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During its one year stay in France, the neutron detector DEMON has performed six experiments. Its excellent characteristics allowed him to study fission time scales, extra-extra-push energies, the neutron halo and hot nuclei. The results of one of these experiments show that at 60 MeV/u bombarding energy Kr projectiles and Ho targets share approximately equally the excitation energy after a two-body damping collision which is only weakly perturbed by neck emission. Some evidence is given that the neck emission of fragments is not to be connected to the formation of some participant zone, but rather to their dynamical emission by one of the two partners of the reaction.

1. Introduction

One of the most significant recent breakthroughs in nuclear physics is the discovery that light particles and even fragments can be emitted all along the collision between two nuclei, and not only long after the reseparation. This was first recognised in fission: it was demonstrated that the path from the equilibrated shape to scission lasts long enough to allow many neutrons to be emitted during this stage [1]. This becomes particularly spectacular at high bombarding energy. The fission of a hot nucleus occurs only after it has cooled down by emitting as many particles as possible [2].

Actually, this phenomenon appears as more general and seems not to be only due to the long time scale of fission when compared to that of the emission of neutrons. Indeed, at bombarding energies higher than 27 MeV/u, light particles and intermediate mass fragments are emitted after the damping of the relative motion, but before the sequential fission of one of the partners [3].

This subject is of course one of the fields of interest of DEMON, a neutron detector recently developed by a french-belgian collaboration [4-10]. The main characteristics of this new detector are its modularity, which allows a fairly easy transportation from one accelerator to another one, and its high efficiency over a 1 to 100 MeV neutron energy range, which allows to tackle a wide domain of bombarding energies.

Run on the basis of an equal time sharing between the two countries, DEMON has been operated in France during one year. It has performed successfully three experiments at Ganil (Caen), and three others at Sara (Grenoble). The aims of these experiments were:

- study of the fission time scales in the Pt mass region
- study of fission time scales in the case of the bi-modal fission of ^{232}Th
- determination of the extra-extra-push by the measurement of the excitation function of pre-scission and post-scission neutron multiplicities, and comparison between the extra-extra push for the ^{40}Ar + ^{238}U, ^{58}Ni + ^{208}Pb and ^{64}Ni + ^{208}Pb reactions.
- study of the neutron halo of ^{19}C [11]
- measurement of neutron spectra in coincidence with very hot evaporation residues produced by the reaction ^{40}Ar + ^{197}Au
- measurement of neutron spectra emitted by projectile-like and target-like nuclei during a binary ^{84}Kr + ^{167}Ho collision at 60 MeV/u.

In parallel to these experiments, an exploratory investigation was performed to test the possibility to measure neutron-neutron and neutron-proton correlations.

In this paper, we shall present the first results of the latter experiment, which was actually the first one performed with DEMON in France.

2. Binary collisions in the Fermi energy domain

At low bombarding energies, the cross section for heavy systems like Pb + Au or Kr + Au is dominated by dissipative collisions, in which the two partners convert partially or totally their kinetic energy into excitation energy before reseparating. Such collisions are characterised by different properties, among which two will be of interest in the following:

- the dissipated kinetic energy is entirely converted into intrinsic excitation energy of the two partners, which decay statistically after they have reseparated
- the excitation energy is shared equally between the two partners for small interaction times, but thermalisation is reached for the longest ones. In this case, the energy deposited in each nucleus is proportional to its mass.

It is now widely recognised that also in the Fermi energy domain (FED) nucleus-nucleus collisions have essentially the same two-body character, although more than 1 GeV kinetic energy may be dissipated [3,12]. However, dynamical emission of light particles and fragments sets in. Can this emission be considered as a perturbation or does it change more fundamentally the characteristics of the mechanism ? Actually, could it be the signature of a transition to a new mechanism ?. To answer these questions, properties like those exposed before have to be investigated in the FED, which has not be done up to now above some 20 MeV/u.

The problem is ideally illustrated by the data which have been obtained for the ^{84}Kr + ^{197}Au reaction with the Nautilus fragment detectors [3]. In this study, two classes of events had been investigated:

- three body events in which the Kr-like and the two fission fragments of the Au-like nuclei were detected
- four body events in which one intermediate mass fragment (IMF) was detected in addition to the three preceding ones.

