PHYSICAL REVIEW C VOLUME 35, NUMBER 2 FEBRUARY 1987

Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Intermediate structures in the excitation functions of heavy ion fusion reactions

M. Lattuada and D. Vinciguerra
Dipartimento di Fisica dell'Universita, Catania, Italy

C. M. Sutera
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy

G. Inglima and M. Sandoli
Dipartimento di Fisica dell'Universita, Napoli, Italy

(Received 29 October 1986)

The oscillations observed in the excitation functions for the fusion of four light heavy ion systems have been analyzed with the spectral density method to extract the values of the coherence width. The hypothesis is made that these structures are due to the excitation of overlapping states of a dinuclear intermediate system. The deduced values of the widths are found to be in agreement with the predictions of the orbiting-cluster model.

The excitation functions of a variety of nuclear reactions involving heavy ions show in many cases fluctuations around an average trend. This effect has been seen in elastic and inelastic scattering,[1–3] quasielastic reactions,[1–3] fusion, [1–14] and also in deep inelastic processes.[15] It is particularly evident in the case of the $^{12}C + ^{12}C$ interaction, still sizable in other reactions involving mostly light α-particle nuclei, and almost absent in other cases.[1–4,11]

These structures have been often interpreted as an indication of the formation of molecular resonances.[1–3] The fragmentation of a single rotational dinuclear state into the many observed resonances with the same J value is considered to be due to further collective modes. The single resonances are thought to be responsible for structures with an intermediate width (a few hundred keV), while the convolution of all the substates with the same J can give rise to gross structures,[1–3] with a width of a few MeV. Both experiment and theory indicate that the width of the resonances does not change appreciably with the excitation energy of the system.

Within this picture it is also possible to explain why the fluctuations are more evident in some cases. For instance, in the orbiting-cluster model (OCM),[2,16] the dinuclear system is thought to live long enough to influence the reaction process only when its coupling with the states of the composite nucleus is weak and the corresponding level density relatively small. For the latter condition, small values of the resonance width Γ are expected mostly when the process involves α nuclei. Note that the model is not able to predict the absolute value of Γ, but only its dependence on the masses of the nuclei involved in the process.[16]

The excitation functions for the fusion of ^{12}C with ^{20}Ne, ^{24}Mg, ^{28}Si, and ^{32}S have recently been reported[10–14] to show fluctuations with a width of a few hundred keV. An interpretation for this behavior has been proposed in connection with the sharp cutoff model for the critical angular momentum of the composite system. In Ref. 12 the oscillations of the excitation functions have been found to correspond to partial waves separated by one unit of angular momentum. This description, however, failed to predict the spacing of the oscillations in the case of the $^{12}C + ^{32}S$ reaction.[13]

In order to study the parameters of the fluctuations of the fusion excitation function, we performed an analysis of the data by using the spectral density method (SDM) introduced in Ref. 17. The SDM essentially performs the Fourier analysis of an autocorrelation function.[18] Each coherence width Γ contributes to the spectral density function $w(\beta)$ with a term $\exp(-\Gamma\beta/dE)$, where dE is the constant energy step of the measurement and $\beta=\pi n/N$, N being the number of the points and n an integer ranging from 0 to N. Thus, the SDM is able to show the presence of more than one coherence width.[17] However, the analysis of the data of Refs. 10–14 indicated that only one width is dominant. One example of the results is shown in Fig. 1. The slope of the exponential fit gives the value of the coherence width Γ searched for.[17]

The excitation function of the $^{12}C + ^{20}Ne$ reaction reported in Ref. 10 shows a steep increase at low energy, remaining then approximately constant. Since we found

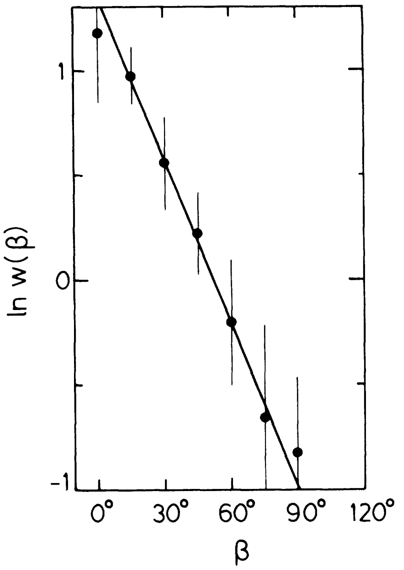

FIG. 1. Spectral density function for the $^{12}C+^{32}S$ reaction. The straight line is a least squares fit to the experimental points and corresponds to $\Gamma=(235\pm31)$ keV.

that this particular behavior introduced an indeterminacy connected with the use of trend reduction techniques,[17] we decided to analyze only the data taken at c.m. energies higher than 19 MeV (Table I). The cross section was measured[10] with an energy step of 160 keV for an excitation energy ranging from 38 to 49 MeV, and with an energy step twice as large between 49 and 52 MeV. Since the SDM requires a constant energy step, it was applied three times: First, to the energy range covered by the $dE=160$ keV measurements (first line in Table I); second, to the wider energy range, by skipping every other point in the $dE=160$ keV region (second line). As a countercheck the skipped points were analyzed apart, giving the results reported in the third line. Table I shows that the three values of Γ for this reaction compare reasonably well.

