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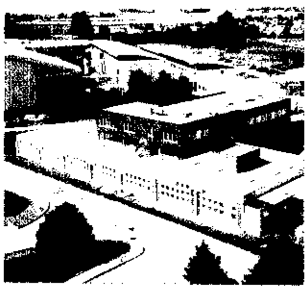

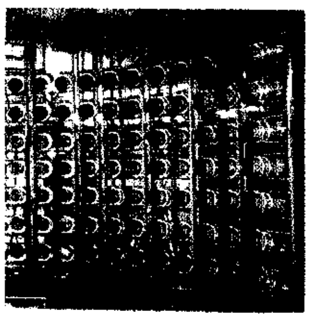

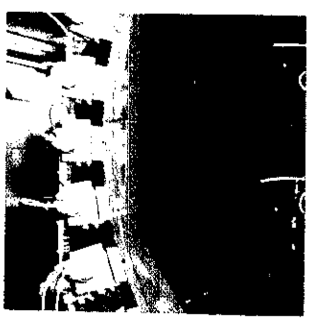

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INSTITUT NATIONAL
DE PHYSIQUE NUCLÉAIRE ET DE PHYSIQUE DES PARTICULES

INSTITUT DES SCIENCES DE LA MATIÈRE ET DU RAYONNEMENT

UNIVERSITÉ DE CAEN

- U.M.R.6534 -
ISMRA - 6, Boulevard Maréchal Juin - 14050 CAEN CEDEX - FRANCE

Téléphone : 02 31 45 25 00 - Télécopie : 02 31 45 25 49
Internet :

Can we really measure the internal energy of hot nuclei with a 4 π detection array ?

E. Vient [a,1], E. Genouin-Duhamel [a], J.C. Steckmeyer [a], G. Auger [b], C.O. Bacri [c], N. Bellaize [a], B. Borderie [c], R. Bougault [a], B. Bouriquet [b], A.M. Buta [a], J.L. Charvet [d], A. Chbihi [b], J. Colin [a], D. Cussol [a], R. Dayras [d], A. Demeyer [e], D. Doré [d], D. Durand [a], J.D. Frankland [b], E. Galichet [c,h], E. Gerlic [e], D. Guinet [e], B. Guiot [a], S. Hudan [b], P. Lautesse [e], F. Lavaud [c], J.L. Laville [b], J.F. Lecolley [a], R. Legrain [d,2], N. Le Neindre [a], O. Lopez [a], M. Louvel [a], L. Nalpas [d], J. Normand [a], M. Pârlog [f], P. Pawłowski [c], E. Plagnol [c], M.F. Rivet [c], E. Rosato [g], G. Tăbăcaru [f], B. Tamain [a], L. Tassan-Got [c], K. Turzo [e], C. Volant [d] and J.P. Wieleczko. [b]

INDRA Collaboration

[a]*Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université, F-14050 Caen Cedex, France*

[b]*Grand Accélérateur National d'Ions Lourds, DSM-CEA/IN2P3-CNRS, BP 5027, F-14076 Caen Cedex 5, France*

[c]*Institut de Physique Nucléaire, IN2P3-CNRS, BP 1, F-91406 Orsay Cedex, France*

[d]*DAPNIA/SPhN, CEA/Saclay, Orme des Merisiers, F-91191 Gif-sur-Yvette Cedex, France*

[e]*Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-69622 Villeurbanne Cedex, France*

[f]*National Institute for Physics and Nuclear Engineering, RO-76900 Bucharest-Măgurele, Romania*

[g]*Dipartimento di Scienze Fisiche e Sezione INFN, Università di Napoli "Federico II", I-80126 Napoli, Italy*

[h]*CNAM, Laboratoire des Sciences Nucléaires, F-75003 Paris, France*

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Abstract

The second generation of high quality detection arrays gave hope to nuclear physicists to finally obtain an experimental equation of state of nuclear matter. In spite of this progress, the measurement of the internal energy of a hot nucleus remains a very difficult task. This paper illustrates this difficulty by a methodological study of a classical technique of excitation energy measurement used in the Fermi energy range. The aim of this study is to verify the validity, the accuracy and the experimental limits of these measurements. It is shown that it is difficult to have a real experimental mastery of the source reconstruction and calorimetry at least for limited bombarding energies and violent collisions.

Key words: Heavy ions; Hot nuclear matter; Calorimetry; Excitation energy; Caloric curve; 4 π detection array;
PACS: 25.70.-z,25.70.Lm,25.70.Mn

1 Introduction

The study of hot nuclear matter is one of the major objectives of the nuclear physicist community, who works in the Fermi energy domain (20-100 A.MeV). To produce hot nuclear matter in laboratory, violent dissipative collisions between heavy ions are induced in the energy range from a few tens A.MeV up to a few A.GeV. During these collisions, a large amount of the incident energy is dissipated in thermal energy, leading this way to the "hot nuclei", i.e. one or several drops of hot nuclear matter which have reached thermodynamic equilibrium. To extract from such experiments a caloric curve of nuclear matter, we have to be capable to isolate and characterise these hot nuclei. We must therefore have a good knowledge and understanding about their formation and decay mechanisms. Experimentally, it is a very ambitious objective. The evolution of a collision in the Fermi energy domain is extremely complex. It is at the boundary between two different energy domains: low energies (<10 A.MeV) and high energies (>100 A.MeV). At low energy, it is now well-established that there are essentially two mechanisms dominating the reactions: fusion in central collisions and deep inelastic transfer in more peripheral collisions [1–3]. At higher energy, the participant-spectator process dominates(fireball) [4–7]. In the intermediate energy domain, deep inelastic processes become the main phenomena [8–14]. However, they are accompanied by an abundant dynamic contribution of light particles [15–18] and an

[1] E-mail:vient@caelav.in2p3.fr
[2] Deceased

important production of intermediate mass fragments (IMF) currently called "neck emission" [19–25]. These productions change according to the studied system, the incident energy and the impact parameter, which confirms a continuity of the physics between the different bombarding energy ranges [26]. Fusion is still observed but its cross-section becomes negligible [27–30]. The de-excitation phase of hot nuclei becomes also more complicated than at low energy. There are several decay processes, which range from classical statistical decay by evaporation to total apparent vaporization of the nuclei, through fission, sequential fragmentation and multifragmentation [31–37]. The origin of some of these processes is still not well understood. The hot nucleus lifetimes become increasingly short with the violence of the collision [38,39]. Thus it becomes difficult to separate temporally formation and decay phases of the hot nuclei [40]. Then the Bohr's assumption of independence [41] between these two phases is no longer valid. Experimentally only the cold residues of disintegration are observed long after they have been produced. The initial nuclei must be reconstructed from a mixing of these decay products and of all particles, which would have been produced dynamically during the collision. The main challenge for the nuclear experimentalists is therefore the detection of all particles produced during the reaction and the determination of their origin [18,26,40,42]. This is why all over in the world, in the late eighties this community has built detection arrays covering the space as completely as possible [43–55]. Now, the experiments are performed with detectors of second generation [56–58]. The study presented in this paper has been achieved within the INDRA collaboration. INDRA is one of the second-generation detection arrays. It allows detection of charged particles produced throughout a reaction, with a solid angle of 90 percents of 4π. A good granularity authorises a perfect identification in charge up to 54 with a good energy resolution. The energy detection thresholds are about 1 A.MeV. The particles are identified in mass up to beryllium. INDRA is constituted of 336 independent modules [56,59,60].

