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SALIENT FEATURES OF HEAVY ION REACTIONS IN THE INTERMEDIATE ENERGY REGION

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ABSTRACT: Experimental results from devoted medium energy heavy ion accelerators are beginning to fill up the gap in our knowledge of the heavy ion reaction pattern between the low energy - binary - side and the high energy - participant/spectator - side. This paper is focused on new results on central, violent collisions in the medium energy region.

1. INTRODUCTION

Compared to the nucleon size, heavy nuclei are strongly extended objects and therefore we expect the impact parameter to be a very important variable in heavy ion reactions along with the collision energy. We have learned that by decreasing the impact parameter in the low energy range we find elastic -, inelastic -, few nucleon transfer -, deep inelastic - and compound reactions. The grazing types of collisions are rather well described by standard optical and distorted wave models throughout a large energy range. When deep enough interpenetration between the nuclei occurs a strong transport of energy and mass between the original nuclei takes place. At low energies, where the reaction time is long but the available excitation energy limited, we find the deep-inelastic type of collisions i.e. a binary reaction followed by a slow equilibrium deexcitation process (evaporation). At higher energies the system may locally reach such high excitation energies that a fast escape of fragments can occur. The dominating parts of the nuclei still remain as evaporating sources and thus we have now a separation between participating and spectating volumes - a separation which becomes clean in the GeV per nucleon region ^{1}). In the participant region we find that nucleon - nucleon collisions become important and therefore we must add to any pure mean-field description or to the any one-body-density equation model also a scattering term ^{2}).

In this lecture I will focus on the most central and therefore generally also the most violent collisions. We must here remember that the participating and non-participating regions could behave differently in symmetric and asymmetric reactions as illustrated in Fig. 1.

The possible onset of the multifragmentation channel or rather the cease of the fusion process is the first topic to be discussed below. This subject is directly related to the limitation in energy- and momentum transfer and thus to the question about nucleon transparency. If the onset of multifragmentation can be established, it is a challenge for theorists to describe such a process properly. Various multifragmentation models do exist 3-8) which treat the breakup process itself but they do seldom include a detailed prehistory for the creation of the sources which break up. Exclusive data on multifragmentation on an event-by-event basis, which may help the model constructors, is presented as the second topic in this report. Observables for critical phenomena which may be related to a liquid-gas phase transition in the hot region of the reaction volume will be discussed as well as data on particle correlations and some suggestions for their origins. Finally we recall that in the medium energy region one finds the thresholds for producing pions and kaons. It seems obvious, that the participating volumes must hide the creation process of these particles, but the processes themselves are still unclear.

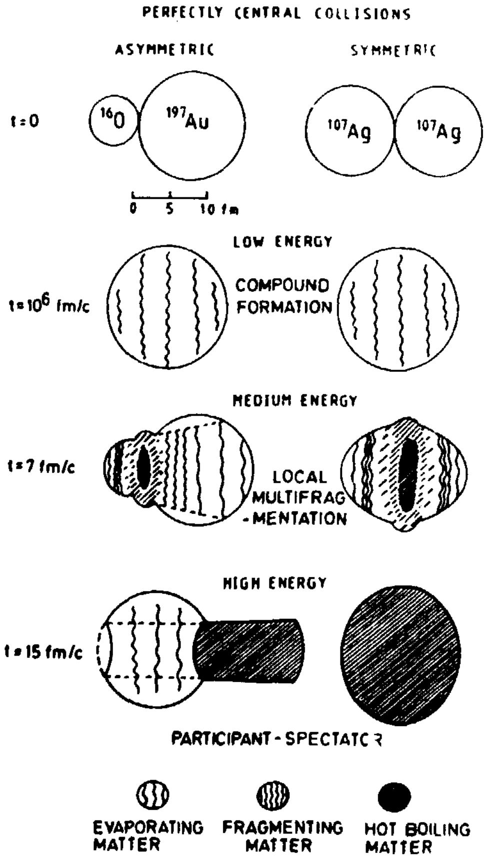

Fig. 1. Schematic picture of participant and spectator volumes in symmetric and asymmetric central heavy ion collisions.

