

# Hot nuclei with high spin states in collisions between heavy nuclei

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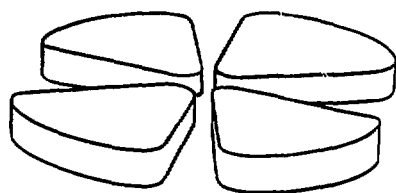
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# GANIL



**HOT NUCLEI with HIGH SPIN STATES  
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# HOT NUCLEI with HIGH SPIN STATES in collisions between heavy nuclei\*.

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## Introduction

It is now well established that nuclei with temperatures exceeding 4-5 MeV can be formed in violent collisions between heavy nuclei at bombarding energies of a few tens of MeV/u<sup>1</sup>). But, at such moderate energies, in order to be violent a collision needs not to be central and, as a consequence, large angular momenta are involved, leading to the formation of hot nuclei with high spin states. In addition, and due to the weak overlap between projectile and target nuclei in such collisions, one deals with initially uncompressed nuclei, in contrast with what happens for more central collisions. In this contribution, we would like to first show how it is possible to select hot nuclei in peripheral collisions, infer their temperature from exclusive neutron multiplicity measurements and, then, demonstrate, by utilizing fission properties, that such nuclei have pretty large spin states.

## Peripheral collisions studied in 32 MeV/u Kr+Au reactions: evidence for the formation of hot nuclei.

Projectile-like fragments have been detected by a standard telescope made of Si detectors. This telescope sits at 7° i.e. close to the grazing angle and two types of events can be distinguished on an identification matrix (fig.1). Those with a velocity close to the beam velocity, extending from Z= 37 down to Z= 2, represent one wing in the matrix. In addition, there is a second wing made of events with similar Z's but with velocities strongly reduced as compared to the beam velocity. Due to the detection threshold, only part of the latter could be investigated (fig.1). Moreover, below Z=20 or so, the two contributions start overlapping, leading to broad energy spectra. A more detailed description of the two types of events is provided in the scatter plot of fig.2 where the number of accompanying detected neutrons is presented as a function of the kinetic energy of the measured fragments. For most of the latter (38>Z>20), one can identify two blobs of data points that could be attributed to two different trajectories, corresponding to well distinct impact parameters. On the one hand, both the high fragment velocity and the relatively low number of neutrons sign a collision at high impact parameter with a trajectory dominated by the coulomb field between projectile and target. On the other hand, the events with a low kinetic energy, correlated with a high

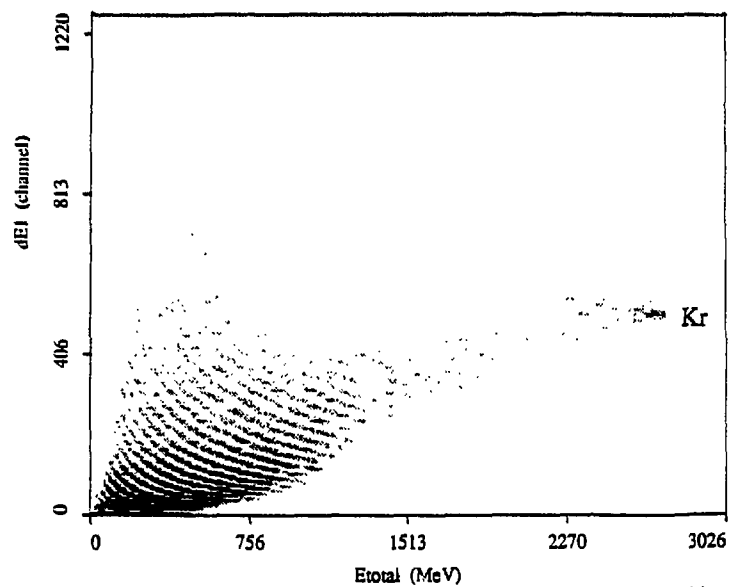


Fig.1  $\Delta E$ -E identification matrix for products of 32 MeV/u Kr+Au at  $7^\circ$