Any study about the equation of state of nuclear matter (caloric curves [61–63] or calorific capacities [64–66]) requires a calorimetry of hot nuclei. To be unassailable scientifically, they need furthermore a real control of the measurement of the excitation energy and of its experimental error. Our approach here is to study whether such an experimental mastery is realistic in the domain of heavy ions collisions. We have therefore performed a methodological study of a classical characterisation technique of hot nuclei detected by a 4π detection array. It has been already used by the NAUTILUS collaboration [14,16,67,68] and the INDRA collaboration [63,69,70] in different forms. The validity of this experimental method has been tested for the symmetric system Xe + Sn at 50 A.MeV. We have tried to unfold the respective influences of physics, of the detector and of the analysis method on the characterisation of the hot nuclei. Thus, we have been able to highlight the dominant factors, which act on the quality of the deduced excitation energy, and to define possible improvements. We have quantified the errors and estimated the limits of application of this

method. In the second section, we present the different tools used during our analysis and describe their use:
- The phenomenological event generator SIMON.
- The INDRA computer Filter.
- The method of analysis.

In the third section, our analysis is explained and presented. We conclude and outline perspectives in the fourth section.

2 The analysis tools

2.1 The phenomenological event generator SIMON

All our calculations have been performed with the event generator SIMON, described in details in references [71,72]. We just remind that it treats each step of the nuclear reaction. The collision dynamic is governed by a generalised Lagrange-Rayleigh equation [73,74]. The excited nuclei decay is described by successive independent emissions according to two different theories depending on the emitted particle mass. For the light particles and fragments, the disintegration is simulated by the standard evaporation theory established by Weisskopf [75], including emission to discrete excited states. For heavier fragments, the emission is treated by the transition state theory of Bohr and Wheeler [76], improved by Kramers [77]. The trajectory calculations are performed by taking into account the Coulomb interactions at each time step, keeping therefore space-time correlations. The entrance channel can be chosen with or without pre-equilibrium particles. To avoid the complexity of the entrance channel, we have chosen to consider only **"pure binary collisions"** without any dynamical emission between the quasi-projectile (QP) and the quasi-target (QT). The fusion events, which represent a very weak cross-section, have also been excluded. This cut does not provoke a sharp cut-off in the cross-section distribution. As a result, we have a total mastery of the entrance channel, setting in the best conditions to apply our method of reconstruction of hot nuclei. The following *reductio ad absurdum* can even be done: if our method does not work in this simple case, it will never work in more complicated and realistic cases. Simulated events have been calculated with input parameters which roughly reproduce the experimental static and kinematic characteristics of both heaviest fragments. This generator presents many important advantages. We can get a lot of events within reasonable calculation time. The origin of each produced particle is perfectly known, because it is labelled. The generator can be filtered in a realistic way.

2.2 *The INDRA computer Filter*

The software simulating the experimental apparatus should ideally be able to account for all experimental phases (detection, charge identification, energy calibration), to treat all simulated data as physics data. The INDRA filter [78,79] allows for the management of particle interactions with the different parts of the detection array, reproducing the geometry and the modular structure of INDRA. It gives theoretical energetic thresholds and identification thresholds for each stage of any INDRA module. It manages multiple detection in a module. When coupled to the SIMON event generator, the INDRA filter allows to keep the labelling of the origin of each particle. It is evidently very important for our analysis because it gives the possibility of doing a "perfect calorimetry". When the simulated data have been filtered, they are analysed using exactly the same program as for the experimental data.

2.3 *The method of analysis*

The experimental method has been developed to characterise the experimental Quasi-Projectiles (QP) and the Quasi-Targets (QT). It will be applied to SIMON events exactly as it is done to the experimental data in references [69,70]. The first step is the reconstruction of the velocities of the QP and the QT, event by event. The two sources are assumed to have reached thermodynamical equilibrium. For this reconstruction, the Light Charged Particles (LCP) are not used to minimise the influence of the eventual pre-equilibrium LCP's. We determine the momentum tensor of the Intermediate Mass Fragments (IMF) and heavy fragments in centre of mass of the reaction [80,81]. We cut velocity space in two halves at the velocity of the centre of mass perpendicularly to the principal axis of the momentum ellipsoid. The method is illustrated in figure 1. Every fragment, located in the forward space, is considered as belonging to the QP and the other ones to the QT. Then the velocity of both primary nuclei can be determined. We must keep in mind that this method favours the binary character of the collision and is not consistent with any dynamical mid-rapidity emission, observed experimentally between both partners of the collision [8–14]. For this reason, our method will be all the more limited that we will study increasingly central collisions. For the second phase of the method, we consider only the LCP's located in the forward hemisphere of the QP source as emitted by the QP to avoid any pre-equilibrium contamination [15–18]. The QP charge is built by adding to the biggest detected fragment twice the charge of the particles emitted in the forward hemisphere of the source. The QP mass is obtained from the QP reconstructed charge by using the projectile ratio N/Z. Neutron multiplicity is estimated from the conservation of the QP mass. The neutron kinetic energy is estimated event by event

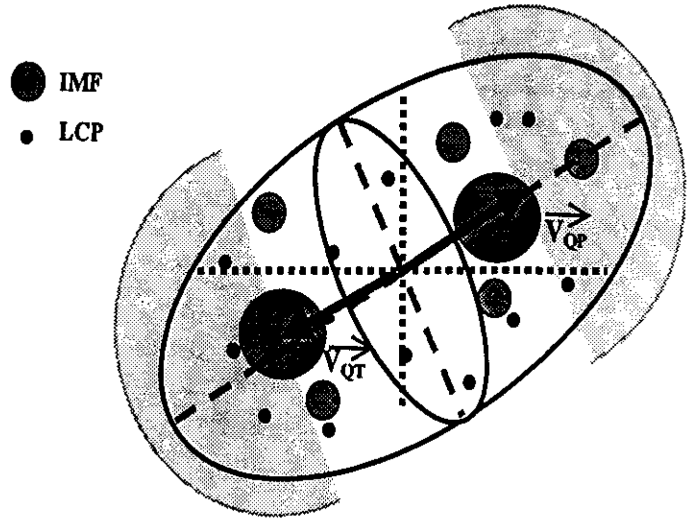

Fig. 1. Scheme describing the Experimental Method of reconstruction of the QP and the QT.

from the mean proton energy corrected for Coulomb barrier. The QP internal energy is obtained by calorimetry, i.e. by performing an energy balance of the QP decay as shown by the following formula:

$$E^*_{QP} = \sum_{k=1}^{Mc} T_k + M_n \times \overline{T_n} - Q \qquad (1)$$

T_k is the kinetic energy of the k^{th} charged particle, $\overline{T_n}$ is the mean neutron energy and M_n is the estimated multiplicity of neutrons. Q is the Q-value (energy release) of the QP disintegration. This study has been made with symmetric systems, therefore the reconstruction methods of the QP and the QT are identical: to find the QT characteristics, by symmetry, we consider only the particles in the backward hemisphere of the QT source and we apply the same calculations. We want to reconstruct at the same time the QP and the QT. Consequently, the method can be applied only if a large fraction of particles in an event are correctly detected and identified. Two experimental variables Z_{tot} and $(ZV_{//})_{tot}$ are defined to characterise the quality of the measured events:

$$Z_{tot} = \sum_{i=1}^{Mul} Z_i \text{ and } (ZV_{//})_{tot} = \sum_{i=1}^{Mul} Z_i \times (V_{//})_i \qquad (2)$$

With Z_i: charge of the i^{th} detected particle.
Mul : detected multiplicity.
$(V_{//})_i$: parallel velocity of the i^{th} detected particle.

3 Application and discussion

3.1 Protocol

The generator SIMON provides us, at a quasi-infinite time after the collision, with all the products of a nuclear reaction and their origin. The initial characteristics of the QP and the QT (charge, mass, momentum, kinetic energy and excitation energy) have been reconstructed by using the conservation laws. For the continuation of this study, these values will be called "True Values" and will be used as values of reference. We want to unfold the respective effects of the reconstruction method, the limitations of the detector and the complexity of the physics on the quality of the excitation energy measure. Firstly, our experimental method is applied to simulated events before they passed through INDRA filter. To be coherent with respect to the experimental method, the neutrons are not taken into account (in this case, it is as if we use a "perfect detector of charged particles"). So we validate our reconstruction method and understand the effect of our ignorance about the particle origin, when they are perfectly detected. Then the filtering is applied and the sources are reconstructed from the detected particles knowing their origin. We can verify like this the filter influence without being disturbed by the ignorance of particle origin. Finally, our method is applied to the simulated data passed in the INDRA filter. All our analysis is done for the quasi-symmetric system Xe + Sn in the case of "pure binary" collisions at 50 A.MeV.