2. THE ONSET OF THE MULTIFRAGMENTATION

No outstanding parameter which selects small impact parameter collisions exist. A large particle multiplicity is a natural consequence of large excitation energy and therefore a reasonable filter for central collisions. In the low energy binary reaction region a maximum momentum transfer to the compound system should also be a hint of a central collision. A nice way to study momentum transfer is via the fusion-fission process. Fig. 2 shows folding angle distributions of the fission products in ^{40}Ar+ ^{232}Th and ^{50}Ni+ ^{232}Th reactions 9). It is quite obvious that the central (small folding angle) fission channel gradually disappears with increasing energy whereas the main peripheral channel remains with the same strength throughout the energy region 20A - 44A MeV. The immediate thought that the strong momentum transfer process becomes limited due to nucleon transparency at 40A MeV is not necessarily correct. One still observes a "background" of fragments in the fission detectors. If we proceed to another experiment where recoil fragments are studied directly with radiochemical technique 10) (see fig. 3) we notice that though in general the recoiling nucleus gets less and less momentum transfer there is even at 49A MeV almost complete momentum transfer events. Consequently it is rather so that we find around 40A MeV the onset of another reaction channel, incomplete fusion - or perhaps (in other words) multifragmentation.

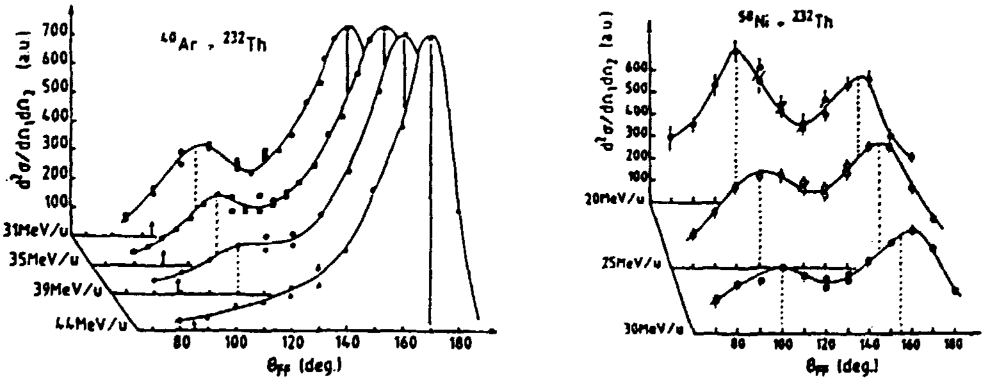

Fig. 2. Fission fragment folding angle distributions 9).

An interesting way to look for the correlation between the folding angle and another impact parameter signal, the neutron multiplicity, has been presented by Galin et al. [11]). In the fusion domain (15A MeV Ne + U) the situation is very clear (Fig. 4). The central fission peak is connected with the largest neutron multiplicity and this multiplicity decreases monotonously with decreasing momentum transfer. It should be noticed that the width of the multiplicity distribution remains nearly the same irrespective of the momentum transfer [11]).

Let us for a second accept that the highest multiplicity - also of charged particles - is associated with b = 0 events. Fig. 5 shows the $^{16}O + ^{107}Ag$ events of highest multiplicity registered in nuclear emulsions [12,13]) at various energies. Obviously the onset of multifragmentation takes place between 30A and 40A MeV since the recoiling compound nucleus is so clearly observed below 34A MeV whereas it is absent above that energy.

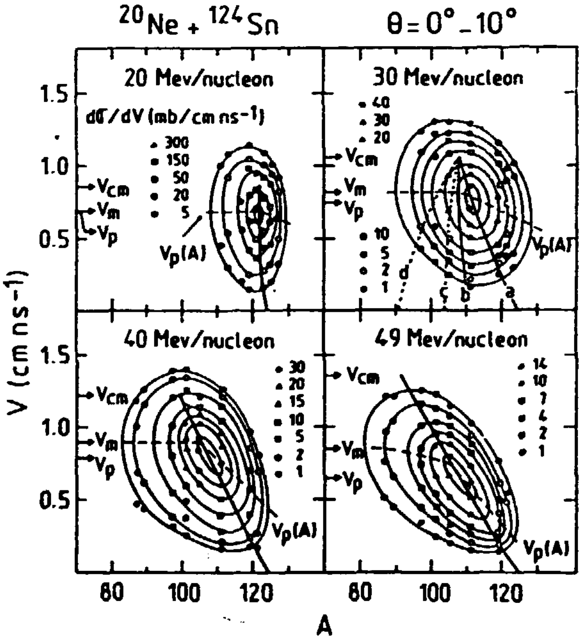

Fig. 3. Mass-velocity distributions of residues in Ne+ Sn reactions at 20A, 30A, 40A and 49A MeV [10]).

