Z. Phys. A - Atomic Nuclei 329, 195–200 (1988)

Zeitschrift für Physik A
Atomic Nuclei

# Statistical Analysis of $^{24}$Mg + $^{24}$Mg Elastic and Inelastic Scattering

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Received October 15, 1987

The data on the excitation functions of $^{24}$Mg+$^{24}$Mg elastic and inelastic ($^{24}$Mg+$^{24}$Mg*($2^+$), $^{24}$Mg*($2^+$)+$^{24}$Mg*($2^+$), $^{24}$Mg+$^{24}$Mg*($4^+$), $^{24}$Mg*($4^+$)+$^{24}$Mg*($2^+$), $^{24}$Mg+$^{24}$Mg*($6^+$)) scattering from $E_{\text{c.m.}}=42$ to 56 MeV have been subjected to a statistical analysis consisting of calculations of deviation function, cross-correlation function, cross-channel correlation coefficients, coherence widths, and the distribution of cross sections. On the basis of the analysis resonant structures at $E_{\text{c.m.}}=45.70$, 46.65, 47.35 and 47.75 MeV have been confirmed. Two new resonant structures at $E_{\text{c.m.}}=44.55$ and 50.50 MeV have been identified.

**PACS:** 24.60.Dr; 25.70.Ef; 25.70.-Z

## 1. Introduction

Observation of 2–3 MeV broad structures in $^{28}$Si + $^{28}$Si elastic scattering excitation functions [1] from about 49 to 65 MeV (c.m.) at $\langle\theta_{\text{c.m.}}\rangle=80°$ and from about 47.5–72.5 MeV(c.m.) at $\langle\theta_{\text{c.m.}}\rangle=90°$ as well as of the concomitant much narrower structures has been a very exciting outcome of experimental studies involving heavy ion collisions. Similar behaviour has been displayed by the $^{28}$Si+$^{28}$Si inelastic scattering. A comparison of the squares of the Legendre polynomials with the measured elastic angular distributions at bombaring energies corresponding to the peaks of these broad structures reveals that the latter are characterised by the grazing angular momenta [2] from 34–42$\hbar$. Subsequent observation [3] of narrow structures having widths of $\sim$100–200 keV(c.m.) which were found to be correlated in the elastic and inelastic scattering excitation functions as well as in the total yield summed over all the final channels turned out to be one of the most striking phenomenon in heavy ion collisions. A quantitative analysis [3] showed that these narrow structures did not arise from the statistical fluctuations but originated from some intermediate structure resonance phenomenon. According to Betts et al. [2] these are compound system resonances in $^{56}$Ni. Certainly they must be some unusual states [4] since at an excitation energy of 64 MeV in $^{56}$Ni the density of $J=36\hbar$ states is $\sim 10^5$/MeV and of $J=40\hbar$ it is $\sim 5\times 10^3$/MeV at 70 MeV and the observed resonances stand out of such very dense continua at these extremely high excitation energies. Such sharp states of $J\approx 40\hbar$ at an excitation energy of $\sim$70 MeV represent qualitatively new aspect of nuclear structure [4]. Langanke and Stademan [5] have attempted, with some success, to explain the gross and intermediate structure in elastic scattering within the framework of Generator Coordinate Method.

Interestingly enough the collisions involving nearby heavy ion combinations, $^{28}$Si+$^{30}$Si and $^{30}$Si+$^{30}$Si, had substantially smaller total cross sections (compared to $^{28}$Si+$^{28}$Si) and exhibited no structures [6]. Similarly, $^{40}$Ca+$^{40}$Ca and $^{32}$S+$^{32}$S scattering showed no resonant behaviour [7]. On the other hand $^{24}$Mg+$^{24}$Mg elastic and inelastic scattering excitation functions between $E_{\text{c.m.}}=42$ and 50 MeV displayed very strong and narrow resonant structures with spins of about 36$\hbar$ that turned out to be about 4–6 units higher than the grazing angular momenta [8]. This is a distinctly different feature when viewed in the light of $^{28}$Si+$^{28}$Si data. Zurmuehle et al. [8] analysed the $^{24}$Mg+$^{24}$Mg correlated structures in terms of single isolated resonances whose reduced widths turned out to be similar to the ones obtained from $^{28}$Si + $^{28}$Si data. It has been particularly noted [8] that the inelastic channels are very strongly populated in the $^{24}$Mg + $^{24}$Mg collision. In fact the $^{24}$Mg + $^{24}$Mg system exhibits most striking structures which correspond to excitation energies between about 60 and 65 MeV in $^{48}$Cr compound system and still have widths of 150–220 keV only.

