.

The non-statistical structure at 10·1 MeV reported by Thornton (1980) cannot be accounted for in our analysis because of our data reduction procedure. Instead of at 15·4 MeV (reported by Thornton (1980) and Dennis *et al* (1979)) our analysis shows a non-statistical structure at 15·32 MeV. Dennis *et al* (1979) reported non-statistical structures at 11·47, 12·4 and 16·2 MeV whereas the present analysis brings out the corresponding non-statistical structures at 11·38, 12·62 and 16·18 MeV. Noting the widths of the structures involved our results are consistent with the ones obtained by Thornton (1980) and Dennis *et al* (1979). However, we have evidence of additional non-statistical structures at 10·66, 10·93 and 13·16 MeV. There are certainly not 16 resonances/anomalies as mentioned by Gomez del Campo *et al* (1977) and Ortiz *et al* (1980). It was mentioned by Ortiz *et al* (1980) that out of the observed 16 (at E_{cm} = 10·43, 10·68, 11·00, 11·32, 11·71, 12·19, 12·71, 13·19, 13·61, 13·88, 14·26, 14·76, 15·12, 15·47, 15·97 and 16·32 MeV) correlated structures some might be purely of statistical origin. On the basis of the present analysis the ones at 10·43, 11·71, 12·19, 13·61, 13·88, 14·26, 14·76, 15·12 and 15·97 MeV appear to be so (of statistical origin).

2.4 *Coherence widths*

The coherence widths in ^{27}Al were obtained by using autocorrelation function technique, peak counting method and by making empirical estimates, and theoretical calculations. The autocorrelation functions were calculated by the usual formula (Ericson and Meyer-Kuckuk 1966)

$$R(\varepsilon) = \frac{\langle x(E)\cdot x(E+\varepsilon)\rangle}{\langle x(E)\rangle\cdot\langle x(E+\varepsilon)\rangle} - 1$$
$$= R(0)/1 + (\varepsilon/\Gamma)^2, \tag{7}$$

where ε is a variable energy interval. The autocorrelation functions for some typical excitation functions are shown in figure 4. An average value of $\Gamma = (167 \pm 37)$ keV was obtained by this technique after applying appropriate corrections due to finite range of data and finite energy resolution (Dallimore and Hall 1966; Halbert *et al* 1967; Richter 1974). In some cases it is possible to determine Γ-values for statistical and intermediate structures separately from auto-correlation analysis (see Kuhlmann *et al* 1979) but we did not attempt this study.

The coherence width was determined by the method of counting the maxima (peaks) in the excitation functions (Brink and Stephen 1963). We regarded the ith point as a maximum if $d\sigma_{i\pm2}(E) < d\sigma_{i\pm1}(E) < d\sigma_i(E)$. With this restriction in identifying the maxima, the width was obtained by counting the number of maxima M in the energy range of $(E_2 - E_1)$ MeV and employing the relation (Brink and Stephen 1963) $\Gamma \approx 0{\cdot}95(E_2 - E_1)/2M$. The factor 0·95 includes appropriate corrections for the target thickness and finite spacing of experimental points (Van der Woude 1965). We thus