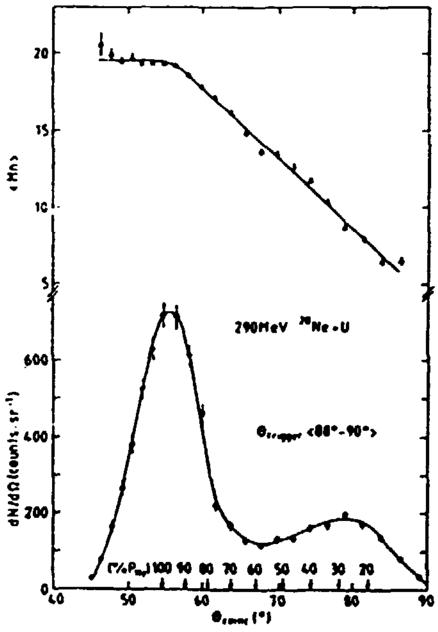

Fig. 4. Folding angular distribution of fission fragments and average neutron multiplicities for a certain folding angle in 15A MeV Ne+ U collisions [11]).

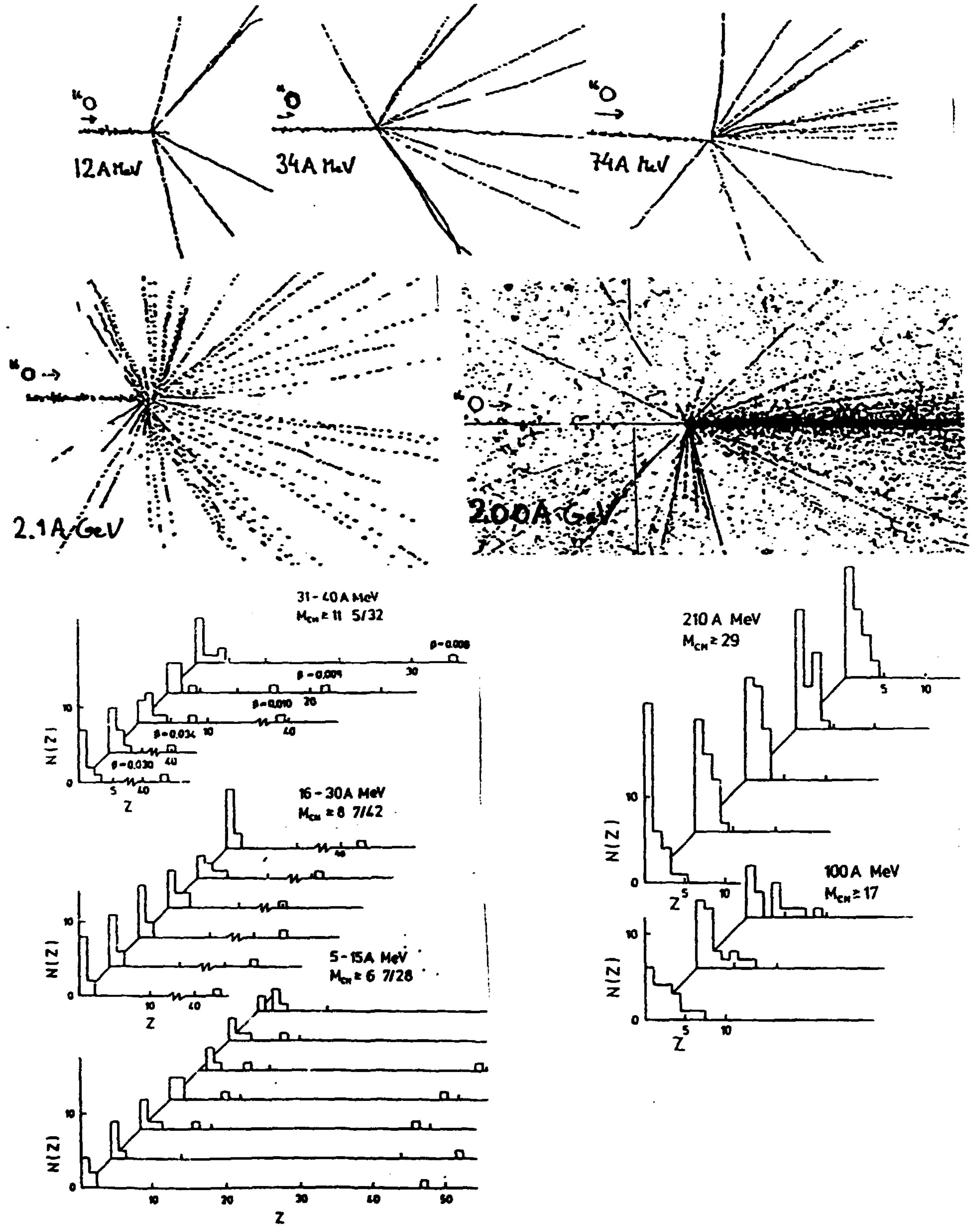

Fig. 5. The largest (highest charged particle multiplicity) $^{16}O + ^{107}Ag$ event observed in 12-14) at various energies and the event-by-event charge distribution in the highest multiplicity bin.