The authors of ref. [3] could show that the emission of this IMF occurs before the Au-like nucleus fissions and is strongly localised between the projectile and the target. This was one of the first indications of neck emission. However, the ultimate mechanism of formation of the IMF was not completely elucidated: is this IMF emitted by the target alone or is it formed by the overlap region between the projectile and the target ? The situation is summarised in Fig. 1. Here, the charge of the Kr-like nucleus is taken as an indication of the impact parameter: when Z is close to 36 the collision is peripheral, and becomes more central when Z decreases. Fig. 1a shows the evolution of the velocities of the Kr-like nucleus (circles), the IMF (diamonds) and the Au-like nucleus (squares). The latter one was determined by reconstructing the target from its detected fission fragments. The data are reproduced nearly as well by two different models:

- a damping collision (full curve) in which, after the slowing down of the relative motion and thus excitation energy deposit in the system, the IMF is emitted by the target alone. Since this emission is not equilibrated but strongly focused in the direction of the projectile, the velocity of the IMF (diamonds) is obtained in this model simply by adding the Coulomb repulsion to the velocity of the target-like nucleus.
- a two-step participant-spectator model (dotted curve) in which, after a damping stage, the overlap region separates [13].

Fig. 1b shows the comparison between the measured charge of the target-like nucleus and the predictions of the models:

- the damping model (full curve) predicts a target charge which compares well with the sum of the charges of the two fission fragments and the IMF (diamonds), while that predicted by the two-step model (dotted curve) compares with the sum of the charges of the two fission fragments alone (squares).

From the closeness of their predictions, one could conclude that the two models are indistinguishable. This is not true, since one essential assumption, which is different in the two models, can be experimentally checked. Indeed, in the case of the two-body model, one has to suppose equal sharing of the excitation energy to obtain a good agreement between the model and the data. In the case of the participant-spectator model on the contrary, one has to admit that the temperatures of the two spectators are identical.

To obtain a handle both on the temperatures and the excitation energies of the two main fragments of the reaction, we decided to measure energy spectra of neutrons emitted in the Kr + Ho reaction at 60 MeV/u. The target was Ho instead of Au in order to lower the sequential fission cross section. The Kr beam was accelerated by Ganil. In this experiment, projectile-like fragments were detected at small angles by two silicon telescopes on both sides of the beam. In coincidence with them, target-like fragments were detected by very low threshold (less than 70 keV/u) avalanche counters. The associated neutrons were measured with DEMON.

