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CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT DES SCIENCES
DE LA MATIERE ET DU RAYONNEMENT

UNIVERSITÉ DE CAEN

Téléphone : 31 45 25 00
Télécopie : 31 45 25 49

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M. Aboufirassi [a], A. Badala [a-e], B. Bilwes [b], G. Bizard [a], R. Bougault [a], R. Brou [a], F. Cosmo [b], J. Colin [a], D. Durand [a], J. Galin [c], A. Genoux-Lubain [a], D. Guerreau [c], T. Hamdani [a], D. Horn [a-f], D. Jacquet [d], J.L. Laville [a], J.F. Lecolley [a], F. Lefebvres [a], C. Le Brun [a], O. Lopez [a], M. Louvel [a], M. Mahi [a], M. Morjean [c], A. Péghaire [c], J. Péter [a], R. Régimbart [a], G. Rudolf [b], F. Scheibling [b], J.C. Steckmeyer [a], L. Stuttgé [b], B. Tamain [a], S. Tomasevic [b]

a) Laboratoire de Physique Corpusculaire, ISMRA, IN2P3-CNRS
14050 CAEN CEDEX, France
b) Centre de Recherches Nucléaires, IN2P3-CNRS, Université Louis Pasteur,
B.P. 20 67037 STRASBOURG CEDEX, France
c) GANIL, B.P. 5027 - 14021 CAEN CEDEX, France
d) Institut de Physique Nucléaire, B.P. 1 - 91406 ORSAY CEDEX, France
e) On leave from INFN - Catania, Catania, Italy
f) On leave from CRL (AECL), Chalk River, Ontario, Canada

Abstract :

Some results related to the disassembly time scales of highly excited nuclear species produced in intermediate energy heavy-ion collisions are presented. First, the space-time correlations between fragments originating from a common equilibrated source are analysed. At moderate excitation energy $\varepsilon^*= 3$ MeV/u, a sequential process corresponding to long times between successive splittings is observed. This mechanism becomes faster and faster as ε^* reaches 5 MeV/u for which fragments are emitted almost simultaneously corresponding to the onset of multifragmentation. Second, preliminary results are shown concerning the possibility to measure the life-time τ of an excited nucleus with respect to fragment emission: i.e the time from thermalization to multifragmentation. To this end, correlations between fragments originating from the two partners of a deep inelastic scattering are studied. By using proximity effects between projectile-like and target-like fragments, a value of τ for a nucleus with ε^* around 5 MeV/u is obtained. This value is compared with those corresponding to different type of instabilities which may be responsible for nuclear disassembly.

1. Introduction

The evolution with excitation energy of the decay modes of excited nuclei is of key interest for the understanding of the fundamental properties of nuclear matter as well as of the dynamics of nucleus-nucleus collisions (1-2). At low excitation energy ε^* the dominant processes are binary fission and/or light particle evaporation. However, we know now for several years that when ε^* increases, new decay modes set in (3). In particular large fragment emission becomes important and as soon as ε^* becomes comparable with the binding energy of the system, a complete disassembly can be observed. The proper characterization of such a process requires to get some insights on the different involved time-scales. Indeed, time scales estimations can put severe constraints on the applicability of theoretical approaches. For instance, the various statistical models (4-5) essentially relies on the assumptions that the decaying system has enough time to explore the whole available phase space. On the other hand, it is also important to disentangle between sequential fragmentation (6) (that is a succession of binary splittings sufficiently separated in time so that equilibrium be restored between each decay) and simultaneous fragmentation in which fragments are all emitted almost at the same time. Therefore, it is important to address such a question from an experimental point of view. This is the aim of this work.