The same kind of analysis was applied and similar results were found for the $^{12}C+^{24}Mg$ data[11] taken with different energy steps. Here the value of about 700 keV for Γ turns out to be definitely smaller than the estimated width of 2 MeV suggested by the authors of Ref. 11.

The fusion excitation functions for the reactions $^{12}C+^{28}Si$ and $^{12}C+^{32}S$ have been measured[12,13] with a constant energy step. We analyzed them twice by doubling the energy step, just to check the validity of the results of our analysis. Table I reports the widths deduced by a complete analysis of the cross sections with the energy step used in the experiment, together with the ones obtained by taking into account only every other point.

Fluctuations have also been found in the excitation function of the $^{12}C+^{20}Ne$ fusion reaction measured at sub-barrier energies.[14] In spite of the large indeterminacy introduced by the need to treat a rapidly changing function, we applied the SDM which gave $\Gamma=567\pm129$ keV, in good agreement with the value deduced at higher excitation energy for the same reaction (Table I).

In the frame of the statistical model of nuclear reactions the structures in the cross section could be considered as statistical fluctuations generated by the excitation of overlapping states of the intermediate system. As the cross sections considered have been determined by summing over many final reaction channels, statistically uncorrelated fluctuations should be washed out. Then the observed coherence energies have to be attributed only to the correlated part of the fusion cross section. A similar approach was recently proposed to explain analogous evidence found in dissipative heavy ion reactions.[15]

In the cases considered here the correlation between the exit channels contributing to the fusion reaction could be introduced by considering the formation, in the early stage of the collision, of a dinuclear system which acts as a doorway to the fusion process. The times related to the deduced coherence widths give an indication of the mean lifetime of the dinucleus. Note that the widths measured[19] for a few reaction channels are smaller than the coherence widths obtained here, giving an indication of the longer rearrangement time spent by the intermediate system before decaying through a definite reaction channel.

Information on the nature of the dinuclear system can be obtained by a comparison with the OCM. In this model the width of the molecular resonances is related to the optical potential of the two interacting nuclei and to the structure of the composite system.[2,16] At an excita-

TABLE I. Relevant parameters for the analysis of the four fusion reactions under consideration. The range of incident and of excitation energy is that for which the analysis has been performed and the width Γ has been deduced (see the text).

Reaction	Ref.	Barrier (MeV)	$E_{\mathrm{inc}}^{\mathrm{c.m.}}$ (MeV)	E_{exc} (MeV)	dE (keV)	Γ (keV)	Note
$^{12}C+^{20}Ne$	10	10.2	19—30	38—49	160	592±46	all points
			19—33	38—52	320	563±31	only odd
			19—30	38—49	320	468±30	only even
$^{12}C+^{24}Mg$	11	12.0	25—38	42—55	330	714±85	all points
			13—38	30—55	670	703±101	only even
$^{12}C+^{28}Si$	12	13.8	18—27	32—40	120	239±66	all points
			18—27	32—40	240	240±49	only odd
$^{12}C+^{32}S$	13	15.6	16—28	28—40	110	235±31	all points
			16—28	28—40	220	251±35	only odd

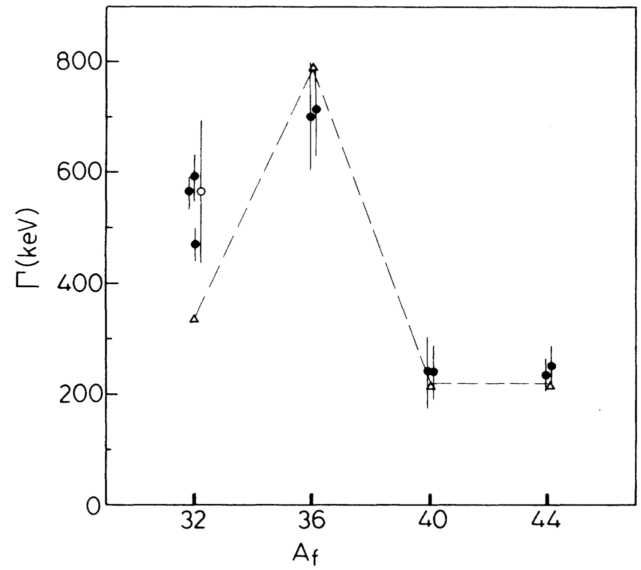

FIG. 2. The full dots represent the experimental widths obtained through the SDM analysis for the various systems reported in Table I. *A* is the mass of the fused nucleus. The empty dot is obtained from the analysis of the data of Ref. 14 (see the text). The triangles are calculated within the OCM, by assuming a value $\Gamma_{cc}=440$ keV. The dashed line is drawn only to guide the eye.

tion energy of about 28 MeV for the ^{32}S, ^{36}A, ^{40}Ca, and ^{44}Ti intermediate systems the ratios of the molecular resonance widths to the reference width Γ_{cc} of the $^{12}C+{}^{12}C$ system are predicted to be 0.77, 1.8, 0.5, and 0.5, respectively.

