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LIGHT PARTICLE EMISSION AS A PROBE OF REACTION MECHANISM AND NUCLEAR EXCITATION

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Light Particle Emission as a Probe of Reaction Mechanism and Nuclear Excitation

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1 Introduction

The development of new heavy ion facilities during the last six years has opened up a wide field of interest in the intermediate energy domain (in the range 20-100 MeV/u). Heavy ion collisions offer an almost unique opportunity to study the energy dissipation over a large range of impact parameters as for various incident energies[1][2][3].

To point out some of the original aspects of this energy domain, let us remind ourselves with the evolution of some characteristic variables with incident energy. Fig. 1 displays the energy evolution of $\lambdabar_r$, the De Broglie wave length for the relative motion of one nucleon of the projectile and one nucleon of the target, λ_{Pauli} the nuclear mean free path as well as t_c, the characteristic time of the reaction (quite arbitrarily defined as the time needed to penetrate the target along 5 fm). In the low energy domain, $\lambdabar_r$ is quite large due to the strong Pauli blocking effects and t_c remains larger than $t_{N/Z}$, the time needed to equilibrate the isospin degree of freedom (the fastest mode known to be equilibrated). This is the well known region of quasi elastic reactions, deep inelastic collisions and complete fusion (depending on the impact parameter).

Around 100 MeV/u. λ_{Pauli} reaches the limiting free value $\lambda_{\mathrm{free}}(\simeq 2$ fm). $\lambdabar_r$ is now much smaller than the intranuclear distance d. and the Pauli blocking gets wiped out. Moreover. the collision time t_c becomes very short. In this region. nucleon-nucleon collisions start to dominate. One is entering the fireball regime and for central collisions. very explosive types of reactions may occur. In this domain. very hot nuclear matter can be formed .

The intermediate energy region is then very attractive as λ_{Pauli}. $\lambdabar_r$ get close to d. In addition. this is the region where one crosses the Fermi velocity. One would then expect to be able to study the transition from the one body dissipation and long mean free path limit to the two body dissipation and short mean free path limit. The central part of these lectures will be dealing with the problem of energy dissipation. A good understanding of the mechanisms for the dissipation requires to study both peripheral and central collisions or, in other words, to look at the impact paramenter dependence. This should also provide valuable information on the time scale.

In order to probe the reaction mechanism and nuclear excitation, one of the most powerful tool is unquestionably the observation of light particle emission, including neutrons and charged particles. Several examples will be discussed related to peripheral collisions (the fate of transfer reactions, the excitation energy generation, the production of projectile-like fragments) as well as inner collisions for which extensive studies have demonstrated the strength of intermediate energy heavy ions for the production of very hot nuclei and detailed study of their decay properties.

2 Triggers and filters

In order to undertake a precise study of the energy dissipation processes and the various classes of collisions, one needs to have powerful triggers capable of filter on the degree of violence of the collisions. Very crucial is indeed the knowledge of the impact parameter. The problem has been already tackled in Tamain's lectures. However, the aim is to focus here on some specific examples clearly pointing out the high selectivity of light particle emission.

The first example has to deal with simple inclusive experiments in which one records, event by event, the number of neutrons emitted during the collision. Figure 2 displays such neutron multiplicity distributions obtained with a 4π detector in 44 MeV/u Ar induced reactions on various targets from C to Th [4] (this detector being essentially sensitive to low E neutrons, one is mainly counting those emitted by the slow moving source, i.e the target-like fragment). In these distributions, easy to measure, all reactions channels are registered according to the number of detected neutrons and their absolute cross sections measured. It then provides information on the energy dissipation and allows to filter on peripheral or central collisions. Fig. 2 shows indeed that. except for very light targets as C, the distributions exhibit two distinct components, one centered at a high multiplicity. associated with the most central (violent) collisions and another peaked at zero neutron. characterizing more peripheral (soft) collisions. As far as heavy targets are concerned. this is a simple way to get a quick estimate of the average excitation energy dissipated in the target for central collisions (as for such systems, neutron evaporation is expected to be by far the dominant decay channel).

Once one knows that looking at light particle emission is a good filter on the degree of violence of the collision. one needs definitely to couple different observables in order to follow more precisely the degree of violence of the collision as a function of the impact parameter. It is worth noticing that recent theoretical calculations. based on the Boltzmann equation. have attempted to find these best observables [5]. The results appear to be. at least qualitatively in good agreement with the experimental observations. Two examples of coincidence experiments are displayed in Figs. 3 and 4. Fig. 3 shows for the reaction 35 MeV/u Ar+U, two dimensional contour plots of folding angle versus the measured charged particle multiplicity ($M_{l.c.p}$). It is quite clear that the detection of (mostly) fast light charged particles (l.c.p) in the forward direction is by no means a good filter on the impact parameter : $M_{l.c.p}$ is staying constant for folding angles smaller than 160° (let us mention that it has been already observed for the system Ar + Au at 60 MeV/u by Saint-Laurent et al. [7]. On the other hand. when no selection is made on l.c.p emission angles of for angles larger than 30° (in this angular range. one mostly selects evaporated particles from the target-like fragment (TLF). one sees an almost continuous increase of $M_{l.c.p}$ with increasing linear momentum transfer (i.e for decreasing folding angles). As will be discussed later. the same result is observed when looking at the neutrons instead of the *l*.c.p.

The correlation between the projectile likle fragments (PLF) detected near the grazing angle and the light particle multiplicity. is also strongly emphasizing that one can easily follow the E dissipation and the impact parameter. This is illustrated in fig. 4 showing the strong correlation between the total number of emitted light charged particles and the atomic number of the detected PLF in the reaction 43 MeV/u Kr + Au [8]. Once again, the same picture can be observed when looking at the neutron multiplicity [9]. Obviously, as there seems to be a clear connection between the PLF charge and the *l*.c.p.multiplicity (i.e. the degree of violence of the collision). heavier the projectile. easier is expected to be the selection of the impact parameter.

The last example is concerning a very good filter on the most violent collisions : the *l*.c.p emitted backwards (in normal kinematics). This appears clearly in fig. 5 displaying for the reaction 27 MeV/u Ar + Th, the inclusive neutron distribution as well as those measured in coincidence with *l*.c.p detected at 160° [10]. In this later case. one sees that the peripheral component (low neutron multiplicities) observed in the inclusive spectrum has completely disappeared. As will be discussed later. the *l*.c.p observed at 160° are mostly evaporated by a very hot system formed in the most violent collisions.

3 From peripheral to central collisions

3.1 Transfer reactions

The sequential decay of either the projectile-like fragment (PLF) or the target-like fragment (TLF) by light particle emission in very peripheral reactions may shed some light on the primary mechanism for generating excitation energy [9][11][12][13]. Due to the very short interaction time, one can get a snapshot on the very early stage of the reaction.

Fig. 6 shows the energy spectra of various chlorine isotopes and the associated number of neutrons evaporated by the TLF in the reaction 27 MeV/u Ar+Au [9].

For the isotopes A = 38, 39, a transfer reaction is indeed well identified :

- a sharp increase of the average neutron multiplicity $< M_n >$ is observed on the high energy side, with a slope of 12 MeV/neutron (after correction for detector efficiency) indicating that the kinetic energy lost by the projectile is almost entirely converted into heat in the TLF.

- This sharp increase is only observed for product velocities larger than the beam velocity, that is for cases where matching conditions are the most favourable, the Fermi momentum of the transferred nucleons(s) being anti-aligned with the beam direction. Linear momentum conservation implies for the momentum imparted to the PLF in the forward direction to be maximum when the nucleon of the projectile is transferred at rest in the target nucleus. This corresponds to a minimum E^* deposition in the TLF and thus to a minimum value for $< M_n >$. PLFs produced with velocities well above the beam velocity should then be associated with almost cold TLF which is actually the case as $< M_n >$ is close to zero.

This transfer process appears to be dominant only for ^{38,39}Cl. With increasing energy loss

(A = 38,39, $V_{PLF} \leq V_{beam}$) and for lighter masses, the dissipated energy per neutron is close to 60 MeV, a very high value not compatible with a pure binary process. Large energy losses are no more correlated with a large increase of the excitation energy in the TLF. This behaviour would strongly support the appearance of significant direct particle emission (or the onset of a participant-spectator process).

Several other experiments demonstrate clearly that the mechanism for generating the excitation energy is the nucleon exchange and that for these transfer reactions, the recipient gets almost all the excitation energy [12][14][15] (the TLF for stripping reaction, the PLF for pick-up reactions). The results are reasonably well reproduced in calculations assuming the expected total excitation energy deduced from the optimum Q value systematics (according to the Siemens prescriptions [16]) to be shared in proportion of the captured mass.

The fact that the recipient gets almost all the available excitation energy is the consequence of very short interaction times involved in these very peripheral reactions. One is getting here a snapshot of the very early stage of the dissipation process. Less peripheral reactions might then differ rapidly by the interaction time and pure transfer reactions are expected to decrease strongly. The evolution of the probability of pure charge transfer reaction has been investigated in the Ar + Ag, Au systems at 35 and 60 MeV/u [11]. In these experiments, the signature of a transfer reaction was the non-observation of a *l*.c.p. in a forward hodoscope (covering ±30°) in coincidence with a PLF, i.e. no observation of a sequential emission from an excited PLF (the neutron emission was not measured). Fig.7 indicates that the charge transfer probability is strongly reduced with decreasing PLF atomic number. However, it does not seem to be sensitive to the nature of the target at a given energy. More surprising, transfer reactions remain quite significant at 60 MeV/u. It might indicate that the particle states in the continuum have a high chance to deexcite by sharing the available excitation energy among particle-hole state excitations instead of emitting prompt fast particles [17].