2. Experimental conditions

The experiments were performed at the Ganil facility in the Nautilus scattering chamber. The data presented in this paper were obtained by bombarding Au targets with various projectiles (Ne, Ar, Kr and Pb) at incident energies between 30 and 60 MeV/u. Light charged particles (not to be discussed here) were detected in Mur and Tonneau while fragments were detected in Delf (7) and XYZT (8). These two detectors constitute an ensemble of 30 position sensitive PPAC each followed by an ionisation chamber. The angular range covered was 3-150 degrees with a geometrical acceptance of 55%. Full detection efficiency for atomic numbers equal to or larger than eight was obtained. The set-up had a low velocity threshold: .5 cm/ns (.13 MeV/u) for Delf and 2 cm/ns (2.07 MeV/u) for XYZT in the forward direction. The measured parameters are the atomic number Z (with a resolution around 10 %), the fragment velocity V and the emission angle with a resolution better than one degree.

In the following sections, we show results concerning the fate of excited nuclei of masses around 200-220 uma produced in incomplete fusion or deep inelastic scattering (these different reaction mechanisms will not be discussed here) in collisions involving the above-mentionned systems. In most cases, the triggering conditions of the experimental apparatus required the detection of at least three large fragments. Events were sorted according to their "quality": i.e with the requirement that at least 70 to 80 % of the total charge be detected.

3. Time-scales for fragment emission from equilibrated highly excited nuclei

In (9), it was shown that the onset of many-body decay as compared with binay fission stood around $\varepsilon^*=3$ MeV/u for nuclei with mass numbers around 200-220. The occurence of multi-body decay is, however, not enough to characterize properly the multifragmentation process. The fragment emission time-scales must be investigated in details. This may be achieved with the help of angular correlations between fragments taken two-by-two (10-11). In particular, when dealing with all the emitted fragments, the angular correlations are very different depending on whether the emission is simultaneous or sequential. Indeed, in case of simultaneous fragmentation, it is expected that small relative angles between all fragments taken two by two be forbidden because of the strong Coulomb repulsion. At variance, low relative angles are allowed in case of sequential emission because of the weak correlation between fragments originating from two different splittings. With help of computer simulations, it is possible to derive the time-scales between each splitting by comparing the experimental angular correlations to the results of classical trajectories calculations using the time between successive fragment emission as the main parameter of the simulations. One must check that detected fragments have a common origin in order for the conclusions to be meaningfull as far as our understanding of the fate of excited nuclei is concerned. Indeed, fast non-equilibrium fragment emission (essentially in the forward direction for direct kinematics) can strongly affect the results. Such a carefull analysis was achieved for example, in (12).

We have done the analysis for several systems in the Fermi energy domain. As an example, we show in fig. 1 results obtained when analysing the kinematical correlations between three fragments emitted by a single equilibrated hot nucleus produced in central Ar+Au collisions at 30 and 60 MeV/u (13). At 30 MeV/u, ε^* has been estimated around 3 MeV/u corresponding to the onset of three-body decay whereas at 60 MeV/u, ε^* is around 5 MeV/u (12). The correlation function displays an impressive evolution as a function of the excitation energy. At low ε^*, it is almost flat while at larger ε^*, it exhibits a strong depletion at low relative angles. This is the indication for a strong decrease of the fragment emission time when one goes from 3 to 5 MeV/u excitation energies. The histograms in the fig. 1 are the results of computer simulations. Best agreement with the data is obtained for long times (more than 500 fm/c) at 30 MeV/u and for very short times (of the order of 50 fm/c) at 60 MeV/u.

A compilation of our results is displayed in fig. 2 with two more points obtained for Ne+Au collisions at 60 MeV/u (14) (ε^* around 4 MeV/u and emission time around 300 fm/c) and Kr+Au at 60 MeV/u (15) (ε^* around 4.5-5 MeV/u and simultaneous emission). We find a strong correlation between the exciation energy (or equivalently the temperature) and the fragment emission time suggesting that the processes may be governed to a large extent by phase space constraints.