3. FRAGMENT SIZES IN MULTIFRAGMENTATION PROCESSES

The close relation between maximal multiplicity and minimum impact parameter is in general well established throughout the energy domain discussed here. Only in nuclear emulsion experiments 12-15) can one so far measure the total charged particle multiplicity and correlate it to other observables. Fig. 6 shows how the maximal multiplicity increases smoothly with energy for almost symmetric collisions (^{84}Kr+ ^{107}Ag) until it crosses the total nucleonic breakup line (M^{CH} = 83) at about 1A GeV and then the increase follows due to pion production. Asymmetric collisions (^{16}O+ ^{107}Ag) do not fully reach the nucleon (or rather Z=1) breakup situation below 2A GeV * which may first be attributed to the fact that a clean spectator - cut exists. However, it has been pointed out in 12) that no spectator-like group of particles are observed when measuring the momenta (vectors) of all particles in such collisions.

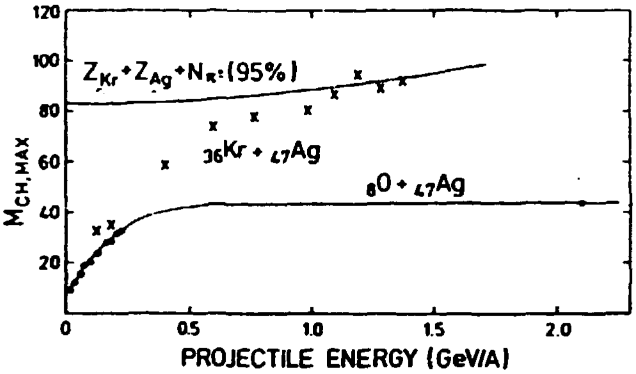

Fig 6. The maximal charged particle multiplicity as a function of bombarding energy in ^{16}O+ ^{107}Ag and ^{84}Kr+ ^{107}Ag collisions. The upper curve shows the expected total breakup + maximum π production (at the 5% probability level) 12).

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* Very recent results with enhanced statistics show that the maximum multiplicity is ≈ 55 (Z_O + Z_{Ag} = 55) at 2A GeV but this number contains about five pions.

More selective information is obtained in measuring the complete charge distribution event-by-event 13). Fig. 5 gave examples of high multiplicity events at energies from 15A to 200A MeV. When comparing perculation calculations and thermodynamical calculations Campi 16) finds that higher moments of the charge (or mass) distribution may be very sensitive parameters for selecting among models. Close to a critical point (transition point) the cluster size distribution should have the simple form (p, (p_c) is the (critical) fraction of occupied sites or the (critical) temperature:

$$n(Z,p) = Z^{-\tau} f\left[(p-p_c)Z^{\sigma}\right] \qquad (1)$$

with f(0) = 1.

The critical exponents τ and σ are 2.2 and 0.45 in a site perculation calculation for infinite systems 16) whereas a perfect liquid-gas phase transition (Van der Waals gas) gives 7/3 and 2/3 respectively. Using the charge distribution moments:

$$M_k = \sum_j Z_j^k n_j(Z,p) \quad ; \qquad S_k = M_k \,/\, M_1 \qquad (2)$$

one finds with the scaling relation given earlier:

$$S_k \sim |p-p_c|^{-(\tau-k-1)/\sigma} \qquad (3)$$

and $\ln(S_2) = \tau-4/\tau-3$, normally written $1 + 1/\sigma\gamma$.

$\sigma\gamma$ is 0.81 in the perculation model and 2/3 for the liquid-gas system since γ here is 1.

Fig. 7 shows recent results from complete Z-distribution measurements 13) in very central (high multiplicity - no target-like fragment) $^{16}O + ^{107}Ag$ collisions at 200A MeV. $\sigma\gamma$ is determined to be 0.87 ± 0.02 thus close to the perculation prediction (slightly larger values for $\sigma\gamma$ are obtained in finite nuclei perculation calculations 16) as compared to 0.81 for infinite systems). Clearly we are far away from a perfect liquid-gas situation (also the fluctuations around the straight line tell us this). However one must notice that e.g. calculations within the Fai-Randrup 5) explosion-evaporation model also give $\sigma\gamma$ values very close to the experimental one.