3.2 The production of projectile-like fragment. Evidence for dissipative phenomena

Besides transfer reactions, extensive studies have been also focused on the origin of the PLF formation [17][18]. Earlier inclusive experiments have already demonstrated that, in this energy range (20-100 MeV/u), the high energy limit as described in the introduction is far from being reached and that the one body dissipation is still playing a significant rôle.

More recently, exclusive experiments have shed light on the excitation energy deposit in the outgoing pieces [11][19][20]. Whereas coincidence measurements between the PLF and TLF lead to some ambiguous conclusion, the observation of l.c.p. or neutrons associated with the PLF (or TLF) appears to be somewhat more promising. It is now well established that quite large energy dissipation can be reached and that the excitation energy sharing between the two outgoing fragments disagrees with the hypothesis of a complete thermalization over the whole system. An example is presented in fig. 8 for the reaction Ar+Au at 60 MeV/u[11]. In this experiment. the PLF have been detected in coincidence with the l.c.p. emitted in the neighbouring direction. Fig. 8a represents the energy correlation between one α-particle and one PLF (Z=15). The existence of two components in this bidimensional representation signs clearly for the sequential emission of the α. These two peaks are nothing more than the two kinematical solutions corresponding to the sequential decay of the PLF (Z=17). Fig. 8b shows the primary PLF excitation energies deduced from a kinematical reconstruction which was taking into account all the sequentially emitted particles. None of the hypothesis considered for the excitation energy sharing can explain the data (equal excitation energy, equal temperature, abrasion-ablation). The fact that the equal temperature hypothesis is not fulfilled (and it is even worse for the Ar+Ag system [11]) may just reflect the rather short timescale of the reaction as compared to the thermalization time. However, it is clear that one has to include in any calculation the inelastic interaction between projectile and target.

Recent measurements of the number of slow neutrons (essentially evaporated by the TLF) have been performed on various systems. Fig. 9 shows for the reaction Ar+Au at three bombarding energies the average neutron multiplicities coincident with the PLF detected near the grazing angle [21]. There is a clear connection between the average neutron multiplicity M_n and the mass of the associated ejectile. Light PLF are obviously resulting from very violent collisions. However, a quite astonishing result is that, for a given PLF mass, no significant change of the neutron multiplicity is observed between 27 and 44 MeV/u. This definitely rules out the hypothesis of a pure massive transfer process as it was observed at lower energies (such a mechanism would have implied an increase of the excitation energy deposit in the TLF in the ratio of the beam velocities). Increasing the incident energy seems to be inefficient to put additional heat in the TLF as expected if one keeps in mind the vanishing of the Pauli blocking. The large energy dissipation which is observed also rules out the hypothesis of a pure abrasion-ablation picture in this energy range.

A comparison has been performed with a phenomenological model developped by Bonasera et al.[22] which takes into account in a very schematic way the coexistence of one body and two body dissipation. During the first step. one has to deal with a one body dissipation in which the Pauli blocking is taken into account. At midway of the calculated reaction time. a transition is operated arbitrarily and nucleons in the overlap region may be abraded. if it is energetically possible. In the exit channel, one has to deal with 3 excited objects, the PLF, the TLF and the abraded zone. The deexcitation of the excited PLF and TLF has been followed using the evaporation code PACE. As for the abraded zone, it has been supposed that half the excitation energy was removed by neutron emission. The contribution of these three components to the measured $< M_n >$ has been estimated through a Monte-Carlo code. The velocity of each source, its direction and the average kinetic energy of the emitted neutrons are taken into account in the calculation.

The agreement with the experiment is rather satisfactory at the three energies (Fig. 9). This is indeed a crude model and more refined models, including for instance preequilibrium emission instead of an abraded zone might be more relevant to explain the results. In any case, large energy dissipation leading to quite high excitation energies in both the TLF and PLF seem to be required in order to explain the results.

3.3 From projectile-like fragments to intermediate mass fragments

Up to now, the discussion has been focused on the energy dissipation associated with reactions where one fast PLF ($V>0.85\ V_{beam}$) was observed in the vicinity of the grazing angle. How does the situation evolve when observing slower framgents and/or larger detection angle ? This is illustrated by fig. 10 showing the average neutron multiplicity M_n in the (E/Z) space at 3°7 and 20° for the reaction 44 MeV/u Ar+Au. At 3°7, while the number of neutrons increases steadily with decreasing Z for the fast fragments, the low energy tail is characterized by large and similar neutron multiplicities whatever the PLF'Z. Moreover, these values are almost identical to those observed for the most dissipative processes observed in central collisions (see section 4). At 20°, the fast component has disappeared and all the detected products are now associated with strongly dissipative collisions (very high neutron multiplicities). These products, very often called intermediate mass fragments (IMF) are thus without any ambiguity associated with the most violent collisions and there is almost no dependence with PLF'Z of the energy deposition in the TLF.

The origin of this IMF production is much debated and the experimental situation is not clear. Let me just mention that their production has been discussed in terms of various processes : evaporation by the TLF in thermal equilibrium, non equilibrium emission from the TLF, a possible decoupling of the fireball, strongly damped collisions and finally multifragmentation. A complete discussion is out of the scope of these lectures. The reader may refer to other lecturers (see Moretto[23] and Pochodzalla [24] lectures).

4 Central collisions - Formation and decay of hot nuclei

In this section, the discussion will be mainly focused on the formation and decay of hot nuclei up to some "limiting temperature". By this term, it is meant below some hypothetical boiling point or below some critical conditions of temperature and pressure beyond which the system would become unstable against for instance multifragmentation. Studying the decay of such hot systems by light particle emission may bring very valuable information on the dynamics, the characterization of the initial nucleus, its nuclear properties and the limiting temperature.

4.1 The origin of the light particle emission in highly dissipative collisions

In order to illustrate the various origins of light particles associated with quite central collisions, I chose the system 30 MeV/u S+Ag recently studied by Wada et al.[20]. The *l*.c.p. have been measured in coincidence with the evaporation residues (ER). Fig. 11 shows α-particle spectra at various angles for different cuts in the ER velocity spectrum (selecting thus linear momentum transfer from 40% to 100% of the full momentum transfer). There is a pronounced evolution of the spectrum shapes with the emission angle (from 5° to 160°). The solid lines result from a moving source fit assuming three emitting sources : the PLF responsible for the high energy peak at very forward angle, the hot TLF (the only source still present at very backward angles) and an intermediate source associated with what is commonly labelled preequilibrium emission.

The latter raises the problem of particle emission at the early stage of the collision and is of course strongly connected with the definition of the thermalization already discussed by Tamain [25]. Can we easily separate in time the preequilibrium stage from the equilibrium one ? Fig. 12 and 13 show two kinds of calculation emphasizing this time evolution of particle emission from the very beginning of the reaction. Fig. 12 is a calculation for the S+Ag system using the preequilibrium model of Blann [26]. In this calculation, the occupation states of the nucleons with respect to the Fermi sea are modified by nucleon-nucleon collisions taking into account the Pauli principle. The time evolution is described by the Boltzmann master equation. The calculated angle integrated proton spectrum is shown for different steps (1 step = 2.10^{-23}sec). It is seen that after 13 steps, there is no change anymore in the shape of the spectrum and one may consider a pure equilibrium emission.

In fig. 13, a quite different theoretical approach has been used,which has to deal with Landau-Vlasov calculations [27]. The number of emitted nucleons, their flux , the anisotropy as well as their mean kinetic energy have been followed as a function of time. The flattening of the main anisotropy and the saturating value of the kinetic energy allow again to define the time from which a pure statistical evaporation can be reasonably considered. It corresponds to about 4.10^{-22}sec. However, there is obviously no clear frontier between the preequilibrium and equilibrium stages and the separation is then somewhat arbitrary. Nevertheless, it is clear that studying such non equilibrum processes may provide us valuable information on the route towards equilibrium.

Let us focus now on the equilibrium component which, according to Wada et al [20] is most easily observed at backward angles (see fig. 11). There are, indeed, strong arguments deduced from several experiments for these backward emitted particles to be evaporated by a hot nucleus in thermal equilibrium.

- First when choosing a very heavy system such as C+Th, and recording coincidences between fission fragments and backward emitted light particles [28], one observes that the measured spectra are identical whatever the correlation angle between the fission fragments: protons and α-particles are emitted by the composite system before the fission (fig.14). It agrees with other experiments dealing with neutron emission. From these very nice results, presented by Hischer [29], it has been possible to get an estimate of the prescission lifetime.

- At backward angles, an isotropic emission from the recoiling composite system is clearly identified as shown in fig. 15 displaying isocontours of invariant cross-sections for α-particles detected in coincidence with two fission fragments following large momentum transfer [30]. Moreover, as will be discussed later, the energy spectra have the expected Maxwellian shape for an evaporation from a thermalized system.

4.2 Evolution of the thermal energy deposit with incident energy

In order to determine with a good accuracy the excitation energy deposited in the system, the ideal experiment would be to identify all decay channels contributing to the decay process of the hot neucleus. This includes the observation of neutrons, light charged particles (l.c.p.), complex fragments and γ-rays . Such a complete experiment has not been undertaken so far, but several groups have concentrated their efforts on one or several of these channels [1-3]. One series of experiments which will be described here as an example is concerning Ar induced reactions on heavy targets (Au and Th) in the energy range 10-77 MeV/u [2-4,10].