Apart from noting from the excitation functions that the cross section maxima at $E_{\mathrm{c.m.}} = 45.70$, 46.65, 47.25 and 47.75 MeV are correlated in several channels [8], there does not exist any quantitative analysis where the origin of the observed structures has been ascertained. We have subjected the data on the $^{24}$Mg + $^{24}$Mg excitation functions for elastic and inelastic scattering from $E_{\mathrm{c.m.}} = 42$–56 MeV [8] to a detailed statistical analysis following the approach of Ericson [9], and Brink and Stephen [10] in order to put the observed behaviour of these data on a quantitative footing. The analysis consists of the calculations of the deviation function, energy dependent cross-correlation function, summed excitation function, cross-channel correlation coefficients, coherence widths, and the distribution of cross sections.

## 2. Analysis

### 2.1. Data Reduction

The $^{24}$Mg + $^{24}$Mg elastic and inelastic ($^{24}$Mg + $^{24}$Mg*(2$^+$), $^{24}$Mg*(2$^+$) + $^{24}$Mg*(2$^+$), $^{24}$Mg + $^{24}$Mg*(4$^+$), $^{24}$Mg*(4$^+$) + $^{24}$Mg*(2$^+$), $^{24}$Mg + $^{24}$Mg*(6$^+$)) scattering excitation function data are from Zurmuehle et al. [8]. They were measured by using a target consisting of 12 $\mu$g/cm$^2$ of $^{24}$Mg metal on a carbon backing from $E_{\mathrm{c.m.}} = 42$ to 56 MeV in steps of 50 keV (c.m.) and averaged over an angular range $67° \leqq \theta_{\mathrm{c.m.}} \leqq 93°$. Before carrying out a statistical analysis of the data the energy dependent gross structure should be removed from the excitation functions. This is usually done by following the approach, first suggested by Papallardo [11], of dividing the experimental cross sections, $\mathrm{d}\sigma(E)$, by the running average $\langle \mathrm{d}\sigma(E) \rangle$ taken over a suitable energy interval $\Delta E_{\mathrm{c.m.}}$. The usual criterion is $\Gamma_{\mathrm{fine}} \ll \Delta E_{\mathrm{c.m.}} \ll \Gamma_{\mathrm{gross}}$ where $\Gamma_{\mathrm{fine}}$ and $\Gamma_{\mathrm{gross}}$ indicate the fine and gross structure widths respectively [12]. If the value of $C(o)$, the normalised variance of the reduced excitation function ($C(o) = \langle x^2 \rangle / \langle x \rangle^2 - 1$; $x = \mathrm{d}\sigma(E) / \langle \mathrm{d}\sigma(E) \rangle$), is plotted as a function of the averaging interval, $\Delta E_{\mathrm{c.m.}}$, one should obtain a plateau that begins when $\Delta E_{\mathrm{c.m.}}$ very well exceeds the coherence width [13]. This plateau generally ends with another rise in such a curve indicating that overaveraging is being done which is improper for such an analysis [13].