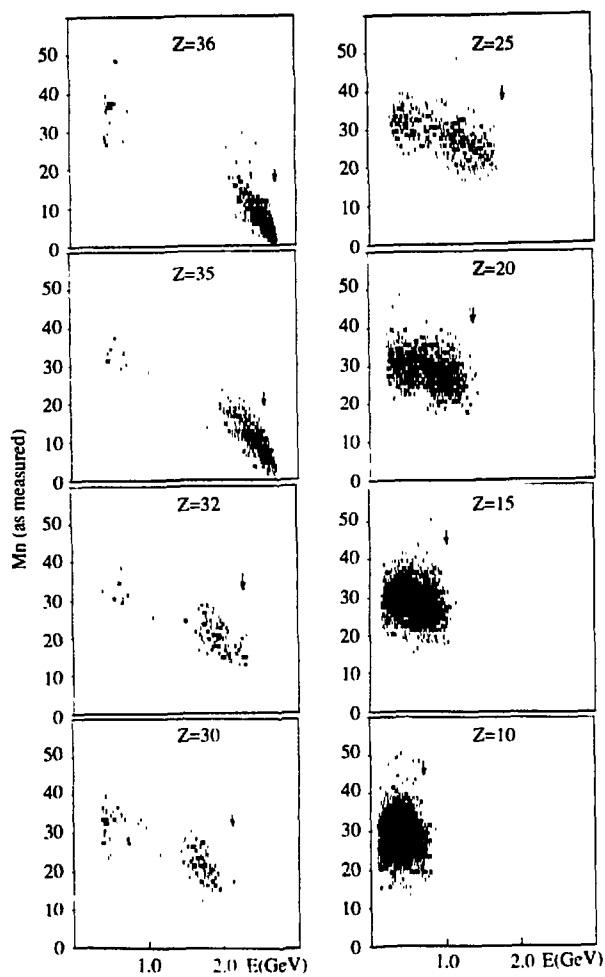


Fig.2 Scatter plot of events of fig.1 identified in Z and characterized by their kinetic energy and associated number of detected neutrons.

neutron multiplicity whatever the  $Z$  of the ejectile, could arise from less peripheral collisions and correspond to trajectories crossing the beam direction, because of the strong attraction of the nuclear field. This interpretation appears to be more likely than the hypothesis of binary fission after large momentum transfer and this is for two reasons. First, the kinetic energy of these nuclei exceeds the one expected for binary fission, even when considering the extreme case of full momentum transfer, and second, above  $Z=37$  this second component vanishes whereas even heavier fission fragments should still be present.

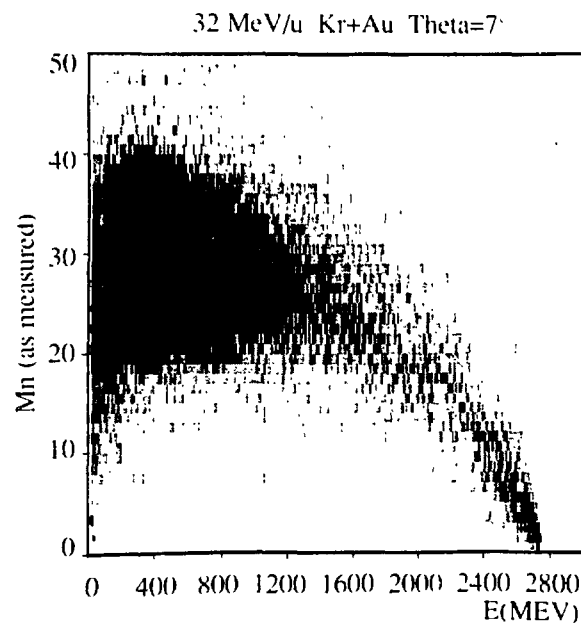


Fig.3 Same as for fig.2 when summed over events of all  $Z$ 's.