4.2.1 The fission channel

For such very heavy systems, neutron evaporation is expected to carry away a large part of the excitation energy. Using a 4π neutron detector essentially sensitive to low E neutrons, i.e. to neutrons evaporated by the slow moving source (the recoiling hot nucleus), the neutron multiplicity has been measured in coincidence with the fission fragments in the reaction Ar+Th at 3 bombarding energies 27, 35 and 44 MeV/nucleon [31]. As pointed out in fig.16. the average neutron multiplicity (M_n) exhibits a very strong dependence with linear momentum transfer . However, for small values of the folding angle, it saturates at somewhat constant value whatever the bombarding energy is ($< M_n >\simeq 20$, a value not corrected for the efficiency of the detector. The real value is close to 34 neutrons). This saturation clearly indicates that the width of the central collision bump is only due to the combined effects of particle evaporation, velocity and mass dispersion of the fission fragments. The observation of events at very small angle by no means indicates the possible existence of some complete fusion events.

The fact that some saturating value of M_n is observed at the three bombarding energies indicates that the same excitation energy is carried out by neutron evaporation. Let us mention that the same behaviour is observed for l.c.p so that we can conclude to a saturation of the thermal energy deposit above 27 MeV/u. However, it might well be that, for this particular decay channel (fission), a saturation is found which will not be observed for other channels . One should keep in mind that binary fission following large momentum transfer seems to vanish completely at 44 MeV/u.

It is then worth selecting a trigger for the most dissipative collisions which allows to probe the energy dissipation by way of all exit channels as opposed to just one as before with the pure binary fission . This minimum bias probe is the evaporation of light particles (n, H, He).

4.2.2 Light particle multiplicity measurements

The observation of light particles is in that sense a very powerful tool as one knows that, irrespective of the decay process, all massive fragments finally cool down by emitting light particles.

For such very heavy systems (Ar+Au. Th), as neutron emission is by far the dominant channel, it is not necessary to perform a 4π measurement of the charged particles. One needs to measure differential multiplicities and integrate over angle. These measurements have been performed at 160° where the contribution of preequilibrium emission is expected to be negligeable. Moreover. most of the l.c.p emitted backwards are associated with very large energy dissipation (see fig.5). Fig.17 shows an example of the l.c.p differential multiplicities (for 44 MeV/u Ar+Au) plotted as a function of the neutron multiplicity M_n [10]. They exhibit a more or less linear dependence with M_n before reaching a saturating value just at the location of the maximum in the inclusive neutron spectrum. Moreover, as illustrated in fig.18, the energy spectra of backward emitted α-particles are identical in shape and in position indicating similar properties for the emitting sources. The temperature parameters deduced from the slopes of the spectra are very similar, close to 5.3 MeV. Absolute multiplicities for each particle have been deduced assuming an isotropic emission in the rest frame of the emitter . Results are summarized in fig.19 together with the efficiency corrected associated neutron multiplicities . Also shown are the values of the thermal energies deduced by summing up the energy carried out by the neutrons and l.c.p [10].

There is a clear evidence for a soft saturation of the thermal energy deposit in the range 27-77 MeV/u. The value of 650 MeV deduced for the reaction Ar+Th corresponds to T = 5.5 $\pm$ 0.5 MeV (assuming a=A/8), a value very similar to the one inferred from the relative population of widely separated states of emitted complex fragments. [7]. Moreover, recent Landau-Vlasov calculations indicate also a similar value for the excitation energy in central collisions for the reaction Ar+Au at 60 MeV/u [32].

The results somewhat contradict previous recoil velocity measurements for the same systems using the folding angle method from which a substantial increase of the excitation energy was deduced in the energy range 30-44 MeV/u [33]. This probably may indicate the limitations of the folding angle method at high energy. As pointed out recently, there can be quite significant distorsions of the folding angle distributions due to increased non equilibrium processes [34]. On the other hand, one may doubt on the validity of the massive transfer hypothesis in this wide energy range used to deduce the excitation energy [2].

On might also imagine that this saturation effect reflects the increasing importance of compression effects at high energy (as suggested by recent Landau-Vlasov calculations [35]). If it were the case, the damping of the collective modes should not contribute to increase the thermal energy. This could be the case if one assumes some multifragmentation process. In that case, the heat capacity of the system will be strongly affected and most of the collective excitation energy would go into surface and Coulomb energy of the fragments and very few into heat. However, this hypothesis does not hold as it would require high intermediate mass fragment (IMF) multiplicities which is not the case (they remain smaller than 2 units)[4,36].

Before to end this chapter, it is worth noticing that this series of experiments, based on the observation of light particle evaporation, has clearly demonstrated that highly excited nuclei can be formed in thermal equilibrium up to 5 MeV temperature. Let us summarize the signatures of the thermalization. More than 40 particles (n, p, α) are evaporated by the hot system (see fig.19), strongly supporting the idea that the excitation is distributed over the whole system. Furthermore, the α-particle spectra have the expected maxwellian shape and they are isotropically emitted in the rest frame of the slow moving target-like fragment (see figs.15 and 18).

4.3 Evidence for the existence of a limiting temperature ? A compilation

One very fundamental question is related to the possible excitation energy that a nucleus can sustain. In other words, how hot can be a self bound system in thermal equilibrium? This problem has been already tackled in the previous section for one given system.Let us look now at some compilation reviewing the existing results concerning only the highest excitation energy reached so far for a given mass of the composite system [2]. The results are displayed in Fig.20. The upper values are evolving from 6.5 MeV/u for the light systems down to 3 MeV/u for the heaviest ones and are obviously far below the corresponding binding energy of the system ($\simeq$ 8 MeV).

Let us look briefly how do these results compare with the theoretical predictions. It is not the place here to compare the advantages and drawbacks of the different methods and more details can be found elsewhere [1]. Theorists have first approached the problem from a static point of view. In these calculations, a sudden heating and the equilibration of the single particle degrees of freedom are a priori assumed. The stability of the system is then defined as the coexistence of the hot nucleus in equilibrium with the surrounding vapour phase (a substraction procedure being used to determine the properties of the hot nucleus without vapour) [37-39]. One example is shown in fig. 21 which shows iso contours of critical temperature in the (N,Z) plane calculated within the hot liquid drop model [40]. The instability is largely influenced by the balance between Coulomb, bulk and surface energies, which explains the variation with the nuclear charge as well as with the isospin. One should notice that these calculated values seem to be in rather good agreement with the present experimental data.

Does it mean that one has a comprehensive picture of the problem ? It might be premature to conclude as there are still open questions. Most of the results obtained so far have been deduced from Ar induced reactions (or lighter projectiles). The observed saturation of the thermal energy deposit above 30 MeV/u for the Ar+Th reaction might reflect the increasing influence of dynamical effects. On the other hand, few measurements of folding angle distributions of fission fragments using heavier beams such as Ni and Kr seem to indicate the capability to transfer much higher linear momentum (up to 13 GeV/c for the reaction Kr + Th) [41].

The best approach to check the influence of the dynamics is probably to use the semi-classical kinetic equations, taking into account the balance between the mean field and individual collisions.

Two reasons may explain the observed saturation of the thermal energy with increasing Ar bombarding energy. First, particle emission at the very early stage of the collision should play an important rôle as the decay time of such a very hot system is becoming comparable to the collision time. Moreover, the possible excitation of collective modes which might be strongly enhanced in heavy ion collisions could strongly limit the thermal energy. Recent dynamical calculations (Landau-Vlasov) have shed additional light on this problem. An example is shown in fig.22 for the system Ar+U at 27 MeV/u. This result from a Landau-Vlasov simulation performed for a head-on collision [42]. It indicates that a complete thermalization occurs in a very short time, 80 fm/c ($\simeq 2.10^{-22}$sec). At that time, the anisotropy of the nucleon momentum distribution indeed tends to zero. At this point, a maximum energy per nucleon of 2.6 MeV has been reached , and the fused system in thermal equilibrium starts to evaporate. One should notice that the agreement with the experiment is quite satisfactory. However, the calculation exhibits a very interesting feature, namely that the collective modes are far from being relaxed so rapidly. This emerges clearly from the study of the system Ar+Au at 60 MeV/u [7,35]. Even at this high energy, the thermal energy of the system remains saturated at 650 MeV. The explanation is found in the balance between thermal and collective energy. Densities up to 1.3 ρ_0 are obtained and the coupling between preequilibrium emission and monopole vibrations contributes to remove a large part of the total available intrinsic excitation energy.

There are still many open questions concerning the limiting temperatures. For instance, a precise study of non equilibrated particle emission with increasing bombarding energy is strongly needed (n,p,α, clusters). Up to now, very few results are available. On the other hand, a precise determination of the excitation energy deposit by means of the light particle multiplicities (n,p,α) are strongly needed using much heavier beams than Ar (Kr, Xe, Au).

The folding angle method, which has been used so extensively should be used cautiously. Several authors have deduced from such studies that the fusion process vanishes completely above some critical bombarding energy. Fig.23 illustrates clearly that, despite the disappearance of the so-called central collision peak in the fission correlation, the cross-section corresponding to highly dissipative collisions (deduced from inclusive neutron multiplicity measurements) remains more or less constant in the energy range 27-77 MeV/u (about 50% of the total reaction cross-section) [43]. The disappearance of the high linear momentum transfer peak in the folding angle has then to be connected with the decay properties of the composite system (vanishing of binary fission ?).