3.2 Calorimetry with a "perfect detector of charged particles "

Firstly, we wanted to verify two important hypotheses of the experimental method: the effective isotropy of the emission of particles in the forward hemisphere of the frame associated with the initial hot nucleus and the unique origin of those. Figure 2 perfectly illustrates this study for the QP. In this figure, only the protons and alphas located in the forward hemisphere of the velocity space are considered. Their angular distributions given by SIMON and those obtained by the experimental Method are compared. We can observe that one of the usual criteria required to assume the thermalisation of a hot nucleus, i.e. the flatness of the cosine(θ) distribution in the frame of the reconstructed source (if there is no significant angular momentum), is not valid for all impact parameters. For peripheral collisions, we perfectly recover the initial angular distributions. We can thus conclude that the experimental method can be applied and authorises a correct determination of the particles origin in this case. We can just notice for the protons a small contribution coming from the QT at the back of the QP source. On the other hand, the separation of particles

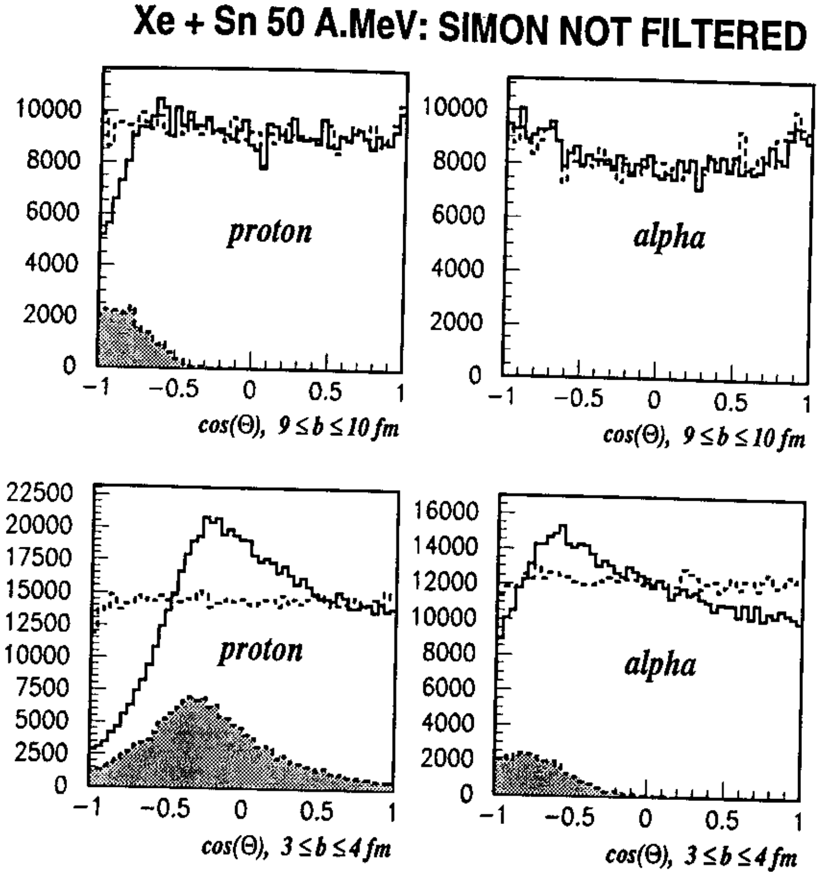

Fig. 2. Cosine(θ) distribution of protons and alphas, which are located in the forward hemisphere of the velocity space (defined in the CM frame), with θ polar angle defined in the frame of the QP. The dashed lines correspond to the true angular distributions given by SIMON. The solid lines are associated with the angular distributions defined in the frame of the QP, which was reconstructed by the experimental method. The grey distributions correspond to particles of the QT, which are located in the forward hemisphere of the velocity space.

appears much more difficult for the mid-peripheral and central collisions. We see that the protons and alphas distributions, which were initially flat, are completely disturbed when the real origin of particles is lost. We can give three explanations to this. When the collision is more central and dissipative, relative velocity between both sources decreases (visible in figures 3 and 4). Consequently the two emission spheres can overlap. The overlap depends on the particle nature according to the size of the associated emission sphere (see figure 3). Particles emitted in the forward hemisphere of the QT can even be found in the forward hemisphere of the QP as can be observed for the protons in figure 2. We have an excess of particles coming from the QT. The apparent lack of particles in the QP backward hemisphere is a complementary effect. It can be explained by the symmetry of the entrance channel. Actually, we have associated particles coming from the QP to the QT exactly in the same way.

Another spurious effect occurs: it is the systematic decrease of the cosine(θ) distribution in the QP forward hemisphere. This trend is stronger for alphas than for protons. It is due to an overestimation of the perpendicular component of the source velocity. This error modifies the cosine(θ) distribution by a Jacobian effect. This error on the perpendicular velocity is intrinsic with

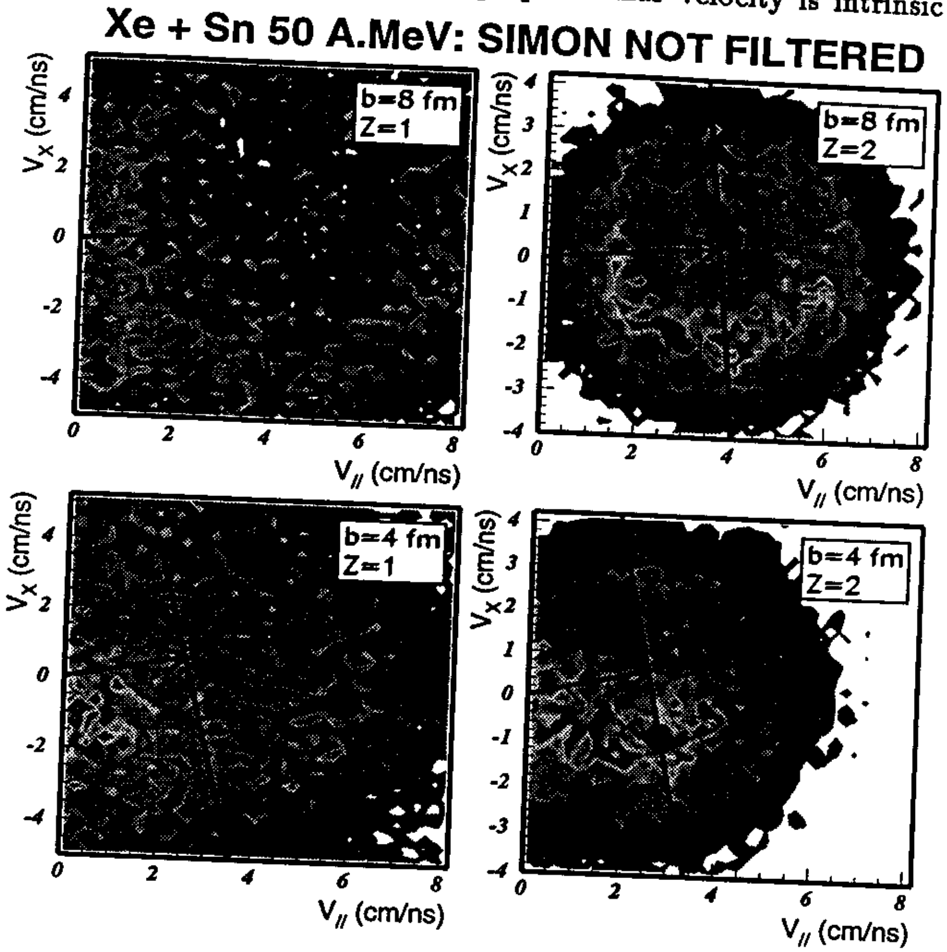

Fig. 3. Invariant cross-sections of alphas and protons in the forward velocity plane (containing the beam and the velocity vector of the source obtained by the experimental method) for two different impact parameters b=4 fermis and 8 fermis. The velocities are defined in the referential of the centre of mass. The arrow indicates the average reconstructed velocity of the QP in both cases. The line shows the experimental chosen cut.

