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# - THE CURRENT EXPERIMENTAL KNOWLEDGE

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INVITED TALK PRESENTED AT THE 4TH NORDIC MEETING ON INTERMEDIATE AND HIGH ENERGY NUCLEAR PHYSICS, GEILO, NORWAY, JANUARY 5-9 1981.

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# INTERMEDIATE ENERGY HEAVY ION INTERACTIONS - THE CURRENT EXPERIMENTAL KNOWLEDGE

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A review of the present experimental situation of intermediate energy heavy ion reactions is presented. The energy range discussed is 20-250A MeV i.e. close to the interval between the nuclear "speed of sound energy" and the pion production threshold. Some approaches from low energy - as well as high energy nuclear reaction physics are discussed.

## 1 Introduction

Heavy ion collisions below 20A MeV have been extensively studied for several years using the numerous conventional Van de Graaff- and cyclotron accelerators that exist. Consequently the behaviour of nuclei in reactions close to the Coulomb barrier is well established as indicated in Fig. 1. Following the energy ladder upwards we find a region of weak knowledge between 20A MeV and 250A MeV i.e. between the UNILAC and BEVALAC regions. In the lower part of the relativistic region we have been bombarded with data from the BEVALAC and the Dubna Synchrophasotron during the last decade. Above 4A GeV we have some information from cosmic ray experiments - less and less with increasing energy due to the cosmic ray energy spectrum ($I_{C.R.} \sim E^{-2.5\pm0.2}$) - ending up at the TeV/nucleon region with the spectacular deficiency of $\pi^0$:s in the CENTAURO-events /1/.

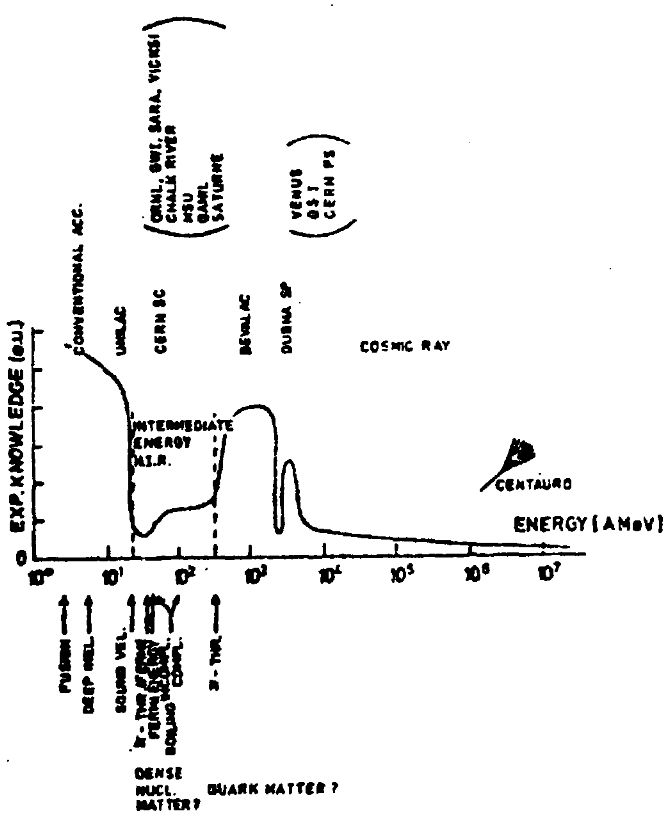


Fig. 1 The experimental situation Jan. 1 1981. Mass dependent thresholds are given for $^{12}C + {}^{107}Ag$ reactions.

In fact we may soon enough come close to the CMS-energy of a CENTAURO event in our laboratories if the colliding beam projects of VENUS-LBL(Berkeley),GSI (Darmstadt) or CERN (ISR) are realized.

The energies between the nuclear "speed of sound energy" and the pion production threshold, where our knowledge is weak, coincide with the topic to be discussed here. The deep ignorance - due to lack of accelerators - is now becoming less deep mainly due to data reaching us from the BEVALAC, which is now operating with lower energies, and from the CERN synchrocyclotron producing intense (> $10^{10}$ $s^{-1}$) beams of C-Ne ions at < 120A MeV as from late 1979. In a near future a few accelerators dedicated to intermediate energy heavy ion beams will start to operate as noted in Fig. 1.

Our intuition of what might go on in a heavy ion interaction at intermediate energies is naturally colored by our experiences from the physics at higher and lower energies. Somewhere there is bound to be a transition from the complete damping as we know it at low energies to the damping only of that part of the $A_1+A_2$ system, determined by a more or less clean cut geometry, which participates in a high energy collision.

We could think of this transition region as the "boiling" region /2/ where the available energy in some participant CMS exceeds the binding energy of the nucleons i.e. where

$$\frac{a_1 a_2}{(a_1+a_2)^2}\,\varepsilon_{inc} - \varepsilon_B > 0 \quad . \qquad (1)$$

Here $a_1$ and $a_2$ are the participating parts of $A_1$ and $A_2$, while $\varepsilon_{inc}$ stands for the beam energy/nucleon and $\varepsilon_B$ the binding energy/nucleon. The transition is hardly abrupt, not even if one single impact parameter (b) is picked out, as indicated in the $\varepsilon_{inc}$-b reaction diagram (Fig. 2) of the kind first suggested by Bondorf /2/.

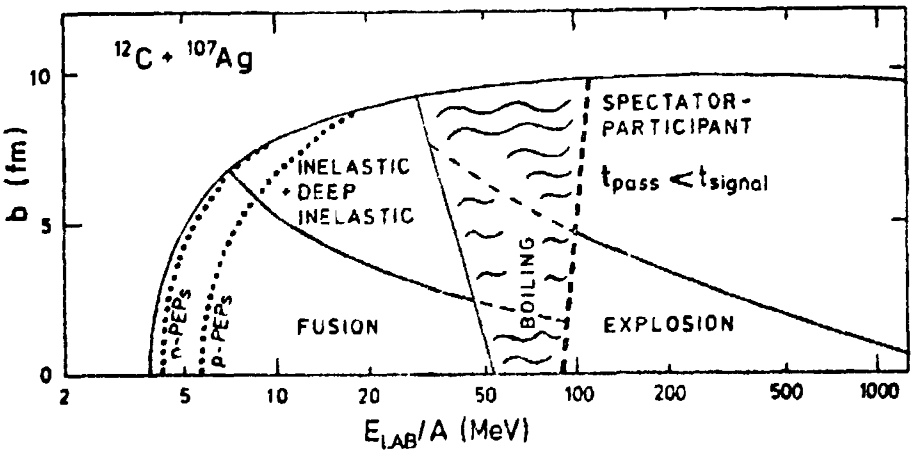


Fig. 2 A beam energy - impact parameter "phase diagram" for $^{12}C + ^{107}Ag$. The passage time ($t_{pass}$) and the communication time ($t_{signal}$) are described in /3/.

The fact that the intermediate energy region contains thresholds (Fig. 1) like the "speed of sound energy", the Fermi energy and the pion production threshold (with or without the Fermi energy boost), which all strongly affect the behaviour of nuclear matter, makes the "interpolation" between compound nucleus formation and explosive reactions, between deep inelastic reactions and spectator-participant reactions extremely complicated.

## 2 The Transparency in Nucleus-Nucleus Reactions

It is annoying that such a fundamental concept as the transparency in heavy ion reactions is not a well-known or easily calculable quantity. Since the reduced de Broglie wavelength in the intermediate energy interval ($\lambdabar = \hbar/p$) is smaller (0.3 - 1.0 fm) than the average spacing of nucleons in nuclei (even if the density is substantially larger than the bulk density ~ 0.17 $fm^{-3}$) one should in principle be able to estimate the transparency well from nucleon-nucleon cross sections. A short mean free path is in fact a necessary assumption to produce the viscous flow in hydrodynamic models /4/ or to produce an early local hot zone in thermal (pre-)equilibrium used in "hot-spot" approaches /6,7/. The use of mean-field theories, as in TDHF calculations /5,8/, is on the other hand relying on a long mean free path. Cascade descriptions, frequently used to describe high energy heavy ion reactions /9/ and also in an exploratory attempt intermediate energy heavy ion reactions /10,11/, can naturally technically use any well-known mean free path to obtain a collision probability function along the intranuclear nucleon paths.

The mean free path for free nucleon-nucleon collisions in normal nuclear matter is

$$\lambda_0 = 1/\sqrt{2}\,\rho_0\sigma_{NN} \,. \tag{2}$$

This results in short mean free paths for intermediate energies (0.4 - 1.5fm) when using the bulk density, $\rho_0$ = = 0.17 $fm^{-3}$ and tabulated cross sections, $\sigma_{NN}$ ,/12/. We know however that the Pauli blocking should play an important role for nucleus-nucleus collisions - especially for lower beam energies. Fig. 3a hint at the small momentum-space that is available when two nuclei collide at 20A MeV. An attempt to estimate the Pauli blocking factor ($\eta$ ; $\lambda = \eta\lambda_o$) has been described by Randrup /13/ for a nucleon passing through a uniform system of Fermi particles with the speed $v_o$. When no blocking is considered the collision rate ($\nu_o$) is

$$\nu_o = \frac{v_o}{\lambda_o} = \int \frac{d\bar{p}}{h^3} f(\bar{p})\, v_{rel}\, \sigma_{NN}(v_{rel}) \quad , \qquad (3)$$

where $V_{rel}$ is the relative speed between the nucleons and the probability function, $f(\bar{p})$, is given by Fermi-Dirac statistics. The probability that a final momentum $\bar{p}'$ is available, is $1 - f(\bar{p}')$ and the collision rate including blocking ($\nu$) is

$$\nu = \frac{v_o}{\lambda} = \int \frac{d\bar{p}}{h^3} f(\bar{p})\, v_{rel} \int d\Omega \left[1 - f(\bar{p}_o')\right]\left[1 - f(\bar{p}')\right] \frac{d\sigma_{NN}}{d\Omega} , \qquad (4)$$

where $d\sigma_{NN}/d\Omega$ is the differential cross section for the process $|\bar{p}_o \bar{p}\rangle \rightarrow |\bar{p}_o' \bar{p}'\rangle$ .

