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Clustering Aspects of Nuclear Structure and Reactions

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Abstract. Some aspects of clustering phenomena in nuclear structure and reactions are reviewed. Particular emphasis is placed on the relationship between cluster-like states and shape-isomeric states which arise as a result of shell effects in deformed potentials. Some recent evidence in favour of this connection is presented and discussed.

The notion of clustering in nuclei dates from the earliest days of nuclear physics following the observation of the spontaneous emission of α-particles from heavy nuclei and the theoretical investigations of this phenomenon by Gamow (1930). The idea of a cluster model of light nuclei was first proposed by Hafstad and Teller (1938) and the structure of many light nuclei has subsequently been interpreted in terms of well defined cluster configurations (Morinaga 1956). This concept has an obvious appeal as a simplification of the nuclear many-body problem and the idea of well-defined clusters of nucleons interacting via some effective cluster-cluster interaction is part of our picture of many aspects of nuclear structure.

The experimental evidence supporting these general ideas is abundant. Examples of states possessing unusually large overlaps with nuclear clusters are found in both resonance scattering studies populating unbound states of the final nucleus and cluster transfer reactions to bound and unbound states. Perhaps the classic example is found in the nucleus ^{20}Ne studied by reactions such as α-particle resonance scattering on ^{16}O and α-particle transfer reactions. A spectrum (Anantaraman 1979) of the ^{16}O(^{6}Li,d) α-transfer reaction is shown in Fig. 1. The reaction is highly selective, showing strong population of relatively few levels despite the known complexity of the ^{20}Ne level scheme above 6 MeV of excitation. Particularly noticable is the population of the ground-state rotational band (0^+, 0.0; 2^+, 1.63; 4^+, 4.25; 6^+, 8.78 and 8^+, 11.95 MeV) as well as the $K^\pi=0^-$ band beginning with the 5.79 MeV $J^\pi=1^-$ level. This splitting between the positive and negative parity bands indicates the importance of the microscopic structure underlying such cluster states which in the extreme cluster model should lie on the same rotational sequence.

The location of $K^\pi=0^+$ bands in ^{20}Ne with large reduced widths for decay into an α-particle and ^{16}O in its ground and excited states are shown in

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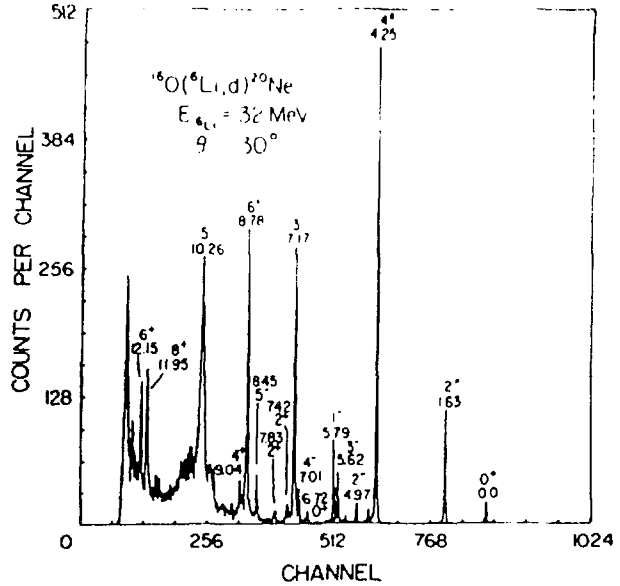

Fig 1. Spectrum of the $^{16}O(^6Li,d)^{20}Ne$ reaction (Anantaraman 1979).

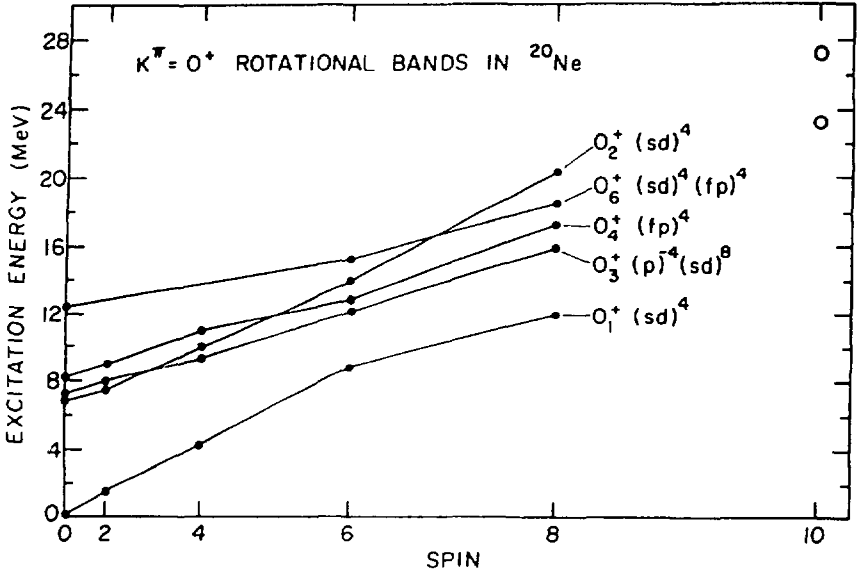

Fig. 2. $K^\pi = 0^+$ cluster bands in ^{20}Ne (Hindi 1983). The location of the lowest 10^+ states (Allcock 1986) is indicated by open circles.

Fig. 2. Also indicated are the proposed dominant shell-model configurations associated with each of the bands (Hindi 1983). Of considerable interest in this respect has been the search for higher spin members of these rotational bands and, in particular, the location of the lowest $J^\pi = 10^+$ level. If the extent which the cluster exists is determined by the shell model sub-space from which its wavefunction is composed, each rotational band should terminate at the maximum spin that can be constructed for an S=0, T=0 cluster within the sub-space. In this case, for the $(sd)^4$ ground-state rotational band, we expect $J_{MAX} = 8$. Much effort has been devoted to this problem over the years and in a contribution to this conference (Allcock 1986) a search for 10^+ states decaying to the ground-state of ^{16}O is reported. No $J^\pi = 10^+$ states are found below 23 MeV but strength is found in a narrow peak near 23.2 MeV and in a broad peak centered at 27.4 MeV -- both these results are in accord with earlier work (Artemov 1977). The location of these two states are shown in Fig. 2. It is clear that they do not lie on any reasonable

extrapolation of the ground-state rotational band, but are most likely members of higher lying bands whose shell model configurations allow them to have spin 10 members. It thus appears that the ground-state band of ^{20}Ne does in fact terminate at J=8 indicating the importance of the shell structure in these apparantly highly clustered bands.