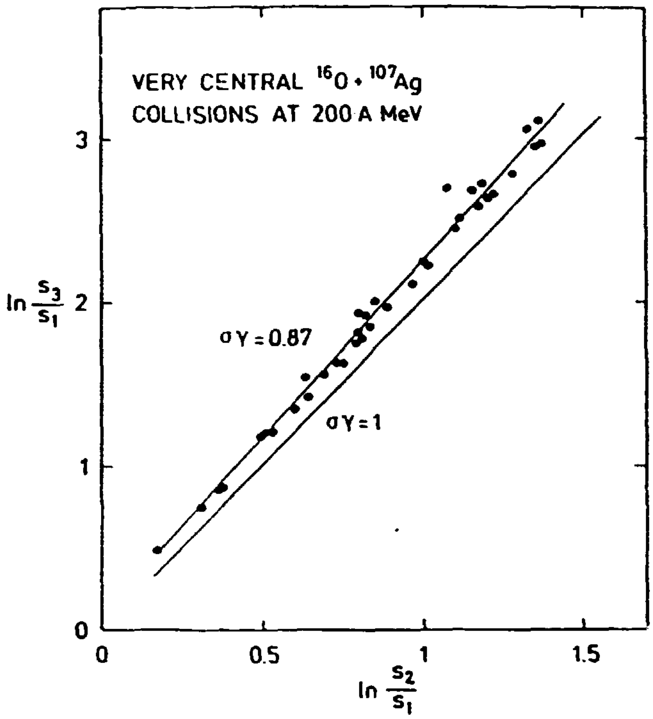

Fig. 7. An S_2 - S_3 plot of the kind described in the text for central 200A MeV $^{16}O + ^{107}Ag$ events [13].

Thus these results raise the question whether "standard" fragmentation models, treating the creation of sources of statistical emission in a reasonable way, are able to come to the same results concerning breakup as the perculation approach. Attempts to find more selective parameters to correlate in order to be able to observe critical phenomena in general is presently under discussion. More experimental data of the kind shown in Fig. 7 is urgently needed and one could hope that counter detector systems will be sophisticated enough, soon enough, to produce multi- fragmentation results without severe kinematical cuts.

4. THE ORIGIN OF LIGHT PARTICLE CORRELATIONS

In many experiments back-to-back correlations have been observed for two protons [17-21]. It is of course easy to accept that direct quasi-elastic NN scattering particularly in peripheral collisions contributes to these correlations. In paper [19] one shows very nicely how the strength of the in-scattering-plane peak is largest when the breakup of the 60A MeV Ar projectile (colliding with a gold nucleus) is small. However one still observes back-to-back correlations in central collisions. This result together with the fact that the in-scattering-plane excess can be even stronger for combinations of heavier particles (Fig.8) [21] makes us believe that other processes than NN scattering must contribute strongly to the correlations.

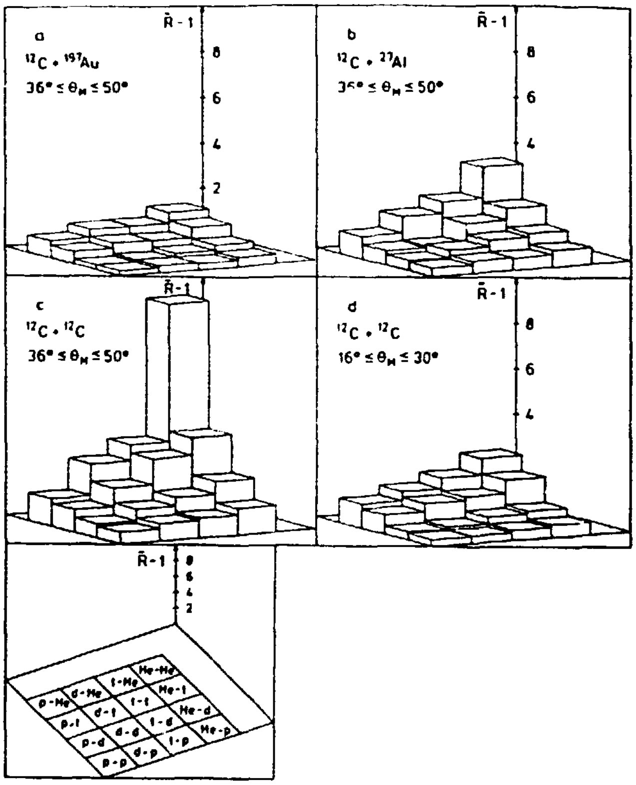

Fig. 8. The correlation function (R; in-plane cross section divided by out-of-plane cross-section for θ_T =45 , 30 $\leq E_M \leq$ 65 MeV/A and 20 $\leq E_T \leq$ 50 MeV/A, θ_M see figure) for various ^{12}C induced reactions at 85A MeV and various particle combinations (see lower figure).