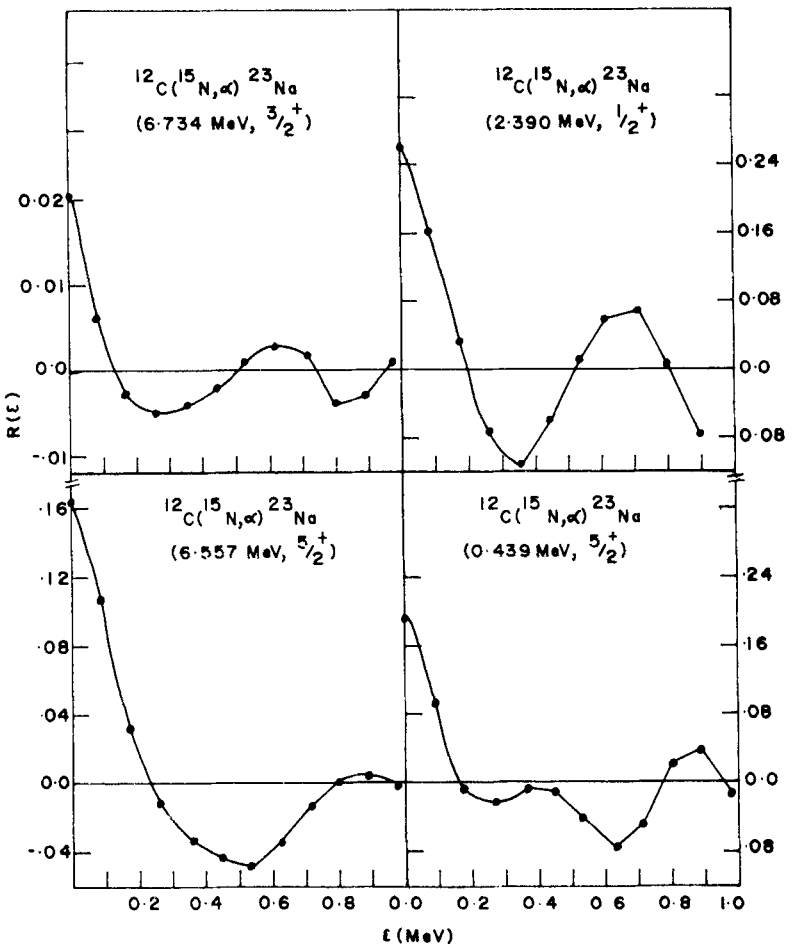

Figure 4. Autocorrelation functions for $^{12}C(^{15}N,^{4}He)^{23}Na$ excitation functions corresponding to the indicated states of ^{23}Na.

obtained an average value of $\Gamma = (286 \pm 76)$ keV after considering all the excitation functions.

Gomez del Campo *et al* (1978) obtained $\Gamma = (140 \pm 23)$ keV as the average width by peak counting method and $\Gamma = (223 \pm 118)$ keV by the autocorrelation analysis. It seems that these authors did not put as stringent a condition as we have for identification of a peak (maximum) and hence obtained such a low value by peak counting method. Since the error in the Γ-value obtained by the autocorrelation method by these authors is very large it agrees with (within errors) the Γ-values extracted by both the methods in the present analysis.

An empirical estimate of the width was also made by using the formula (Stokstad 1974)

$$\Gamma = 14 \exp[-4{\cdot}69(A/E_x)^{1/2}]\ \text{MeV}, \tag{8}$$

where A is the mass number and E_x is the excitation energy of the compound nucleus in

MeV. According to this estimate the value of Γ ranged between 125 and 223 keV (over the energy range of the excitation function).

The mean level width was also calculated by using the relation (Barrette *et al* 1979)

$$\Gamma_J(E^*) = \frac{1}{2\pi\rho_{CN}(E^*, J)} \sum_{iJ_2\pi_2 S,L} \int_0^{E^*} \rho_2(E_2, J_2, \pi_2) T_L^i(\varepsilon)\, d\varepsilon, \tag{9}$$

where $\Gamma_J(E^*)$ is the compound nucleus level width with excitation energy E^* and spin J, ρ_{CN} is the level density in the compound nucleus at excitation energy E^* with spin J, and ρ_2 the level density in the residual nucleus at an excitation energy E_2 with spin J_2 and parity π_2. The channel spin and orbital angular momentum in the exit channel i are denoted by S and L respectively. Here $T_L^i(\varepsilon)$ is the optical model transmission coefficient (assumed to be independent of spin) for ith decay channel. For calculating the values of widths this way we used the same optical model and level density parameters as employed for the calculation of Hauser-Feshbach cross-sections mentioned earlier. Thus the value of $\Gamma = 84$ keV obtained at an excitation energy of 27·3 MeV is smaller than the ones obtained by the autocorrelation method, the peak counting method and the empirical estimates. Since for a purely statistical ensemble of the data the two methods should give identical results (within errors, see Ortiz *et al* 1980), the difference in the values of Γ obtained by the autocorrelation method and the peak counting method indicates the presence of non-statistical structures in addition to the statistical fluctuations. These non-statistical structures might very well be appearing as a result of population of high-spin states close to or at the yrast line in ^{27}Al compound nucleus as pointed out by Ortiz *et al* (1980).

3. Conclusion

The disagreement between the experimental and theoretical distributions of the cross-section and difference in the values of the coherence widths obtained by autocorrelation and peak counting methods indicate the presence of non-statistical structures in $^{12}C(^{15}N,^{4}He)^{23}Na$ excitation functions. Strongly correlated structures are exhibited by the deviation function, summed excitation function, and energy-dependent correlation function at $E_{cm} = 10{\cdot}66$, 10·93, 11·38, 12·62, 13·16, 15·32 and 16·18 MeV. These maxima lie well beyond the statistical limit allowed for the correlation function, and are, therefore, of the non-statistical origin. Therefore, the additional structures at $E_{cm} = 10{\cdot}43, 11{\cdot}71, 12{\cdot}19, 13{\cdot}61, 13{\cdot}88, 14{\cdot}26, 14{\cdot}76, 15{\cdot}12$ and 15·97 MeV, reported to be correlated by Ortiz *et al* (1980), seem to be of statistical origin. Thus in addition to the statistical fluctuations the non-statistical structures are present in the excitation functions.

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