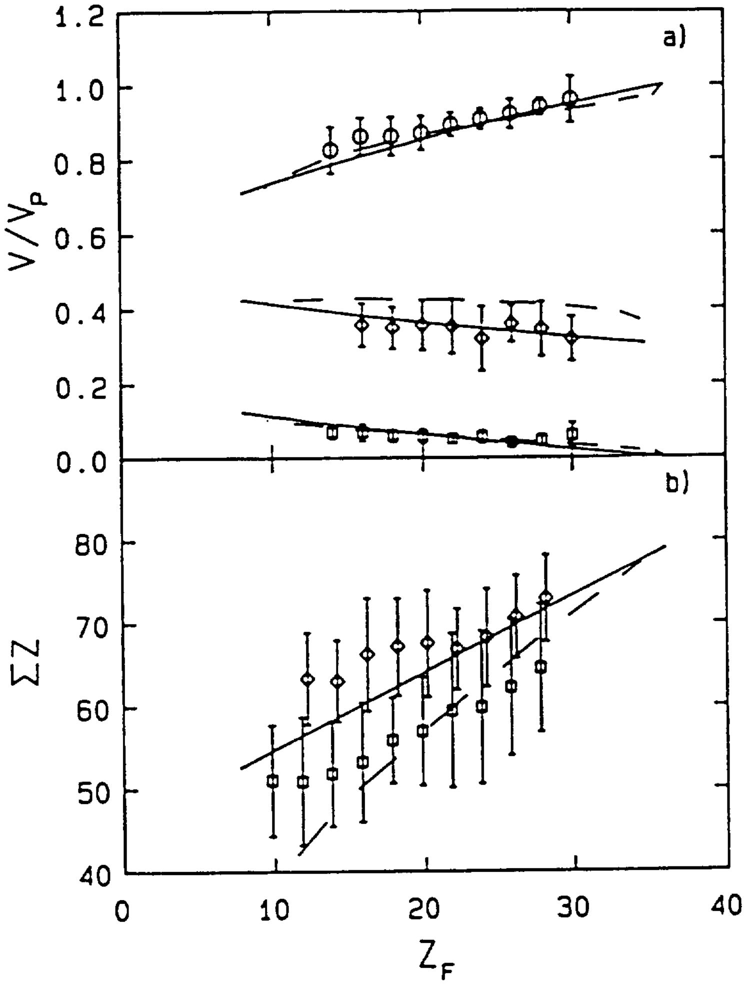

Fig. 1. Main characteristics for quadruple coincidences between fragments in Kr + Au collisions at 44 MeV/u. See text for the definitions.

3. DEMON

DEMON [4-10] is made of 96 modules. The characteristics of the 20 cm deep liquid scintillator (NE213) and of the photo multiplier (XP4512B) were chosen so that the intrinsic efficiency of each module is high at low and intermediate neutron energies. Typical values obtained during the experiments are 50% at 10 MeV and 30% at 60 MeV. The neutron-γ discrimination in DEMON is obtained by a pulse-shape analysis method. The neutron energy was determined through its time-of-flight over a 175cm flight path. With a time resolution of 1ns, this yields an energy resolution of about 10%. At this distance, the cross-talk is less than 1% and the solid angle about 4% of 4π. Thus DEMON is able to measure energy distributions and angular distributions but only mean multiplicities.

4. Experimental results

Fig. 2 shows a typical $V_{//}$ spectrum (top) for neutrons detected in coincidence with a projectile fragment, either alone (full histogram) or in coincidence with the target (dashed histogram). The spectrum in Fig. 2 shows two major components, centred one close to beam velocity and the other near 0. They correspond clearly to the projectile and the target. The non-gaussian shape of the target-component is of course due to the 1 MeV threshold. The $V_\perp$ spectra corresponding to these two components are shown in the lower part of Fig. 2. The structure which appears in the $V_\perp$ spectrum associated with the projectile is only due to geometrical effects. The identity between the spectra associated to singles and to coincidences

