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Abstract :

The time dependence of the ^{40}Ca + ^{40}Ca deep inelastic collisions is studied from the charge and mass distributions of fragments. Two time-components are unfolded. The "fast" one exhibits all features of "quasi-fission". The characteristics of the "slow" component cannot be distinguished from compound nucleus fission.

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The observation of "strongly-damped" heavy-ion reactions has prompted many experimental studies. The main features of these reactions are now well established (1-2). It has been shown (2-3) how the so-called "deep inelastic collisions" (D.I.C.) and "quasi-fission" essentially result from the same physical process but manifest themselves differently, according to the relative importance of the Coulomb repulsion. Although the quasi-fission phenomenon exhibits features which rule out any confusion with the compound nucleus fission, the situation is not so clearcut in the D.I.C. case where broad Z-distributions and nearly $(\sin \theta)^{-1}$ dependence of the angular distributions at backward angles are observed for large mass and charge transfers. For products closer to the projectile, the forward peaked angular distributions and the narrow Z-distributions can be considered as evidence for a non-compound mechanism.

An earlier experiment (4) has shown that the main characteristics of the ^{40}Ca + ^{40}Ca D.I.C. remain in good agreement with the general trends mentioned above. This letter reports on some new data on the same system. In discussing the observed angular and charge distributions, we attempt to discriminate between the "fast" and "slow" reaction mechanisms which manifest themselves in the studied reaction.

The mass and charge symmetry of the chosen system (^{40}Ca + ^{40}Ca) significantly simplifies an interpretation of the results because the entrance-channel symmetry leads to the symmetry in the exit channel as far as binary processes are considered. Therefore, even an inclusive experiment for such a symmetric system may provide information on emission of light particles from the reaction products. Moreover, studying the D.I.C. in a symmetric system one can easily determine the diffusion parameter (2,5) entering the Fokker-Planck equation, because the drift coefficient must be equal to zero in case of the mass and charge symmetry. Among other symmetric systems the ^{40}Ca + ^{40}Ca combination seems to be especially interesting because the closed-shell structure of ^{40}Ca is very suitable for microscopic calculations of the reaction dynamics (6). It is important also that the elastic (7) and fusion (8) channels are well-known for this particular reaction.

In this paper we discuss some aspects of the reaction mechanism using a part of the data on the ^{40}Ca + ^{40}Ca reaction obtained previously (9 -10), together with new data obtained at $E_{lab} = 256$ MeV for many Z's of the reaction products ($5 \lesssim Z \lesssim 28$) detected in a wide angular range ($7.5^{\circ} \lesssim \theta_{lab.} \lesssim 50^{\circ}$) using the Δ E-E telescope technique (11).

The measured energy spectra were transformed to the center-of-mass energy spectra $d^2\sigma/d\,\theta_{c.m.}\,dQ$ assuming the two-body kinematics. All the spectra exhibit the deep inelastic component. (The quasi-elastic component which is present only for $Z \gtrsim 20$ is not discussed in this letter). The most probable c.m. energy corresponding to the deep-inelastic maximum is plotted in fig. 1 as a function of Z and compared with the energy of the Coulomb repulsion calculated for two touching spheres. It is seen from fig. 1 that heavy products ($Z > 20$) have significantly lower energies than the calculated Coulomb energy. This may suggest that the heavy fragments evaporate more nucleons that the light ones. It is worth emphasizing that the average c.m. energies for Z's close to 20 largely exceed the energy of the Coulomb repulsion (especially at forward angles). This means that these products do not undergo the complete relaxation of the kinetic energy.

Strongly-relaxed ($-110 \lesssim Q \lesssim -30$ MeV) cross sections, when plotted as a function of Z for different c.m. angles exhibit two distinct features : at $\theta_{c.m.} = 20^{\circ}$ the Z distribution is narrow and peaks close to Z = 20 ; with increasing angle the maximum of this distribution shifts towards smaller Z's and its width increases. The first two moments of this distribution, $\bar{Z}$ and $\sigma^2_z = \overline{(Z - \bar{Z})^2}$, are shown in fig. 2 as a function of angle. Both curves exhibit a rapid variation from 20° to 40° (c.m.) then become flat at larger angles. It was checked that these characteristics remain the same if the analysis is performed for a much narrower range of

Q values ($-80 < Q < -70$ MeV). This is consistent with our previous study of the isotopic distributions in the $^{40}Ca + ^{40}Ca$ reaction at E_{lab} = 284 MeV (10). It was found that the whole (Z, N) distribution shifts when $\theta_{c.m.}$ increases. Its maximum goes from (Z, N) = (19, 20) for $\theta_{c.m.} = 15^{\circ}$ to (17, 18) for $\theta_{c.m.} = 30^{\circ}$. It is thus confirmed that light particle emission is not a dominating mode of deexcitation of the fragments emitted at forward angles.