Information on states with large cluster decay widths involving other than α-particles came with the beginnings of the study of heavy-ion reactions. In some of the very first studies of the energy dependence of heavy-ion scattering and reactions evidence was found for the existence of long-lived resonance states with large overlaps with complex nuclear clusters. I refer of course to the experiments on ^{12}C+^{12}C and other light systems by Bromley, Kuehner and Almquist (1960). Subsequent to this, similar phenomena have been observed in much heavier systems (Braun-Munzinger 1977, Betts 1984) and, indeed, whenever accelerator and experimental technology has allowed such studies in a new region of target and projectile mass, evidence has been found for the formation of long-lived, cluster-like states at high excitation energy and in many cases at high angular momentum.

Examples of this kind of behaviour for the ^{12}C+^{12}C (Reilly 1973) and ^{16}O+^{16}O systems (Maher 1969) are shown in Fig. 3 where the the θ_{cm}=90° elastic scattering cross-sections are shown as a function of center-of-mass bombarding energy. In the case of ^{16}O+^{16}O, the broad structures observed are generally interpreted as a series of potential or shape resonances formed in pockets which occur in the ion-ion potential -- the absorption for the surface partial waves being weak enough to keep the resonance widths small. Studies of the scattering of ^{16}O+^{16}O in the

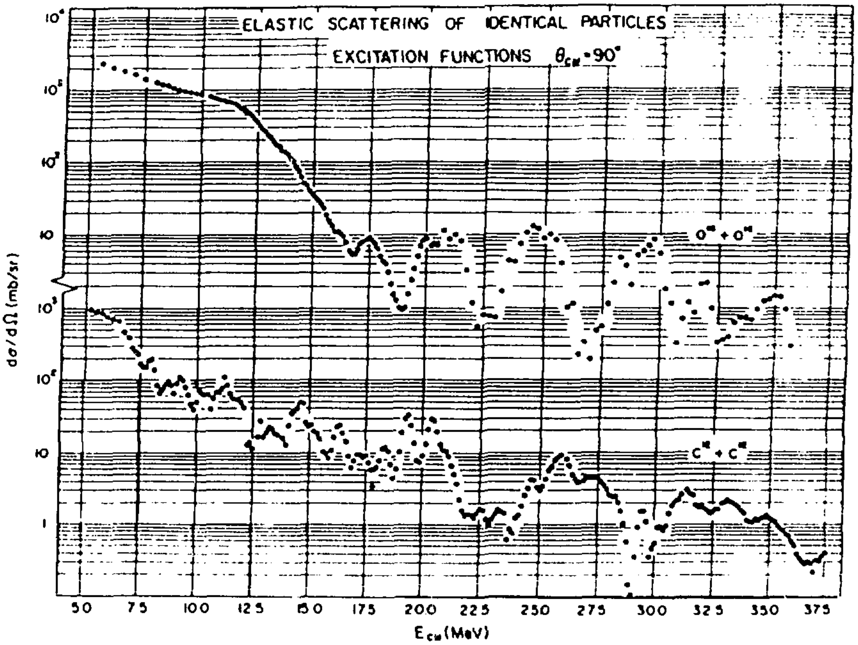

Fig. 3. Energy dependence of the θcm=90° elastic scattering of ^{12}C + ^{12}C (Reilly 1973) and ^{16}O + ^{16}O (Maher 1969).

framework of the Generator Coordinate method (Langanke 1981) have led to the identification of these broad resonances as a rotational band with a structure closely related to the lowest states allowed by the Pauli principle which can be formed in the compound nucleus ^{32}S from two ^{16}O nuclei. Consideration of this in rather general terms, according to the ideas of Harvey (1975), lead to some interesting insights into the general problem of resonance formation in heavy-ion collisions. In this picture, the two separated ^{16}O nuclei are described by simple harmonic oscillator wavefunctions as shown in Fig. 4. The two nuclei approach each other along the z axis which connects the centers of the two nuclei. As the two nuclei overlap the x and y degrees of freedom are assumed to remain unchanged. The number of oscillator quanta in the z direction, however, has to change to satisfy the Pauli principle. In the case of $^{16}O+^{16}O$ coalescing to form ^{32}S, this results in the formation of a state with four particles (2n-2p) in the N=3 shell outside a ^{28}Si core. This so-called "diabatic" configuration is that which is expected to be formed in the early stages of the collision process as it represents the configuration reached by applying the minimum changes to the wavefunctions of the colliding nuclei consistent with the Pauli principle. (These ideas are supported by investigations (Norenberg 1985) into the nature of dissipation in collisions of much heavier systems). It is now interesting to ask to which shape this diabatic configuration will relax. This may be answered by considering the distribution of oscillator quanta between the x, y and z directions and then applying an equilibrium condition (Bohr 1975) to obtain the shape. For the oscillator configuration shown in Fig. 4

$$\Sigma_x = 24, \quad \Sigma_y = 24, \quad \Sigma_z = 48$$

where

$$\Sigma_K = \sum_{i=1}^{A} (n_K+1/2)_i$$

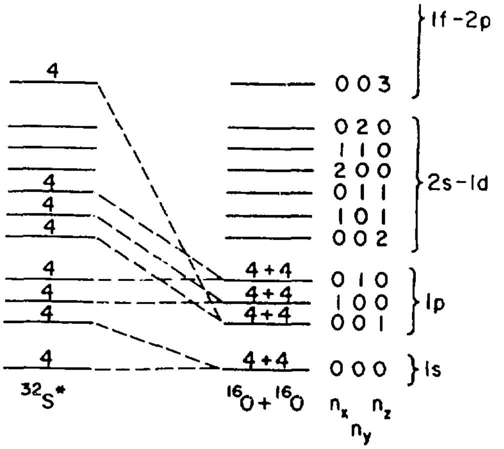

Fig. 4. Schematic drawing of the excited state in ^{32}S reached in the diabatic collision of $^{16}O+^{16}O$ (Harvey 1975).