In particular the concept of a sequentially recoiling thermal (participant source) has been introduced with some success [17]) especially when the rotation of the source is included. However, when comparing results at 25A MeV, 60A MeV and 85A MeV one observes some differences in the correlation spectra. E.g. one finds a different target mass dependence and different relative correlation strengths with the azimuthal angel between the particles 0°, 90° and 180° [21]).

This could possibly be due to shadowing effects but complete calculations which treat the reaction dynamics properly must be performed to investigate this point further.

Another kind of correlations which may carry direct information about the hot zone in central collisions has been very clearly established at all energies between 20A an 2000A MeV [20-25]). The typical result is the peak in the two-particle cross-section for small momentum differences (Δp). Fig. 9 shows how similar the results are for asymmetric collisions from 25A to 85A MeV [20-23]). With second order quantum interference calculations one is able to extract sizes of the emission sources for these non-evaporation protons. These sizes are all of the order of 3-4 fm [26,27]).

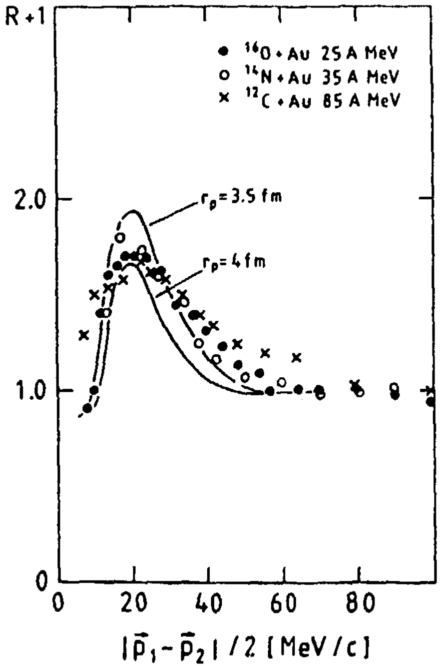

Fig. 9. The ratio (R) of the two-proton cross section and the product of the inclusive cross-sections as a function of $\Delta\vec{p}$ in asymmetric heavy ion collisions at three energies. Source size estimations from D. Boal [28]).

Some doubt has however been thrown on the source radius extraction from small Δp-correlations in particular since there is a lifetime (t) dependent term in the expression for the radius [29]:

$$R = \frac{\left[J_1\ (\Delta p_\perp,\ r)\ /\ \Delta p_\perp r\right]^2}{1 + (\Delta E)^2\ t^2} \qquad (4)$$

$\Delta p_\perp$ is the relative transverse momentum between the particles and ΔE the corresponding relative energy. J_1 is the first order Bessel function.

In order to measure the impact parameter dependence of the source radius two different methods have been introduced. The multiplicity of protons or projectile-like fragments have been measured and the folding angle in low energy (35A MeV) reactions has been measured in coincidence with the two-fragment correlation function. Two-proton correlation results at 400A MeV [24] (symmetric reactions) (Fig. 10) and d-α correlation results [20] at 60A MeV (asymmetric reactions) (Fig. 11) agree on the statement that the height of the correlation peak decreases with larger multiplicity i.e. with smaller impact parameter. In the interferometry description this means a larger source for central collisions which of course is naively expected. If we however now look at a 35A MeV (asymmetric) folding angle experiment [31] this has the opposite tendency (Fig. 12).