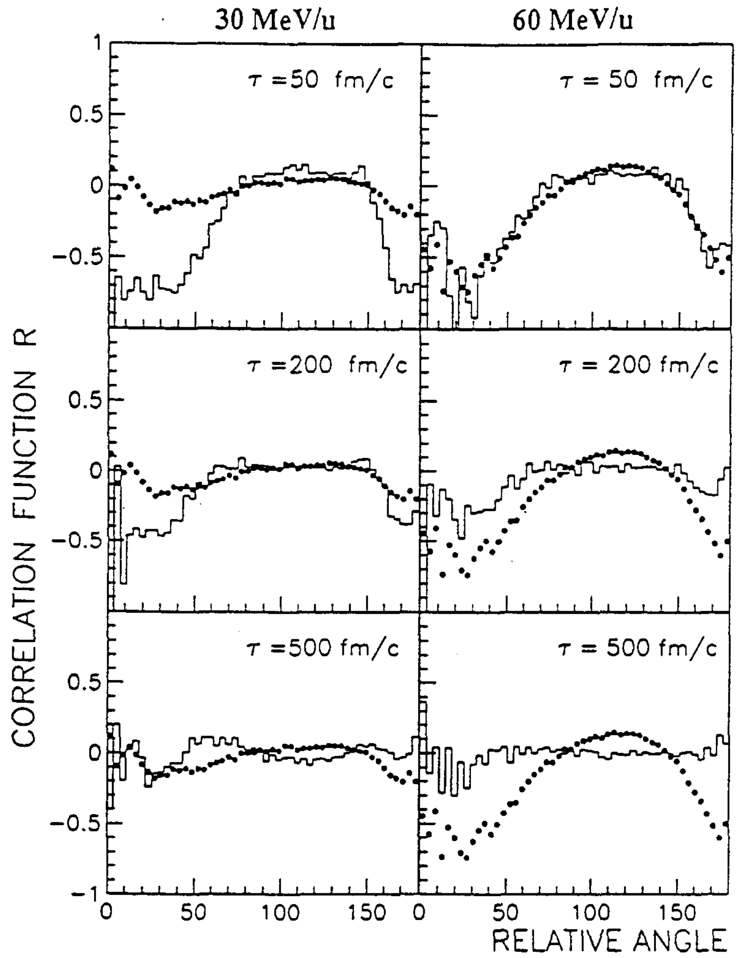

Fig. 1: Correlation function for the relative angle distributions between three fragments taken two by two emitted by a single equlibrated hot nucleus for central Ar+Au collisions at 30 and 60 MeV/u. The dots are the experimental data and the histograms are the results of the calculations described in the text for various splitting times. At 30 MeV/u on the left, the decay is clearly sequential (τ > 500 fm/c) whereas at 60 MeV/u, it is simultaneous ($\tau \leq$ 50 fm/c). From (13).

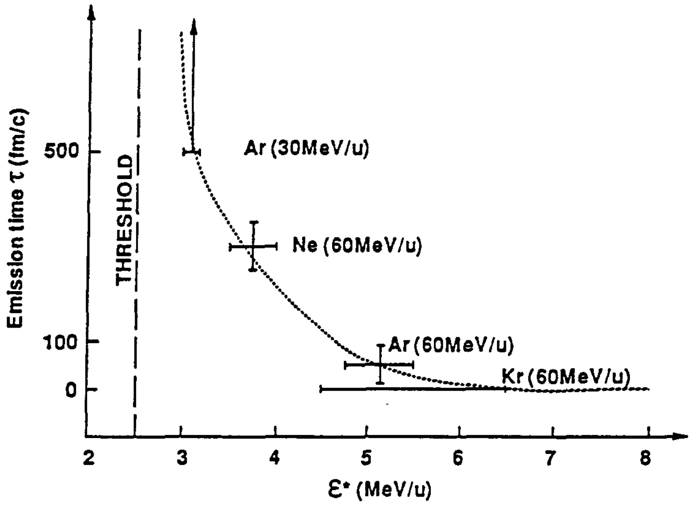

Fig. 2: Fragment emission time as a function of the excitation energy.