The evolution from "positive" to "negative" trajectories as a function of impact parameter has been observed in dynamic calculations of the Landau-Vlasov type, for Ar+U at a similar beam velocity, by D. Jacquet et al<sup>2)</sup>. When gathering all experimental data obtained at 7° (fig.3) on a single scatter plot, one is struck by the strong correlation between kinetic energy of the ejectile and neutron multiplicity. As it will be shown later on, most detected neutrons can be assigned to target-like evaporation, therefore a large number of neutrons means the achievement of high temperatures in the target-like nucleus, thus indicating strong correlation between the size (or/and the kinetic energy) of the detected ejectile and the temperature reached by its partner. Such a correlation has also been observed in Ar induced reactions at similar bombarding velocity by M. Morjean et al<sup>3)</sup> and could be essentially understood, at bombarding energies lower than 30 MeV/u, in the frame of a massive transfer reaction: the missing part of the projectile is

essentially captured by the partner nucleus and the kinetic energy of the transferred nucleons degraded into heat. Here, more than the reaction mechanism itself, we are interested in assessing the amount of thermalized energy in the partners and for this purpose we have utilized the data collected by the  $4\pi$ -neutron detector.

As presented elsewhere by J.Galin et al<sup>4)</sup> and in this meeting by Jahnke<sup>5)</sup>, the ORION detector is a liquid scintillator detector, loaded with Gadolinium, made of four independent sectors, covering  $4\pi$ , whose main virtue is a high detection efficiency ( $>75\%$ ) for neutrons of less than 10 MeV. In contrast, the detection efficiency decreases steadily for high energy neutrons. Such a detector is thus well suited to register those neutrons evaporated by a target-like hot nucleus recoiling at moderate velocity, whereas those issued from a rapid projectile-like nucleus are poorly recorded. The second advantage of such a sectorized detector is to provide information on the spatial distribution of these neutrons, making it possible to unfold the data between two major contributions. An example has been chosen in order to illustrate how sensitive this procedure can be. Events with  $Z=28$  have been selected with average kinetic energies of 1600 MeV. The distribution of the coincident neutrons in the four sectors of ORION (A, B, C, D from backward to forward) as well as in the full detector (labeled E) are given in fig.4 by open dots. A Monte Carlo simulation has been utilized to determine the neutron distribution from two sources: the detected fragment (hatched area) and its complement (open area) assuming binary kinematics and isotropic emission in their respective rest frames. The absolute number of emitted neutrons from each source is left as a free parameter. Detection efficiency is taken care of for each emitted neutron, characterized by its velocity vector as obtained from the output of the Monte-Carlo evaporation simulation code in such a way that experimental data, as measured, can be directly compared with the simulation output. It can be seen that, as expected, most of the registered neutrons (95% in the present case) are emitted by the target-like nucleus. A severe constraint on the number of neutrons evaporated by the target-like nucleus is provided by the backward measurements. Thirty evaporated neutrons are needed to reproduce the data. As for the neutron emission from the projectile-like nucleus, it cannot be entirely fitted by considering the complementary part measured forward. There is some room left for an extra contribution in the most forward sector (D) and that could be due to preequilibrium emission, disregarded in the present simulation. Therefore, the uncertainty on the actual number of projectile-like neutrons remains large and this makes difficult an estimate of the corresponding thermal energy (3 have been considered in the fit of

fig.4). Moreover for such a medium mass nucleus, charged particle emission cannot be ignored.