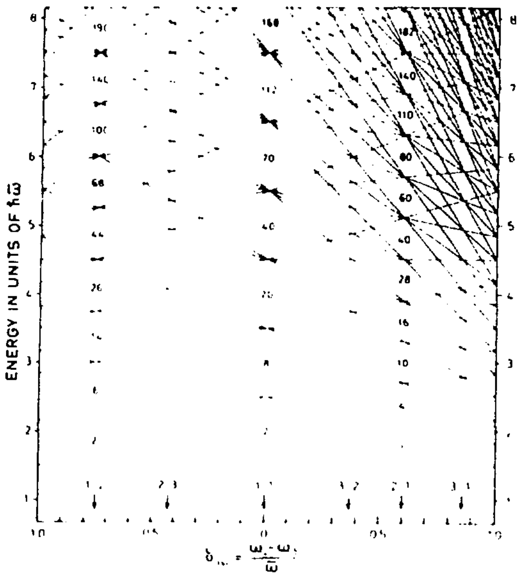

Fig. 5. Energy levels of a particle in a deformed axially symmetric harmonic oscillator. The energies are measured in units of units of $\bar{\omega} = (2\omega_1+\omega_3)/3$.

the equilibrium condition

$$\Sigma_x \omega_x = \Sigma_y \omega_y = \Sigma_z \omega_z$$

then gives

$$\omega_x : \omega_y : \omega_z = 2:2:1$$

which corresponds to an axially symmetric ellipsoid with r.m.s. axes in the ratio

$$\bar{x} : \bar{y} : \bar{z} = 1:1:2$$

This shape is of particular significance in the present case for, as shown in Fig. 5, this ratio of oscillator frequencies corresponds (Wong 1970) to a deformed shell closure which thus, as can be seen in Fig. 6, gives rise to a secondary minimum in the potential energy surface of ^{32}S (Ragnarsson 1981). These ideas, which as outlined above are for angular momentum zero, can be extended to rotating systems by cranking and, for not too high rotational frequencies or too large deformations, can be shown to lead to the same conclusions as is shown in Fig. 6 for spin 8.

The configuration discussed above corresponds to an $^{16}O+^{16}O$ cluster-like band with 2N+L=24 which has been identified in the GCM calculations of Langanke, Stademann and Timm (1981) with a rotational band of bound states in ^{32}S. The observed broad structures are associated with a band with 2N+L=28 which differs only from the lowest configuration by promotion of four nucleons to the next major shell. We see therefore that the entrance channel resonances in $^{16}O+^{16}O$ are closely related to deformed shape isomers in the compound nucleus and may be thought of as simple excitations based on the lowest state of ^{32}S in the secondary minimum with a 2:1 axis ratio.

Returning to Fig. 3, the data for $^{12}C+^{12}C$ show considerably more complexity than for $^{16}O+^{16}O$. Within the framework of the above discussion this can be seen to arise from the non-spherical nature of the ^{12}C ground-state which leads to an orientation dependence of the collision process (Harvey 1975). It is also clear from the potential energy surface (Leander 1975) for ^{24}Mg shown in Fig. 7 that this too possesses a richness of structure. Insight into the cluster structure of the potential energy minima can be obtained by comparing the results

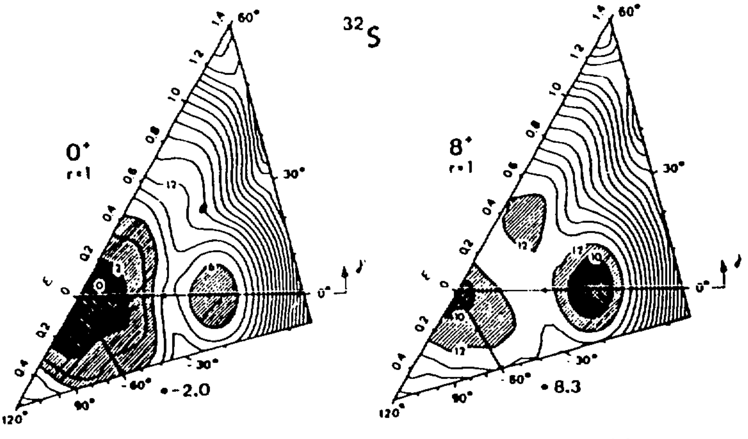

Fig. 6. Calculated potential energy surfaces for ^{32}S at spin 0 and spin 8 (Ragnarsson 1981).

of a recent calculation (Marsh 1986) of ^{24}Mg within the cranked cluster model. In this calculation, based on the cluster model of Brink (1966), the positions of six 0s α-clusters were allowed to vary without constraint and local minima in the total energy of the system searched for. The nucleon-nucleon force used was the Brink-Boeker B1 force (1967). The density contours of the solutions with large deformations are shown in Fig. 7 associated with the appropriate Nilsson-Strutinsky minima -- the association having been made using estimates of the deformation parameters from the cluster calculation density distributions and their shell model configurations. It is important to note that the stability of these deformed cluster configurations arises as a consequence of the shell structure of the deformed mean field and the spin-isospin degeneracy of the single-particle orbits and not from any inherent stability of the clusters themselves.