physics. The primary QP angular distribution given by SIMON is strongly forward peaked. The sequential characteristic of the decay, the limited nucleus size and the cooling of the nucleus imply a systematic difference between the velocity of the centre of mass of LCP's and the one of IMF's and of heavy fragments. It is due to the successive recoils after each emission. Even if the evaporation is fundamentally isotropic (it is the case in SIMON), it appears very difficult to compensate the recoil due to the first evaporations by the subsequent emissions, because they are usually on average less energetic. We can see this effect in figure 3 for the alphas. There is a contribution more important on the opposite side of the reconstructed velocity of the QP with respect to the beam. We have called this phenomenon : the "right-left effect". It has been observed experimentally and is described in references [69,70]. To confirm and better understand the importance of this problem, the absolute values of different variables characterising the QP and the QT obtained by using the Experimental Method (EM) are presented in figure 4-a. In figure 4-b the relative errors on these different variables characterising the QP and the QT have been added. The relative errors are calculated in the following way:

$$Vrel\ error\ (\%) = \frac{(V_{EM} - V_{True})}{V_{True}} \times 100 \tag{3}$$

We notice the good reconstruction of the parallel velocity. It is comprehensible because only IMF's and fragments are used in the reconstruction. The mixing of these particles coming from the QP and the QT is weak and appears only for the most central collisions. Furthermore, the biggest fragments keep an important memory of the entrance channel. On the other hand, we see a very bad determination of the perpendicular velocity due to the decoupling of IMF's and LCP's in the reconstruction of the source velocity.
The graphs concerning the charge and mass are equivalent, as the mass is obtained from isospin conservation. Some charges are lost progressively when the impact parameter decreases. In figures 5-a and 5-b, we present the "True Values" and the values obtained by the experimental method of the multiplicity and the mean kinetic energy (in the frame of emitter) of neutrons, Z=1, and Z=2, as well as the relative errors between the "True Values" and those determined by the experimental method. There is a similar determination of the multiplicity of neutrons and protons, which are measured correctly (slightly underestimated because "right-left effect", around one percent) above 3 fermis. Then they are overestimated because of the presence of protons of QT in the QP forward hemisphere and reciprocally. For alphas, the graphs are very different. The absolute and relative graphs indicate an underestimation. For central collisions, it is twice greater for the alphas than for the other light particles. There is a regular increase of the relative error when the impact parameter decreases. The mass and charge charts follow the same trend. The quality of the charge measurement is effectively linked to this lack of alphas. Figure 3 well shows why alphas are lost because of the cutting, which favors alphas located on the same side as the QP with respect to the beam. The more we overestimate the QP perpendicular velocity less we take in consideration the alphas in the region where they are the most numerous. We must remind that this forward contribution is multiplied by two. Therefore automatically, the importance of this error is doubled. We find this also for the QT, slightly increased because the QT is lighter than the QP. Thus the estimation of the charge of the QT is a little worse than the one of the QP.
The total excitation energy and the excitation energy per nucleon are cor-

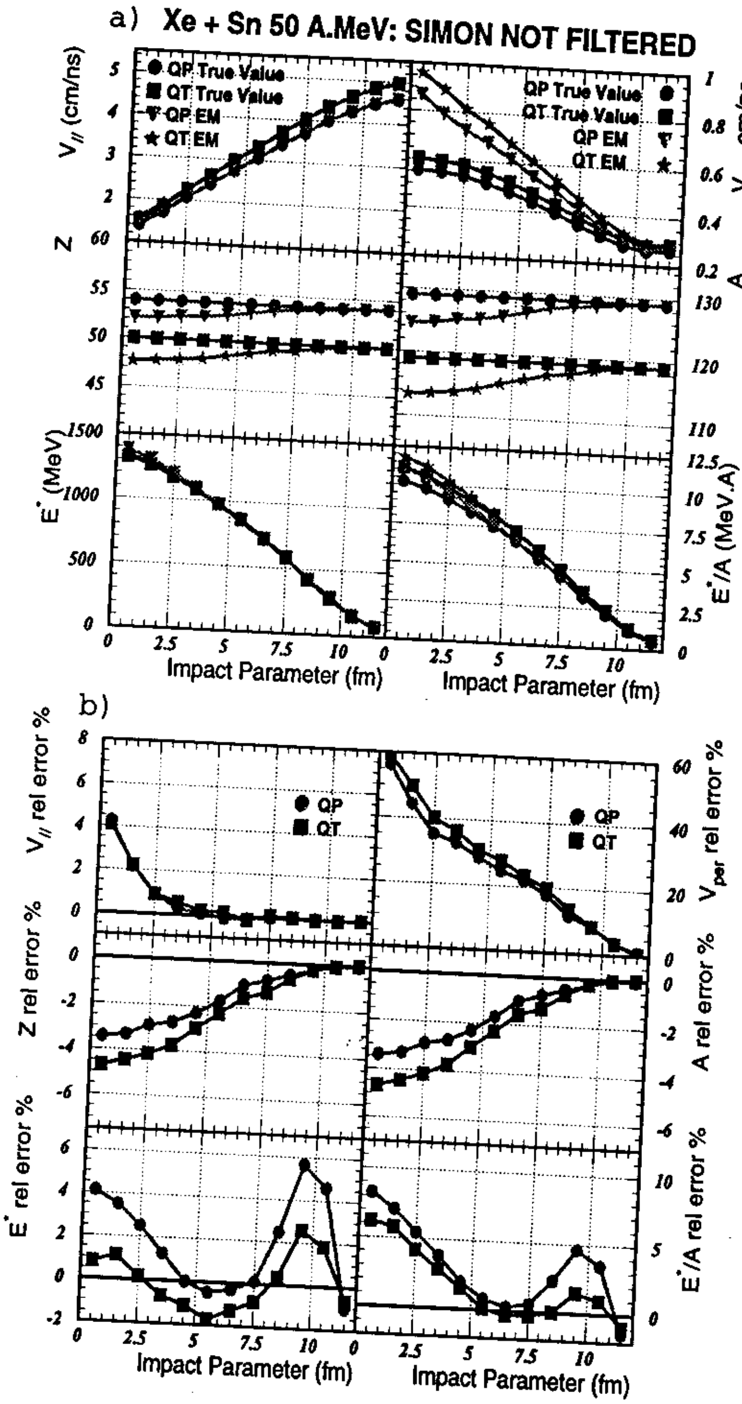

Fig. 4. a) The "True Values" and the values obtained by the Experimental Method (EM) of the parallel velocity, perpendicular velocity, charge, mass, total excitation energy and of the excitation energy per nucleon of emitting nuclei as a function of the impact parameter. Only the pure binary collisions are taken account. b) Relative errors on the parallel velocity, perpendicular velocity, charge, mass, total excitation energy and the excitation energy per nucleon of the emitting nuclei between the "True Values" and the values obtained by the experimental method. All these variables are defined as a function of the impact parameter.