Assuming as molecular widths the coherence energies of the previous analysis, it is possible to determine the reference width Γ_{cc}. This was done by a least squares fitting procedure using for each nucleus a weighted average of the widths reported in Table I. A value $\Gamma_{cc}=440$ keV was thus obtained (Fig. 2).

This value compared favorably with the experimental total width of 300—400 keV obtained in Ref. 20 for the $^{12}C+{}^{12}C$ system. We do not want to stress the meaning of the overall agreement between the calculated and experimental value of Γ, since the model is admittedly[2,16] crude. However, the present result supports the idea that fluctuations in the excitation function of the fusion channel are related to the lifetime of a doorway dinuclear configuration of the composite system, thus indicating that structural models are suitable for their description.

It is a pleasure to thank N. Cindro for enlightening conversations and continuous interest. The authors also acknowledge useful comments of G. Pappalardo, C. Spitaleri, and F. Riggi. This work was supported in part by Istituto Nazionale di Fisica Nucleare, Italy.

---

[1] *Nuclear Molecular Phenomena, Hvar, Yugoslavia, 1977,* edited by N. Cindro (North-Holland, Amsterdam, 1978); *Resonant Behavior of Heavy-Ion Systems, Aegean Sea, Greece, 1980,* edited by G. Vourvopoulos (National Printing Office, Athens, 1981), and references therein.

[2] N. Cindro, Riv. Nuovo Cimento **4**, 1 (1981).

[3] T. M. Cormier, Annu. Rev. Nucl. Part. Sci. **32**, 271 (1982).

[4] P. Sperr, T. H. Braid, Y. Eisen, D. G. Kovar, F. W. Prosser, J. P. Schiffer, S. L. Tabor, and S. Vigdor, Phys. Rev. Lett. **37**, 321 (1976).

[5] M. Conjeaud, S. Gary, S. Harar, and J. P. Wieleczko, Nucl. Phys. **A309**, 515 (1978).

[6] B. Dasmahapatra, B. Cujec, and F. Lahlou, Nucl. Phys. **A384**, 257 (1982).

[7] J. J. Kolata, R. M. Freeman, F. Haas, B. Heusch, and A. Gallmann, Phys. Lett. **65B**, 333 (1976).

[8] J. J. Kolata, R. M. Freeman, F. Haas, B. Heusch, and A. Gallmann, Phys. Rev. C **19**, 408 (1979).

[9] J. J. Kolata, R. M. Freeman, F. Haas, B. Heusch, and A. Gallmann, Phys. Rev. C **19**, 2237 (1979).

[10] P. A. DeYoung, J. J. Kolata, R. C. Luhn, R. E. Malmin, and S. N. Tripathi, Phys. Rev. C **25**, 1420 (1982).

[11] K. Daneshvar, D. G. Kovar, S. I. Krieger, and K. T. R. Davies, Phys. Rev. C **25**, 1342 (1982).

[12] R. A. Racca, P. A. DeYoung, J. J. Kolata, and R. J. Thornburg, Phys. Lett. **129B**, 294 (1983).

[13] J. J. Kolata, R. A. Racca, P. A. DeYoung, E. Aguilera-Reyes, and M. A. Xapsos, Phys. Rev. C **32**, 1080 (1985).

[14] G. Hulke, C. Rolfs, and H. P. Trautvetter, Z. Phys. A **297**, 161 (1980).

[15] A. De Rosa, G. Inglima, V. Russo, M. Sandoli, G. Fortuna, G. Montagnoli, C. Signorini, A. M. Stefanini, G. Cardella, G. Pappalardo, and F. Rizzo, Phys. Lett. **160B**, 239 (1985); A. Glaesner, W. Dunnweber, W. Hering, D. Konnerth, R. Ritzka, R. Singh, and W. Trombik, *ibid* **169B**, 153 (1986).

[16] N. Cindro and D. Pocanic, J. Phys. G **6**, 359 (1980); N. Cindro, Nukleonika **27**, 137 (1982).

[17] A. De Rosa, G. Inglima, V. Russo, and M. Sandoli, Nuovo Cimento **A58**, 254 (1980), and references therein.

[18] I. Hall, Phys. Lett. **10**, 199 (1964).

[19] N. Cindro, J. D. Moses, N. Stein, D. M. Drake, D. L. Hanson, and J. W. Sunier, Phys. Lett. **84B**, 55 (1979); N. Alamanos, C. Levi, C. Le Metayer, W. Mittig, and L. Papineau, *ibid.* **151B**, 100 (1985).

[20] R. J. Ledoux, C. E. Ordonez, M. J. Bechara, H. A. Al-Juwair, G. Lavelle, and E. R. Cosman, Phys. Rev. C **30**, 866 (1984).