It appears very attractive to relate the variations of $\bar{Z}$ and σ_z and the shape of the differential cross section (fig. 2) to the existence of an incompletely relaxed component in the energy spectra observed at forward angles. To shed some light on to this problem, we have split the relaxed cross section into two components. This was achieved in attributing the whole of the cross section at 90° (c.m.) to a "slow component", with a $(\sin\theta)^{-1}$ angular distribution. For this component, a broad Z-distribution is then obtained, the mean value of which is close to 17. This component is thus observed after a sizeable amount of evaporation (a noticeable odd-even pattern is observed which fits well into this frame). Substracting this component, one is faced with a fast process characterized by exponentially decreasing angular distributions and very narrow, angle-independent, Z-distributions ($\bar{Z} \simeq 19$ and $\sigma_z \simeq 3$) as shown in fig. 3. The resulting spectra are peaked approximately 20 MeV above the exit channel Coulomb barrier. By these properties which are characteristic of a short interaction time, this "fast component" behaves in all respects as the so-called "quasi-fission". As it was pointed out above, the number of evaporated particles from the reaction products corresponding to the "fast component" is very small, in spite of the high excitation energy. One can suppose, therefore, that the excitation energy is shared mostly among collective modes.

Before further discussion, attention should be paid to the effects of the entrance channel symmetry. Events occuring at $(\pi - \theta)$ cannot be distinguished from those at θ. The deep inelastic processes at backward angles are expected to be completely relaxed and to have angular distributions nearly like $(\sin\theta)^{-1}$. In case of the symmetric system, they must contribute to the "slow component" at forward angles.

There is no doubt that the "slow component" includes the compound nucleus fission which, in this particular system, cannot be distinguished from the two-body completely-relaxed reactions. The total cross section of the "slow component" is found to be 280 mb. This agrees with predictions of the fusion-fission cross-section based on the liquid drop model (12). It should be mentioned that a similar ambiguity seems to appear in experimental data on non symmetric systems where broad Z-distributions are observed.

The "fast component" exhibits an angle-focusing which immediately calls for a rainbow effect usually associated with less damped collisions. It should be noted that the grazing angle for the ^{40}Ca + ^{40}Ca collisions at E_{lab} = 256 MeV is quite small (θ_{gr} (c.m.) $\simeq 30^{\circ}$). The observation of the "fast component" up to 50° c.m. shows that the relaxed ($Q \lesssim -30$ MeV) ^{40}Ca + ^{40}Ca collisions feeding this component can be ascribed to trajectories which cross the beam direction. The cross section for this process becomes negligible with respect to the "slow component" cross-section at angles larger than 50° cm.

Maybe our arbitrary way of removing the fission part from the D.I.C. can lead us to too sharp a discrimination between fast processes (similar to "quasi-fission") and slow decays of the "composite system". However, it must be emphasized that removing the "slow component", one obtains a completely different time scale of the remaining part of the D.I.C. as compared with usual analysesin the frame of the diffusion models (2,5). Moretto and Sventek found (2) that the characteristic diffusion time is comparable with the rotational period of a colliding system. However, the fusion-fission cross-section was not substracted in the analysis (2). It seems very probable that the diffusion time scale is much closer to the energy damping time scale than that reported in ref (2).

The diffusion model formalism must now be applied to the only "fast" non-compound part of the cross section. However, the variance is found to be constant, whereas Nörenberg (5) predicts a linear dependence with angle. One possible explanation of the discrepancy may be attributed to the fact that the ^{40}Ca + ^{40}Ca collisions do not fulfil very well the requirements for a classical description, and therefore the classical correspondence between time and the scattering angle is not valid.

To summarize this letter, it is proposed that one can understand the D.I.C. as resulting from two coexisting phenomena : a slow one, indistinguishable from fission and a much faster one, showing all the characteristic features of the so-called "quasi-fission". Only the "fast component" of the cross-section can be related to the diffusion mechanism, but the time scale of the diffusion is quite short, comparable with the time scale of the energy damping. This mechanism leads to high excitation energies, but Z-distributions of the reaction products remain narrow. Only a small part of the excitation energy is dissipated in particle emission. This indicates that collective modes are excited predominantly.

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Figure Captions

Figure 1 : Average c.m. total kinetic energy of the deep inelastic part of the energy spectra as a function of Z for various angles. The kinetic energies resulting from the Coulomb repulsion of two spherical fragments, $B_c = Z_1 Z_2 e^2/1.225(A_1^{1/3}+A_2^{1/3})+2)$ are also shown (full line).

Figure 2 : Characteristics of the deep inelastic processes in the $^{40}Ca + ^{40}Ca$ reaction at 256 MeV, as a function of angle :

a) angular distributions $d\sigma/d\theta$ for various elements close to Z = 20 ;

b) average Z-value, and

c) variance σ_Z of Z distributions.

Figure 3 : Z-distributions of the "fast deep inelastic component" at various c.m. angles.