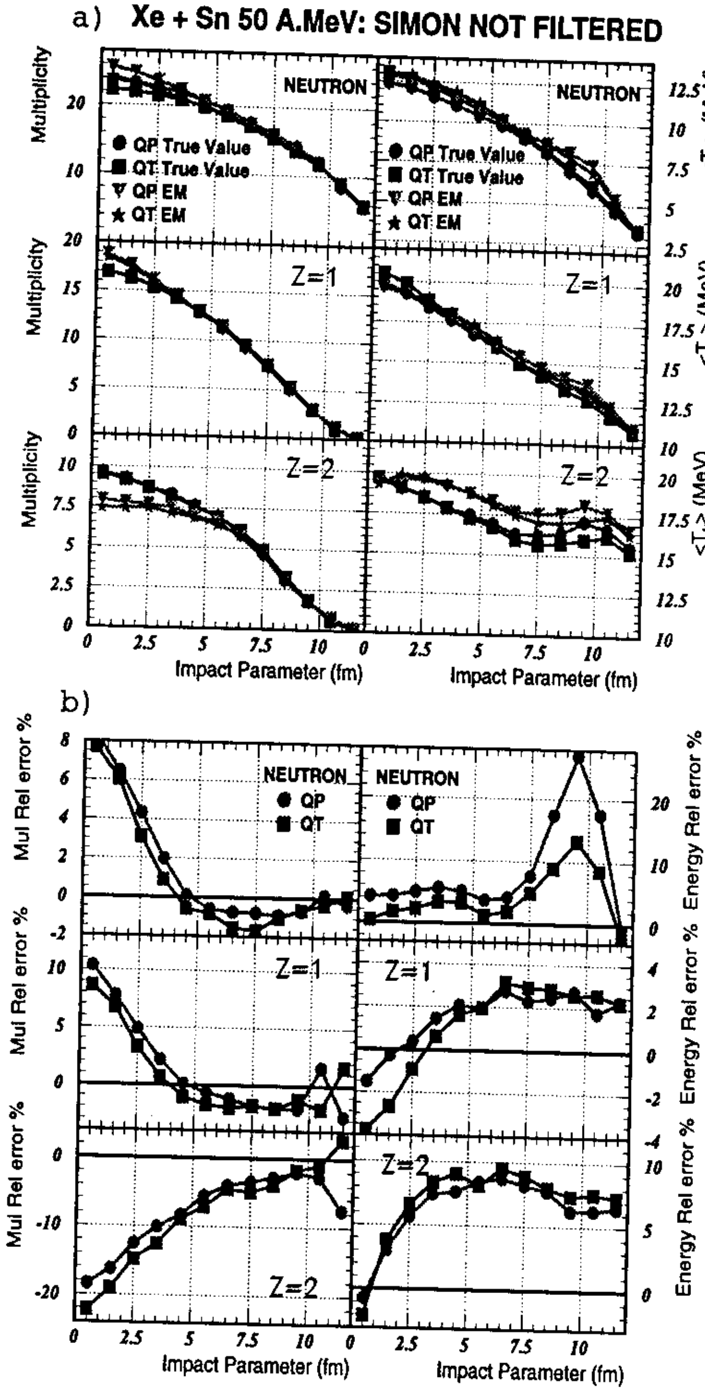

Fig. 5. a) The "True Values" and the values obtained by the experimental method of the multiplicity and of the mean kinetic energy (in the frame of emitter) of neutrons, Z=1, and Z=2. Only the pure binary collisions are taken account. b) Relative errors between the "True Values" and the values obtained by the experimental method on the multiplicity and the mean kinetic energy (in the frame of the emitter) of neutrons, Z=1, and Z=2. The circles concern the QP and the squares the QT.

rectly estimated for all impact parameters (4-a). The relative errors about the total excitation energy and the excitation energy per nucleon remain below 6-7 %. The error on the mass estimation explains the difference between both variables.

It is interesting to study a little more in details these two variables according to the violence of the collision. For the highest impact parameters, we remark a systematic bump in the errors around b=9 fm. It is due to the determination of the kinetic energy of neutrons. The curve in figure 5-b concerning the errors on the mean kinetic energy of neutrons rises and falls exactly in the same way for these impact parameters as the one of the excitation energy. In this range as shown in figure 6, the kinetic energy of neutrons represents 25 to 30 % of the excitation energy of the QP or the QT at the same impact parameter. To estimate this energy, we use the mean energy of protons minus the Coulomb barrier. In fact, this problem is clearly due to an underestimation of this Coulomb barrier for protons. We have chosen a fixed value 3.5 MeV. We have also a slight overestimation of the mean kinetic energy of protons (3 %) which is a direct consequence of the "right-left effect". This effect is confirmed by the

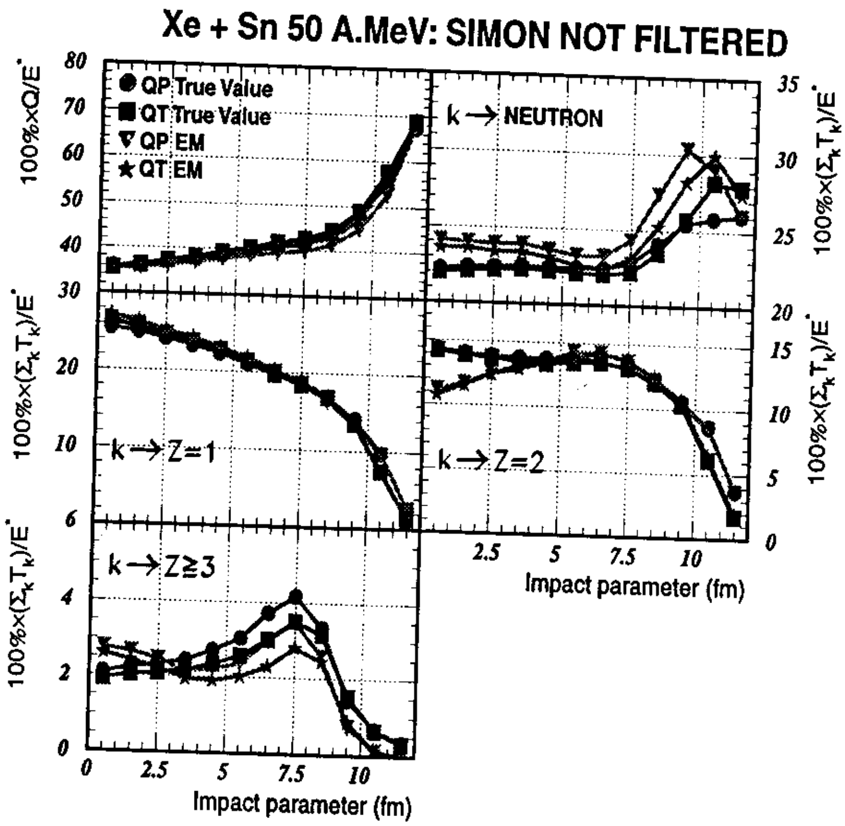

Fig. 6. The "True Values" and the values obtained by the experimental method for the relative yields of Q-value, energetic contributions of neutrons, Z=1, Z=2 and of IMF in the excitation energy of the QP and of the QT.

important errors (two times as high as the one for the protons) about mean kinetic energy of alphas.

For the mid-peripheral collisions, the error on the excitation energy is weaker (less than 2 %). But it is negative. Indeed, we lost light particles. The overestimation of the kinetic energy of the light particles begins to diminish because the influence of the "right-left effect" decreases with the centrality of the collision. There is another explanation. The contribution of particles coming from the QT and wrongly associated to the QP, leads to a velocity distribution inside the Coulomb circle of the QP, consequently it gives a weaker energetic contribution than the particles coming really from the QP. The reciprocity exists for the QT by symmetry.

For central collisions, the error on the excitation energy increases again essentially because we add some protons coming from the QT and consequently some neutrons. We find also an increase of the error on the excitation energy per nucleon up to around 8 %. It is mainly due to the underestimation of the mass by the lack of alphas, which is not compensated by the surplus of protons and of neutrons. To complete and confirm this analysis, we have studied the respective yields of the Q-value and of the kinetic energy of each type of particles in the total excitation energy of the QP and of the QT. We see in figure 6 the essential role played by the neutron contribution and that of the protons to a less degree, in the slight overestimation of the excitation energy concerning the more central collisions.