The triaxial minimum (ϵ=1.26, γ=42°) shows a distinct planar structure in which can be clearly discerned two triangular groups of three clusters. This structure of three is the same structure found for the ^{12}C ground-state in this model before parity projection, and we therefore expect this configuration to have a large overlap with two ^{12}C nuclei in their ground-states and, when rotating, two ^{12}C nuclei in the excited 2^+ state with the spins aligned parallel to the rotation axis. This connection has been pointed out by Mosel (1981) who noted the effects of the relative orientation of the two ^{12}C nuclei on the potential calculated in a two-center shell model (Chandra 1978). It was

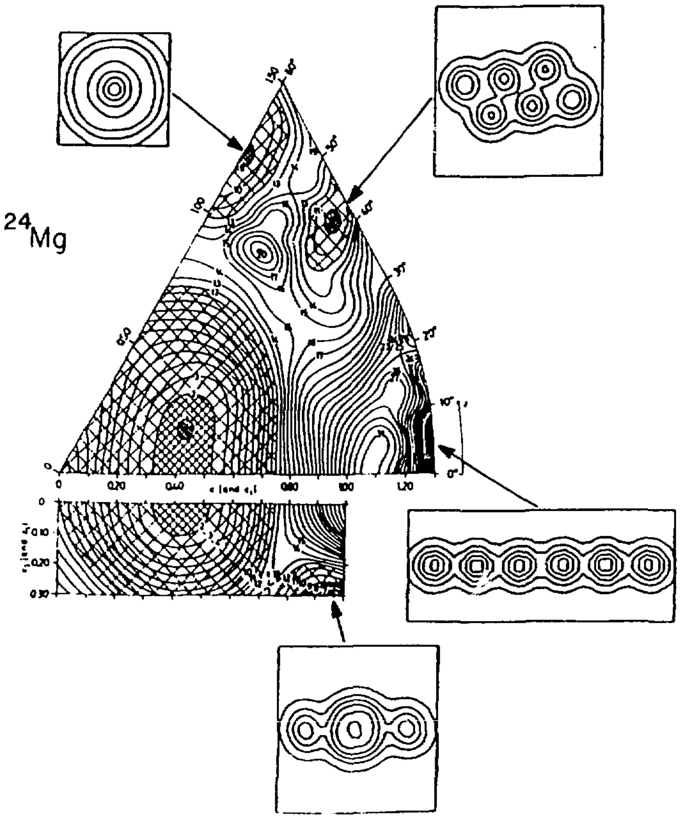

Fig. 7. Potential energy surface for ^{24}Mg (Leander 1975) together with density contours for the stable cluster configurations (Marsh 1986).

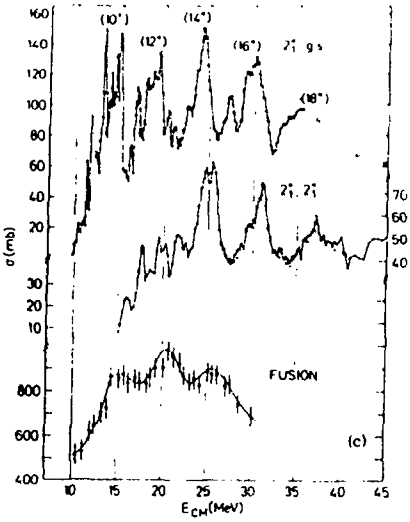

Fig. 8. Cross-sections for the single and mutual inelastic scattering of ^{12}C+^{12}C shown as a function of center-of-mass bombarding energy (Cormier 1978).

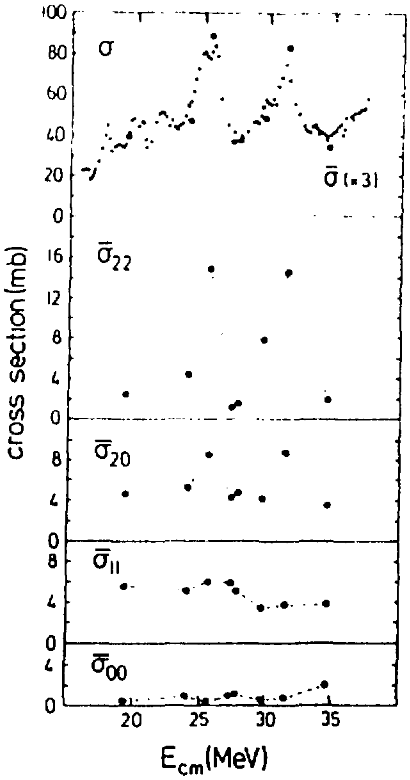

Fig. 9. Decomposition of the ^{12}C+^{12}C mutual inelastic scattering cross-section into contributions from different substates $\bar{\sigma}(m_1 m_2)$ $\bar{\sigma}(22)$ corresponds to the aligned configuration (Konnerth 1985).

further noted by Mosel that dynamical coupling effects in the entrance channel tended to align the ^{12}C nuclei in the appropriate fashion and thus enhance the population of the triaxial isomeric shape. This configuration may therefore be associated with the band of broad resonances observed (Cormier 1977, 1978) in the elastic and single and mutual inelastic scattering of ^{12}C+^{12}C, data for which is shown in Fig. 8, and which have been seen to decay with the spins of both ^{12}C nuclei aligned (Konnerth 1985) as suggested above and as displayed in Fig. 9.

Of particular interest is the prolate minimum with ε=1.0, γ=0° and ε_3=0.3. The cluster model also predicts this minimum to be reflection asymmetric -- the density contours shown are those obtained after parity projection. This minimum lies somewhat below the triaxial minimum in energy and from the density contours and shell model configurations appears to have a structure based on a ^{12}C nucleus in its ground state together with another in the chain-like excited 0^+ state. A similar shape has been found in (Umar 1986) Hartree-Fock calculations and studied (Strayer 1984) in Time-Dependent Hartree-Fock calculations of ^{12}C(g.s.) + ^{12}C(0_1^+). The energy of this minimum suggests that this configuration be identified with the narrow resonances observed (Bromley 1960, Erb 1980) in ^{12}C+^{12}C in the vicinity of the Coulomb barrier (Fig. 10). Two questions arise, however, as a result of this interpretation. Firstly, the proposed cluster configuration has no obvious overlap with two ^{12}C nuclei in their ground states which leaves the ^{12}C