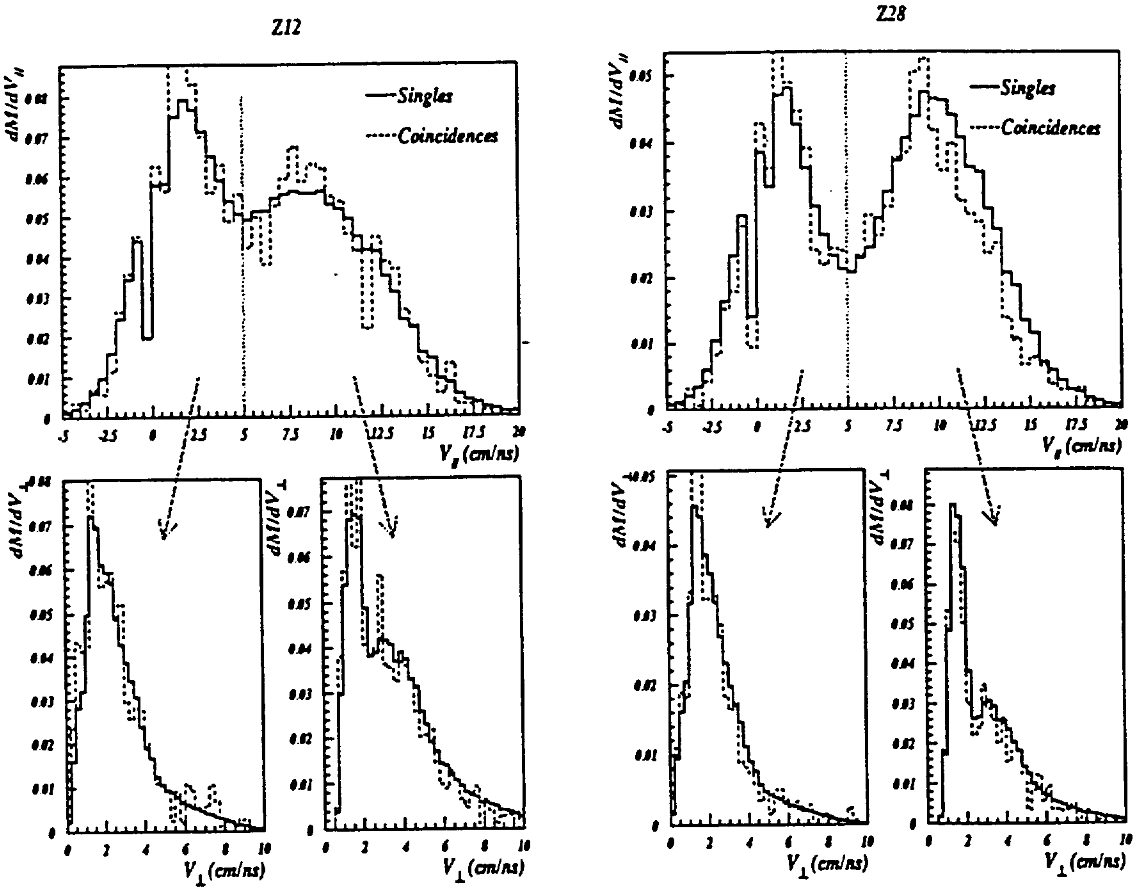

Fig. 2. Experimental neutron spectra associated with a charge of the quasi-projectile Z=10-14 (left) and Z=26-30 (right).

shows that the decay of the target has little influence on the neutron emission. Thus, in the following, we shall analyse only data associated with singles, since the statistics is much larger than for the projectile-target coincidences.

To reproduce the spectra in Fig. 2, we have used a moving source parametrization, in which the emission by each of the two sources is isotropic and has a maxwellian shape:

$$dM / dE_{SYS} = M \cdot E_{SYS} / T^2 \exp(-E_{SYS} / T)$$

The energy in the source system E_{sys} was transformed in the lab system, so that the simulated event could be submitted to the experimental filter. Fig. 3 shows the result which leads to the lowest χ^2. The agreement is fairly good. The strongest deviation is observed at mid projectile velocity, revealing the contribution of a third source, probably related to the neck emission.