Recent results indicate indeed that even for very dissipative collisions, the remnant projectile has to be taken into account in the momentum balance and that the detection of fission-like fragment should not be restricted in the reaction plane [44].

5 Conclusion

These lectures were intended to emphasize what could be learned from light particle emission in heavy ion induced reactions in the energy range 20-100 MeV/u. The observation of light particles appears indeed to be a very powerful tool to probe the reaction mechanism and study the energy dissipation. It provides snapshots of the collision at different time intervals and sheds light on the reaction mechanism. It is of a large interest in studying peripheral processes (transfer reactions, projectile-like fragment production, mechanism for excitation energy generation and energy sharing between the fragments, preequilibrium emission...).

It is an excellent probe of the thermalization of hot nuclei produced in central collisions and to measure properly their excitation energy and temperature and study their decay properties . We learned already a great deal from these studies : it is now unambiguously established that heavy hot nuclei can be formed in thermal equilibrium up to T=5 MeV. Whether or not this temperature can be associated with the maximum excitation energy that a nucleus can sustain is still an open question. It might not be the real limiting value and just reveal the strong influence of dynamical effects which could be overcome using heavier projectile at moderate energies.

Among the open problems, one has for instance still to understand the saturation of the thermal energy deposit with increasing projectile energy which has been observed in the reaction Ar+Th. Very exclusive experiments are needed in order to understand where goes the missing energy. Do the dynamical effects lead to high compression of the system as predicted by Landau-Vlasov calculation ? This raises the question of the relaxation mode of these collective degrees. Light particle evaporation could help to solve part of the problem as their kinetic energies might be sensitive to the collective expansion of the system.

Finally, momentum transfer measurements, performed with heavy beams as Kr, provide some clues for depositing higher excitation energies in the composite system. In order to further explore this possibility, more complete experiments are needed in which all exit channels could be identified (light particles. intermediate mass-fragments. heavy residues and fission).

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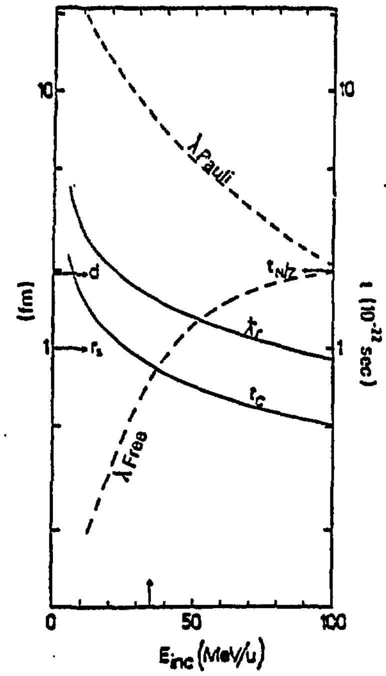

Figure 1 : Evolution of some characteristic variables with incident energy (for more details, see text).

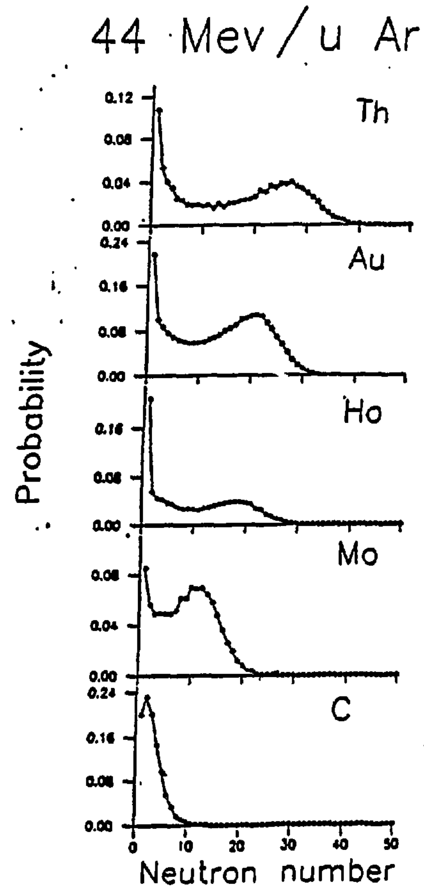

Figure 2 : Inclusive neutron multiplicity distributions for 44 MeV/u Argon induced reactions on various targets (C, Mo, Ho Au and Th)[4]. Multiplicities have not been corrected for the efficiency of the detector.

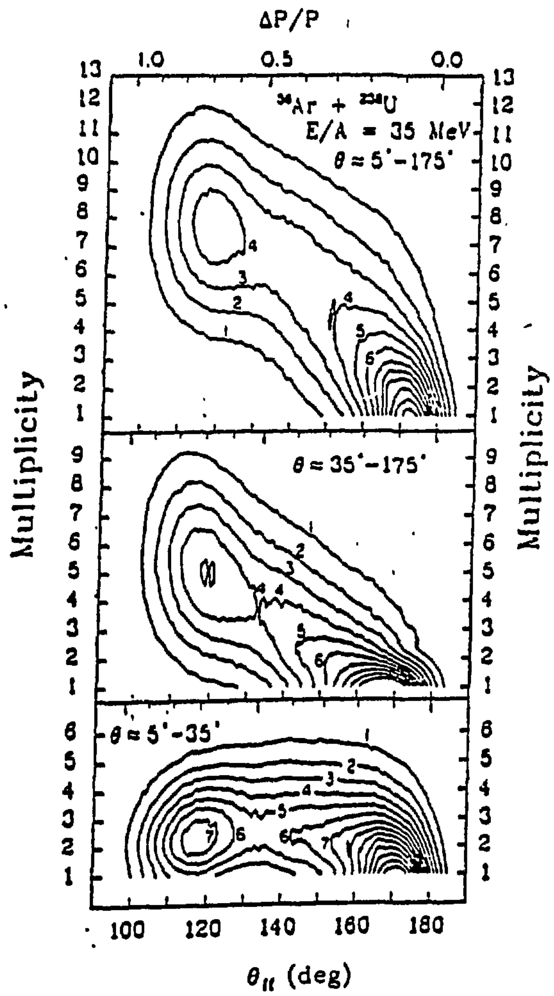

Figure 3 : Correlation between the charged particle multiplicity and folding angle for the 35 MeV/u ^{36}Ar+^{238}U reaction. The three contour plots correspond to different angular domains for the detection of the charged particles[6].

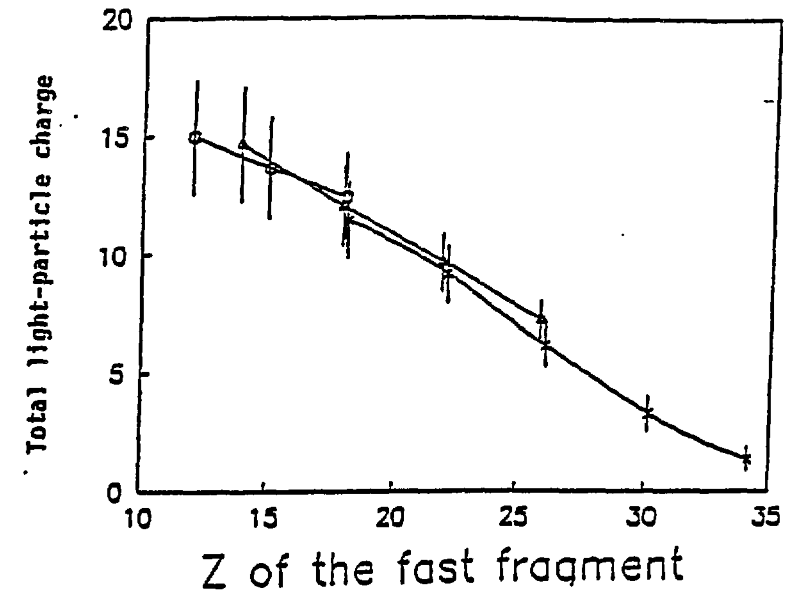

Figure 4 : Correlation between the charged particle multiplicity and the charge of the projectile-like fragment detected near the grazing angle for the reaction 43 MeV/u Kr+Au.[8]