4. Estimates of the life time of excited nuclei with respect to fragment emission

In this section, we show how to get estimates of the life time of excited nuclei with respect to fragment emission: that is the time between thermalization (or any other initial time) and the emission of the first fragment (or all fragments in the case of simultaneous emission). The estimation of this quantity is important for the theoretical models (in particular the statistical ones) as already stated in the introduction. Moreover, as far as dynamical models are concerned, it is often argued that the time scales for nuclear disassembly should be very different according to the various types of instabilities which may be responsible for the decay processes. In particular, it is believed that bulk instabilities (corresponding to a spinodal decomposition of the system occuring at very low density) should set in very rapidly after the system reaches the maximum compression phase (if any). Time of the order of 50 to 100 fm/c are often quoted in the litterature (16) although recent calculations indicate that this value could be larger depending on the type of effective forces used in the models (17). At variance, longer times are expected if the disassembly proceeds through more gentle shape (surface and Coulomb) instabilities. In this case, multifragmentation might be a "natural" continuity at high excitation energies of the observed low energy-like standard binary fission, then one should find times ranging between say 300 fm/c and values larger than 1000-2000 fm/c found by studying pre-scission neutron emission in fusion-fission reactions (18).

The following analysis is an extension of the method described in the previous section to space-time correlations between fragments originating from two different sources. Such studies have already been performed (19-20) in case of binary fission but to our knowledge it is the first time that it is used to get some piece of information on fragmentation processes. We take advantage of the proximity effects induced essentially by Coulomb forces between the two partners of a deep inelastic scattering. To this end, the system must be as heavy as possible and the relative velocity in the entrance channel sufficiently slow so that the effect be enhanced due to long interaction time. In addition, the collision must remain of a two-body type (we mean by this no complete or incomplete fusion). It appears that these conditions are fullfilled in Pb+Au collisions at 29 MeV/u (21). Then the idea is to measure momentum and angular distortions in the kinematical characteristics of the fragments emitted by one of the excited nucleus in the Coulomb field of its partner as schematically illustrated in fig. 3. In case of a very long time between separation and subsequent decay of one of the two partners, one expects that the projection of the velocities of the emitted fragments estimated in their own center-of-mass on the axis connecting the two primary fragments be forward-backward symmetric (i.e flat or with a minimum at 90 degrees according to the value of the angular momentum). At variance, in case of a fast disassembly, a depletion around $\theta_{axis}=0°$ is expected due to the strong Coulomb repulsion between the fragments.

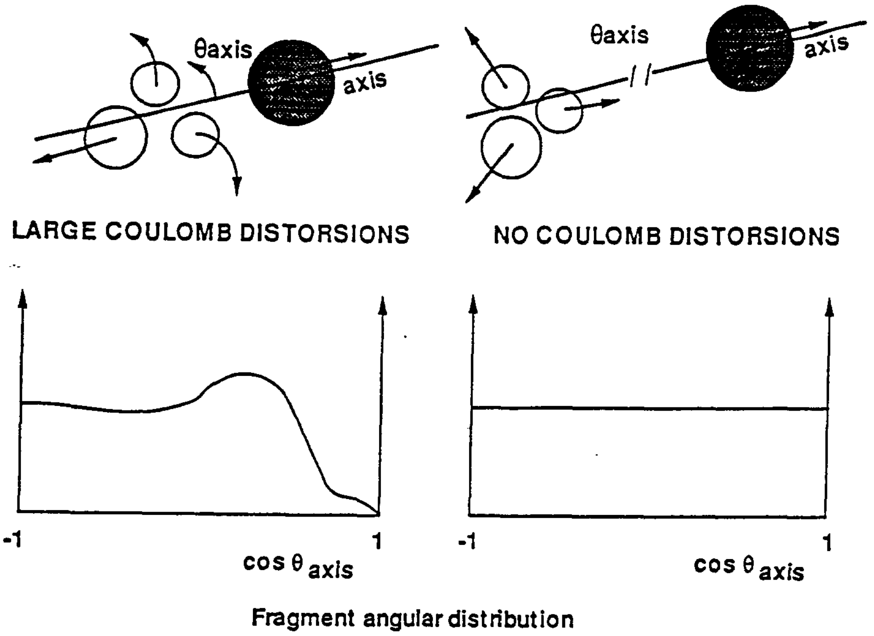

Fig. 3: Proximity effects between the two partners according to a short life time (left) and a long life time (right)