The blocking factor has been calculated assuming an isotropic and energy independent nucleon-nucleon cross section and using the Fermi gas temperature as a variable quantity (Fig. 3b) /13/. What we observe is that although the blocking factor is large in the low energy limit,this is compensated by the smaller free cross section and we find a mean free path of the order of 2-3 fm in the whole intermediate energy range. In fact, if the nuclear surface region could be excited by some collective mechanism acting prior to the nucleon-nucleon scattering process /14/ the mean free path could be even shorter.

This picture is valid as long as the nucleon density is reasonably high, i.e. preferentially for central and near-central collisions. Peripheral collisions, which are frequent due to the large impact parameter weight (~b), must be exposed to a much larger transparency since the density in the surface regions of the nuclei is smaller. The fundamental question about the strength of the nucleus-nucleus transparency is closely related to heavy ion reaction cross section experiments which only recently have started in the intermediate energy region /15, 16/.

A modified Bethe/Renberg reaction cross section formula /17,18/ could form the base for a transparency discussion.

$$\sigma_R = \pi R_{eff}^2 \left(1 - k_c \frac{Z_1 Z_2}{R_{eff} E_{CM}}\right)\left(1 - T\right),$$
$$R_{eff} = r_0 \left(A_1^{1/3} + A_2^{1/3} + ƛ\right). \qquad (5)$$

Here $k_c$ is the Coulomb constant (1.44 MeV·fm), $E_{CM}$ the total CM-energy and T the transparency function given in /18/ as

$$T = T(\sigma_{NN}) = \frac{1 - (1 + 2R_{eff}/\lambda)\exp(-2R_{eff}/\lambda)}{2R_{eff}^2/\lambda^2} \qquad (6)$$

With a constant T we would find a monotonically decreasing $\sigma_R$ with increasing beam energy (≈15% decrease between 20A MeV and 250A MeV for the case of $^{12}C + {}^{12}C$). Any large deviation from this behaviour must come from an energy dependent transparency function. A more elaborated calculation of heavy ion reaction cross sections with a transparency related to the Glauber thickness of the ion-ion system, has been performed by de Vries et al. /15,19/. The result of the calculations follows reasonably well the energy dependence of collected $\sigma_R$ data for $\alpha + {}^{12}C$ and $^{12}C + {}^{12}C$ and thus hint at the fact

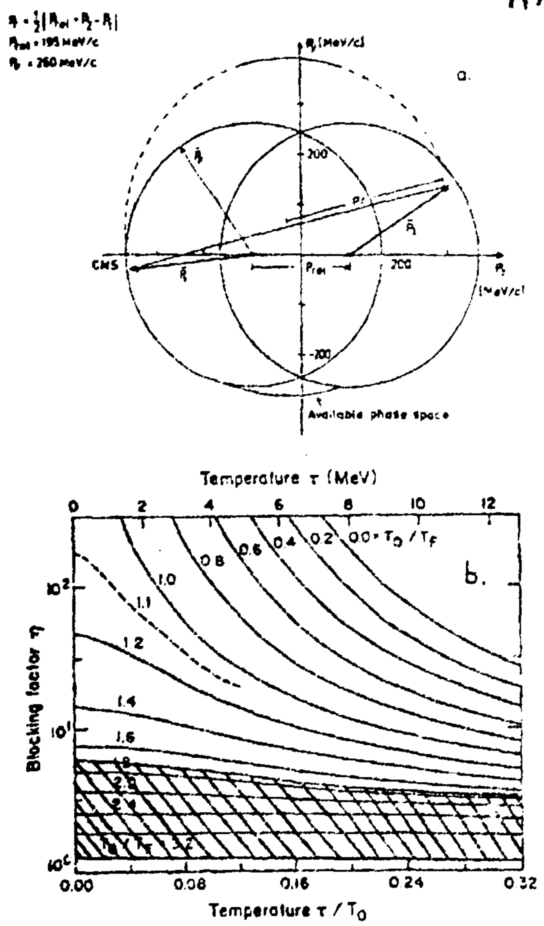


Fig. 3a Available phase-space for one (favourable) $|\bar{p}_1\bar{p}_2\rangle \to |\bar{p}_1'\bar{p}_2'\rangle$ nucleon-nucleon reaction in a 20A MeV heavy ion collision.

3b The Pauli blocking factor as a function of the Fermi-Dirac temperature /13/. The intermediate energy region corresponds to the hatched area.

that the ion-ion transparency is strongly related to the nucleon-nucleon cross section (Fig. 4).

The large gap of experimental data in the intermediate energy region has made the test of the theory difficult. In a recent experiment at the CERN SC, /16/ reaction cross sections at 86A MeV have been obtained from optical analysis of elastic scattering data. The open point in Fig. 4b at a CM energy of 43A MeV from this experiment supports the idea of an increasing transparency in the region where the corresponding nucleon-nucleon cross sections fall rapidly. Large transparencies are also found in this experiment for $^{12}C$ induced reactions in heavier targets (30-50% transparency for targets C - Pb).

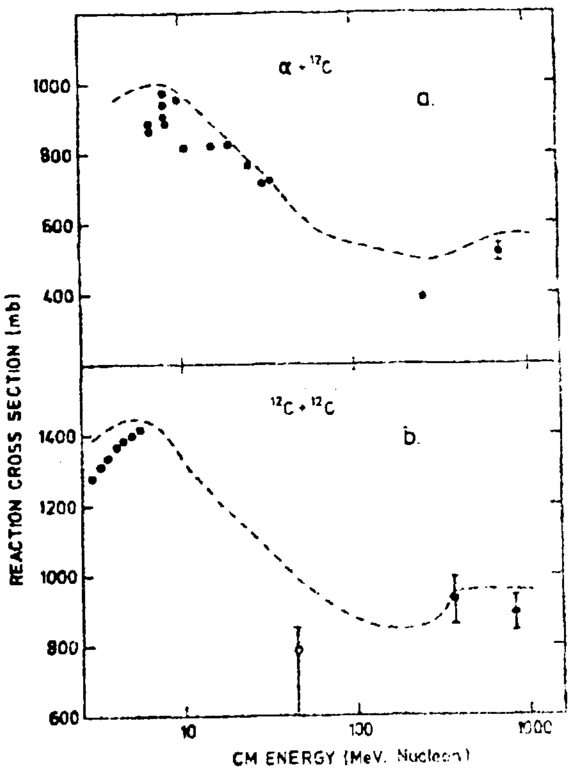


Fig. 4. Reaction cross sections in $\alpha + {}^{12}C$ and $^{12}C + {}^{12}C$ collisions. The curves are the results of the transparency calculations in /19/.

What has been said so far indicates that the simple nucleon-nucleon process plays an essential role in peripheral heavy ion collisions. However, one warning could be relevant to place here. Reaction cross section measurements are of different kinds, namely transmission measurements where the beam flux is measured before and after the target and measurements of elastic scattering angular distributions in combination with optical analysis. It is not obvious that the two methods must give the same result and only systematic experiments (preferentially transmission measurements) in the whole intermediate energy region (+ relativistic region) can give us fully reliable information about the beheaviour of $T(\varepsilon_{inc})$. In fact the close similarity of the reaction cross sections in 20A MeV and 2100A MeV $^{16}O + {}^{208}Pb$

collisions, which was presented in /20/ and indicated a transparency with a less dramatic energy dependence, could suffer from the above mentioned experimental ambiguities.

## 3 Giant resonances

In studying the nuclear response function it is likely that intermediate energy heavy ion reactions could play an essential role /21/. The giant resonances dominate the multipoles $\ell$ = 0, 1 and 2. Three giant resonances are well established essentially from (e,e') (p,p') and ($\alpha$,$\alpha$') experiments, namely the isovector dipole resonance (GDR) and the isoscalar monopole (GMR) and quadrupole (GQR) resonances. Bacause of the large importance of Coulomb excitation in intermediate energy heavy ion reactions and the reduced importance of multi-phonon excitation /21/ it is possible that "cleaner" spectra of giant resonances could be found here.

In the first attempt to study the inelastic ($^{16}$O, $^{16}$O') spectra in $^{16}$O + $^{208}$Pb reactions at the limit of our energy region (20A MeV), Doll et. al. /22/, found a promising structure. However, the difficulties in isolating the GR:s from the background of neutron pickup $^{17}$O made the results somewhat uncertain.