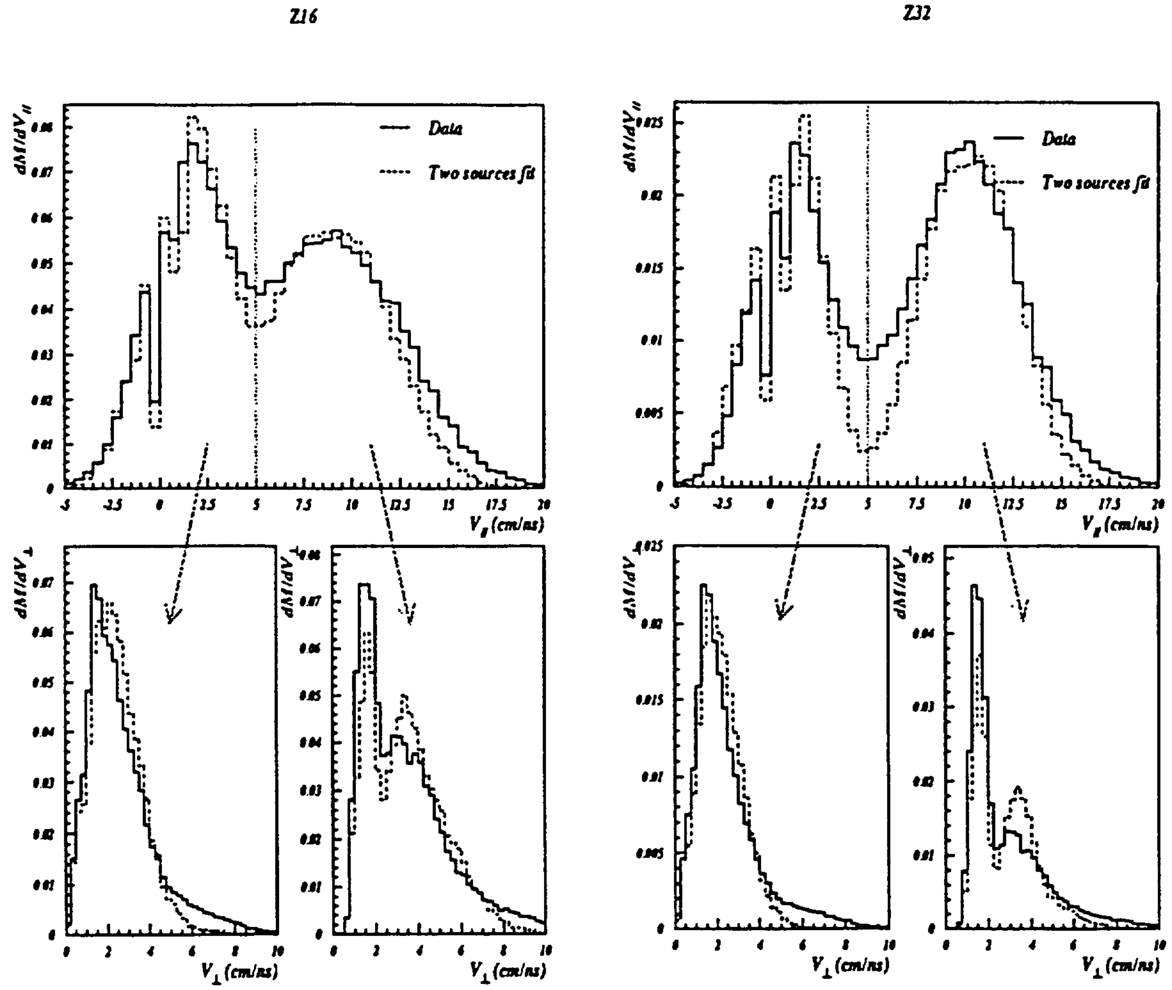

Fig. 3. Comparison between data and the two-sources fit for a charge of the quasi-projectile Z=14-18 (left) and Z=30-34 (right).

The best-fit parameters are reported in Fig. 4. The data have been analysed as a function of the charge Z of the quasi-projectile. The velocities evolve little with Z. However, one must be aware of the fact that a 20% variation in the velocity means a variation of about

40% of its kinetic energy which, in the case of the projectile, is more than 1 GeV. The velocities obtained from the neutron spectra compare well with those obtained from the fragments (Fig. 1). The temperatures and the multiplicities increase when Z decreases. If, as assumed by the above mentioned formula, the emission has a Maxwellian shape, the mean kinetic energy of a neutron is 2T. Thus the mean excitation energy taken away by each neutron is approximately 8+2T if one admits a binding energy of 8 MeV. Fig. 4 shows that the total energy removed by neutron emission E* increases when Z decreases. The decrease of the slope is due to the fact that, at small excitation energy, the nucleus emits mostly neutrons, while charged particle emission sets in progressively. The most significant features in Fig. 4 are:

- the temperatures of the projectile and the target are very different
- the energy taken away by neutrons emitted from the projectile and from the target are quite close.