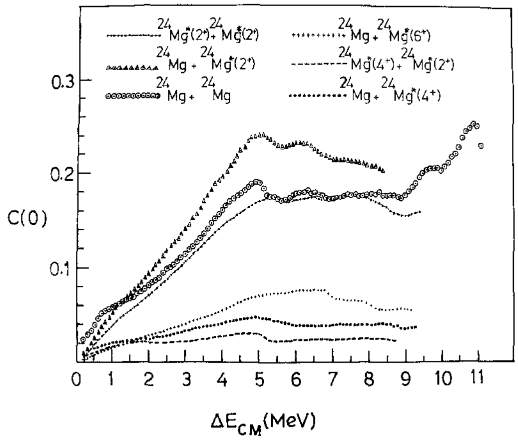

**Fig. 1.** Variation of the variance, $C(o)$, with the variation of averaging interval, $\Delta E_{\mathrm{c.m.}}$ (in MeV) for the indicated excitation functions of $^{24}$Mg + $^{24}$Mg

We have studied the behaviour of $C(o)$ as a function of $\Delta E_{\mathrm{c.m.}}$ for all the six excitation functions of $^{24}$Mg + $^{24}$Mg elastic and inelastic scattering for which the data were available [8]. Figure 1 shows all the $\Delta E_{\mathrm{c.m.}}$ versus $C(o)$ plots. All the excitation functions tend to display the plateau-type behaviour (with no real plateaus). Noting the widths of the two types (fine and gross) of structures in the excitation functions and keeping in mind the $C(o)$ versus $\Delta E_{\mathrm{c.m.}}$ behaviour we decided to choose $\Delta E_{\mathrm{c.m.}} = 1$ MeV for obtaining the trend reduced data, $x$, that has been subjected to the analysis.

### 2.2. Deviation Function and Energy Dependent Cross-Correlation Function

In order to locate the nonstatistical structures in the excitation functions it is very useful to calculate the deviation function and energy dependent cross-correlation function as defined below [14]

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

$$C(E) = \frac{2}{N(N-1)} \sum_{i>j=1}^{N} \left( \frac{\mathrm{d}\sigma_i(E)}{\langle \mathrm{d}\sigma_i(E) \rangle} - 1 \right) \cdot \left( \frac{\mathrm{d}\sigma_j(E)}{\langle \mathrm{d}\sigma_j(E) \rangle} - 1 \right) [C_i(o)\, C_j(o)]^{-1/2}, \tag{2}$$

where $\mathrm{d}\sigma_i(E)$ is the differential cross section for the $i^{\mathrm{th}}$ excitation function at bombarding energy $E$ and $\langle\,\rangle$ denotes the corresponding running average taken over an energy interval mentioned earlier. The $C_i(o)$ and $C_j(o)$ are the variances of the $i^{\mathrm{th}}$ and $j^{\mathrm{th}}$ excitation