From this first study with a "perfect detector of charged particles", we can

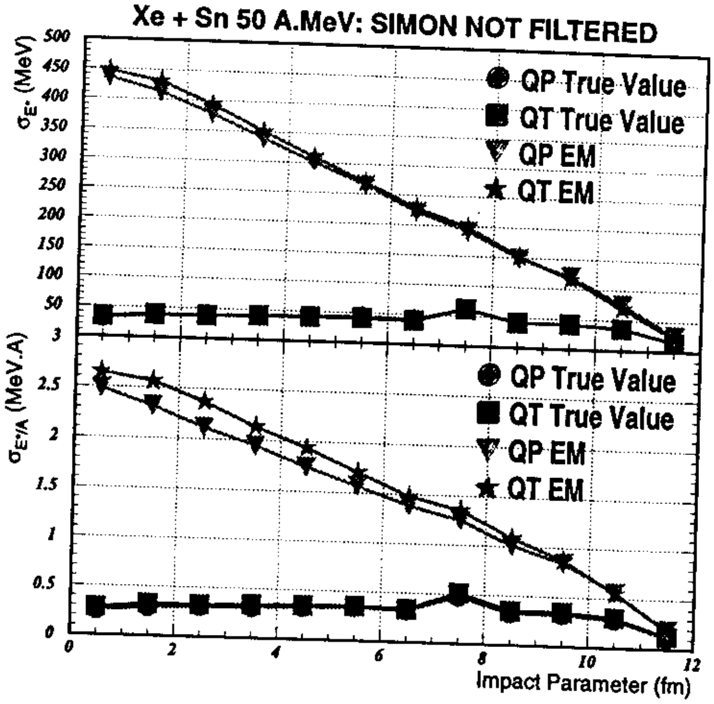

Fig. 7. The "True Values" and the values obtained by the experimental method of the excitation energy and the excitation energy per nucleon fluctuations as a function of the impact parameter.

conclude partially about the experimental method. It gives a good measure (if we improve effectively our method to estimate the characteristics of neutrons from those of protons) of the excitation energy per nucleon. On the other hand, the measurement of the velocity vectors of sources is disturbed by not including the alphas in our reconstruction of these sources. More precisely their perpendicular components are distorted. We can note that it is not hindering from measuring the excitation energy for peripheral collisions in the experimental frame that we have fixed i.e. "pure binary collisions". To end with this study with a "perfect detector of charged particles", it seems interesting to observe the effect of the experimental method on the measurement of the intrinsic fluctuations of the excitation energy and excitation energy per nucleon. The measured excitation energy per nucleon is used to sort the events in the new methods of characterisation of the phase transition of nuclear matter [64–66]. In fact, figure 7 shows an important increase of the fluctuations determined by the experimental method when the impact parameter decreases. They are not correlated with the real fluctuations and they are larger by almost one order of magnitude. The mixing of events of different excitation energies is therefore very important. Therefore the use of this method, in the case of binary collisions of intermediate mass nuclei, seems problematic for such studies as addressed in reference [82].

3.3 Calorimetry with INDRA

The second step of this study will allow us to study two aspects: the intrinsic influence of the experimental filter and the cumulated effects of the experimental method and of the filter on the quality of the measures. With the criteria of quality about the detection defined in part 2.2, an event category has been defined and called "complete events". It corresponds to events for which 80% of the initial Z_{tot} and of the initial $(ZV_{//})_{tot}$ have been measured. Only these events are kept because we want to characterise not only the QP but also the QT. The QT detection is disturbed by the thresholds of detection. Taking into account acceptance of the experimental device, our criterion of event selection implies that we can examine only 40 % of the total reaction cross-section. Indeed this criterion of completion favours the mid-peripheral and central collisions as seen in figure 8. Events are also sorted according to the violence of the collision, with the help of the total transverse energy of LCP's E_{t12} [83].

$$E_{t12} = \sum_{i=1}^{Mul_{LCP}} T_i \times sin^2(\theta_i) \qquad (4)$$

With T_i: kinetic energy of detected LCP i.
Mul_{LCP}: detected multiplicity of LCP (z=1 and 2).

θ_i: Polar angle of detected LCP i.
In figure 8, the mean impact parameter is drawn as a function of E_{t12}. To study

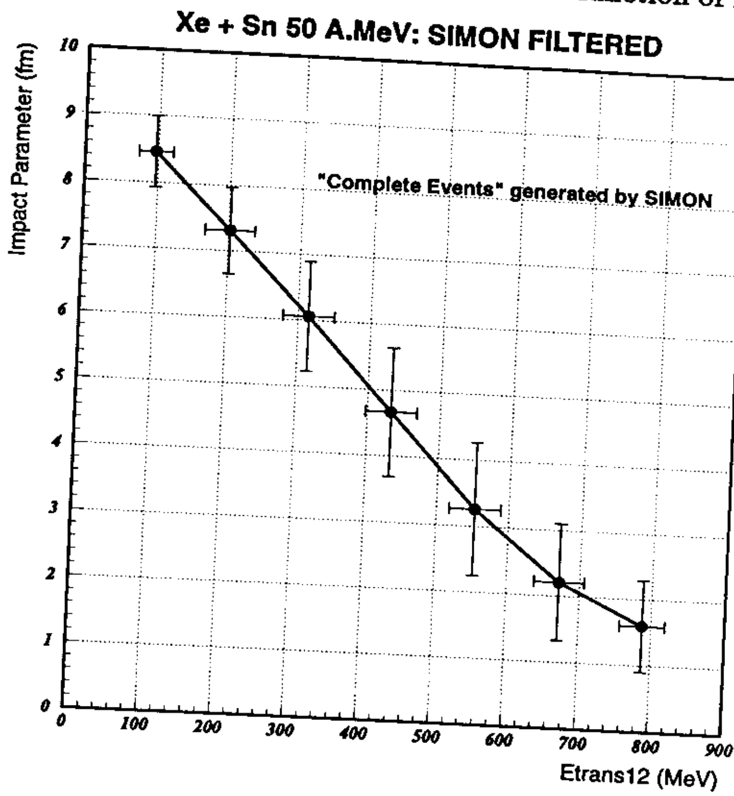

Fig. 8. Impact Parameter as a function of the E_{t12}.

the effect of the INDRA filter only, a "perfect calorimetry" has been done, i.e the labelling of particles, given by the generator SIMON, has been used to recontruct the QP and the QT. Every variable obtained by this method will be called Known Origin (KO) in the figures presented below. The Experimental Method (EM) has been also applied. Figure 9 shows the comparison of the results obtained by these two methods with the "True Values". We notice immediately a very important result: the experimental method and the "perfect calorimetry" are quite equivalent for the QP and the QT. After the filter, the experimental method is as efficient as a "perfect calorimetry". If we look in details at the measurements of the different variables characterising the QP and the QT, we remark that the parallel velocity of the QP and QT are measured with a precision better than 5 %. The perpendicular component of the velocity of the QP and of the QT are widely overestimated. We have observed the same effect with perfectly detected events. It is more important after the filter and principally for the QT from peripheral collisions. It is due to the "right-left effect" and to the angular resolution of the ring in which has been detected the heaviest fragment coming from the QT. The mass and the charge of the QP are reasonably determined with a relative error below 10 %. On the other hand, the mass and the charge of the QT are underestimated by 20 %. This effect is very important for peripheral collisions, because the charge of