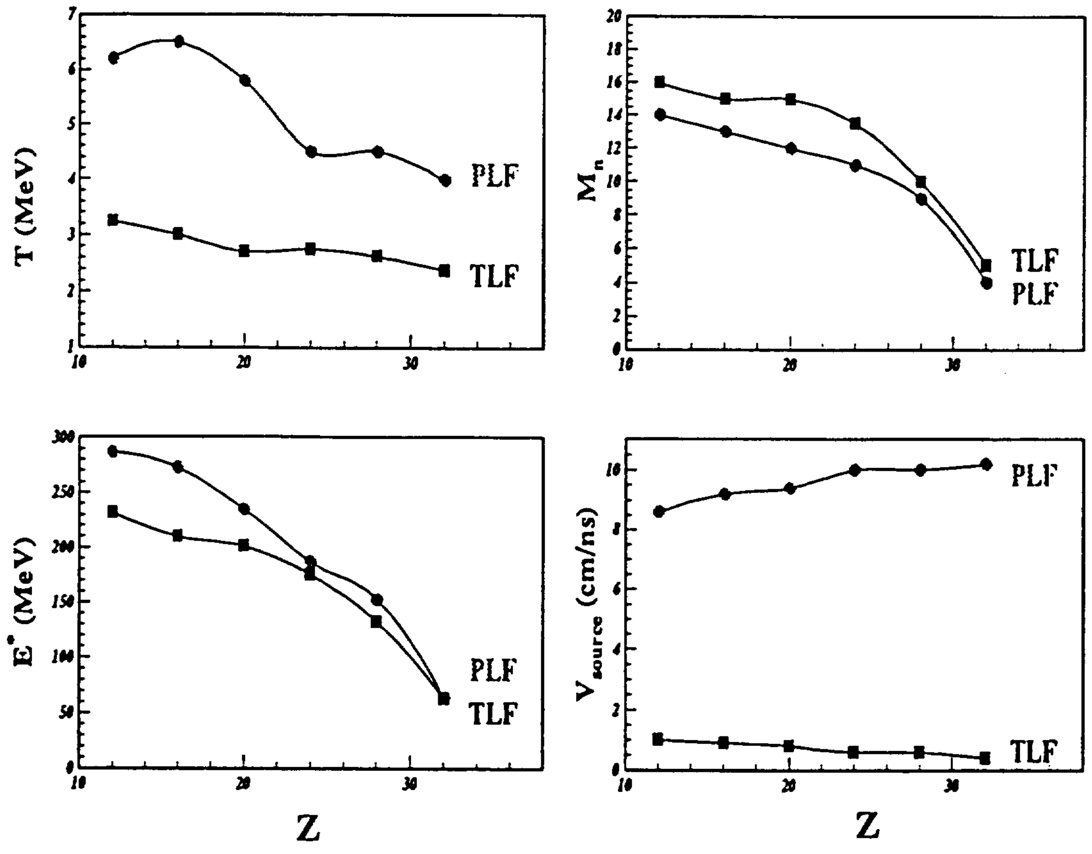

Fig. 4. Best fit parameters obtained by the two-sources fit. E is the total energy removed by neutron emission.*

To confirm that our data are more in favour of equal excitation energy sharing than to thermalisation, we have performed a calculation with Simon, an improved version of the event generator Eugene [14]. To compare such a calculation to the data one would have to apply the experimental filter to them. But since the statistics obtained with this simulation is small, we have preferred to compare it to the unfiltered two-sources fit. Simon was run with the hypothesis of equal excitation energy sharing. As shown by Fig. 5, the agreement is rather good, qualitatively and quantitatively. Even, it seems that, for the most central collisions observed here, there is more excitation energy in the projectile than in the target. This may be due to the fact that the target cools down faster than the projectile through IMF emission.