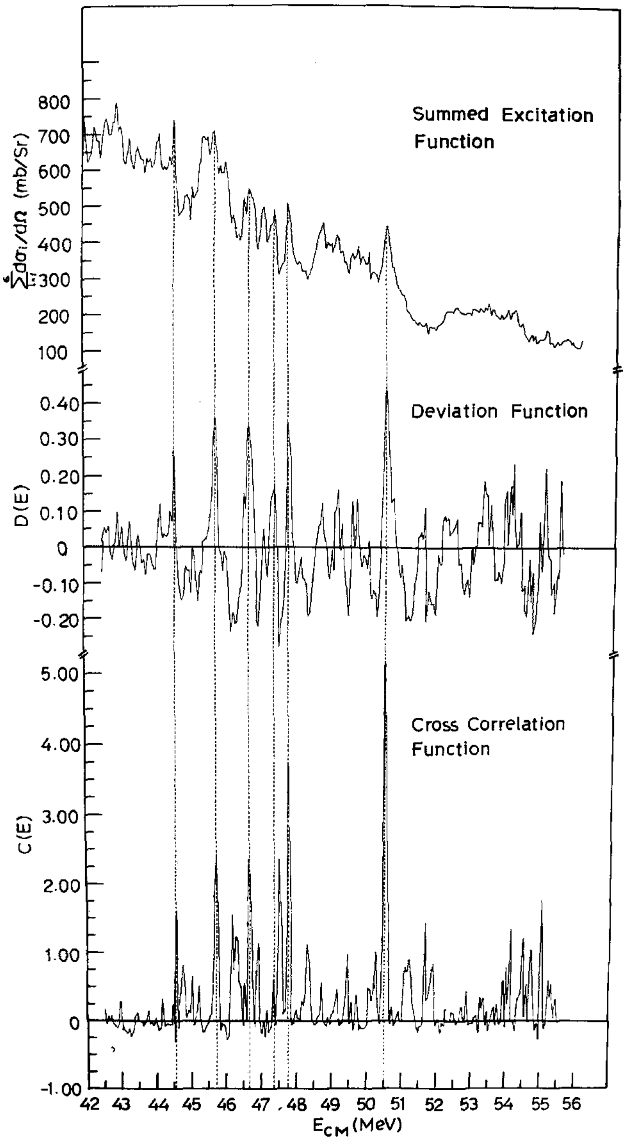

Fig. 2. Summed excitation function $\left(\sum_{i=1}^{6} \frac{d\sigma_i(E)}{d\Omega}\right)$, deviation function ($D(E)$), and the energy dependent correlation function ($C(E)$) for the $^{24}$Mg+$^{24}$Mg data. The vertical dashed lines indicate the location of the resonant structures (see text)

functions and $N$ is the total number of excitation functions. The deviation function and the correlation function are shown in Fig. 2. In the same figure is shown the summed excitation function $\left(\sum_{i=1}^{6} d\sigma_i(E)\right)$. The correlated structures at $E_{\text{c.m.}}=44.55$, 45.70, 46.65, 47.35, 47.75 and 50.50 MeV stand out clearly in all the three functions and qualify to be originating from some nonstatistical mechanism. The structures at $E_{\text{c.m.}}=44.55$ and 50.50 MeV are being reported for the first time. It may be mentioned in passing that there is an indication of another correlated structure at $E_{\text{c.m.}}=55$ MeV but it is weak in the summed excitation function as it is in the individual excitation functions.

The standard deviation for $C(E)$ due to finite range of data is given by [15]

$$\sigma_c=\left[\frac{2}{N(N-1)(n-1)}\right]^{1/2}, \tag{3}$$

where $N$ is the number of excitation functions and $n$ is the number of data points in the averaging interval. For the present data on $^{24}$Mg+$^{24}$Mg system $\sigma_c=0.058$. For an uncorrelated statistical ensemble the values of $C(E)$ are expected to be within $3\sigma_c=0.174$. Thus the above-mentioned correlated maxima are well outside the statistical limits and are, therefore, the intermediate structure resonances. Of all the one at $E_{\text{c.m.}}=50.50$ MeV is clearly the most prominent.

### 2.3. Cross-Channel Correlation Coefficients

According to the standard statistical model [9, 16] there should be no cross-correlations between different reaction channels. We calculated the cross-correlation coefficients between different channels by using

Table 1. Cross-channel correlation coefficients for $^{24}$Mg+$^{24}$Mg elastic and inelastic channels (upper half) and the coherence widths obtained from the autocorrelation analysis and peak counting method (lower half)

Cross-channel correlation coefficients

| Pair of channels | Correlation coefficient | Pair of channels | Correlation coefficient |
|---|---|---|---|
| g.s. $-(0^+,2^+)$ | $0.70\pm0.11$ | $(0^+,2^+)-(0^+,6^+)$ | $0.08\pm0.04$ |
| g.s. $-(2^+,2^+)$ | $0.48\pm0.05$ | $(2^+,2^+)-(0^+,4^+)$ | $0.47\pm0.02$ |
| g.s. $-(0^+,4^+)$ | $0.37\pm0.06$ | $(2^+,2^+)-(4^+,2^+)$ | $0.43\pm0.01$ |
| g.s. $-(4^+,2^+)$ | $0.11\pm0.03$ | $(2^+,2^+)-(0^+,6^+)$ | $0.01\pm0.02$ |
| g.s. $-(0^+,6^+)$ | $0.07\pm0.06$ | $(0^+,4^+)-(4^+,2^+)$ | $0.40\pm0.02$ |
| $(0^+,2^+)-(2^+,2^+)$ | $0.70\pm0.03$ | $(0^+,4^+)-(0^+,6^+)$ | $0.11\pm0.01$ |
| $(0^+,2^+)-(0^+,4^+)$ | $0.47\pm0.04$ | $(4^+,2^+)-(0^+,6^+)$ | $0.19\pm0.01$ |
| $(0^+,2^+)-(4^+,2^+)$ | $0.25\pm0.02$ | | |