A new exploratory attempt to search for GR:s at higher energies /23/ have been made especially for $^{12}$C + $^{40}$Ca at 86A MeV. A preliminary excitation spectra at $\theta_{LAB}$ = 2.25$^{o}$ (i.e. slightly above the grazing angle) can be seen in Fig. 5 together with the well established A-dependence of the isoscalar GQR excitation energy /24/. It is obvious that the large cross section contained in the bump at ~ 18 MeV should at least partly represent the GQR. The possible isolation of higher multipole resonances, such as the isoscalar octupole resonance which has been observed recently in 800 MeV (p,p') experiments /25/, are now under investigation.

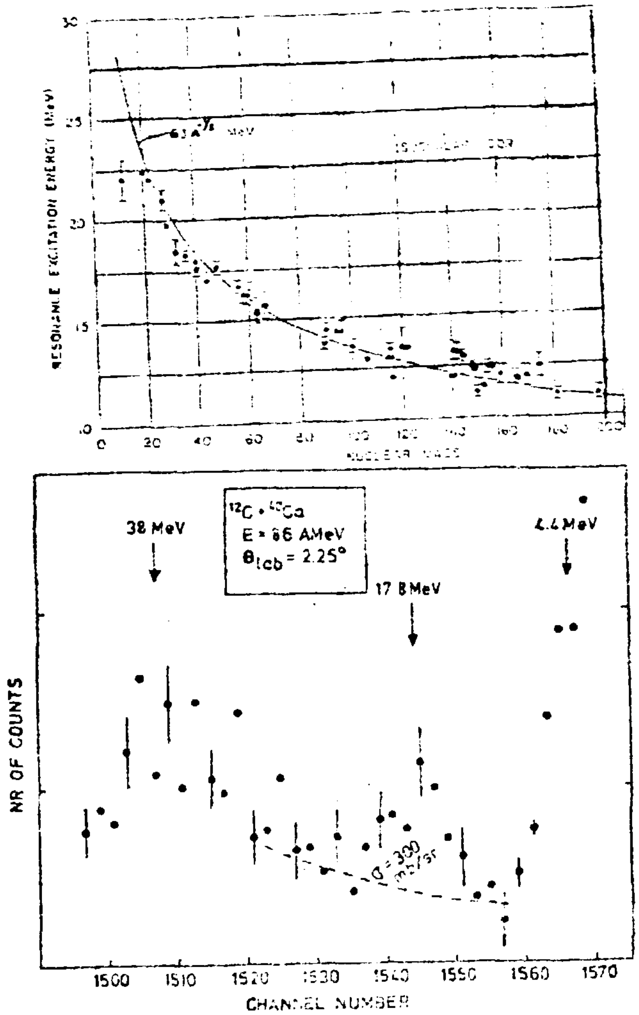


Fig. 5 Upper: The A-dependence of the isoscalar GQR excitation energy /24/.
Lower: An excitation energy spectrum of ($^{12}$C, $^{12}$C') reactions at 86A MeV /23/.

## 4 Projectile fragmentation

As mentioned in the previous section some elastic scattering data is now available in the intermediate energy region. The CM angular distribution of $^{12}$C scattered elastically on $^{12}$C at 86A MeV gives the characteristic Fraunhofer pattern, shown in Fig. 6 (dashed curve), which is typical when the Sommerfeldt parameter ($Z_1 \cdot Z_2 e/\hbar v$) is small enough. The shift to Fresnel "one maximum" spectra when the target nucleus is a strong Coulomb source has also been clearly observed /16/. In view of the large transparency observed for peripheral reactions from the analyses of this data it is interesting to find out also how the collective excitation channels appear in a CM-angular plot. Fig. 6 shows such a plot for $^{12}C$ excited to the strong 4.4 MeV $2^+$ state, again in 86A MeV $^{12}C$ + $^{12}C$ reactions /16/. The oscillatory structure has the signature of a strongly absorbed projectile and the spectrum seems to be in opposite phase to the elastic spectrum.

The next experimental step towards more violent - but still peripheral - reactions is to look for few-nucleon transfer reactions and to find out where this kind of reactions disappear with increasing beam energy. We know that in the fusion/deep inelastic region, simple mass transfer processes as one-body dissipation /26/ govern these kind of reactions. However, naturally when we increase the beam energy, less and less time when the nuclei are in contact is available for particle transfer. Typical reaction times for a light projectile-heavy target intermediate energy collision may be from a few tens of fm/c at the lower energy limit to about 10 fm/c at the higher limit, i.e. times which are still comparable to the time it takes the average Fermi particle to pass a neck region between the nuclei.

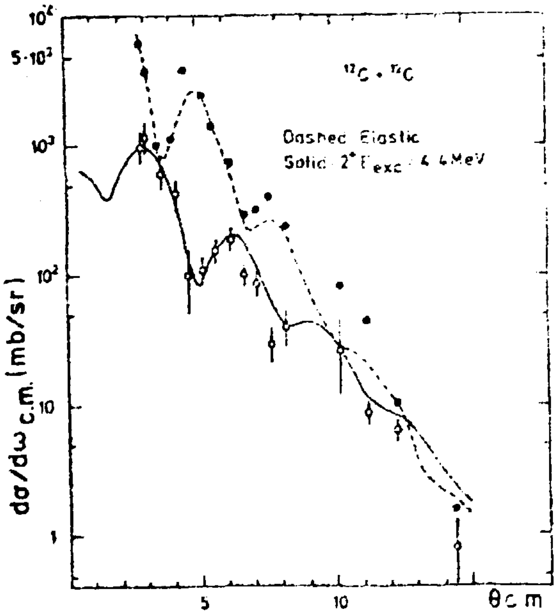


Fig. 6 Elastic and inelastic $2^+$ angular distribution of $C^{12}$ in $C^{12}+C^{12}$ reactions at 86A MeV /14/.

The disappearance of projectile like fragments with $A>A_{beam}$ should be one simple experimental sign for the ceasing of few-particle transfer processes. At 20A MeV Buenerd et. al. /18/ have for instance given a very large ($^{16}O$, $^{19}F$) cross section (20±2 mb) when the $^{16}O$ beam impinges on $^{208}Pb$. Furthermore it seems to be established that 86A MeV ($^{12}C$, $^{13}C$) and ($^{12}C$, $^{13}N$) reactions appear with cross sections which are fairly well understood in terms of a simple one-step DWBA description /23/. The next set of data comes from the relativistic region /27,28/ where no $A>A_{beam}$ fragments have been reported. A further search for such fragments in intermediate energy collisions could give us essential information about ion-ion dynamics and the particle transfer processes.

It is of special interest to notice that a substantial cross section for the charge exchange ($^{12}C$, $^{12}B$) reaction at 86A MeV has been found by Mougey et. al. /29/. These cross sections, 2.8 mb for C+C and 6.7 mb for C+Au, could be explained neither by a two-step nucleon transfer reaction or by some one-pion charge-exchange process /30/. Much smaller cross sections for the ($^{12}C$, $^{12}B$) reaction at 1A GeV has been reported by Lindström et. al. /26/ (0.1 mb for $^{12}C + ^{12}C$). The charge exchange reaction is thus another process which should be studied systematically in the intermediate energy region since a dramatic change in its probability is expected.

In contrast to the poor data of few-nucleon transfer processes the general behaviour of beam fragmentation has been studied in many intermediate energy heavy ion experiments already /20,29 31-34/. The early BEVALAC results on relativistic projectile breakup /35/ showed gaussian momentum distributions ( $\exp(-p_x^2/2\sigma^2)$) for a long range of fragments. The widths of the spectra followed a parabolic formula:

$$\sigma^2 = \sigma_0^2 \frac{A_F(A_1 - A_F)}{A_1 - 1} , \qquad (7)$$

where $A_F$ is the fragment mass number. $\sigma_0$ is at high energies typically 70 - 105 MeV/c. Goldhaber /36/ and Bhaduri /37/ showed that (7) is exactly the mass dependence to be expected if the projectile break-up distribution acts as a shapshot of the projectile Fermi-distribution. In this case is $\sigma_0 = p_F/\sqrt{5} \approx$ 78 MeV/c for a $^{12}C$ breakup. Such a reaction mechanism means that the target acts only as excitation energy injector and the expression "limiting fragmentation" - frequently used in high energy physics - has been adapted for this process.

In view of the above discussion it was not surprising that the energy spectra of projectile-like fragments in 213A MeV

$^{40}$Ar induced reactions /34/ exhibited essential the gaussian shape as seen in Fig. 7b. Much more surprising are the results of Gelbke et. al. at 20A MeV /32/. An example of an energy spectrum at $15^0$ of carbon fragmented from $^{16}$O is seen in Fig. 7a. The authors claim that all fragmentation spectra are to essential parts reproduced by the sudden liberation formalism (eq. (7)). Is it thus the same simple process throughout the intermediate energy region? The answer is no! The first clear deviation from eq. (7) was shown by van Bibber et. al. /33/ when measuring the 93A MeV $^{16}$O+Al and $^{16}$O+Au fragmentation spectra with a multielement Si-Ge telescope in a wide enough angular range ($2^0$ - $8^0$).