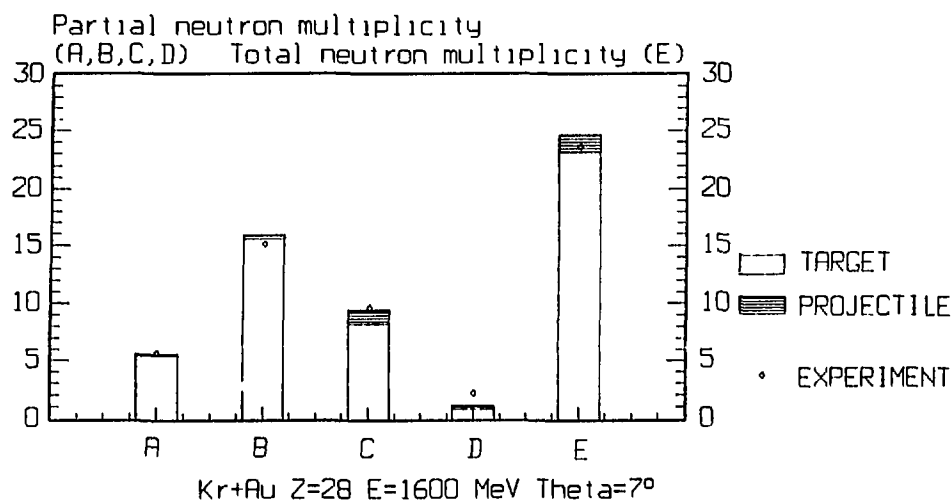


Fig.4 Number of neutrons detected from backward (A) to forward (D) and in the whole ORION detector (E). Experimental data are given by the open dots. Emission simulated from projectile and target-like nuclei are given by histograms. For detail see text.

On the contrary, there is no such an ambiguity for the target-like emission. In order to infer an excitation energy from the deduced multiplicity of 30 evaporated neutrons, evaporation codes have been used, leading to  $E^*=700$  MeV or  $T=6$  MeV. There is thus strong evidence that pretty hot nuclei can be formed, even in rather peripheral collisions. Indeed, for the collisions considered before it must be stressed that a nucleus of  $Z$  equal to 28 has survived with about 85% of the beam velocity. This implies that projectile and target have overlapped very little, as it was illustrated by M.F. Rivet<sup>(6)</sup> in Landau-Vlasov calculations performed on a different system but at a similar beam velocity .

#### Peripheral collisions studied in the 29 MeV/u Pb+Au collisions: evidence for the formation of nuclei with high spin states.

When an excited, spinning nucleus decays by particle emission or by fission, these particles (or fission fragments) are focused in a plane perpendicular to the spin vector and this effect is all the more important that the spin value is large. One can thus exploit out-of-plane measurements to infer the strength of the spin alignment and the spin modulus. When such measurements are performed in peripheral collisions the reaction plane is defined by means of the beam axis and the scattering direction of either the projectile-like or target-like nucleus. Emitted particles or fission

fragments are distributed preferentially in this plane (see for instance R. Babinet et al <sup>7</sup>), P. Dyer et al <sup>8</sup>), D.V. Harrach et al <sup>9</sup>), J.C. Steckmeyer et al <sup>10</sup>). In all previous experiments the violence of the collision and reaction plane were selected by detecting a given projectile-like fragment. In the following, we would like to show that a selection on impact parameter (or violence of the collision) can be performed using the neutron multiplicity as a filter.

The studied system is 29 MeV/u Pb+Au (S.Bresson et al<sup>11</sup>), E.Piasecki et al<sup>12</sup>) and the data analysis being not completed yet, we will restrict ourselves to semi-quantitative arguments. The experimental set-up was made of a large area (24\*24 mm<sup>2</sup>) telescope built from two silicon strip-detectors with thicknesses of 200  $\mu$ m and 500  $\mu$ m for  $\Delta E$  and E respectively. The projectile-like fission fragments could be identified in Z without any ambiguity and their position in theta and phi was determined from the fired strips in  $\Delta E$  and E, mounted orthogonal to each other.