Coherence widths

| Excitation function | $\Gamma$ (autocorrelation function) (keV) | $\Gamma$ (counting the maxima) (keV) |
|---|---|---|
| $^{24}$Mg+$^{24}$Mg | $58\pm10$ | $190\pm22$ |
| $^{24}$Mg+$^{24}$Mg*$(2^+)$ | $98\pm29$ | $214\pm27$ |
| $^{24}$Mg*$(2^+)$+$^{24}$Mg*$(2^+)$ | $83\pm24$ | $239\pm32$ |
| $^{24}$Mg+$^{24}$Mg*$(4^+)$ | $63\pm11$ | $340\pm59$ |
| $^{24}$Mg*$(4^+)$+$^{24}$Mg*$(2^+)$ | $74\pm14$ | $367\pm67$ |
| $^{24}$Mg+$^{24}$Mg*$(6^+)$ | $84\pm17$ | $204\pm25$ |

the expression [14]

$$C_{ij}=\left\langle\left(\frac{\mathrm{d}\sigma_i(E)}{\langle \mathrm{d}\sigma_i(E)\rangle}-1\right)\left(\frac{\mathrm{d}\sigma_j(E)}{\langle \mathrm{d}\sigma_j(E)\rangle}-1\right)\right\rangle \cdot [C_i(o)\, C_j(o)]^{-1/2}, \qquad (4)$$

where subscripts $i$ and $j$ denote the two particular channels in question. The cross-channel correlation coefficients thus obtained are given in Table 1. The indicated errors are due to the finite range of data. From this table it can be noted that there are rather strong correlations between different channels. For example there are large positive correlations between channels corresponding to g.s. and $0^+2^+$, g.s. and $2^+2^+$, g.s. and $0^+4^+$, gs. and $4^+2^+$, $0^+2^+$ and $2^+2^+$, $0^+2^+$ and $0^+4^+$, $0^+2^+$ and $4^+2^+$, $2^+2^+$ and $0^+4^+$, $2^+2^+$ and $4^+2^+$, $0^+4^+$ and $4^+2^+$, $0^+4^+$ and $0^+6^+$, and $4^+2^+$ and $0^+6^+$ states of $^{24}$Mg+$^{24}$Mg system. Here g.s. obviously indicates the elastic channel. Such large values of the cross-channel correlation coefficients clearly point to the non-statistical origin of the observed structures.

### 2.4. *Coherence Widths*

The coherence widths in $^{48}$Cr were obtained by the autocorrelation analysis, empirical estimates, and peak counting method. The autocorrelation function is given by [17]

$$C(\varepsilon)=\frac{\langle x(E)\cdot x(E+\varepsilon)\rangle}{\langle x(E)\rangle\cdot\langle x(E+\varepsilon)\rangle}-1 = \frac{C(o)}{(1+\varepsilon^2/\Gamma^2)}, \qquad (5)$$

where $\varepsilon$ is a variable energy interval and $\langle\,\rangle$ denotes the energy average. The autocorrelation functions for all the six excitation functions are shown in Fig. 3. The extracted values of $\Gamma$ appropriately corrected for the finite range of data effects [18] are listed in Table 1.

The coherence widths were estimated using the empirical relation [19]