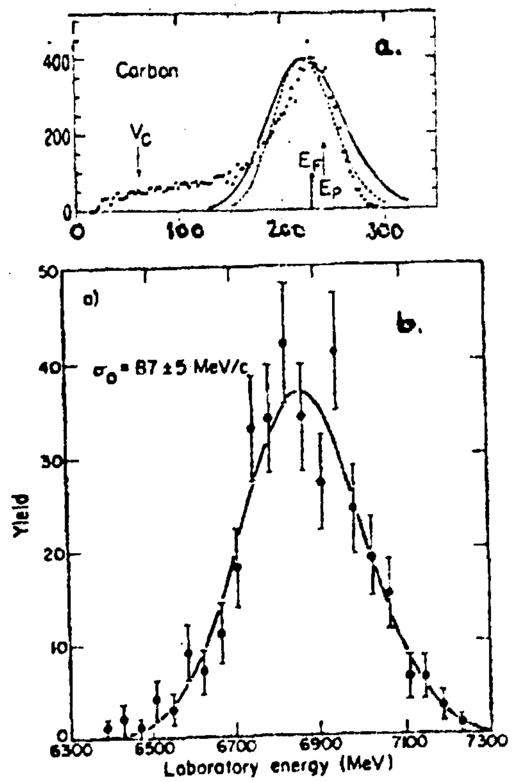


Fig. 7 Examples of projectile fragmentation spectra.
Upper: $^{12}$C at $15^0$ from 20A MeV $^{16}$O + Pb collisions /32/.
Lower: $^{34}$S at $1.5^0$ from 213A MeV $^{40}$Ar+Pb collisions /34/.

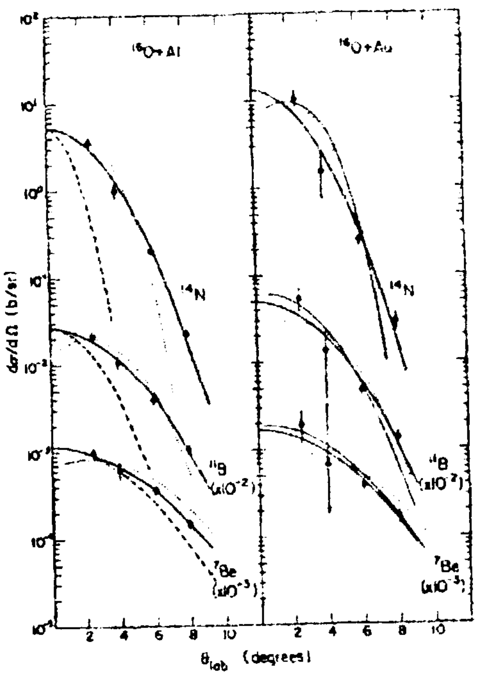


Fig. 8 Typical angular spectra of $^{16}O$ + Aℓ and $^{16}O$ + Au at 93A MeV. The solid curves are the best fits of gaussian momentum distributions with $\sigma_{\parallel} \neq \sigma_{\perp}$ while the dashed curves have $\sigma_{\parallel} = \sigma_{\perp} = 86$ MeV/c. The dotted and fine line curves are the results from folding the deflection function with the momentum distribution due to intrinsic nucleon motion /33/.

Fig. 8 shows such results. It is obvious that the dashed curves representing the gaussian distributions for each cartesian momentum component with the same $\sigma$ fails to describe the data. The authors offer a simple and appealing explanation. In the intermediate energy range we cannot neglect the orbital deflection of the projectile due to the coulomb and nuclear potentials. With a modified width of the transverse momentum distribution,

$$\sigma_{\perp}^2 = \sigma_1^2 \frac{A_F(A_1 - A_F)}{A_1 - 1} + \sigma_2^2 \frac{A_F(A_F - 1)}{A_1(A_1 - 1)} \qquad (8)$$

$$\sigma_2^2 = \frac{1}{2} \langle \bar{P}_{A_1 \perp} \rangle_{\text{at breakup}} \quad ,$$

one can explain the extended widths of the angular distributions. The same kind of less steep angular distributions were observed in /29/ for 58A and 86A MeV $^{12}C$ induced reactions.In this experiment it was also shown that the width of the transverse momentum distribution depends not only on the fragment mass but also on the fragment charge. It was stressed that also the Coulomb repulsion between the two parts of the projectile in a binary breakup may be of importance. However, it is difficult to discuss such details since the choice of the nuclear potential at close ion-ion distances, which is indeed uncertain, plays an essential role for the orbital deflection /38/.

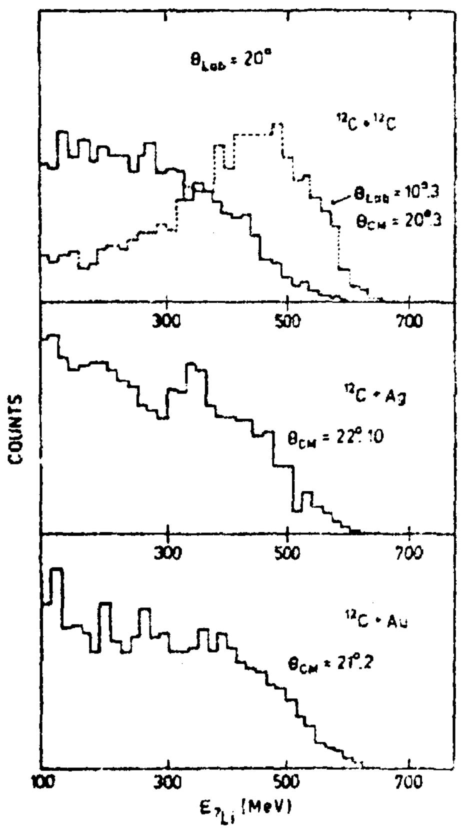


Fig. 9 Energy spectra of $^{7}Li$ emitted from $^{12}C$-induced reactions at 86A MeV /29/.

In measuring the fragment distributions out to large laboratory angles in /29/ interesting new phenomena were found. In Fig. 9 we see first of all that very broad energy distributions of $^{7}Li$ are found at $\theta_{LAB} = 20^{0}$. This indicates much more relaxed ion-ion processes than the ordinary projectile breakup + orbital deflection picture can account for. One also notices that for the same laboratory angle (not CMS angle) the spectra are found to be nearly independent of the target mass. Possibly, this tells us that at least the fragments produced far off the projectile rapidity region are coming from other, more violent processes than projectile breakup and that the same projectile- and target volumes are involved in this fast reaction mechanism irrespective of the target mass.

Before finishing the story of beam fragmentation it must be mentioned that this process has been used to produce a considerable number of new nuclei near the limit of stability /39/ from a 212A MeV neutron-rich beam, namely $^{48}Ca$ from the BEVALAC. As an example of these nuclei one could mention that $^{22}N$, identified with a combination of a spectrometer and a solid-state detector telescope, was produced with a cross section of ~1 μb from the fragmentation on a Be-target. Since this nucleus is predicted to be particle unstable in modified liquid-droplet models /40/ whereas it should be stable according to other nuclear models /41/, this example shows the use of intermediate energy heavy ion reactions for nuclear structure physics. The intensity of the $^{48}Ca$ beam in the experiment described here was $10^7$ $s^{-1}$, so it is obvious that with future dedicated accelerators, where one could think of much more intense primary or even secondary neutron-rich or proton-rich beams, we can expect an explosion of information on stable (and unstable) new isotopes /42/.

## 5 Heavy Recoils and Explosive Events

The possibility so far to produce only relatively light ions in the accelerators has restricted the experiments to symmetric light ion collisions or light ion-heavy target collisions. The latter asymmetric type of reactions should in principle always produce a slow heavy recoil in the laboratory system, no matter whether the fusion/deep inelastic picture or the participant-spectator picture is valid. A recent calculation within a hot spot model including evaporation /7/ gives for instance recoils in central collisions with velocities slightly above the CM velocity and with mass numbers $98 \leq A < 107$ for 35A MeV $^{12}C + ^{108}Ag$ and $72 \leq A \leq 82$ for 86A MeV $^{12}C + ^{108}Ag$. The complete fusion recoil velocity is,

$$\beta_f = \frac{A_1 \beta_{inc}}{\sqrt{A_1^2 + A_2 (2A_1 + A_2)(1-\beta_{inc}^2)}} , \qquad (9)$$

for a beam velocity of $\beta_{inc}$. In the intermediate energy interval we would find (for $^{12}C$ + $^{238}U$) typical recoil energies of 0.05A MeV $\leq \epsilon_r \leq$ 0.6A MeV. Such slow recoils are naturally difficult to observe by direct methods - except maybe in short range sensitive track detectors like nuclear emulsions - but indirect methods like radiochemical investigations /43/ will soon contribute to the information on the possibility of complete or incomplete fusion. If heavy ion reactions follow the scheme of d and $\alpha$ induced reactions one could expect a drastic decrease of the complete fusion process in the energy interval 30-50A MeV /44/.