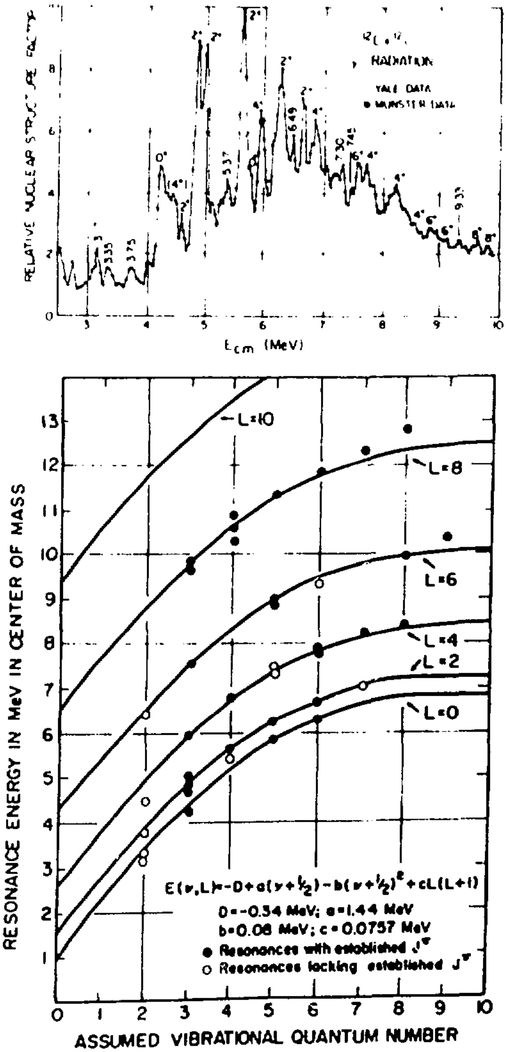

Fig. 10. Energy dependence of the low-energy $^{12}C+^{12}C$ reaction cross-section (Erb 1980) together with a rotation-vibration fit to the observed spectrum (Erb 1981).

width of the barrier resonances to be accounted for and secondly, the multiplicity of observed resonances in this energy region (see Fig. 10) require additional degrees of freedom beyond the simple rotation of this shape. A resolution of the first question comes from the work of Takigawa and Arima (1971) who found that, in order to reproduce the electromagnetic decay properties of these states in ^{12}C, a 20% mixing of the excited 0^+ chain configuration was required in the ^{12}C ground-state which would then give the barrier resonances the desired ^{12}C decay properties. The question of other degrees of freedom coupled to the rotation of this configuration has been addressed in the Hartree-Fock calculations of Umar and Strayer (1986) who find a low frequency isoscalar monopole vibrational mode ($\hbar\omega \approx 1$ MeV) corresponding to the vibration of the excited ^{12}C through the ^{12}C in its ground-state as shown in Fig. 11. A similar result is obtained in the cranked cluster model. The energy of this mode agrees well with that extracted from a vibration-rotation model fit (Erb 1981) to the spectrum of barrier resonances shown in the lower portion of Fig. 10 and it can therefore be concluded with reasonable certainty that the observed complexity results from the coupling of this vibrational mode to the rotation.

Fig. 11. Isoscalar density contours obtained in a TDHF calculation of the time evolution of a $^{12}C(g.s.)+^{12}C(0_1^+)$ configuration (Strayer 1984).

Some observations are relevant to future experiments seeking to confirm the above speculations. The wavefunction of the proposed configuration for the barrier resonances has an α-particle in the (sd) shell and an α-particle in the (fp) shell outside a closed ^{16}O core -- in agreement with that obtained in the Harvey prescription for a $^{12}C(0_1^+)$ incident along the symmetry axis of the oblate $^{12}C(g.s.)$. This configuration has not only an obviously large overlap with the ^{16}O ground-state and ^{8}Be but also the relationship between the $^{12}C+^{12}C$ barrier resonances and the various rotational bands in ^{20}Ne now becomes clear. In particular, we would expect to see enhanced α-decays to the ground-state, 0_2^+ and 0_6^+ rotational bands which are thought to be based on configurations which would have large overlap with the above $^{12}C+^{12}C$ isomer. This expectation is qualitatively in agreement with the suggestions of Cosman (1981) and Ledoux (1984) who, however, assigned the triaxial minimum to the $^{12}C+^{12}C$ barrier resonances. Finally, the reflection asymmetric shape found in the Nilsson-Strutinsky and cluster model calculations raises the question of the existence of negative parity members of the bands built on this configuration. These would not, of course, have been observed in the $^{12}C+^{12}C$ entrance channel due to the spin zero nature of ^{12}C but could, for example, be observable via non-symmetric entrance and exit channels such as $^{20}Ne+\alpha\to^{16}O+^{8}Be$.

The extremely deformed minimum at $\varepsilon=1.25$, $\gamma=0°$ in the Nilsson Strutinsky calculations also appears as an α-particle chain structure in the cluster model calculations. Similar structures appear in all A=4n nuclei. In ^{24}Mg this structure should decay into ^{12}C nuclei in the chain-like excited 0^+ state with subsequent decay into three α-particles thus giving rise to "jet" like events. The location of these states will involve the kinematic reconstruction of a multiparticle final state and their investigation is an exciting experimental challenge.

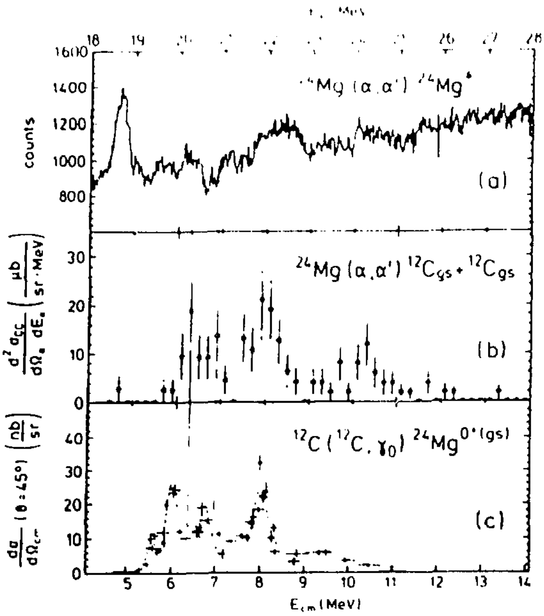

Fig. 12. Comparison of inelastic α-scattering on ^{24}Mg with coincidence events for ^{12}C(g.s) + ^{12}C(g.s.) and with the radiative capture of ^{12}C+^{12}C (Lawitzki 1986).