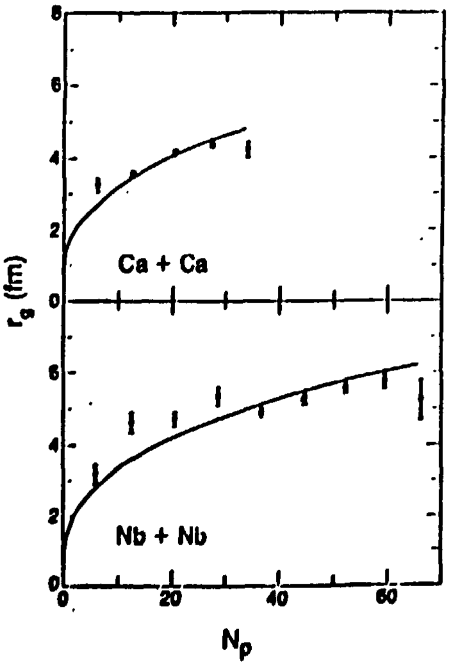

Fig. 10. Extracted source radius as a function of high energy proton multiplicity in 400A MeV collisions [23].

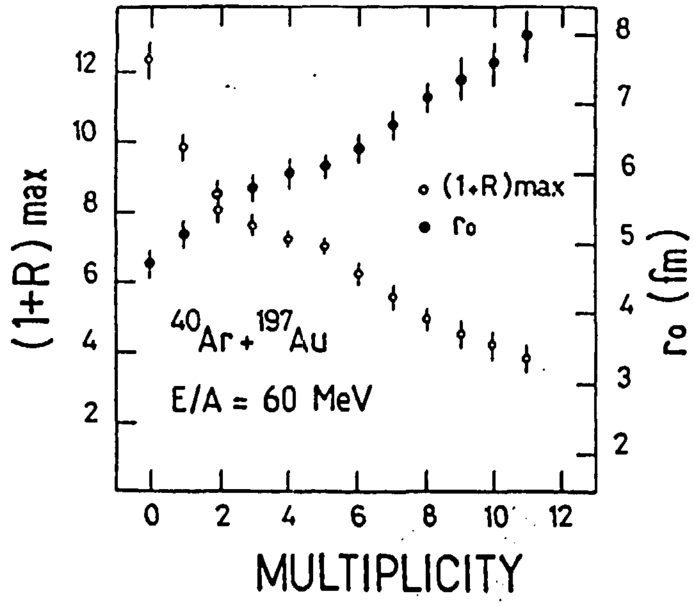

Fig. 11. Source radius and maximum correlation level for d-α correlations [30].

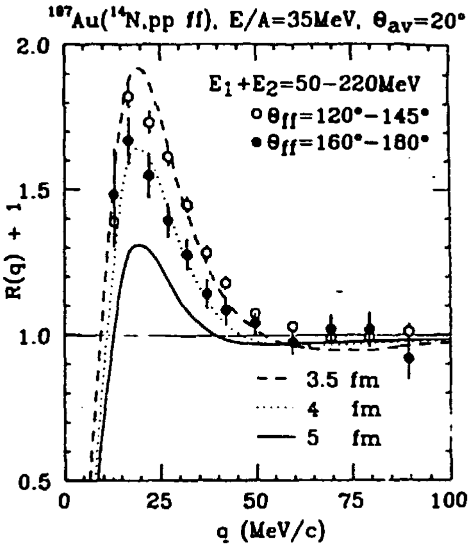

Fig. 12. p-p correlation function gated on small (central collisions) and large (peripheral collisions) folding angles of fission fragments [31]).

One possible explanation for this effect is that it is rather the difference in the reaction time than a difference in the source size which is observed. In this way one could also explain the results in Fig. 11 simply by saying that the source size is constant but that the emission time is proportional to the collision time which increases for decreasing impact parameter.

Concerning two-particle correlations I would like to finish by reminding about the possibility that particle-instable fragments (e.g. ^{2}p) could contribute substantially to the observed peaks. It would be helpful if calculations which include the complete emission and decay scheme for particle-instable states could be performed within the framework of "standard" (e.g. thermal) models.

5. EMISSION OF PIONS AND KAONS CLOSE TO THE THRESHOLD

Not even well above the nucleon-nucleon scattering threshold is impact parameter selected data on pion production easily reproduced by "standard" models. This fact is illustrated in Fig. 13 where experimental yields of π^- in central Ar + KCl reactions [32]) are compared to microscopic model predictions [33]). Pure cascade models, which in general reproduce particle production in high energy collisions well, severely overestimate the π^- yields.