We have selected events corresponding to the configuration in which three fragments emitted by one of the two primary nuclei were detected in coincidence with its partner. To this end, we required the detection of three and only three fragments of charge lower than 25 and one and only one with charge larger than 35. We checked by reconstructing the center-of-mass velocity of the decaying nucleus by averaging the velocities of the three emitted fragment as done in (21) that the collision remained binary (i.e no fusion). By calculating the relative velocity V_R betwen the reconstructed primary nucleus and its partner, we were able to calculate the TKEL (Total Kinetic Energy Loss) of the two primary nuclei and then to estimate the amount of dissipated energy in the collision. We have :

$$\mathrm{TKEL} = E_{CM} - \mathrm{TKE}$$

and

$$\mathrm{TKE} = \frac{1}{2}\mu V_R^2$$

where μ is the reduced mass of the system. Thus, it was possible to follow the evolution of several quantities of interest as a function of the excitation energy per nucleon ε^*, this latter being approximately related (for symmetric systems) to TKEL by the following relation:

$$\mathcal{E}^* = \frac{\mathrm{TKEL}}{A_P + A_T}$$

in which A_P and A_T stand for the mass number of respectively the projectile and the target. As an example, we show in fig. 4 the two-dimensional plots V_{par} -V_{per} of the three emitted fragments (calculated in their own center-of-mass and such that their parrallel velocity is along the line connecting the two primary partners of the collision). The average velocity in this frame of the associated heavy partner is indicated in each panel by an arrow. Four different excitation energy (or equivalently TKEL) bins have been considered. In the first one corresponding to low TKEL and thus to rather peripheral collisions, the isocontours exhibit no distorsions and are forward-backward symmetric as expected from the decay of a long-lived equilibrated nucleus and no proximity effects of the associated partner. However, as one goes to larger dissipation, there is a gradual transition towards stronger and stronger distorsions (repulsion in momentum space of the three fragments with respect to the heavy one) indicating the rising of proximity effects and thus shorter and shorter life time for the decaying excited nucleus.