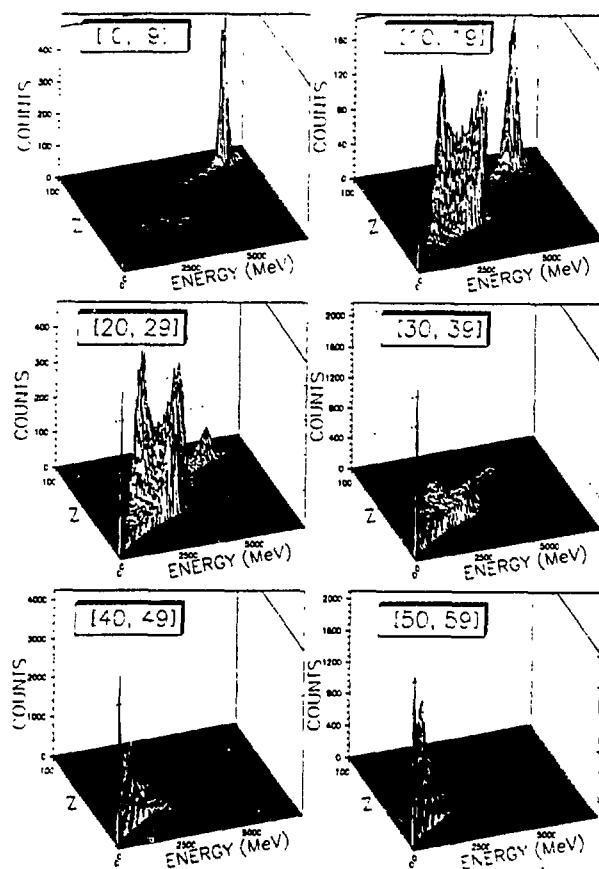


Fig.5 Distribution of reaction products detected between 6° and 20° for the 29 MeV/u Pb+Au system, as a function of their Z and kinetic energy for several neutron multiplicity gates (in brackets)<sup>11</sup>).



As shown in fig.5<sup>11</sup>), fission fragments of the projectile-like ejectile, defined as fragments with a velocity close to the beam velocity and a Z of about one half of the projectile Z, extend in a domain of collisions characterized by intermediate neutron multiplicities. For the most peripheral collisions (low neutron multiplicities) the projectile-like nucleus does not receive enough spin or/and excitation energy to undergo binary fission; instead it ends up in an evaporation residue. At the other extreme i.e. for the most violent collisions (high neutron multiplicities) binary fission might either be followed by a sequential fission of the primary formed fragments or give way to a one-step multifragmentation process. Whatever the decay process might be, mostly fragments of Z=30 and below (the so-called intermediate mass fragments) are then detected. In the following we will mainly focus on binary fission-like events and, accordingly, events with measured neutron multiplicities between 5 and 34 will be selected. The number of detected neutrons should be roughly increased by 50% to correct for the detector efficiency and get the actual number of emitted neutrons. Indeed, a Monte Carlo simulation shows that, on the average, about 64% of the neutrons emitted by both target-like and projectile-like nuclei are registered. The actual neutron gates, after efficiency correction, thus extend from about 7 up to 51 neutrons (i.e. from about 3 to 25 neutrons for either the projectile-like or target-like nucleus of the nearly symmetric system). The fission fragment data have been sorted as a function of Z for several gates in neutron multiplicity. Their invariant cross sections are given in fig.6<sup>11</sup>) as a function of the two components in velocity, parallel and perpendicular to the beam direction. Since only the Z's and kinetic energies have been measured, masses were

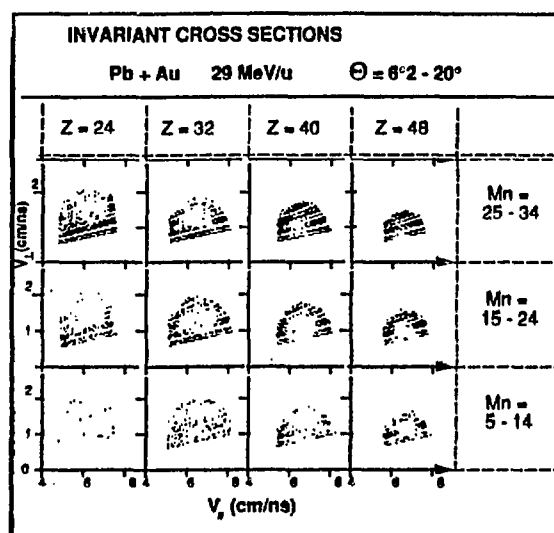


Fig.6 Galilean invariant cross sections of fission fragments versus  $v_{\text{par}}$  and  $v_{\text{per}}$  for several Z's and neutron multiplicity gates.

assigned as following the bottom of the  $\beta$  stability valley, in order to determine the velocity. As it could be discussed later on, this assumption may have some influence on the derivation of several quantities.