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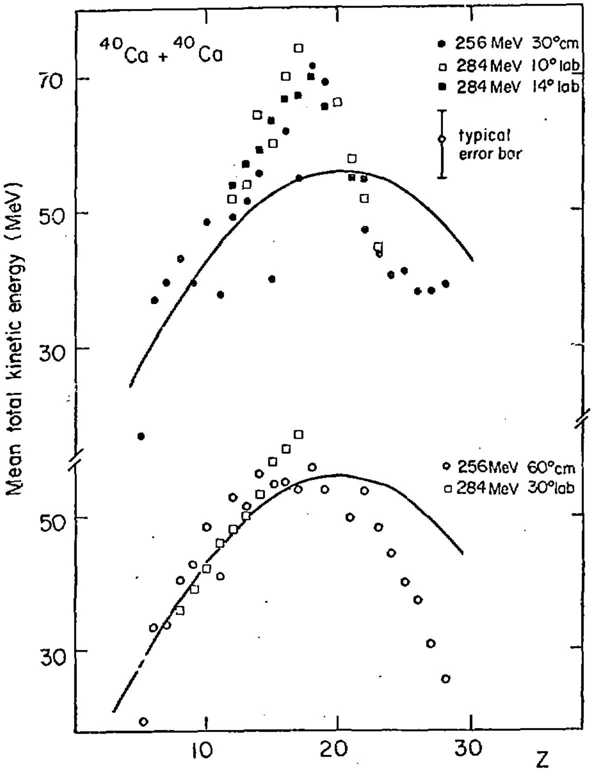
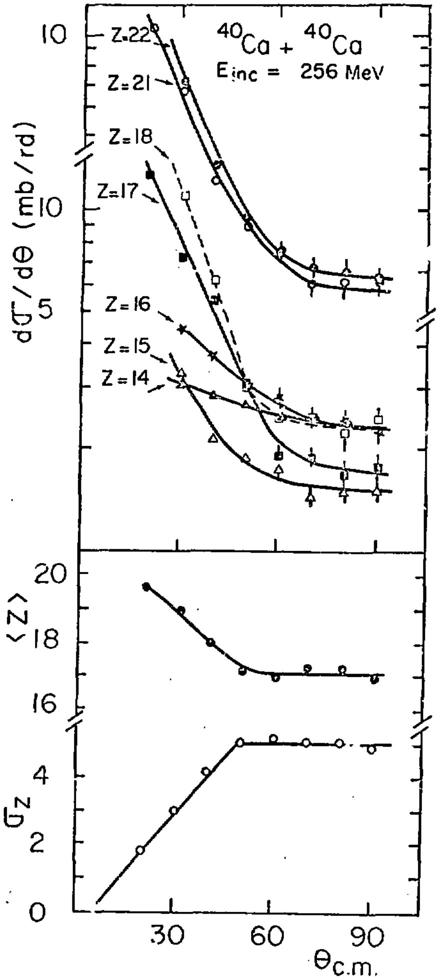
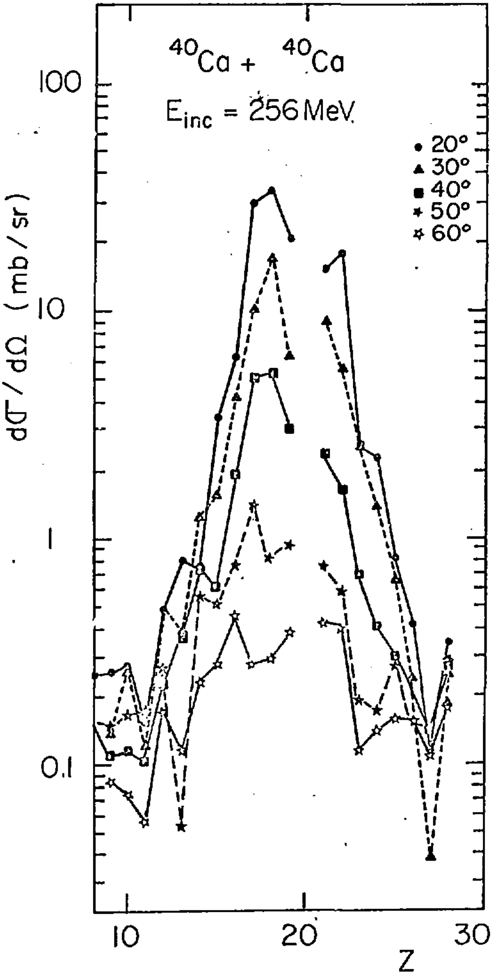

^{40}Ca + ^{40}Ca
● 256 MeV 30°cm
□ 284 MeV 10° lab
■ 284 MeV 14° lab
typical error bar
○ 256MeV 60°cm
□ 284 MeV 30°lab
Mean total kinetic energy (MeV)
70
50
30
50
30
10
20
30
Z

1



$^{40}Ca + {}^{40}Ca$
E_{inc} = 256 MeV
Z=22
Z=21
Z=18
Z=17
Z=16
Z=15
Z=14
$d\sigma/d\theta$ (mb/rd)
10
10
5
20
18
16
⟨Z⟩
σ_Z
4
2
0
30
60
90
$\theta_{c.m.}$

2


^{40}Ca + ^{40}Ca
E_{inc} = 256 MeV
● 20°
▲ 30°
■ 40°
★ 50°
☆ 60°
$d\sigma / d\Omega$ (mb/sr)
100
10
1
0.1
10
20
30
Z

3