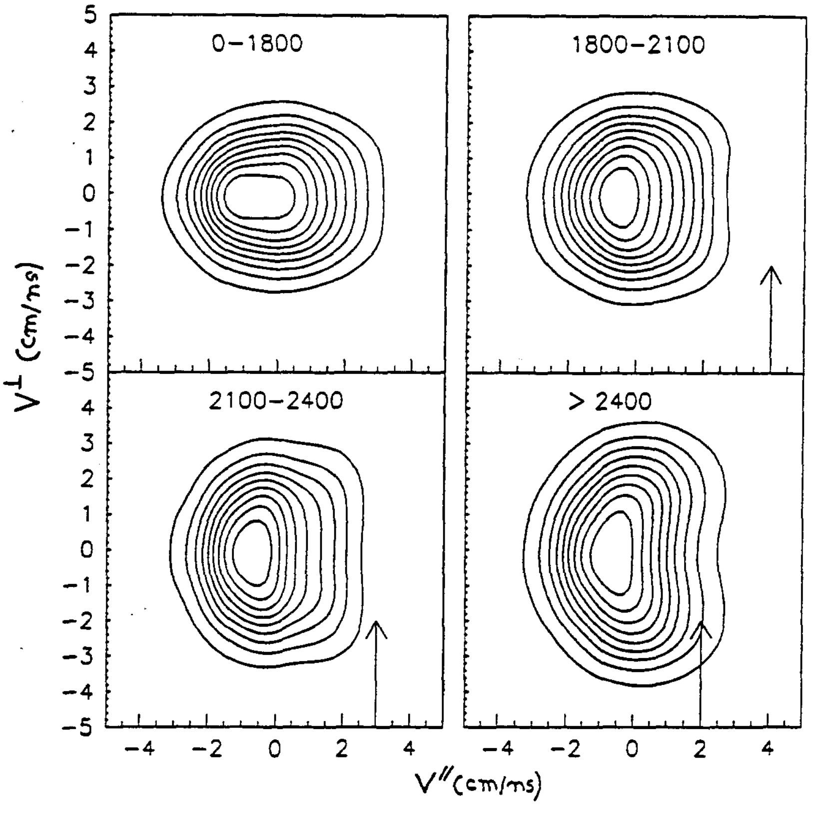

Figure 4: 2-d plots Vpar-Vper (calculated in a frame specified in the text) for the three fragments resulting from the disassembly of one of the two partners of the reaction. The figures in the panel correspond to four different TKEL windows. The arrows indicate the velocity of the heavy partner.

In order to gain some quantitative insights on the life time, we have performed computer simulations. The entrance channel of the collision, that is the deep inelastic scattering of the two nuclei has been described using standard trajectory calculations with conventionnal nuclear, coulomb and centrifugal potentials (22). The dissipation has been taken into account using the window formula and the angular momentum transfer was estimated in the sticking limit. No deformation of the two partners was taken into account. We have included light particle evaporation in the course of the reaction using the standard Weisskopf theory. With this simple model, we were able to reproduce the θ_{cm} vs TKE correlation (Wilczynski plot, not shown here). Then, at a given time τ (which is the main parameter of the model), the decay of one of the two partners is considered. A three fragment (A_i, Z_i) partition is chosen randomly and its statistical weight calculated according to (23). The three fragments are placed in space according to a triangle and a minimum distance (corresponding to a freeze-out (4-5) or a saddle-point configuration (23)) of 2 Fermi between the fragments is assumed. The post-dynamics of the decay process is considered by solving the equation of motion for both the three fragments and the heavy partner. Fragments are initially hot and their excitation energy is obtained assuming equilibrium so that the dissipated energy (at the given time τ) is shared among them in proportion of their mass. Evaporation is considered along the dynamics until fragments are cold. The results of the simulation have been filtered taking into account the limitations of the experimental set-up in order to get a reliable comparison with the experimental data.

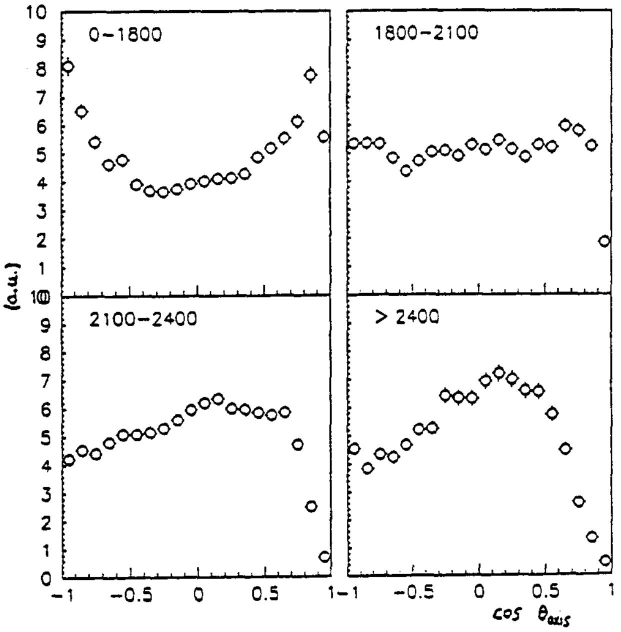

Figure 5: Angular distributions of the three fragments resulting from the disassembly of one of the two partners of the reaction. These distributions are obtained by projecting the velocities of the fragments (calculated in a frame corresponding to the center-of-mass of the three fragments) on an axis connecting the two primary partners of the reaction. The orientation is so that cos θ axis=1 corresponds to a velocity pointed towards the heavy partner (see fig 3). The numbers in each figure correspond to different TKEL (in MeV) windows.