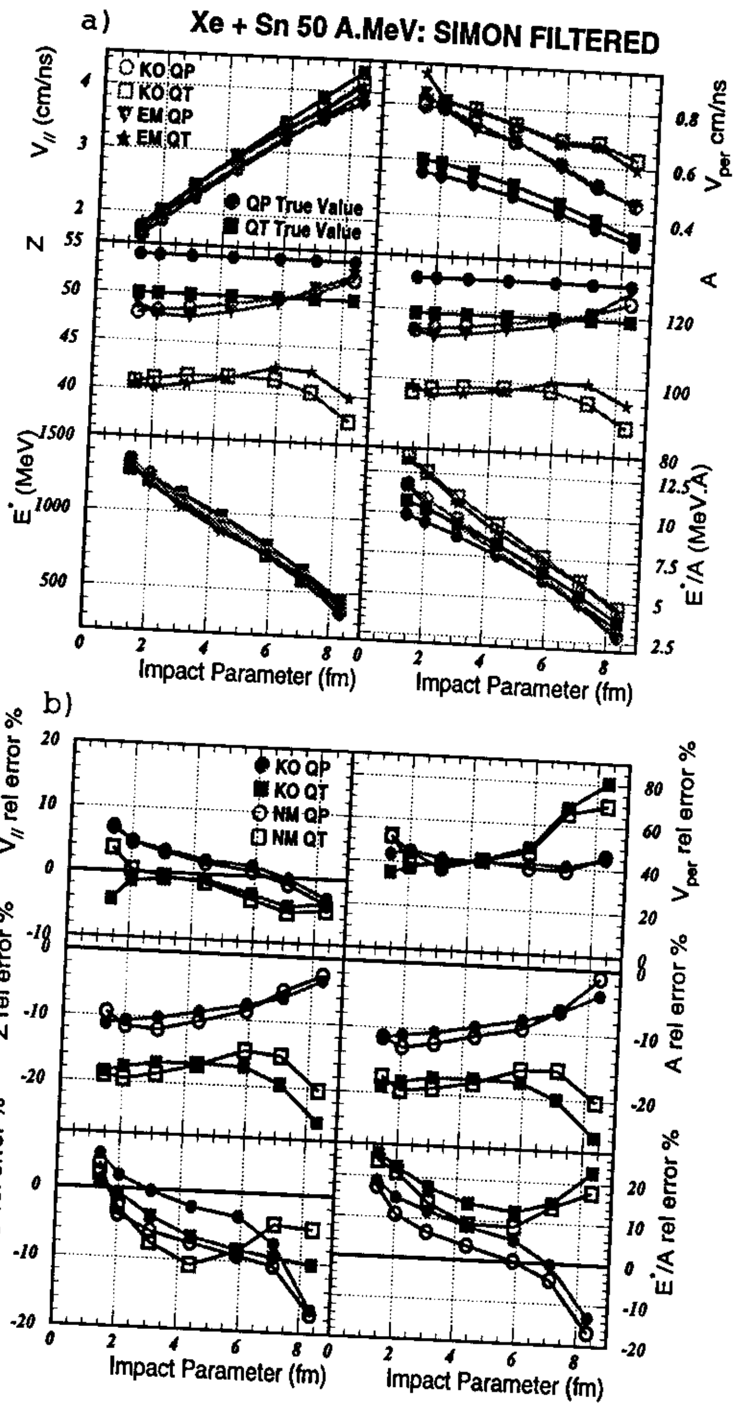

Fig. 9. a) The "True Values" and the values, obtained by the experimental method and the "perfect calorimetry", of the parallel velocity, perpendicular velocity, charge, mass, excitation energy and of the excitation energy per nucleon of the hot nuclei as a function of the impact parameter. Only the pure binary collisions are taken into account. This work is made for complete events. b) Relative errors on the parallel velocity, perpendicular velocity, charge, mass, total excitation energy and excitation energy per nucleon of emitting nuclei between the "True Values" and the values obtained by the experimental method and the "perfect calorimetry". All these variables are defined as a function of the impact parameter.

the heaviest fragment is systematically underestimated experimentally. As the energy of this fragment is smaller than that corresponding to the maximum of the stopping power, it can only be attributed a minimum Z value. To understand this loss of charge and mass, we have also studied the multiplicity of light particles. The results of this study are presented in figures 10-a and 10-b. Because of the geometrical efficiency of INDRA, all multiplicities are systematically underestimated whatever the reconstruction method. This lack is accentuated for the alphas coming from the QT principally because of the detection thresholds and of the "left-right effect" seen above. The excitation energy is measured with an error of less than 10 %. It is underestimated mainly for the peripheral collisions, as a consequence of the inefficiency of detection of INDRA. It is a surprising result because we have seen above that we lost 10 to 20 % of the mass of the QP and the QT. In fact, this lack is compensated by an overestimation of the mean kinetic energy of the neutrons and of the light charged particles. We see in figures 10-a and 10-b that the estimation of the neutron energy is questionable. The knowledge of the particle origin does not imply a better determination of their kinetic energy because the error comes from the bad measurement of the perpendicular component of the velocity. For the experimental method, we find again for the light charged particles the same trends as mentioned earlier with a perfect detector of LCP's. When we analyse now the graphs concerning the excitation energy per nucleon, we see the cumulated effects of the errors on the mass and the excitation energy. We have therefore an overestimation up to about 20 % for the QP and about 25 % for the QT. We can observe for example the effect of the bad estimation of the biggest fragment of the QT for the peripheral collisions. We notice also an effect due to the lack of estimated neutrons of the QP for the most peripheral collisions. We present in figure 11 the measured fluctuations of the excitation energy and of the excitation energy per nucleon by both methods. We can observe the respective influences of the experimental filter and of the experimental method. We notice a relatively weak effect of the filter on the width of the excitation energy distribution, looking at the curves obtained with a perfect calorimetry. It is therefore essentially the experimental method which prevents a correct measurement. The estimated width of the excitation energy per nucleon distribution is strongly disturbed by the quality of the mass measurement of the QP and QT. The use of our experimental method, such as it is, to sort the events according to the excitation energy per nucleon and then to study the calorific capacity of a hot nucleus, seems problematic. The results of this study show that we determine the excitation energy with a reasonable precision due to compensation effects between the different measured variables. In spite of a simplistic mechanism of reaction, a relatively correct and surprising agreement is even found between the experimental data and the data simulated by SIMON as shown in figure 12.