The fission process could naturally compete with the above discussed reaction channels for light projectile-heavy target collisions. Experiments have been performed where two fission-like fragments are detected directly by thin solid state detectors or ionisation chambers at 20A MeV /45/ and at 86A MeV /46/. At the lower beam energy one can clearly observe two components in the folding angle ($\theta_A + \theta_B$) distributions of the fission-like fragments from $^{16}O$ + $^{238}U$ reactions (Fig. 10). The dominant peak corresponds to very large momentum transfer to the recoil and it can well be reproduced by an assumption of fusion or "massive transfer" /47/ reactions. Folding angle distributions in coincidence with a proton emitted at various angles are also presented in Fig. 10. The big bump in the folding angle always remains and its position agrees with the assumption of an isotropic thermal component of light particles (arrows in Fig. 10). If we believe that such fission-like events are associated with central events then it is reasonable to think that the second bump in the folding angle spectrum, found much closer to 180$^0$ and remaining only

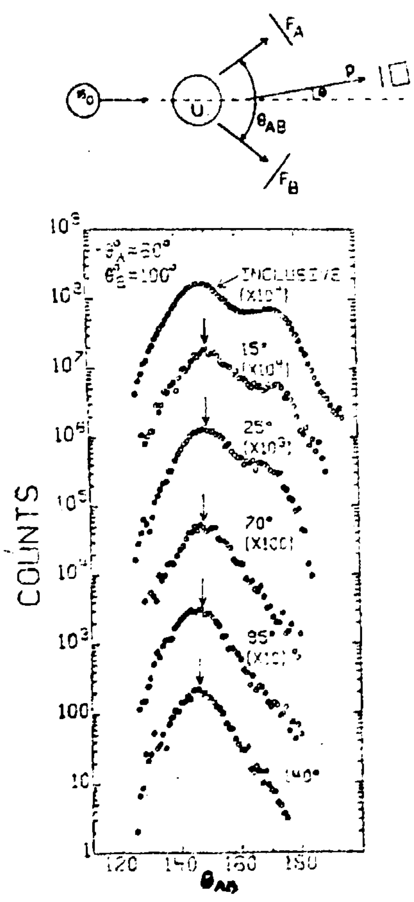


Fig. 10 Opening angle distributions of fission-like fragments in $^{16}O$+ +$^{238}U$ collision at 20A MeV. The lower distributions are obtained in coincidence with a proton emitted at 15$^0$, 25$^0$, 70$^0$, 95$^0$ and 140$^0$ respectively /45/.

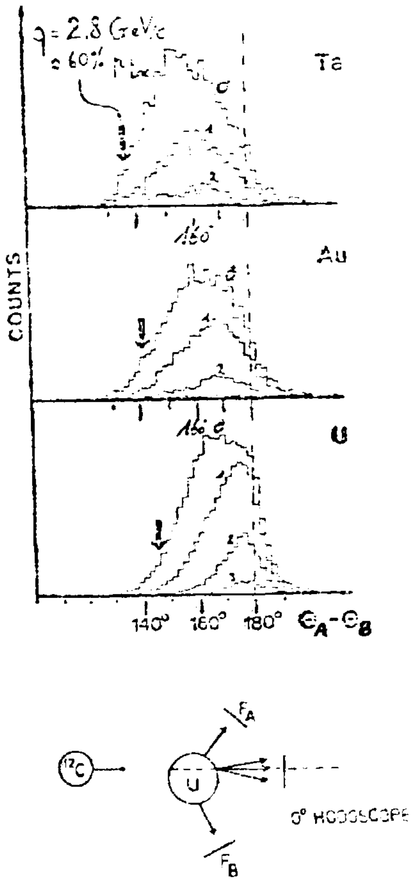


Fig. 11 Opening angle distributions of fission-like fragments in $^{12}C$+Ta,Au, U collisions at 86A MeV in coincidence with 0,1, 2 or 3 particles registered by the 0° hodoscope /46/.

in coincidence with small angle protons, should be attributed to peripheral collisions. The second experiment /46/ at 86A MeV is of similar nature. One interpretation of the differencies between the folding angle spectra from this experiment and the low energy experiment has been given by Scott /48/ who claimes that the spectra in Fig. 11 shows that only the peripheral type of fission-like processes remains at 86A MeV. The one-maximum characteristics and the strong fall-off with increasing forward multiplicity are indications supporting this interpretation. Nevertheless, Lynen et. al. /46/ have observed events with an opening angle close to that expected for full momentum transfer to the fission fragments. These events are not "clean" fission events but rather associated with a strong α-production /46/ (which is thus isotropic in CMS). It is therefore maybe relevant to pose the question. "Are these strange events of the explosive type suggested for small impact parameters in Fig. 2"?

In order to answer this question it is obvious that experiments of 4π-character should be made. While waiting for sophisticated experiments with several hundreds of counter telescopes /49/ one could look for these events in track detectors. A few nuclear emulsion experiments in the intermediate energy region have been performed /50-53/. In one of them /53/ a special effort has been made to search for very high multiplicity $^{12}C$ induced events (in Ag or Br) at 50 - 110A MeV and to identify all charged particles emanating from them. Fig. 12 shows two

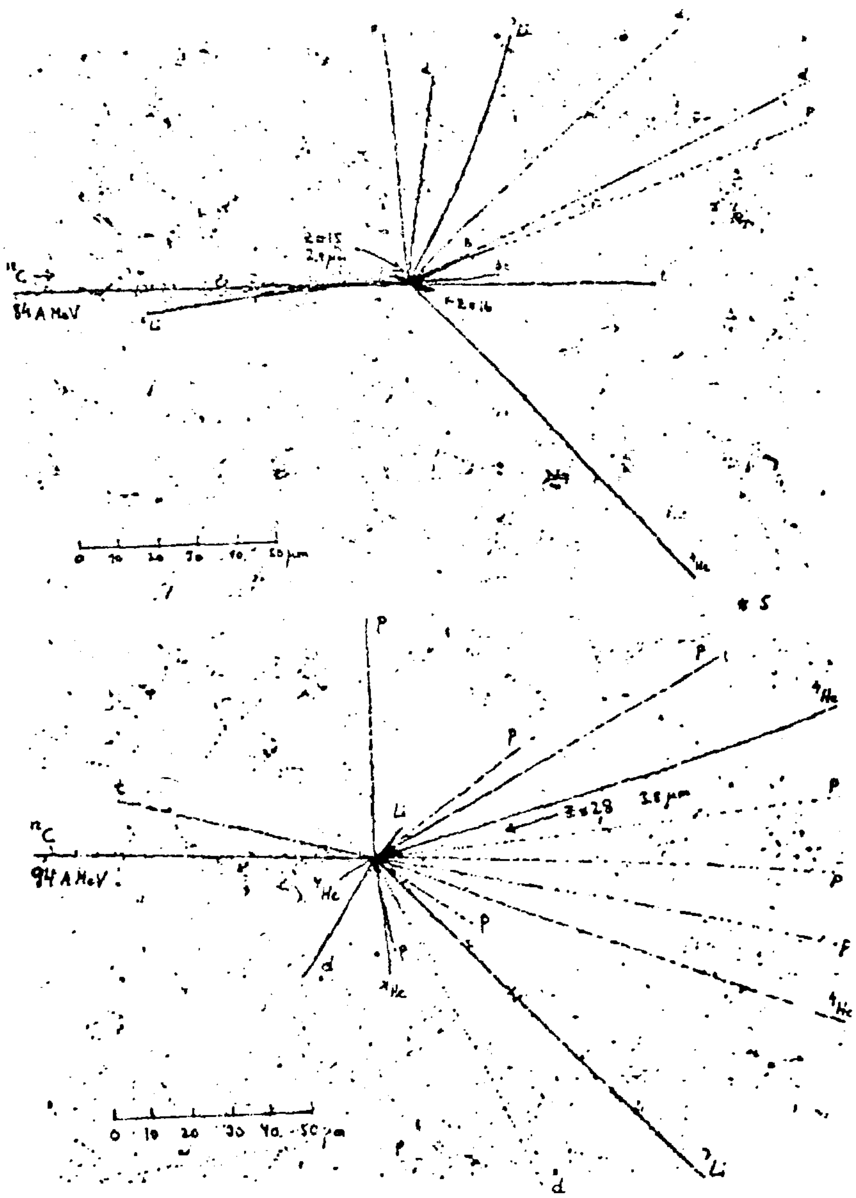


Fig. 12 Two examples of explosive heavy ion collisions in nuclear emulsions /53/ initiated by $^{12}$C nuclei at 84A MeV and 94A MeV. The target is an Ag nucleus in both cases.

such events. The upper event has two short range heavy fragments together with 11 other charged particles with a wide charge and mass distribution ($1 \leq Z \leq 5$). The second event has only one heavy recoiling nucleus, with $Z = 28 \pm 4$ and a remarkably small velocity ($\beta_r \approx 0.01$) compared to (9), together with 17 light charged particles ($1 \leq Z \leq 3$). Both these events must be very central and may be representatives of the "explosive" type of heavy ion collisions.

## 6 Light Particle Emission

It is a well-known fact that the main features of proton and neutron emission both in low energy and high energy heavy ion collisions are described in terms of statistical emission from an ideal nucleon gas. At low energies the source is a compound nucleus or a deep inelastic fragment. At high energies, where the contact time is too short for full relaxation, it is believed that spectators defined by straight line geometry are the sources which evaporate nucleons.