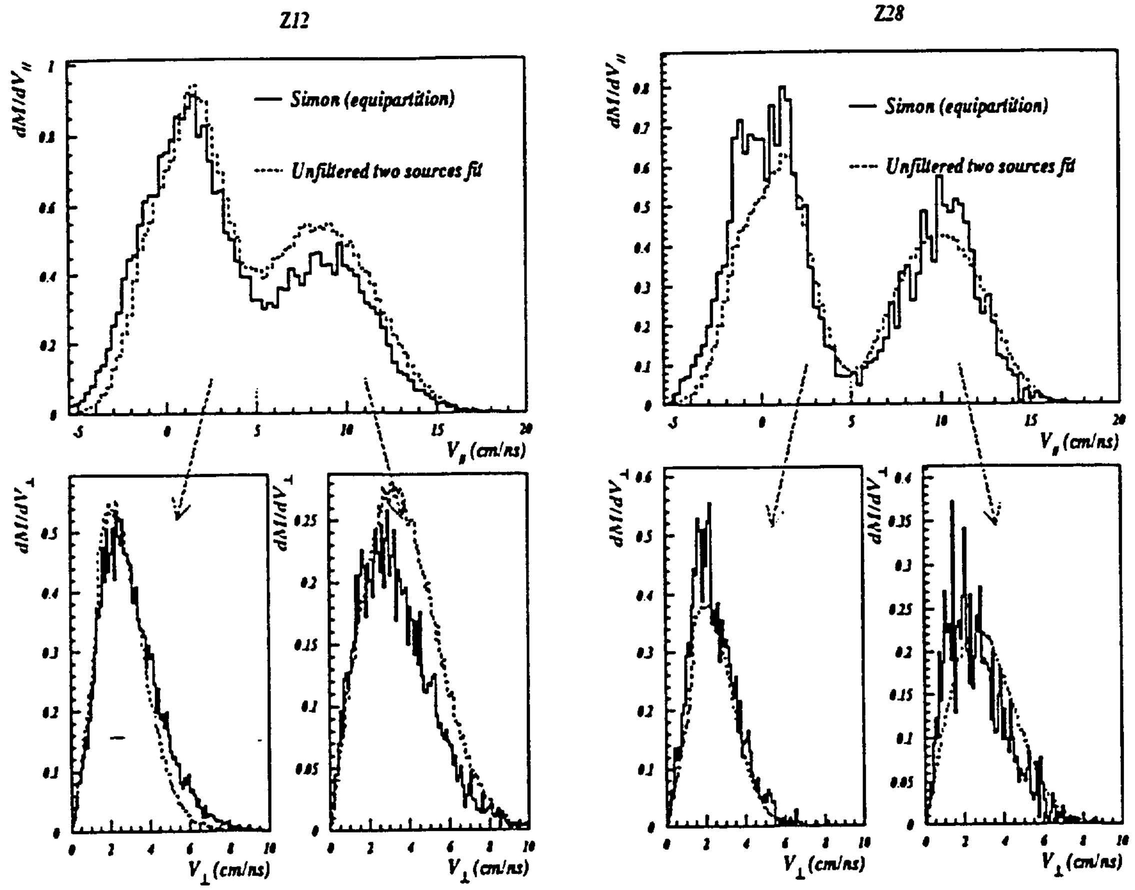

Fig. 5. Comparison between the predictions of the event generator Simon and the unfiltered best two-sources fit.

One could conclude here that we have obtained a good indication that the projectile and the target share equally the excitation energy in the FED. However, several points must be clarified before this can be considered as definitely proven:

- this measure was performed at 60 MeV/u bombarding energy, where the damping is not complete. Therefore, a new measure is being planned at 27 MeV/u, where full relaxation of the energy has been observed.
- a third source is clearly necessary to fit the data at mid-velocity (Fig. 3). Preliminary results show however that the parameters in Fig. 4 are not strongly modified when this source is added.
- a long tail appears in all spectra shown in Fig. 3 and 4. When plotted on a logarythmic scale, the deviation from the maxwellian shape appears clearly (Fig. 6). Preliminary attempts to

analyse these data by adding a pre-thermalization component [15] seem to confirm that neutrons are emitted by the projectile before it attains thermal equilibrium. In the case of the charged particles with Z=1-3, it was shown [15] that the shape of the spectra as well as the absolute multiplicities depend much more on the total kinetic energy loss than on the bombarding energy. Moreover, this component is isotropic in the frame of the slowed down projectile, i.e. that it corresponds to an emission which occurs after the damping. In the case of neutrons, it seems also that the long tail seems not focused at very small angles (Fig. 6). This component should thus not be confused with pre-equilibrium emission.