$$\Gamma=14\exp(-4.69\sqrt{A/E_x})\ \mathrm{MeV}, \qquad (6)$$

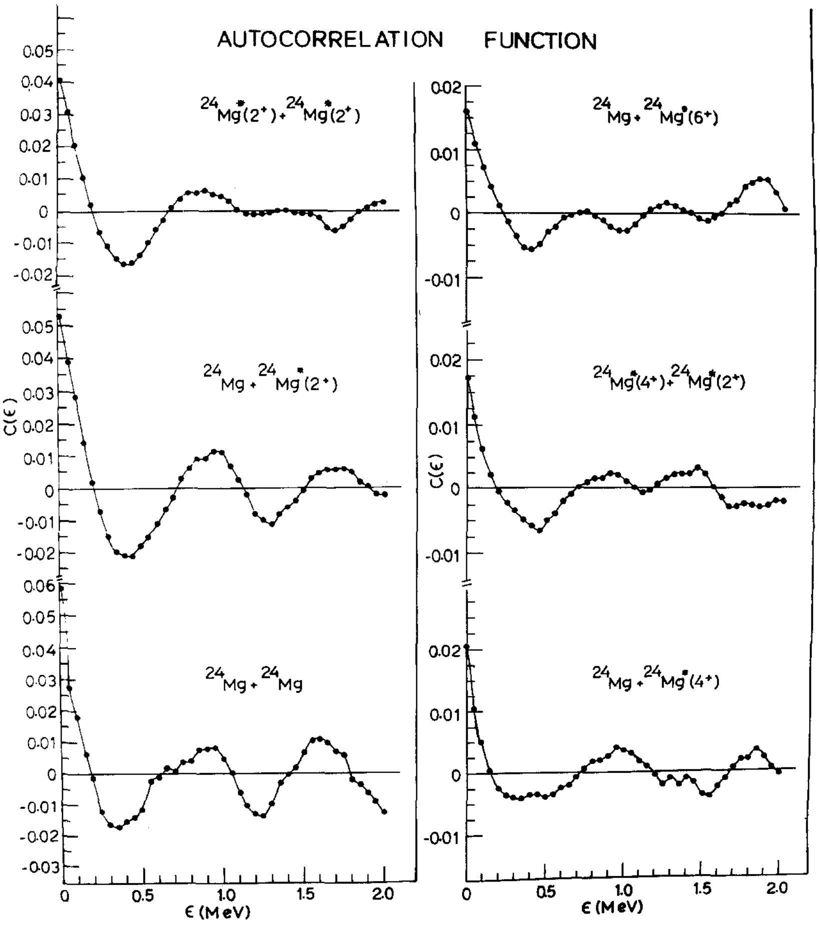

Fig. 3. Autocorrelation functions for the indicated excitation functions of $^{24}$Mg+$^{24}$Mg

where $A$ is the mass and $E_x$ the excitation energy of the compound nucleus. According to this estimate the values of $\Gamma$ ranged between 189 and 296 keV. The values of the coherence width were also determined by the usual method of counting the maxima in the excitation functions [10]. These values of $\Gamma$ were appropriately corrected for the target thickness and finite spacing of experimental points [21]. The values thus obtained are also listed in Table 1. These values agree well with the empirical estimates. The difference between $\Gamma$-values obtained from autocorrelation function and peak counting methods points to the presence of nonstatistical structures [20].

### 2.5. *Distribution of Cross Sections*

In presence of the direct reaction contributions, the distribution of cross sections is given by [10, 16]

$$P(x) = \left(\frac{N}{1-Y_d}\right)^N x^{N-1} \exp\left(-N\frac{x+Y_d}{1-Y_d}\right) \cdot \frac{I_{N-1}[2N\sqrt{xY_d}/(1-Y_d)]}{[N\sqrt{xY_d}/(1-Y_d)]^{N-1}}, \tag{7}$$

where, as mentioned earlier, $x = \mathrm{d}\sigma(E/\langle \mathrm{d}\sigma(E)\rangle$, $N$ is the number of effective channels, $Y_d$ is the ratio of the average direct (noncompound) to total cross section, and $I_{N-1}$ is the modified Bessel function of order $N-1$. The quantities $N$ and $Y_d$ are related to each other via the relation

$$C(o) = \frac{1-Y_d^2}{N}, \tag{8}$$

where $C(o)$ is the variance of the data, as mentioned earlier. Noting that $N=1$ for elastic scattering excitation function we obtained $Y_d = 0.96$ which indicates that as much as 96% of the cross section is of nonstatistical origin. The experimental and theoretical distributions of cross sections for $^{24}$Mg + $^{24}$Mg have been compared in Fig. 4. The agreement between the experimental and theoretical distributions of cross sections clearly points to the large nonstatistical component in the cross sections [22]. For inelastic scattering excitation functions the maximum value of $N$, $N_{\max}$, was estimated by using the approximate expression

$$\begin{aligned} N_{\max} &= g/2 \text{ (for even } g) \\ &= (g+1)/2 \text{ (for odd } g) \\ \text{with } g &= (2i+1)(2I+1)(2i'+1)(2I'+1), \end{aligned} \tag{9}$$

where $i$ and $I$ are the spins of the projectile and target and $i'$ and $I'$ are the spins of the final fragments [9].