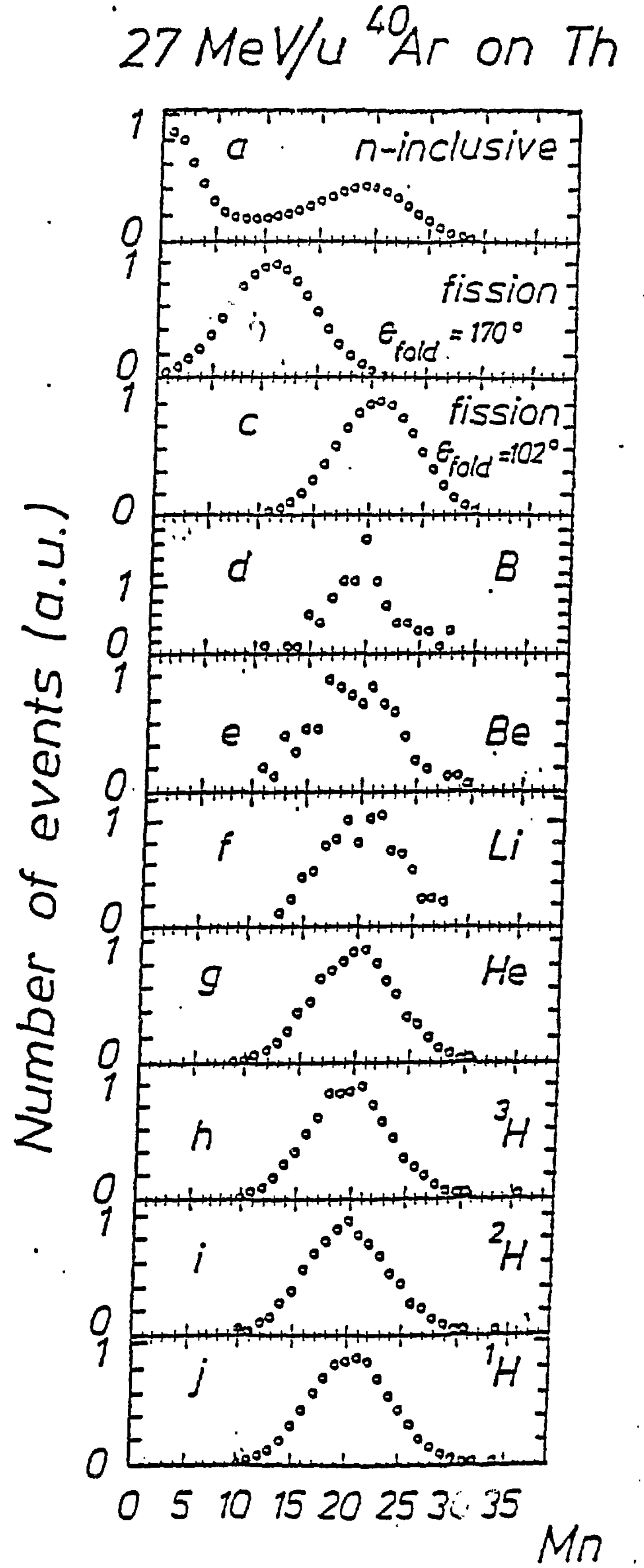

Figure 5 : Neutron multiplicity distributions (not corrected for the efficiency of the detector), inclusive as well as coincidence with light charged particles detected at 160°. The system being studied is the reaction Ar+Th at 27 MeV/u [10].

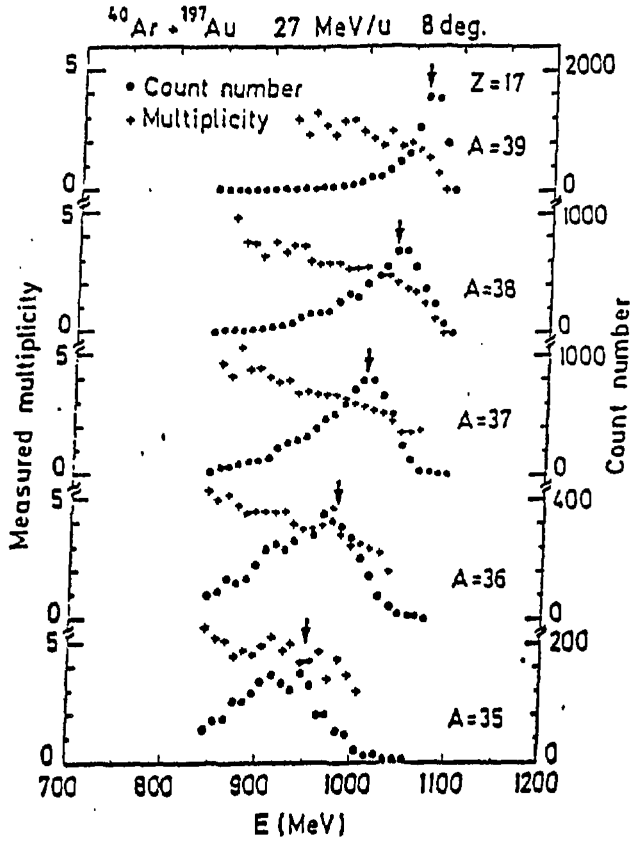

Figure 6 : Energy spectra of chlorine isotopes detected at 8° in the reaction 27 MeV/u Ar+Au [9]. The evolution of the average neutron multiplicity $< M_n >$ is also plotted as a function of the kinetic energy of the outgoing fragment. *Arrows indicate the* beam velocity.

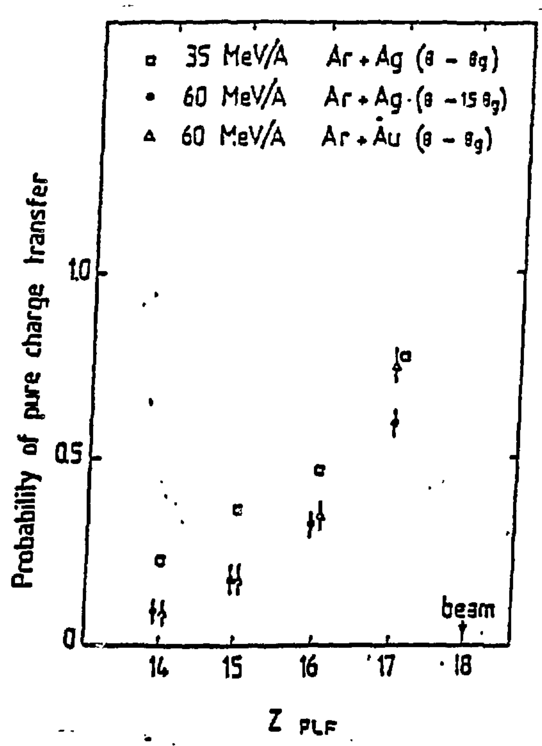

Figure 7 : Charge transfer probability for stripping reactions in the Ar+Ag system at 35 and 60 MeV/u and Ar+Au system at 60 MeV/u [11].

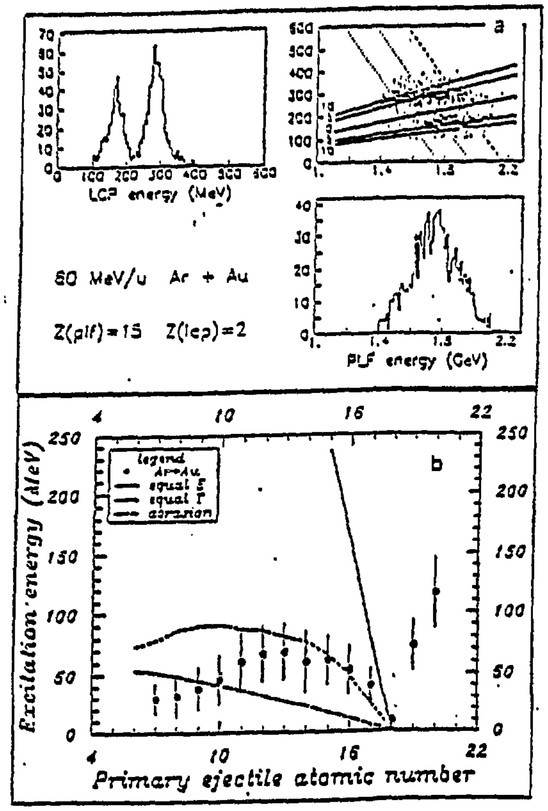

Figure 8 : a) Energy correlation between a Z=15 PLF and one α-particle emitted in close direction (for the 60 MeV/u Ar+Au system) [11].

b) The excitation energies of the primary ejectile produced in the 60 MeV/u Ar+Au reaction are compared with various hypothesis concerning the energy sharing between the partners [11].

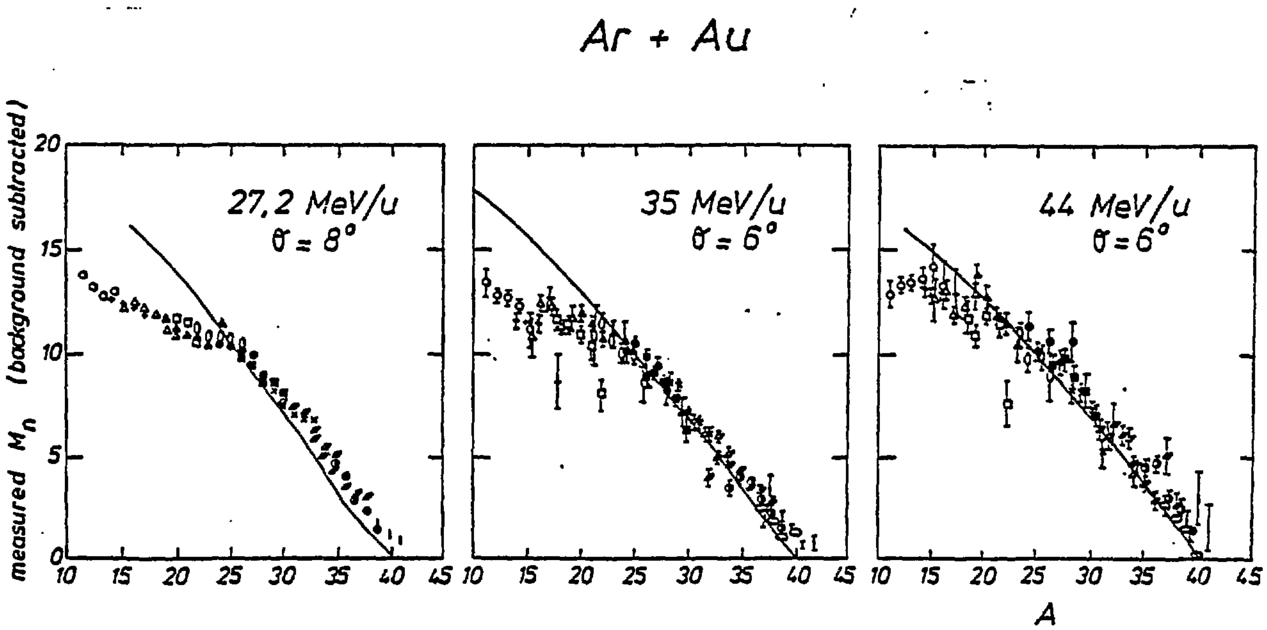

Figure 9 : Correlation between the average neutron multiplicity (not corrected for detector efficiency) and the mass of the projectile-like fragments. Evolution with incident energy [21]. Solid curves result from a calculation (see text).