We first show in fig. 6 the TKEL distribution for both the data (points) and the results of the simulation (histogram). A rather correct agreement is obtained although the model is unable to reproduce the largest values obtained experimentally (this could be due to a lack of fluctuations in our crude model). It is found that most of the selected events correspond to rather central collisions in which a large amount of the avalaible energy has been dissipated. This is confirmed by analysing the impact parameter distribution as given by the simulation. From the model, we then get the following results concerning time scales: the time between contact and minimum distance between the two primary partners is around τ_{min}= 50 fm/c and the interaction time defined as the time between first contact and re-separation τ_{inter} is around 200-250 fm/c.

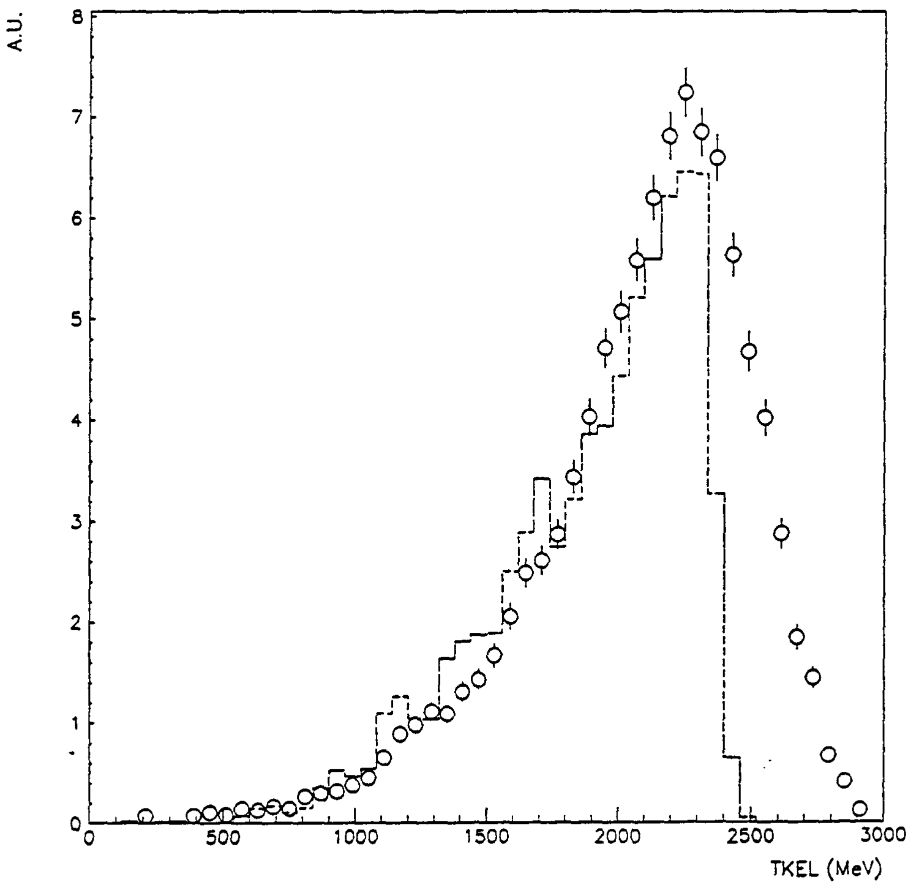

Figure 6: Distribution of the TKEL for the selected events (see text). Points are the data while the histogram are the results of the calculation described in the text.