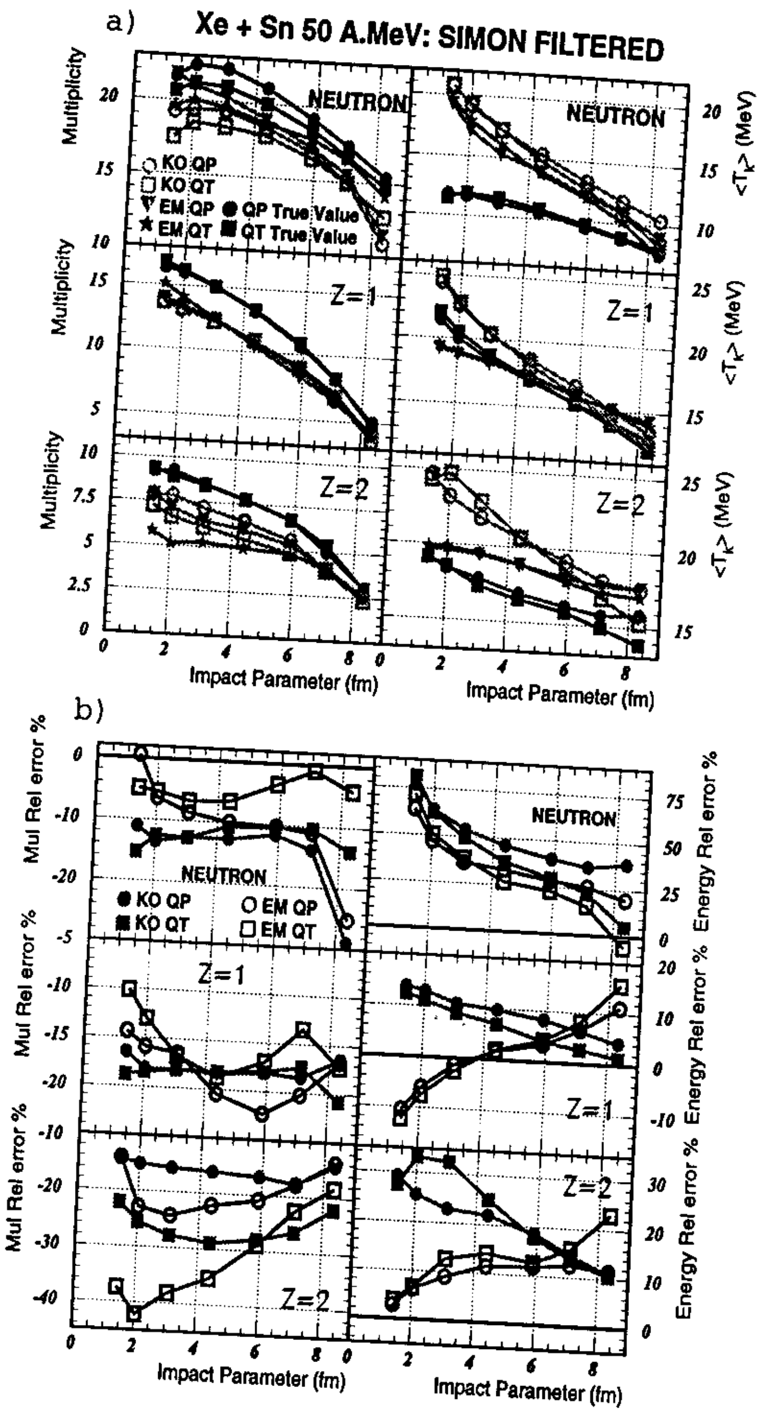

Fig. 10. a) The "True Values" and the values, obtained by the experimental method and the perfect calorimetry, of the multiplicity and the mean kinetic energy (in the frame of emitter) of neutrons, Z=1, and Z=2. This work is made for complete events. Only the pure binary collisions are taken into account. b) Relative errors between the "True Values" and the values obtained by the experimental method and the perfect calorimetry on the multiplicity and the mean kinetic energy (in the frame of the emitter) of neutrons, Z=1, and Z=2. The circles concern the QP and the squares the QT.

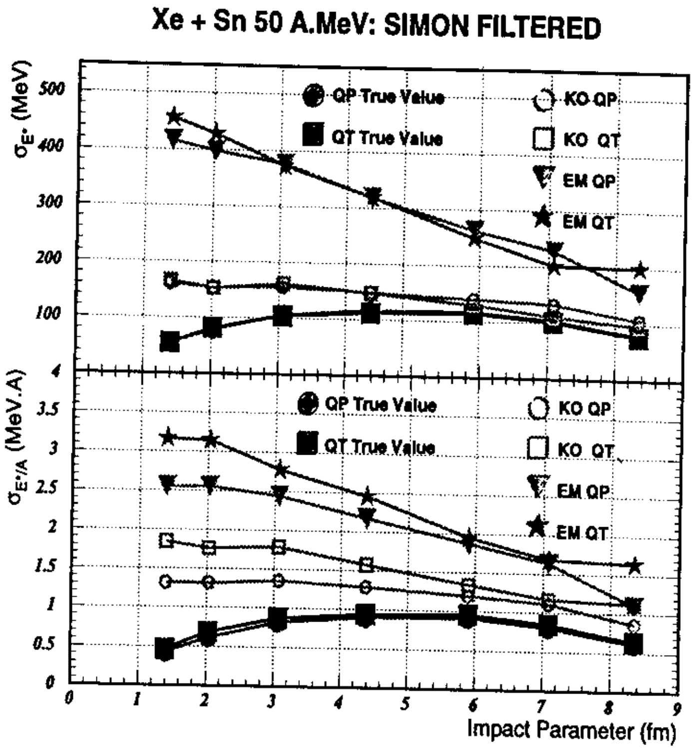

Fig. 11. The "True Values" and the values obtained by the experimental method and the perfect calorimetry, of the fluctuation of the total excitation energy and the excitation energy per nucleon as a function of the impact parameter.

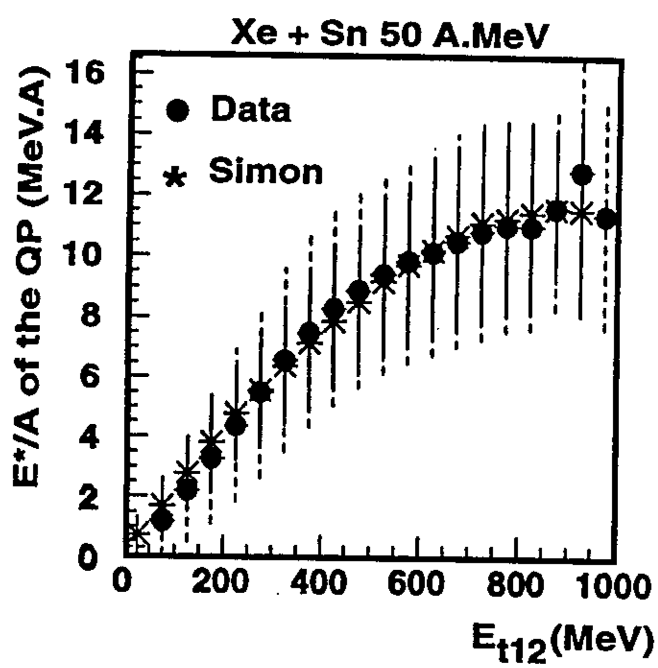

Fig. 12. The excitation energy per nucleon obtained by the experimental method as a function of the E_{t12}. The black circles correspond to the experimental data and the crosses to the data simulated by SIMON.

4 Summary, conclusions and prospects

In a clear experimental frame: pure binary collisions Xe + Sn at 50 A.MeV, we have been able to make a methodical study to better understand a classical nuclear calorimetry used by the NAUTILUS and INDRA collaborations. By a specific protocol, we have tried to unfold and extract from this study the important factors acting on the measurements of the excitation energy and of the mass. We have shown that the determinations of the emitter velocity and of the neutron contribution are the crucial points which act on the quality of our measures. We have seen that the calorimetry can be considered as correct even when the contributions of the QP and the QT are mixed thanks to effects of compensation in this case. We have demonstrated the fundamental importance of the recoil effects by revealing the "right-left effect" for these nuclei of intermediate mass around 100 u, as observed experimentally by the INDRA collaboration [70]. It implies that the determination of the velocity of the emitter nucleus requires to use all charged particles to be correct. The excitation energy and the excitation energy per nucleon of the QP are measured with about 6-7 % of error before the filter and with 10 up to 20 % after the filter in the frame of pure binary collisions Xe + Sn at 50 A.MeV. The experimental thresholds degrade the quality of the QT characterisation. The non detection of the neutrons is problematic to make calorimetry. The estimation of the neutron contribution remains the main problem. To improve the neutron multiplicity evaluation, it seems interesting to employ the semi-empirical code EPAX [84] or the parametrization given in reference [85] rather than the β-stability valley to determinate the mass of cold fragments from their charge. Concerning the estimation of mean kinetic energy of neutrons, we should have calculated the apparent Coulomb barrier as the mean value between the barriers of the initial nucleus and of the residue. For binary collisions Xe + Sn at 50 A.MeV, the calorimetric methods like our experimental method do not allow a precise measurement of the variances of the excitation energy and of the excitation energy per nucleon. The multiplication of the evaporative contribution isolated in a part of space increases systematically the width of the distributions.

We hope to have proven that such a methodological study is essential to quantitatively study the thermodynamics of the hot nuclear matter created in heavy ions collisions. But it appears also that the estimated errors are only valid for the reaction of interest, for the considered mechanism of reaction and the experimental array. It must be performed as soon as one of these parameters is changed. The experimental method allows to hold account partially of the "neck emission" for the reconstruction of the hot nuclei but not for the determination of their velocity. Its nature and influence on the division of the matter and of the energy between the quasi-projectile (QP) and the quasi-target (QT) are not still well understood. We did not study in this paper the disturbances generated by the preequilibrium particles to reconstruct the hot nuclei. In fact, to test the influence of these last factors, we would need a simulation which could manage really every step of the reaction. It is not yet available. Now, we have envisaged two solutions to overcome these difficulties. Firstly, we could use dynamical models to estimate the dynamical component and to subtract it. Secondly, we can pass by a statistical model and a "backtracing" technic to characterise the statistical components of the hot nuclei. A interesting try have been done in reference [70] to measure thus the angular momentum of the quasi-projectile.

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