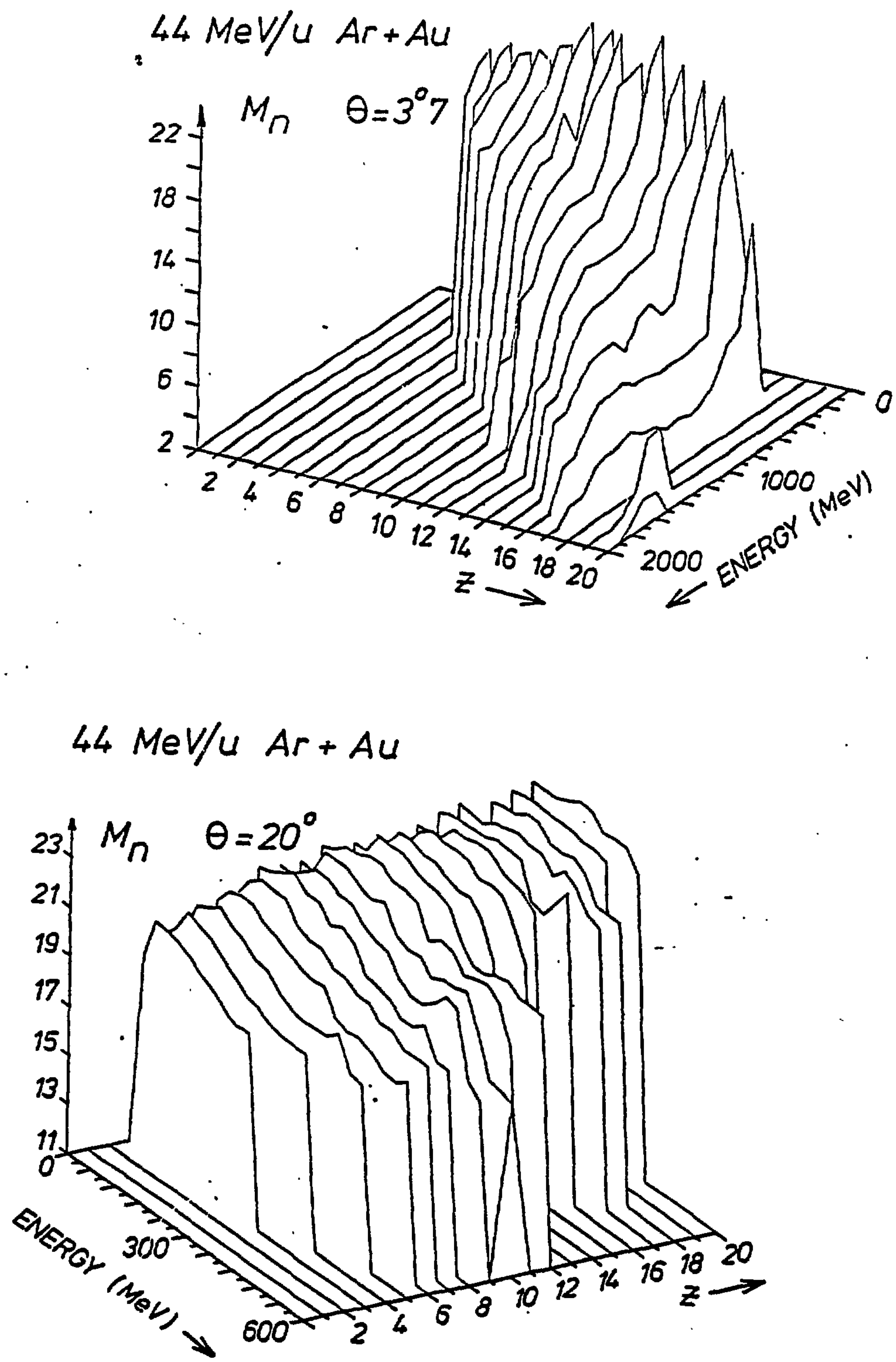

Figure 10 : Average neutron multiplicity (not corrected for detector efficiency) as a function of Z and kinetic energy of the fragments detected at 3°7 and 20° for the reaction 44 MeV/u Ar+Au [4].

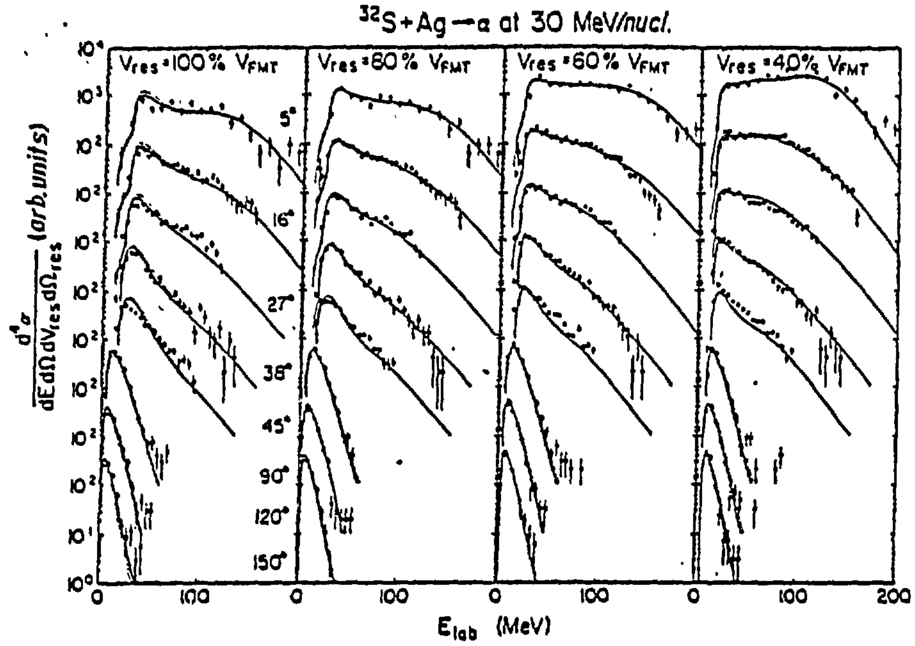

Figure 11 : Alpha-particle energy spectra observed for different ER velocity windows (i.e. different momentum transfers) in the reaction 30 MeV/u S+Ag. Solid lines result from a moving source fit (see text) [20]

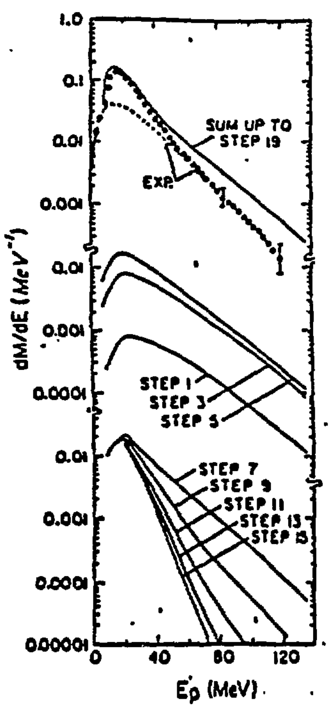

Figure 12 : Preequilibrium calculation using the Blann model for the 30 MeV/u S+Ag system. The calculation has been performed for different time intervals (1 step = 2.10^{-23}sec). At the top, the summed spectrum is compared with the experimental spectrum (solid circles) [20].

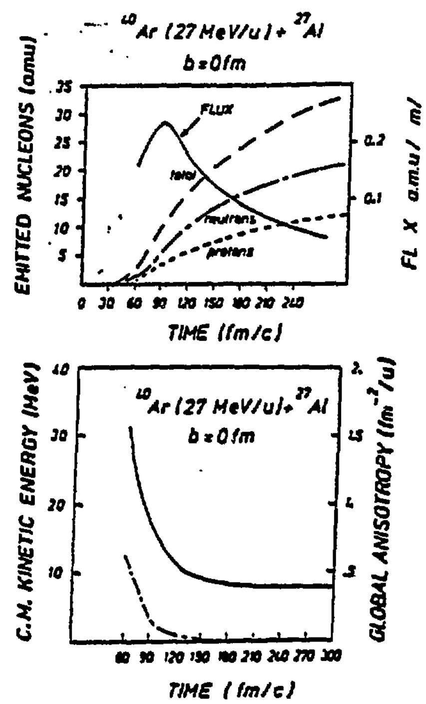

Figure 13 : Landau-Vlasov calculations describing the time evolution of the number of emitted particles, flux, mean kinetic energy and anisotropy for the reaction 27 MeV/u Ar + Al [27].