However, more and more experiments have reported high energy tails of nucleons which cannot come from the same sources, (limited in temperature to 8 MeV by the binding energy/nucleon) neither at 10A MeV /54/ nor at 10A GeV /55/. At relativistic energies a great variety of models have been developed which unfortunately almost equally well describes the experimental inclusive proton spectra /56/. In order to make any selection among the models by inclusive experiments one is forced to investigate very carefully the highest proton energies. The other way to do it,is to perform coincidence experiments. Being in its infancy, the intermediate energy heavy ion physics can so far only present inclusive light particle data. Fig. 13 shows $d^2\sigma/d\Omega dE$ spectra of protons from very asymmetric reactions at 20A MeV /57/, 86A MeV /58/ and 250A MeV /59/. Obviously the backward spectra are in all three cases falling off in a simple exponential way and it is tempting to believe that some kind of Fermi- (or Boltzmann source constructed from the active parts of the nuclei is the dominant origin for these protons. A classically transformed Boltzmann spectrum has been fitted to the spectra i.e.

$$\frac{d^2\sigma}{d\Omega\, d\varepsilon} = C\sqrt{\varepsilon}\, \exp\left[-\left(\varepsilon + W - 2\sqrt{\varepsilon W}\cos\theta\right)/T\right] \quad (10)$$

where W is the source energy per nucleon ($\approx \varepsilon_{inc}/4$) and $\theta$ the emission angle in the laboratory system. The temperatures obtained in this way for the backward (in reality the $90^0$) spectra are 7 MeV at 20A MeV, 17 MeV at 86A MeV and $\sim$ 35 MeV at 250A MeV. It was pointed out in /57/ that Coulomb repulsion from the source must be introduced, which means that $\varepsilon$ should be replaced by $\varepsilon-\varepsilon_c$ where $\varepsilon_c$ is the Coulomb energy boost. The temperatures given by such fits are however not very different, though the correction is important for the overall fits in the 20A MeV spectra (solid curves in Fig. 13a). The curves in the

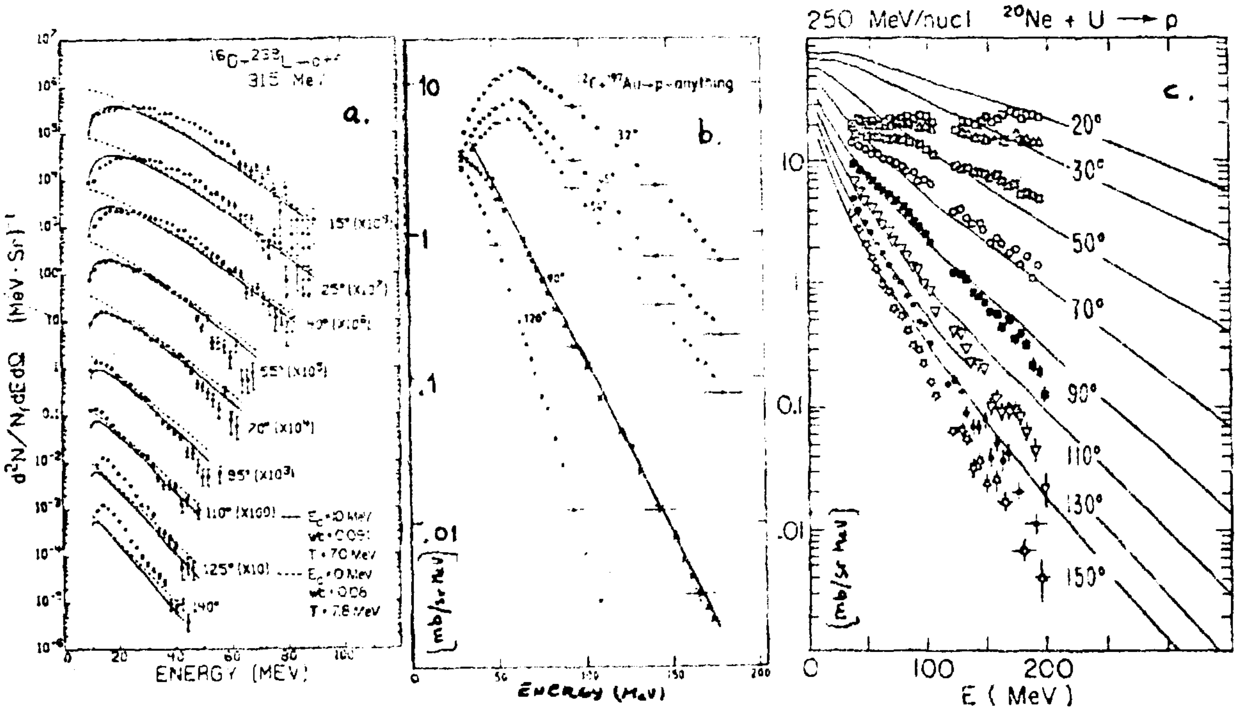


Fig. 13 $\frac{d^2\sigma}{d\Omega dE}$ for protons emitted from asymmetric heavy ion collisions at (from the left to right) 20A MeV, 86A MeV and 250A MeV /57, 58, 59/.

250A MeV figure are obtained from a firestreak calculation /60/ i.e. a straight line participant model where the participant is sliced up in streaks resulting in temperature and velocity gradients along the impact parameter axis /61/. The increase of the apparent temperature with increasing beam energy has been discussed for the Fermi gas approach and for the hot-spot/fire-ball approach by Scott /62/. The temperatures found above seem to follow the latter approach reasonably well. In principle the forward spectra should follow the same moving Boltzmann source picture except in those regions of proton energies where the "spectator" (recoil) evaporation is contributing considerably. Fig. 14 is a presentation of the invariant $1/p\ d^2\sigma/d\Omega d\varepsilon$

contours in a $P_\perp$ - $P_\parallel$ plane (corresponds to the $P_\perp$ -rapidity plane at relativistic energies). Three equally strong thermal sources have been used with velocities and temperatures (0,3 MeV), (0.2c, 14 MeV) and (0.4c, 3 MeV) respectively. Thus this calculation represents approximately a symmetric 86A MeV heavy ion collision. It is obvious that we must select only very high energy protons at forward angles in order to find the "participant" Boltzmann source undisturbed.

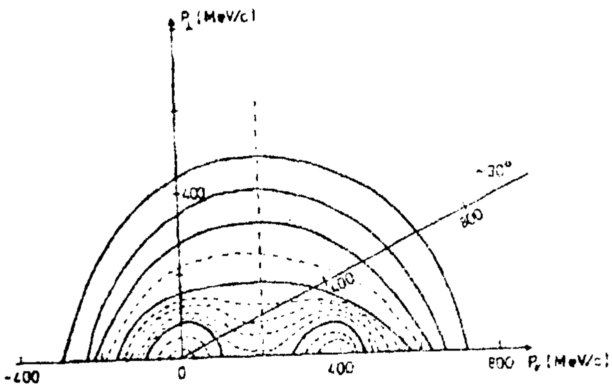


Fig. 14 $\frac{1}{p}\frac{d^2\sigma}{d\Omega d\epsilon}$ contours in the $P_\perp$ - $P_\parallel$ plane of a symmetric 86A MeV heavy ion collision in the three-thermal source picture described in the text. There is one order of magnitude in cross section between each solid curve.

Nevertheless, also the complete forward energy spectra of the 20A MeV experiment in Fig. 13 are reasonably well reproduced by one single thermal source. This hints at the fact that some sort of fusion process including pre-equilibrium (hot-spot) emission could dominate the proton emission. Already at 86A MeV this must be drastically changed because of the very poor overall fit /58/ with one single source. Not even if a projectile spectator source is included one is able to fit the data very well. In /58/ it is instead suggested that a strong contribution from a quasi-elastic knock-on process must be considered. If so, one is forced to believe that this component should be even more pronounced at higher energies and the poor fit of the firestreak calculation to the 250A MeV spectra at forward angles is indeed supporting this thought. Chemtob and Schürmann /63,64/ have compared the same spectra to their calculation in the framework of a two-component knock-on + thermal model and the improvement for forward angles is indeed promising.