One important question involves the relationship of these extremely deformed states with the less deformed "normal" states of ^{24}Mg. Obviously the mixing between the two must be rather small in order to preserve the observed narrow widths. Some new insight into this question has come from studies of the "fission" of ^{24}Mg following inelastic excitation. In one of these, the results of which are shown in Fig. 12, the decay of ^{24}Mg into two ^{12}C nuclei following inelastic excitation by α-particles was measured (Lawitzki 1986). The data show some correlation with fragments of the giant quadrupole resonance seen in the inelastic scattering singles spectrum and with the results of ^{12}C(^{12}C,γ_0)^{24}Mg radiative capture (Nathan 1981) which must also proceed through 2^+ states in the continuum. Looking at the Nilsson-Strutinsky diagram in Fig. 7 we can see that this

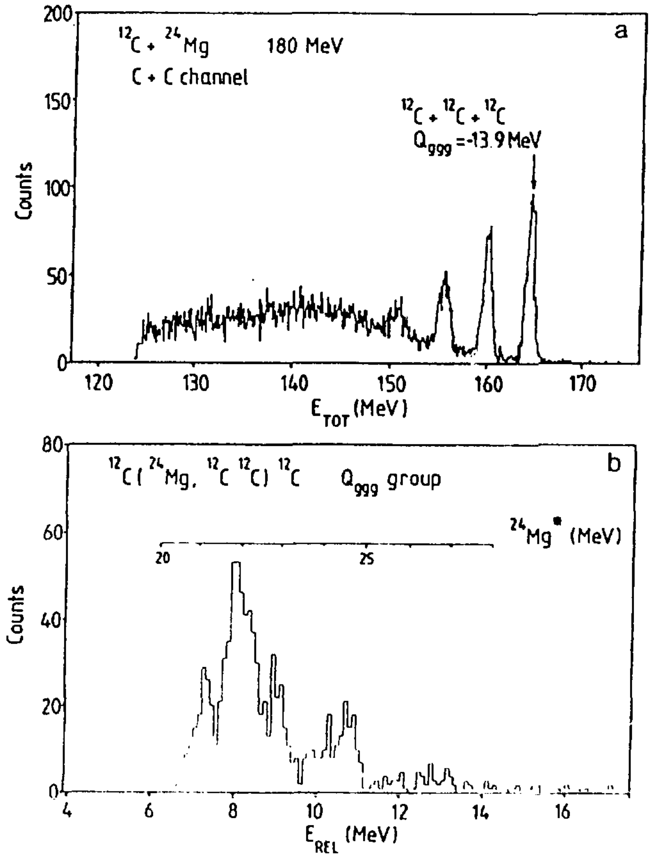

Fig. 13. (a) Total energy spectrum for fission of ^{24}Mg into two ^{12}C nuclei following inelastic scattering. (b) Excitation energy spectrum for ^{24}Mg fissioning into ^{12}C(g.s.) + ^{12}C(g.s.) (Fulton 1986).

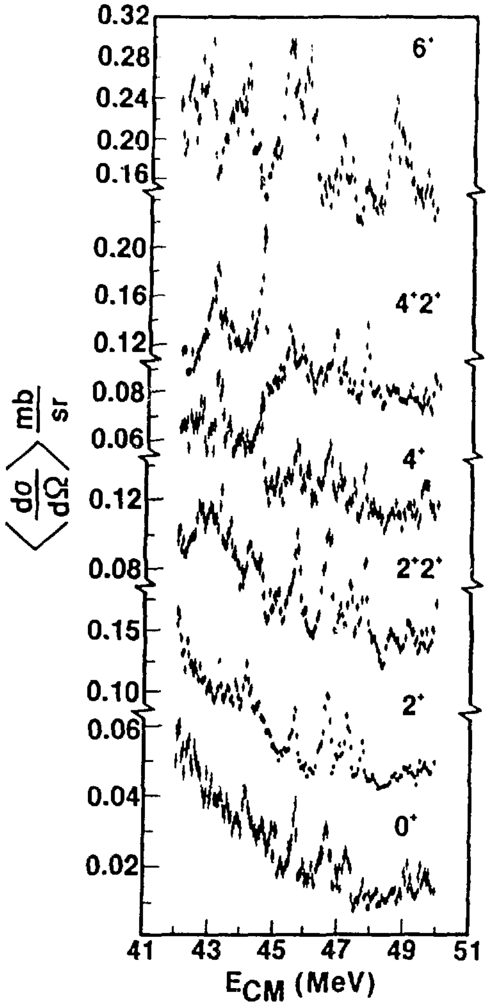

Fig. 14. Angle-average cross-sections for the large-angle scattering of $^{24}Mg+^{24}Mg$ (Zurmühle 1983).

reaction may proceed either through the K=0 component of the GQR via the prolate deformed minimum or through the K=2 component which might mix with the oblate minimum at ε=1.23, γ=60°. These questions remain to be explored in more detail.

An interesting new technique (Fulton 1986, Wilczynski 1986) for studying this connection has recently been reported. A ^{24}Mg beam was inelastically excited by collision with a ^{12}C target. Coincident ^{12}C nuclei were then detected at forward angles and each event kinematically reconstructed. For events in which all three ^{12}C nuclei were emitted in their ground-states the excitation spectrum of ^{24}Mg (Fig. 13) shows distinct structure similar to that observed in the "fission" following inelastic scattering and the radiative capture. This technique has many experimental advantages and its future pursuit should prove most profitable, especially as it might then prove possible to study deformed configurations which are otherwise inaccessible.