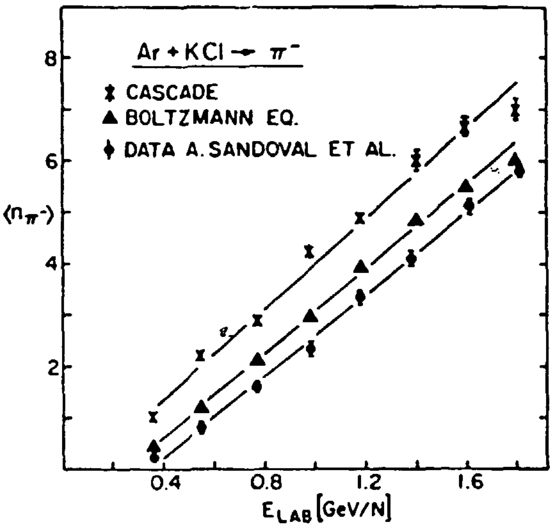

Fig. 13. Average π^- multiplicity in central Ar+ KCl reactions as a function of bombarding energy [32]) together with cascade- and VUU predictions [33]).

Below the NN threshold there has been some success in explaining inclusive cross-sections from simple first NN collision models where the nucleon momenta are boosted by the internal momentum distributions. Below a certain energy limit, say 100A MeV, such descriptions underestimate the cross-sections severely [34-36]) and collective processes must apparently be introduced. It is beyond the frame of this paper to discuss the flurry of collective models which exists and for a review about the present status concerning confrontation between these models and data I refer to [37,38]).

More exclusive pion production data is still sparse and here I make only two comments about it. The first concerns the comparison between π^0 production and hard photon production which exhibits great similarities [39]). Measurements of the projectile energy dependence of the cross-sections and the energy slope parameter for π^0 and γ with the same detector system [40]) are shown in Fig. 14.

Obviously photons with energies 100-150 MeV are emitted with spectra very close to the intergrated π^0 spectra. Speculations around similar radiative processes have been made and the preliminary conclusion 39) is that non-equilibrium processes, like incoherent bremsstrahlung with the help of the high momentum components of the internal nucleon velocities, could possibly explain the data. This should then be a hint of that early nucleon-nucleon collisions may create enough pions. If so central collisions result in emission spectra similar to those in peripheral collisions. Since the later breakup of the nuclei still may be very different in central and peripheral collisions it is important to measure pions in correlation with impact parameter selective signals.Several experiments have been performed very recently to provide us with such data but very little is so far published and I can here only cite one statement made by A Oskarsson et al. 41) concerning

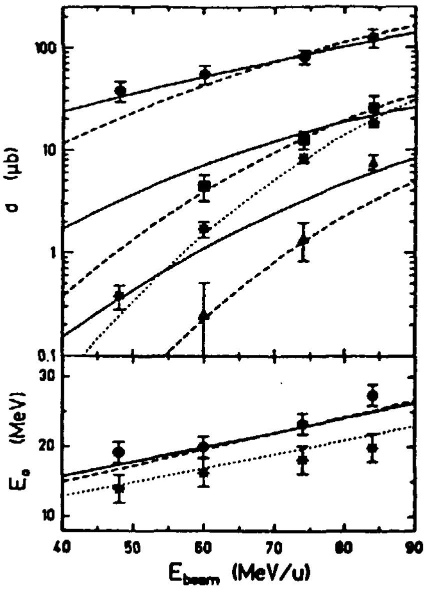

Fig. 14. Projectile energy dependence of photon production and production in $^{12}C + ^{12}C$ collisions.

Top: Cross-section for $50 \leq E\gamma \leq 100$ MEV ( )

$100 \leq E\gamma \leq 150$ MEV ( )

$E\gamma \geq 150$ MEV (Δ)

π_0 Integrated (*)

Bottom: Energy slope parameters (E_0) for $E\gamma \geq 3E_0$ and $E\gamma \geq m_\pi + 3E_0$. For further details see paper 39).

projectile-like fragment measurements in 48A MeV $^{12}C + {}^{12}C$ collisions: "Pion producing collisions seem to have a much lower probability to emit projectile-like fragments than the average type of collision". The conclusion should thus be that central collisions are preferred.The final question to be answered is then whether pions indeed are emitted at a very early (pre-equilibrium) stage of the reaction or not. This question is indeed a challenge for the experimentalists!

Finally I would like to stress that if subthreshold kaons could be measured [42]), possibly with new high luminosity heavy ion accelerators in the hundreds of MeV per nucleon region, this would give us a probe for the hot participant region much less affected by the surrounding matter than pions.

6. CONCLUSIONS

It may appear as if more questions than answers have been given in this collection of medium energy heavy ion reaction topics. I am convinced that this is a healthy sign for a field of physics being in its "second stage" of the experimental evolution. The richness of this field - indeed a transition region in the map of heavy ion reactions - has become obvious only now and I am sure of that the investments in dedicated medium energy accelerators which we see today will pay off well.

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