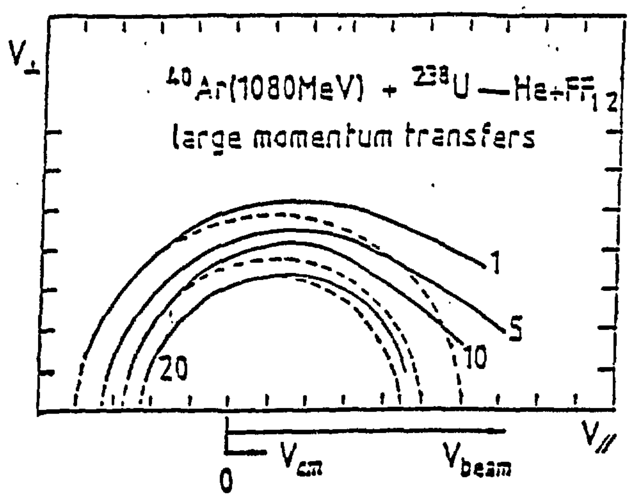

Figure 14 : Invariant cross sections for ^{1}H and ^{4}He measured at 135° in coincidence with a fission fragment detected at various angles [28].

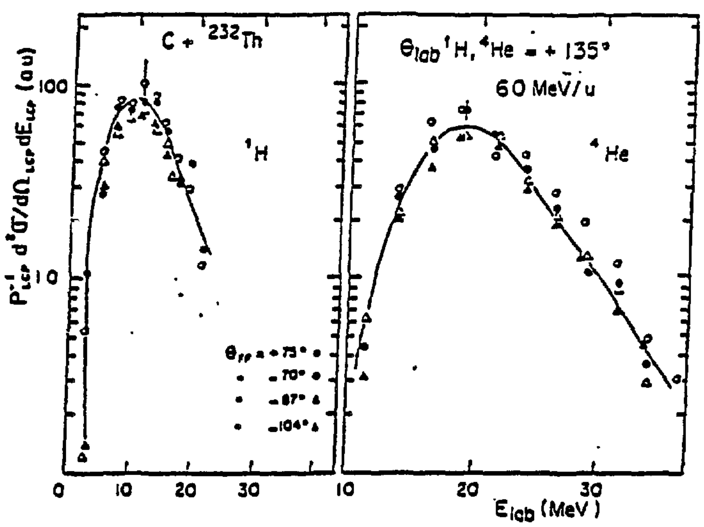

Figure 15 : Isocontours of invariant cross sections for α-particles in the velocity plane measured in coincidence with fission following large momentum transfer (solid lines). Dashed lines correspond to an isotropic emission from a source moving with the c.m. velocity [30].

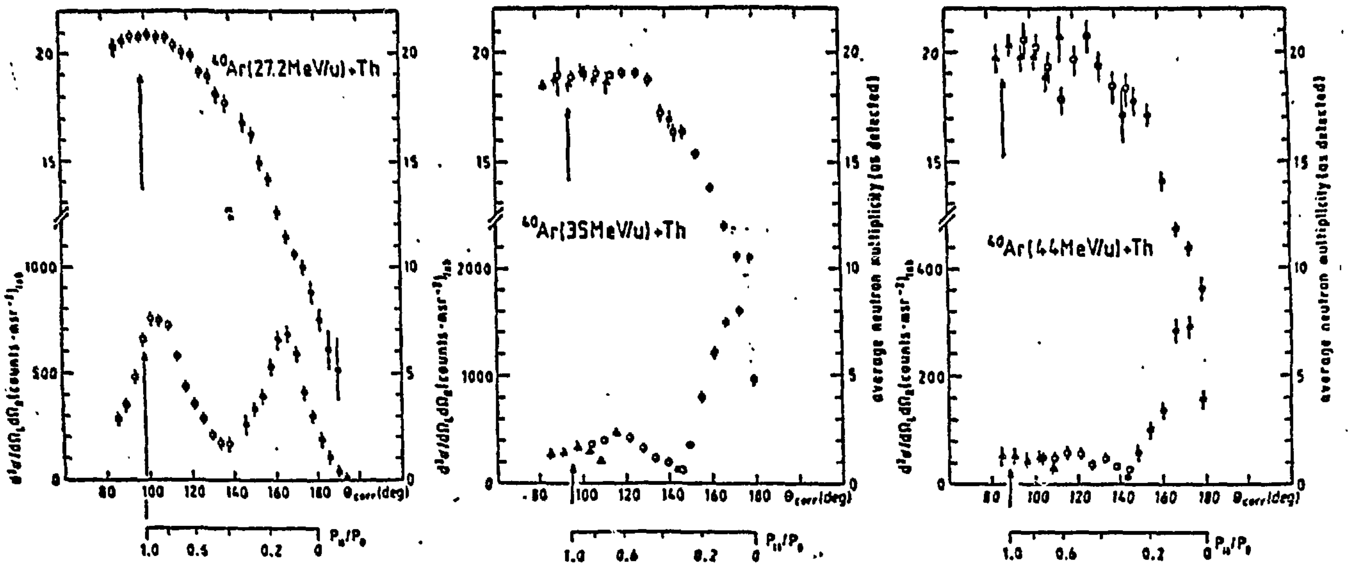

Figure 16 : Folding angle distributions (bottom) of the fission fragments and associated average neutron multiplicities (not corrected for detector efficiency) for ^{40}Ar + Th at 27, 35 and 44 MeV/u [31].

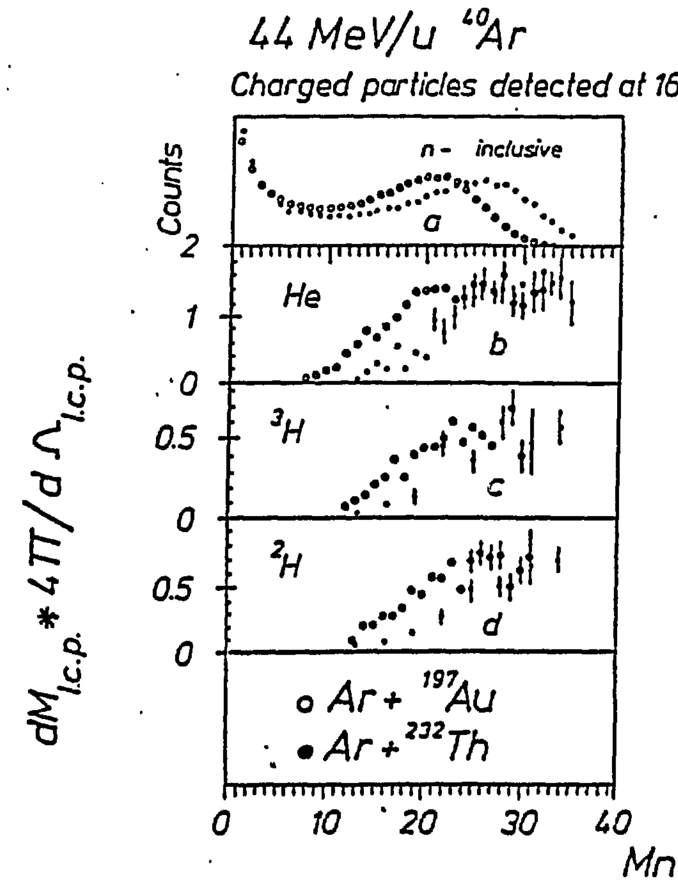

Figure 17 : Differential multiplicities of light particles detected at 160° as a function of the average neutron multiplicities [10].

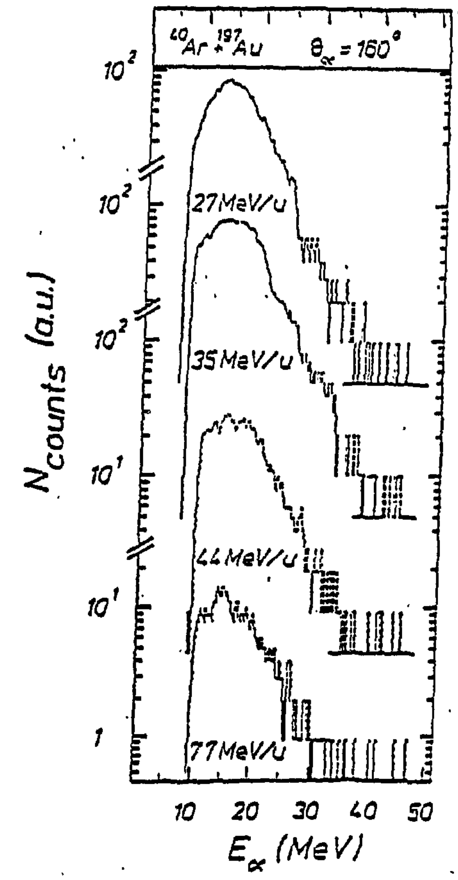

Figure 18 : Energy spectra for α-particles detected at 160° for the reaction Ar+Au between 27 and 77 MeV/u [10].