Phenomena similar to those observed in systems such as $^{12}C+^{12}C$ have also been seen in much heavier systems such as $^{24}Mg+^{24}Mg$ (Zurmühle 1983) and $^{28}Si+^{28}Si$ (Betts 1979, 1981, 1981a). An example is shown in Fig. 14, where excitation functions for the angle-averaged large-angle scattering of $^{24}Mg+^{24}Mg$ are shown. The observed narrow structures appear in a correlated fashion in all the reaction channels and have been shown (Saini 1984) to be inconsistent with statistical fluctuations and thus correspond to more or less isolated resonances in the composite system. In one case (Betts 1986) a series of measurements of elastic scattering angular distributions over one of the narrow $^{24}Mg+^{24}Mg$ resonances has been made which together with a constrained phase shift analysis, leads to a spin assignment of J=34. These results imply that the observed resonances correspond to a set of rather high spin states lying somewhat above the yrast line of the compound nucleus ^{48}Cr. A theoretical discussion along the lines of that presented above for $^{12}C+^{12}C$ and $^{16}O+^{16}O$ indicates that for two prolate ^{24}Mg nuclei incident end on end the diabatic configuration has an equilibrium shape which is close to the 3:1 shape for which the deformed oscillator potential has a shell gap for 24 nucleons. The effect of this shell gap on the adiabatic potential energy surface (Ragnarsson 1984) of ^{48}Cr is shown in

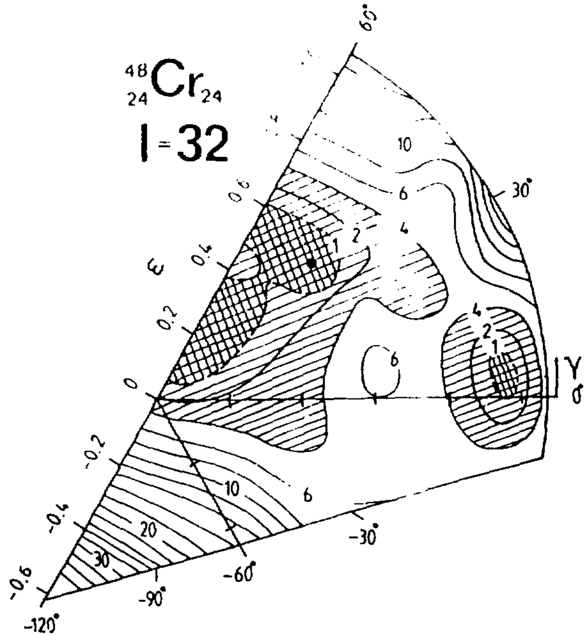

Fig. 15. Potential energy surface for ^{48}Cr at spin 32 (Ragnarsson 1984).

Fig. 15 which clearly displays the deformed minimum. Again it is likely that entrance channel interactions play an important role in aligning the two colliding nuclei thus enhancing the formation of the isomeric configuration. The experimental evidence that the two ^{24}Mg nuclei are aligned in this way comes primarily from the energy spectra (Saini 1986) at large angles, an example of which is shown in Fig. 16. The spectrum is dominated by peaks corresponding to single and mutual excitations of high spin states which, if their spins are aligned perpendicular to the

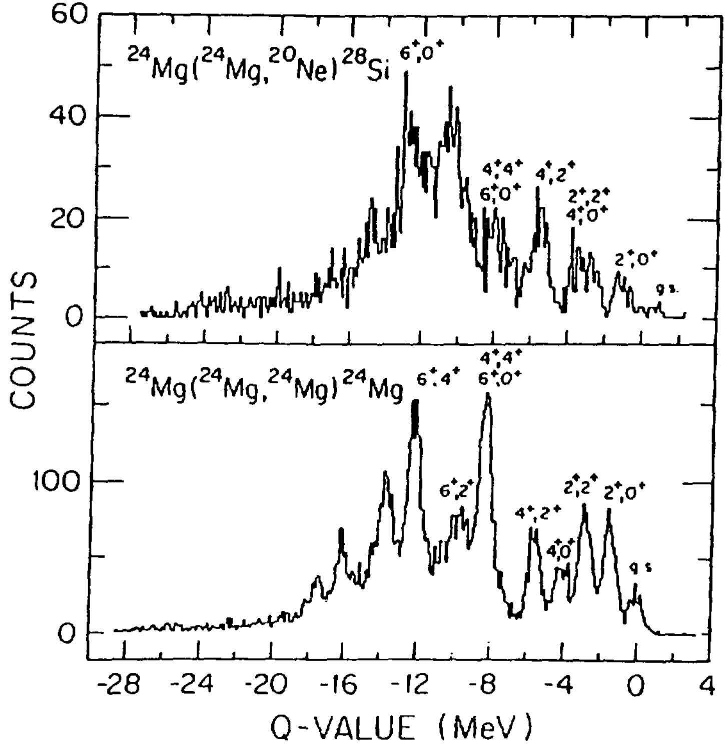

Fig. 16. Energy spectrum of inelastically scattered ^{24}Mg+^{24}Mg measured at large scattering angles (Saini 1986).

reaction plane, are favoured by simple kinematic matching conditions. More definitive evidence on this point comes from some preliminary results on direct measurements of the fragment spin alignment (Mattis 1985).

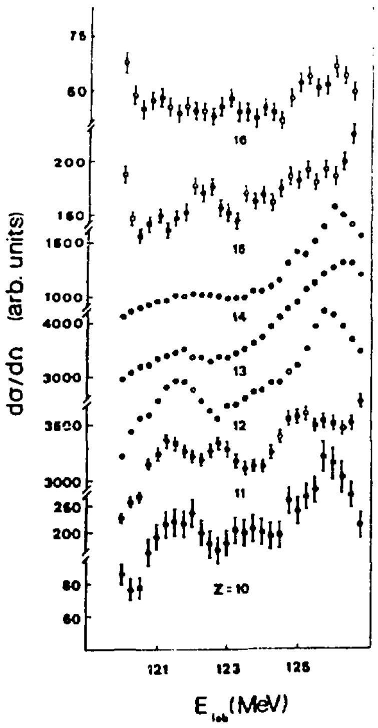

Fig. 17. Excitation functions for different Z fragments produced in the ^{28}Si+^{64}Ni reaction (de Rosa 1985).