The form of the inclusive proton spectra are indeed independent of the target mass as was shown in /58/ (Fig. 15). The absolute cross sections, which the authors claim are measured within 30%

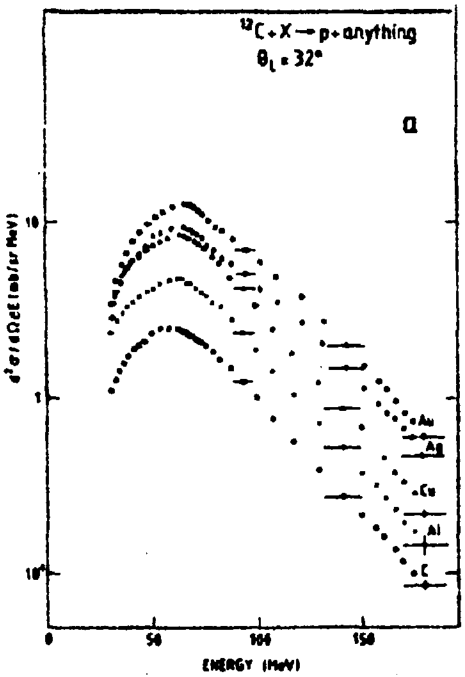


Fig. 15 $\frac{d^2\sigma}{d\Omega dE}$ for protons emitted at $32^0$ in 86A MeV $^{12}C$+C, Al, Cu, Ag, Au collisions /58/.

uncertainty hint at an $A^{2/3}$ dependence in the high energy tail changing to an $A^{1/3}$ dependence in the "projectile" peak region. The conclusions which can be drawn from these results are that the projectile participant to target participant ratio is independent of the target mass and that the participant system is never larger than two C-nuclei, a suggestion which was in fact given also in the fragmentation experiment of Mougey et al. /29/

A comparison between the applicability of the above mentioned models and the hydrodynamical models /4/ or mean field models /5,8/ is difficult to make. Nucleon spectra in coincidence with beam fragments, target recoils and overall multiplicity, in order to get rid of the impact parameter averaging, are necessary to see before such detailed comparisons could be made. Two-proton correlation studies is a type of experiments necessary for the confirmation of the direct knock-on process. Composite particles must be studied! A first step in this direction has been taken in /57/ where it was shown that the simple coalescence model describes d and t spectra well. This model tells us that the composite particles are produced in the same source as the protons and with a probability which depends on the probability of finding the relevant number of nucleons in a small enough volume in momentum-space /65/. The Coulomb corrected formula for such spectra is,

$$\frac{d^2\sigma(Z,N)}{d\Omega\, dE} = \left(\frac{N_1+N_2}{Z_1+Z_2}\right)^N \frac{A}{N!\,Z!}\cdot\left(\frac{4\pi p_0^3}{3\sqrt{2}\, m^{3/2}}\right)^{A-1} \frac{(E-ZE_c/A)^{1/2}}{(E-E_c)^{A/2}}\left(\frac{d^2\sigma(1,0)}{dE\, d\Omega}\right)^A , \qquad (11)$$

where N and Z are the neutron and proton number for the produced particle and $N_1$, $N_2$, $Z_1$, $Z_2$ are the neutron and proton contributions to the source from nucleus 1 and 2 respectively.

## 7 Pion Production

The whole intermediate energy region, 20A MeV $\leq \epsilon_{inc} \leq$ 250A MeV, falls below the free nucleon-nucleon $\pi$-production threshold. This means that the environment of nuclear matter must be responsible for the production of pions. The reason for pion production can be:

i) Regions of high density and high temperature are created.

ii) Particularly violent nucleon-nucleon collisions occur.

iii) Collisions between clusters or between nucleons and clusters occur.

In studying the backward emission of pions in proton-nucleus collisions one finds pion energies far above the kinematical limit for a nucleon-nucleon reaction /66/. Reason i) above is ruled out. Instead various nucleon-cluster collision models have been developed /67, 68/. The light ion collision experiments of Aslanides et al. /69,70 / are extremely sensitive to small pion yields ( $\sim$ 1 pb/sr.MeV/c for $\pi^-$) due to the effective combination of strong dipole fields and a Čerenkov telescope (Fig. 16).

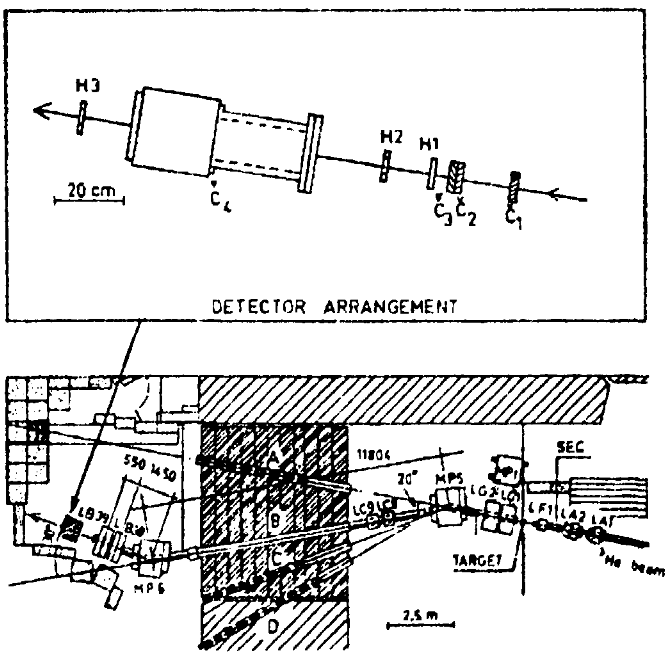


Fig. 16 Detector arrangement in /70/ . L:lenses, M:dipoles, H:hodoscopes, C:Čerenkov detectors.

These experiments give clear indications for cluster-nucleon collisions occuring in 303A MeV $^3$He induced reactions /69/, seen in fig. 17a as bumps occuring at the same energy in $^3$He+p, $^3$He+d and $^3$He+C reactions. A further search for the doubly coherent $^3He+^4He \rightarrow ^7Be+\pi^-$ and $^3He+^6Li \rightarrow ^9C+\pi^-$ reactions /69/ resulted in weak indications (fig. 17b) of deviations from the smooth falloff in the spectra at the right energies.

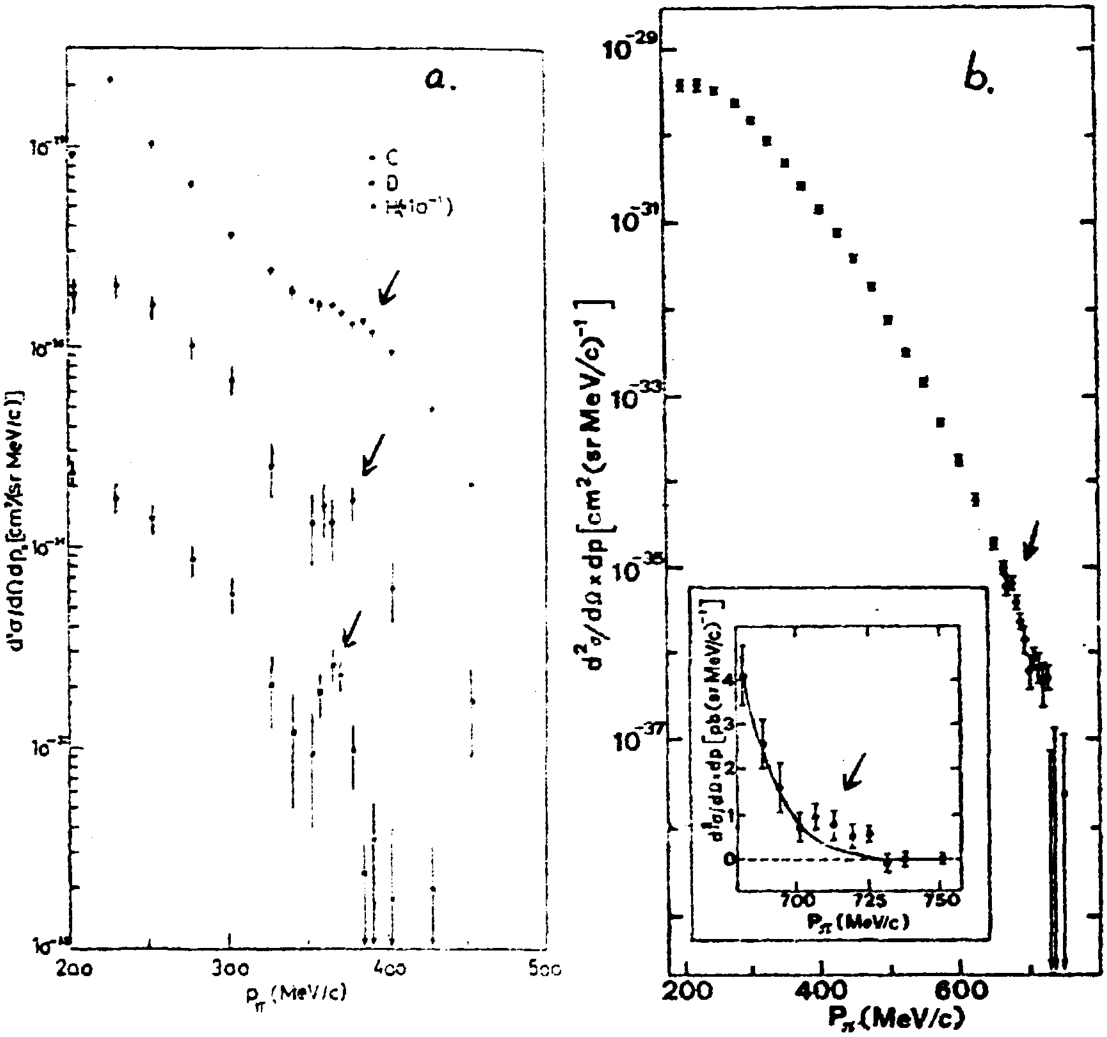


Fig. 17 Momentum distributions of pions from $^3$He induced reactions at 303A MeV.

a. $\pi^+$ from $^3$He+p,d,C reactions /69/.
b. $\pi^-$ from $^3$He+$^6$Li reactions /70/.