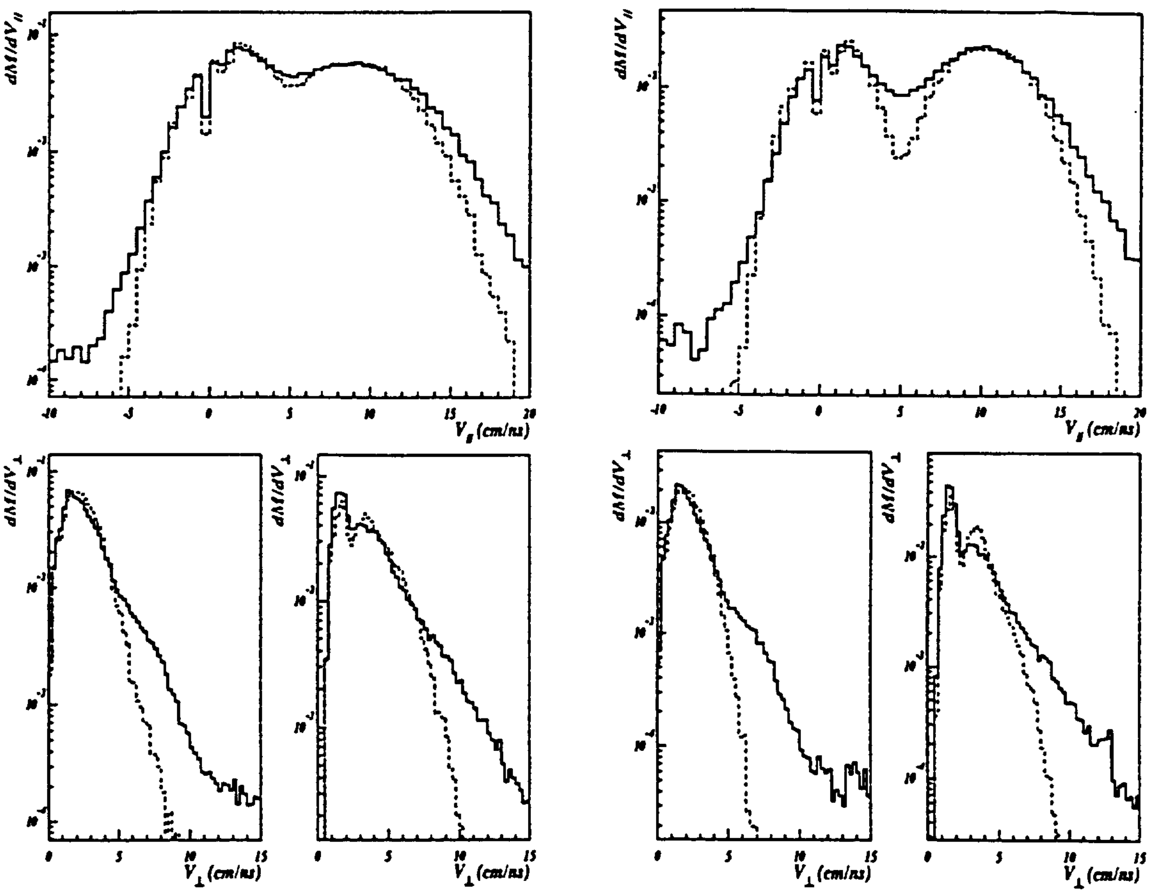

Fig. 6. Same as Fig. 3, but the ordinate is in log scale, and the abscissa cover a larger range

5. Conclusions

From these results, it seems quite likely that at bombarding energies as high as 60 MeV/u, the two main bodies of the reaction, the quasi-projectile and the quasi-target, pick up approximatively the same excitation energy. This is expected in a pure participant-spectator picture. It is not astonishing in a damping collision picture, since this is also observed for partially damped collisions at near-barrier energies. Even in a pure ststistical model, charged particles and neutrons are emitted on a time scale which decreases as the energy deposit increases. It is quite evident then that in the Fermi energy domain, this emission occurs already during the collision. However, it occurs not at the very begining of the collision, but after a sufficient amount of kinetic energy has been damped. It is therefore a dynamical emission, which allows the system to limit the energy deposit. While it is not welcome when one tries to heat nuclei at temperatures as high as possible, it may of great interest for the synthesis of very exotic nuclei.

References

[1] D. Hilscher et al., *Phys. Rev. Lett.* **62** (1989) 1099

[2] M. Gui et al., *Phys. Rev.* **C48** (1993) 1791

[3] L. Stuttgé et al., *Nucl. Phys.* **A539** (1992) 511

[4] M. Moszynski et al., *Nucl. Instr. and Meth.* **A307** (1991) 97

[5] G. Bizard et al., *Nucl. Phys. News* **1** (1991) 97

[6] M. Moszynski et al., *Nucl. Instr. and Meth.* **A317** (1992) 262

[7] M. Moszynski et al., *Nucl. Instr. and Meth.* **A343** (1994) 563

[8] S. Mouatassim, *Ph.D. thesis*, Université Louis Pasteur, preprint CRN 94-40 (1994)

[9] S. Mouatassim et al., *Nucl. Instr. and Meth.* **A365** (1995) 446

[10] I. Tilquin et al., *Nucl. Instr. and Meth.* A365 (1995) 530

[11] F.M. Marqués et al., *Phys. Lett.* **B381** (1996) 407

[12] R. Bougault et al., *Nucl. Phys.* **A587** (1995) 499

[13] A. Bonasera et al., *Nucl. Phys.* **A463** (1987) 653

[14] D. Durand, *Nucl. Phys.* **A541** (1992) 266

[15] G. Rudolf et al., *Phys. Lett.* **B307** (1993) 287