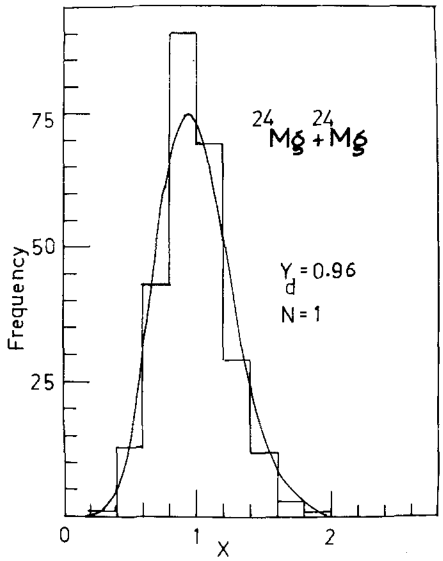

**Fig. 4.** Comparison of experimental and theoretical distributions of cross sections for $^{24}$Mg + $^{24}$Mg elastic excitation function (see text)

The estimates of $Y_d$ made by using the values of $N_{\max}$ so obtained also pointed to large nonstatistical components in the cross sections but since the approximate expression (9) frequently breaks down for the reactions involving heavy ions [23] and $N_{\max}$ is not really the correct value of $N$, such estimates of $Y_d$ might not be free from the ambiguities. Therefore, we do not show the distributions of cross sections for inelastic scattering excitation functions.

## 3. Conclusion

The deviation function, energy dependent correlation function, and summed excitation function very clearly reveal the existence of correlated structures at $E_{\mathrm{c.m.}} = 44.55$, 45.70, 46.65, 47.35, 47.75 and 50.50 MeV, which stand out well beyond the statistical limits. Large values of the cross-channel correlation coefficients among various pairs of exit channels support the nonstatistical nature of these correlated structures. A comparison of the experimental and theoretical distributions of the cross sections for elastic scattering (where $N=1$) indicates rather large nonstatistical component in the cross sections. Large differences in the $\Gamma$-values obtained from autocorrelation analysis and peak counting method also indicates the presence of nonstatistical structures. Thus the present analysis confirms that the structures at $E_{\mathrm{c.m.}} = 45.70$, 46.65, 47.35 and 47.75 MeV (reported earlier [8]) are of nonstatistical origin and suggests the existence of two more structures at $E_{\mathrm{c.m.}} = 44.55$ and $E_{\mathrm{c.m.}}$

$=50.50$ MeV of the similar nature. The latter are being reported for the first time. Like $^{28}$Si+$^{28}$Si system the most observed features of the occurrence of resonances and of the cross sections of $^{24}$Mg+$^{24}$Mg system may also be explained in terms of high-spin fissioning shape isomers which are theoretically expected to occur in the Cr−Ni region [6]. In the absence of a clear understanding of the microscopic structure of these states it is obvious that more experimental information of different nature should be sought. Recent measurement of spin alignment in the energy region of two strong resonances ($E_{\mathrm{c.m.}}=45.7$ and 46.7 MeV) already indicates the presence of a large molecular component in the wave function of $E_{\mathrm{c.m.}}=45.70$ MeV resonance [24]. Thus a dinuclear molecule type of an explanation of the observed behaviour of $^{24}$Mg+$^{24}$Mg system cannot be ruled out.

The authors are thankful to the Council of Scientific and Industrial Research, New Delhi for the financial assistance in the form of a Research Scheme. They are grateful to Prof. R.W. Zurmuehle for making available the nicely tabulated data for this analysis.

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