The maximum kinetic energy available for a pion produced in a nucleon-nucleon collision if the Fermi energy boost ($\varepsilon_F$)

is considered for both nuclei is:

$$\mathcal{E}_{\pi,max} = m'\left(\sqrt{2+\frac{2(1+\beta_1\beta_F)}{\sqrt{1-\beta_1^2}\,\sqrt{1-\beta_F^2}}}-2\right)-m_\pi \qquad (12)$$

where $\beta_1 = \beta_{inc}\beta_F/(1+\beta_{inc}\beta_F)$, $\beta_F$ is the Fermi velocity ($\approx 0.27$), $\beta_{inc}$ the beam velocity, m' the bound nucleon mass ($\approx$ 931 MeV/$c^2$) and $m_\pi$ the pion mass. The higher pion momenta in fig. 17b are far above $\mathcal{E}_{\pi,max}$ from (12) even if $\mathcal{E}_F$ is taken to be 37 MeV for the light ions.

Detailed experiments are not yet available for heavy ion reactions below 250A MeV but the spectra in fig. 18 for Ne+NaF collisions in the energy range 100-400A MeV /71/ shows clearly that both thermal models and first order nucleon-nucleon collision models, i.e. production models i) and ii), have difficulties in explaining especially the low beam energy data. It has however been pointed out that the introduction of energy dependent pion reabsorption mean free paths from optical models can improve the agreement with a nucleon-nucleon scattering model substantially /72, 73/. The very large $\pi^-/\pi^+$ ratio in certain rapidity intervals is remarkable. So far it has been interpreted as Coulomb focusing effects from a projectile like fragment /71/ since it appears close to the beam rapidity (arrows in fig. 18).

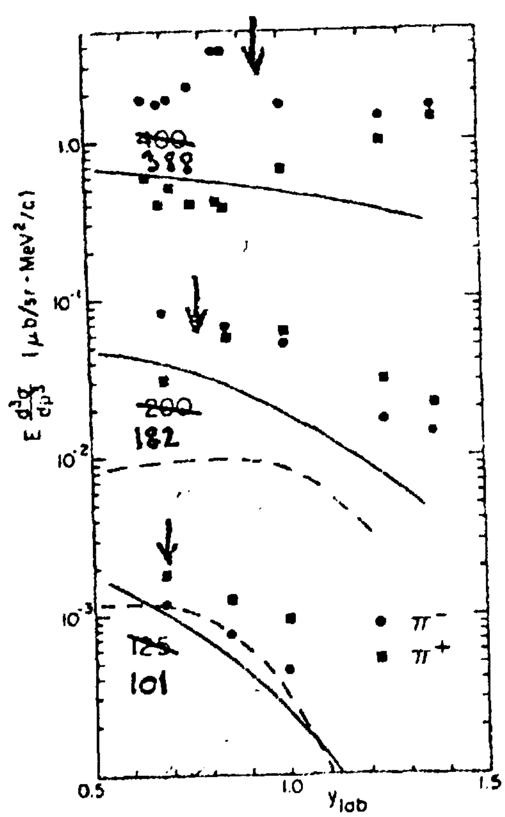


Fig. 18 Pion production cross sections for Ne+NaF reactions at three different beam energies. The solid lines are predictions from a thermal (firestreak) model and the dashed curves from a first-chance nucleon-nucleon collision model /70/.

Experiments at lower beam energies /74/ have recently started at the CERN synchrocyclotron. Thereby it has been proved that a simple sandwich scintillator telescope (fig. 19) can be used, when the proton rejection power is good enough, to measure the $\pi^+$ cross sections at 86A MeV. The resolution obtained with the delayed muon signal in coincidence with $\Delta$E-E start coincidence signals is presented in fig. 19b. Typical $\pi^+$ cross sections(at $\theta=90^0$)are ~ 0.1 $\mu$b/sr.MeV for $^{12}$C+C collisions at 86A MeV /74/. Pion energies up to ~ 100 MeV have been observed i.e. energies close to the kinematical limit of eq. (12).

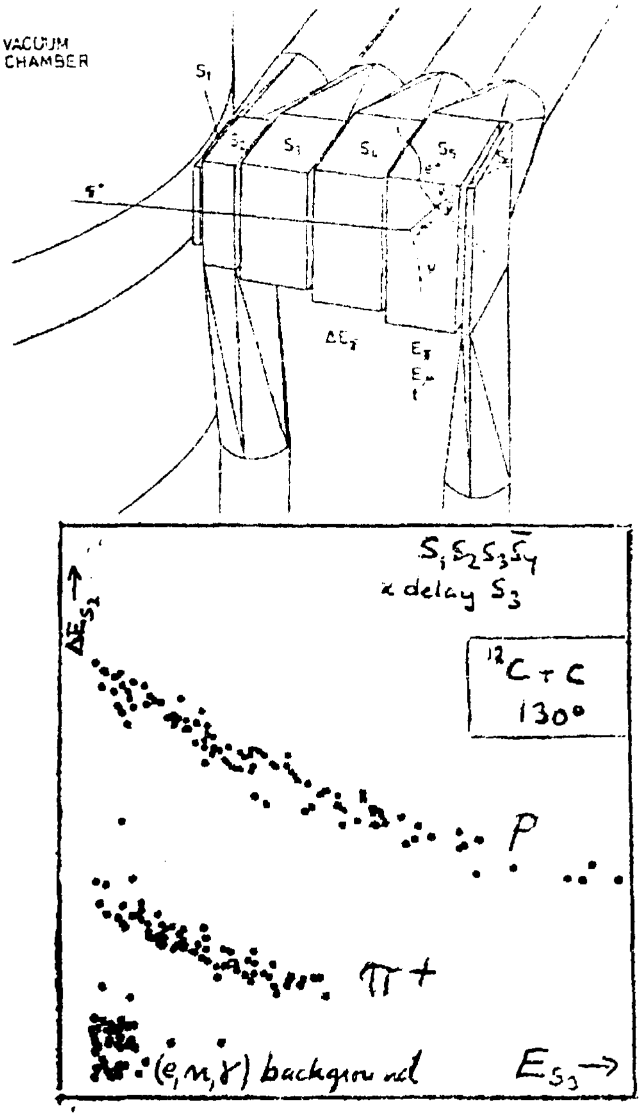


Fig. 19 Detector arrangement in /74/ together with an example of a $\Delta$E-E registration of particles that have stopped in $S_3$.

## 8 Conclusion

Intermediate energy heavy ion physics is a young field of research and as such it suffers from the teething troubles characterised by much more theoretical speculations than experimental data. The first set of experimental data is however in many respects as filled of complexity as one would believe it to be in a transition region where classical physics comes across relativistic physics and naturally also quantum mechanics. In fact all the names used for low energy and high energy heavy ion collisions have already been introduced - fusion, incomplete fusion, deep inelastic reactions, fission, massive transfer reactions, nuclear boiling, participant-spectator processes, explosive reactions etc.

The experimental results are, however, already complete enough to draw up some lines for the transition from low energy to high energy collisions. When calculating the impact parameter one must indeed remember to include the Coulomb (and nuclear-) potential. Most reactions are peripheral so let us start with a large impact parameter. Obviously the optical description is well suited to describe the elastic ion-ion scattering. Looking at the inelastic (reaction-) cross section from the elastic results by the use of optical analysis, one finds that the single nucleon-nucleon scattering is a strong candidate for the first violent process occuring when the impact parameter gets smaller. It seems also from other experimental results as if the time when the two nuclei are in contact, is long enough at 20A MeV for an effective opening up of a neck region through which particle transfer occures. At this energy one also finds signs of normal fusion and fission processes. Somewhere between 20A MeV and 200A MeV all such low energy processes disappear and instead one finds after the fast and violent part of the reaction two fragments which are excited to a temperature of a few MeV.

When decreasing the impact parameter further, particularly for a collision between real heavy nuclei, one fundamental question arises "Do we reach such hot and dense parts of the system that phase transitions may occur"? Let me make it clear immediately that no clear experimental evidence for pion condensation or density isomers exists so far, but judging from the discussions at this conference /75/

the intermediate energy region should be the most favourable region in the search for such phenomena. The explosive kind of central reactions which have been discussed, but not really outlined, seems to exist at intermediate energies, and it is an exciting task to isolate such reactions in many experiments in order to get a good experimental background for their description.

To find out the strength of the collective behaviour of nuclei in intermediate energy heavy ion collisions is another important goal for the experiments. The collective excitation of surface modes have been studied and will indeed be studied in giant resonance experiments, but it seems to be too early for a clear statement at this point. The same is true for the status of the search for collective pion production. Pions are indeed produced far below the nucleon-nucleon threshold but so far one cannot rule out the possibility of producing them simply from the Fermi energy boosts of the nucleons in the nuclei.

Many new and improved experiments are needed before the above sketched lines could turn into a model for intermediate energy heavy ion collisions. We need however not to be pessimistic since dedicated accelerators are on their way. In the proceeding towards the model it would be surprising if not new and exciting physics - or at least results difficult to explain immediately - will turn up like the anomalous fragments with short mean free paths which have been found at 2A GeV /76/. Why not begin, by looking for such fragments in intermediate energy heavy ion reactions?

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INTERMEDIATE ENERGY HEAVY ION INTERACTIONS - THE CURRENT EXPERIMENTAL KNOWLEDGE

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A review of the present experimental situation of intermediate energy heavy ion reactions is presented. The energy range discussed is 20-250A MeV i.e. close to the interval between the nuclear "speed of sound energy" and the pion production threshold. Some approaches from low energy - as well as high energy nuclear reaction physics are discussed.

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