Many of the features observed in the resonance data for heavy systems are similar to those of fully-damped orbiting or "deep-inelastic" collisions. Namely, complete damping of the entrance channel kinetic energy together with the formation of a relatively long-lived intermediate complex which subsequently decays, the fragments emerging with energies characteristic only of the Coulomb repulsion and orbital angular momentum of the system. These kind of processes have been studied over the range of target and projectile combinations but only recently has the detailed energy dependence of such collisions been studied (de Rosa 1985, Cardella 1986, Lucas 1986). Some of these data are shown in Fig. 17 in which excitation functions for different Z fragments produced in the ^{28}Si+^{64}Ni reaction are plotted. These data show a number of broad structures which appear in a similar fashion in the excitation functions for several different Z fragments. It thus appears that resonance phenomena and therefore the existence of cluster-like deformed states may occur over an even wider range of nuclei. It is an open question as to whether the diabatic approach discussed above for light systems or the adiabatic approach familiar from fission will be more appropriate for the heaviest systems. The fact that the most recent evidence for fluctuating cross-sections comes from studies of damped collisions, however, does suggest that the former may be more correct.

In summary, the connection between cluster states and shape isomeric states which arise as a consequence of shell effects in the deformed single particle potentials has been discussed. It appears that many of the features observed in the resonance scattering of heavy ions can be understood in terms ofthe interplay of reaction dynamics and the formation of deformed shape-isomers in the compound nucleus. This discussion leads us to assign the ^{12}C + ^{12}C barrier resonances to a reflection asymmetric configuration which has a large parentage with ^{12}C(g.s.) + ^{12}C(0_1^+) and the broad higher energy resonances to a configuration similar to two oblate ^{12}C nuclei lying in the same plane. These results, we believe, firmly establish resonances seen in heavy-ion collisions as a feature of the nuclear structure of the composite system.

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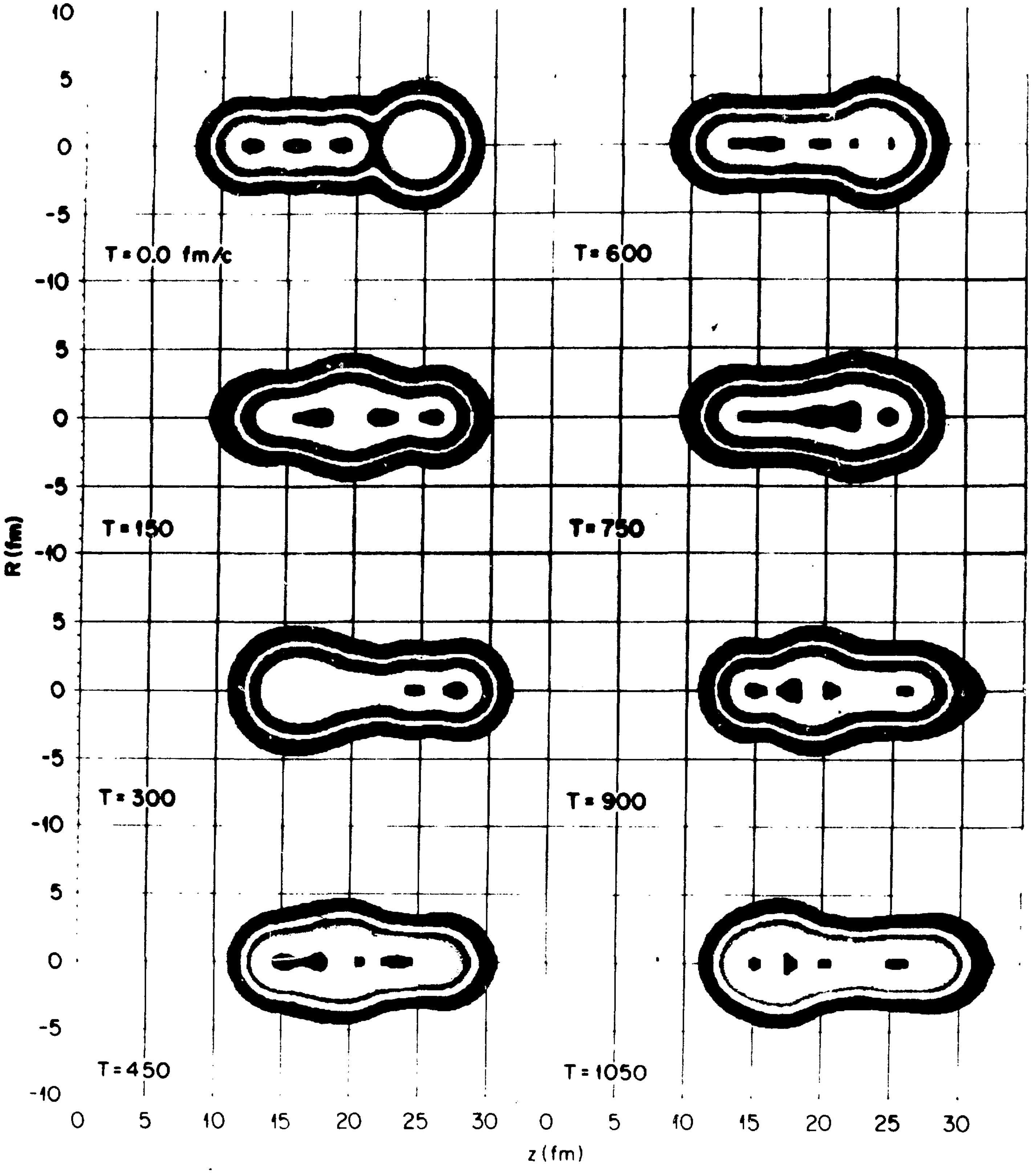

R (fm)
z (fm)
10
5
0
-5
-10
T = 0.0 fm/c
T = 150
T = 300
T = 450
T = 600
T = 750
T = 900
T = 1050
0
5
10
15
20
25
30

Fig. 11