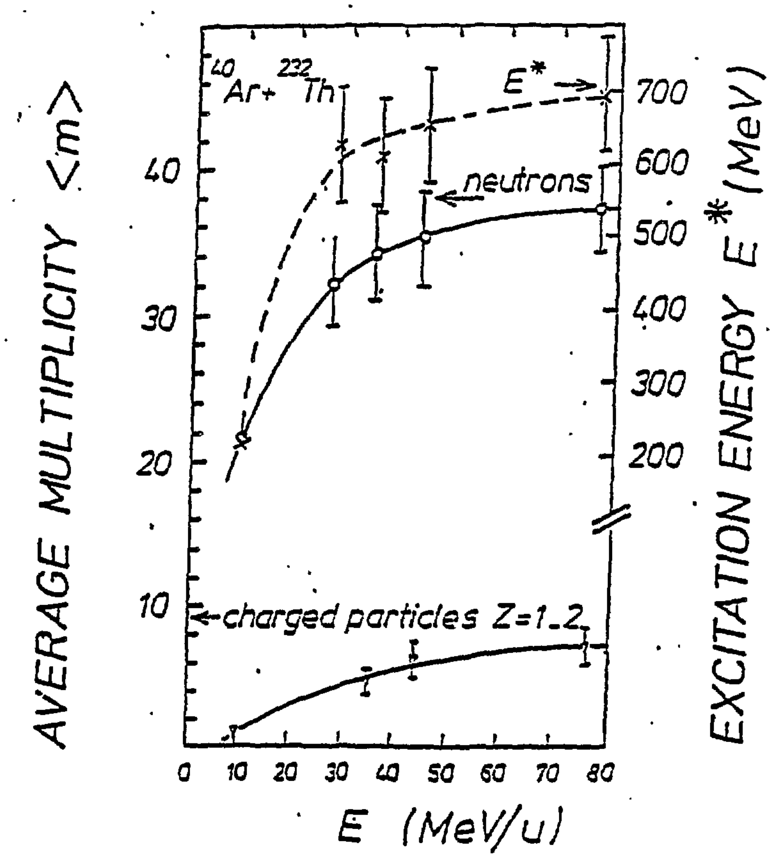

Figure 19 : Total multiplicities for evaporated charged particles and neutrons (after efficiency correction) as a function of bombarding energy. Crosses indicate the estimated thermal energy deposit [10].

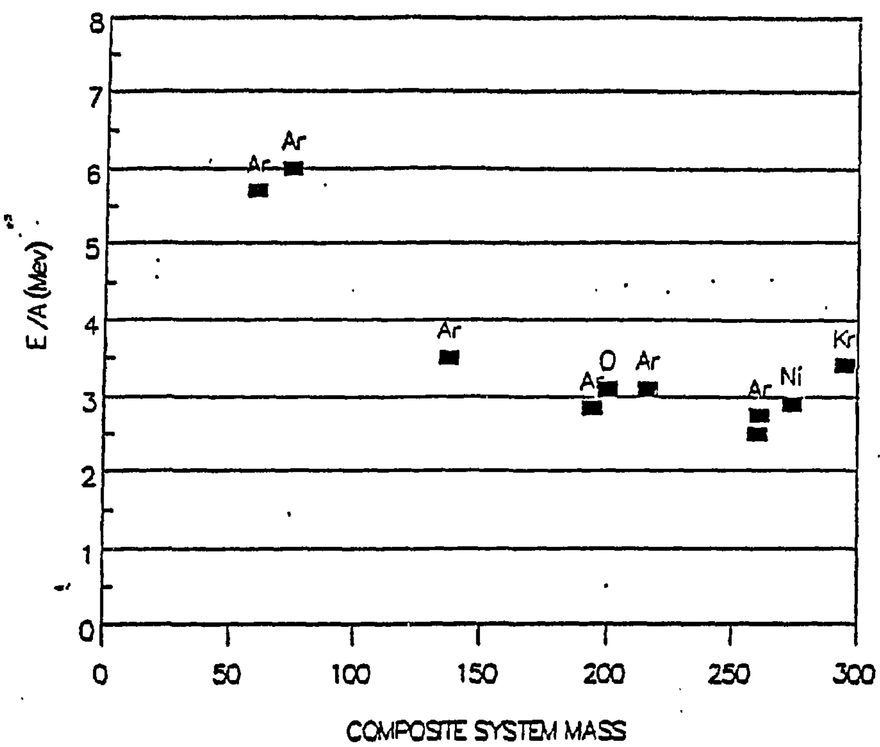

Figure 20 : Systematic of the highest excitation energy per nucleon reached so far in heavy ion induced experiments for a given mass of the composite system. The labels above the points are referring to the projectiles used for the experiments.

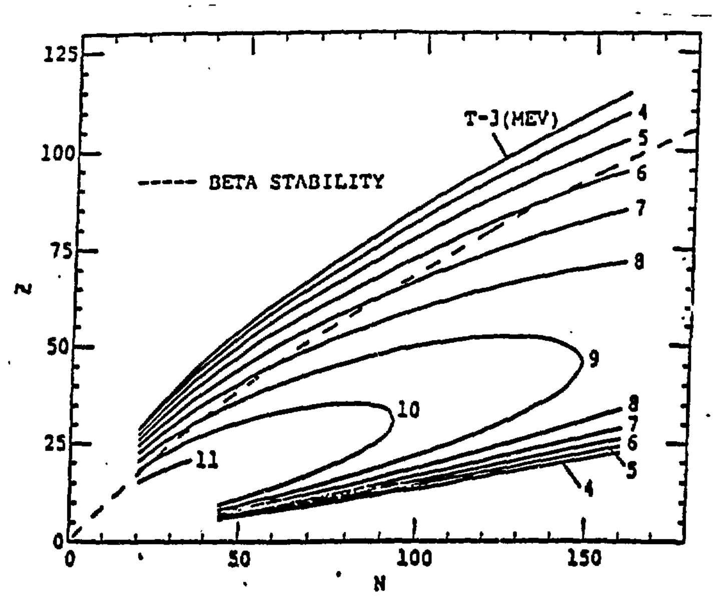

Figure 21 : Lines of constant limiting temperature calculated within the hot liquid drop model [40].

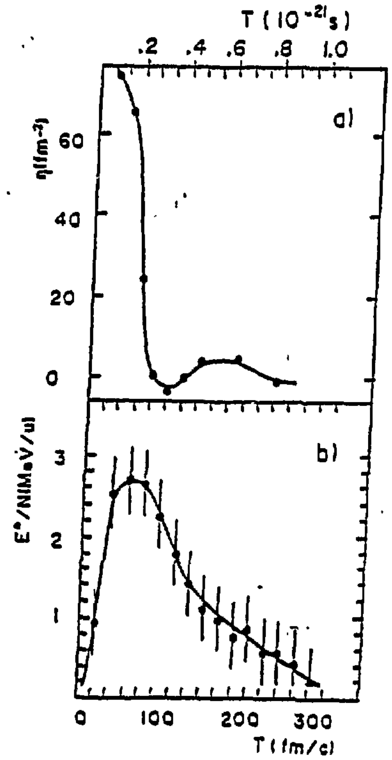

Figure 22 : Dynamical calculation (Landau-Vlasov) performed for the system Ar+Au for a central collision [42].

a) Anisotropy η of the momentum distribution of nucleons in the composite system.

b)excitation energy per nucleon of the composite system.

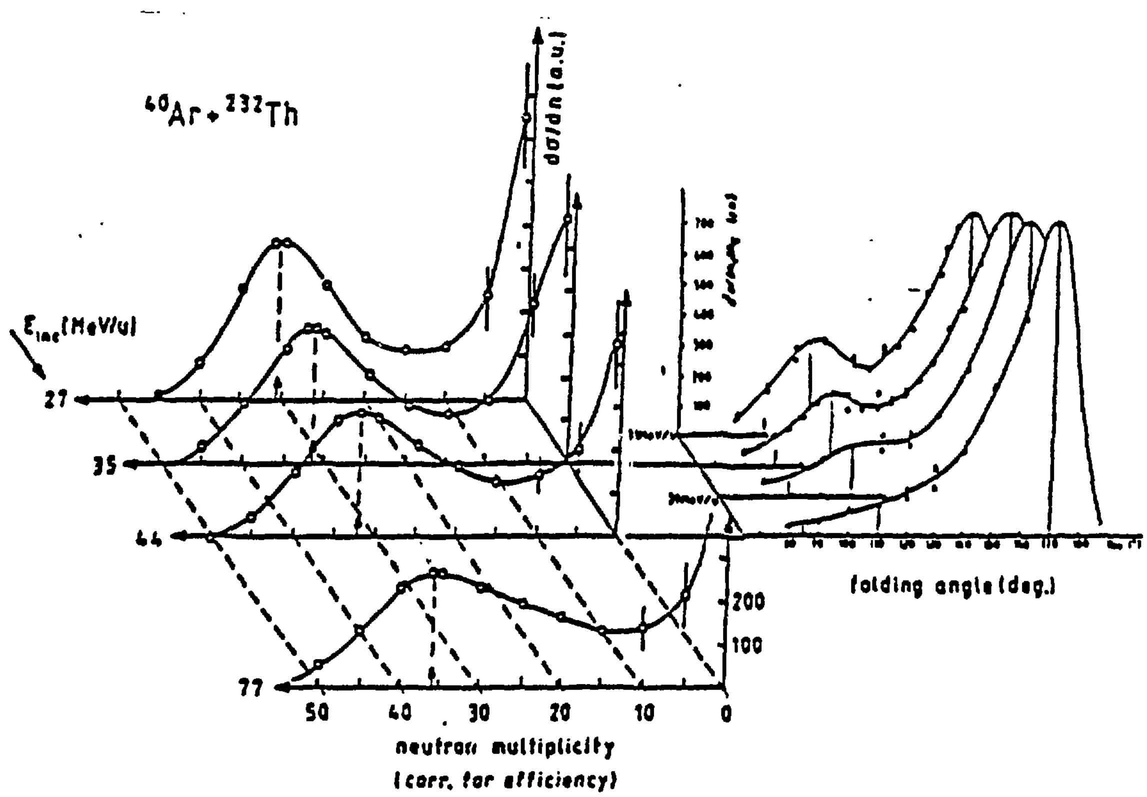

figure 23 : Neutron multiplicity [43] and folding angle distributions [33] from the reaction ^{40}Ar + Th within the incident energy range 27 to 77 MeV/u.