We now compare the results of the model with the experimental angular distributions displayed in fig. 5 considering only the last two TKEL bins which have been summed. This corresponds to excitation energies larger or equal to 5 MeV/u. Several values of τ have been considered with respect to τ_{inter}. Values lower than τ_{inter} correspond to a situation in which the fragmentation has occured before the separation of the two partners. In this case (two first panels upper left in fig. 7) we found a strong disagreement with the data. We believe that further refinements of the model would not change significantly the results so that we can probably ruled out the possibility for the system to break before separation. When the value of τ is increased and that it becomes significantly larger than the separation time, the agreement is better and better until we reach values around $\tau=\tau_{inter}$ + 100-150 fm/c. Estimating the time from the minimum distance of approach until fragmentation, we thus find a value of the order of 300-350 fm/c. It is clear that the sensitivity of the signal is limited to short times. Therefore, we can only give lower limits (τ longer than 300-400 fm/c after separation) for low values of the excitation energies corresponding to the first two bins in fig. 5 .

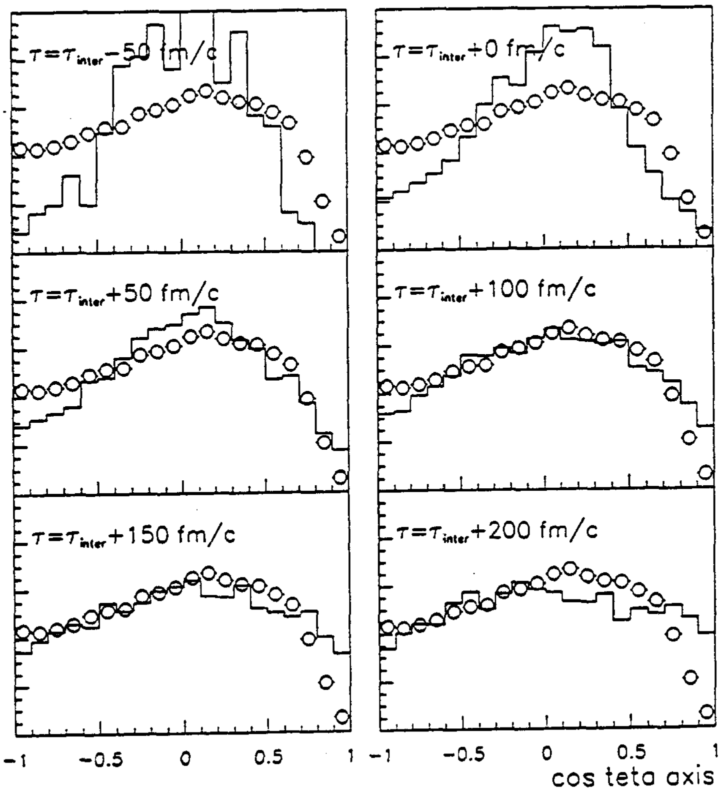

Figure 7: Comparison between the results of the model described in the text with the experimental data corresponding to the last two TKEL bins of fig. 5. The value of τ in each panel corresponds to different time for the disassembly of one of the two partners. τ_{inter} is the time for re-separation of the two partners as given by the trajectory calculations.

5. Conclusion

Using fragment-fragment space-time correlations in nuclear collisions at intermediate energies, we have been able to estimate two different times concerning nuclear disassembly. Firstly, by considering fragments emitted by a common equilibrated source, we have found that the fragment emission time evolves from a long time scale at moderate excitation energies (around 3 MeV/u) suggesting a low energy-like behaviour (sequential fragmentation) towards much shorter (compatible with zero) values around 5 MeV/u indicating the onset of multifragmentation (simultaneous fragmentation). Secondly, by extending the method to fragments originating from two different sources (the two partners of a deep inelastic scattering), we could estimate the life time of a nucleus with excitation energy around 5 MeV/u by comparing the data with a computer simulation. A rather long value corresponding to 100-150 fm/c after re-separation of the two partners has been found suggesting maybe a rather gentle process. We think that extensive comparisons of our data with dynamical models could put strong constraints on these latter and give new interesting insights on the type of instabilities that are responsible for nuclear disassembly.

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