The regular pattern observed in fig.6 calls for several comments about the general features. First, nice rings show up which are experimentally truncated at small angles, simply by lack of measurements, and at low energy because of the finite thickness of the  $\Delta E$  detector. Second, it is obvious that the rings are not centered in the beam direction but rather at  $5-6^\circ$ , but, despite of this, the pictures are not blurred. This can be interpreted as due to a strong selectivity in impact parameter and deflection angle thanks to the neutron multiplicity filter. The quasi-projectile deflected by the Coulomb field of the target nucleus undergoes fission and the fission fragments sit, in a velocity diagram, on a circle centered at the tip of the velocity vector of the parent nucleus. By fitting the locus of the data points with circles one can precisely determine the characteristics of the fissioning nucleus (velocity in modulus and angle) and of the fission fragments (velocity).

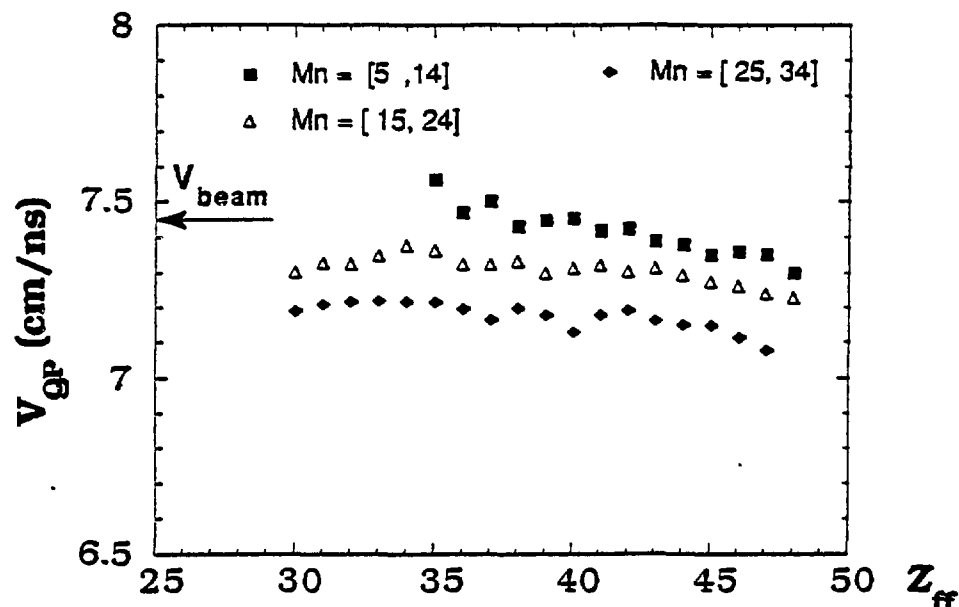


Fig.7 Velocity of the fissioning nuclei as a function of the fission fragment  $Z$ 's for several neutron multiplicity gates.

As expected, the fissioning nucleus has a velocity identical to the beam velocity for the less violent collisions(fig.7). More dissipation, selected by larger neutron multiplicities, is connected with a slowing down of the fissioning nuclei (fig.7). As mentioned earlier, the fact that the velocities were not directly measured but inferred

from E and Z may slightly modify the velocities given in fig.7, but qualitatively the evolution with neutron multiplicity is the expected one. As for the deflection angle of the fissioning nucleus, its precise determination suffers the fact that only fraction of the circle has been actually measured. All primary scattering angles are determined as being slightly below the grazing angle but an evolution with neutron multiplicity could not be derived unambiguously. The intrinsic velocity of the fragments follows what is expected from the Viola systematics and momentum conservation laws (fig.8). The slow evolution towards lower velocity in the more dissipative collisions is not yet understood. The Z distribution centered at Z= 41 (half the projectile Z) for the less dissipative collisions is shifted by a few units for hotter fissioning nuclei as expected if charge particle evaporation competes with neutron emission either before or after fission (fig.9).

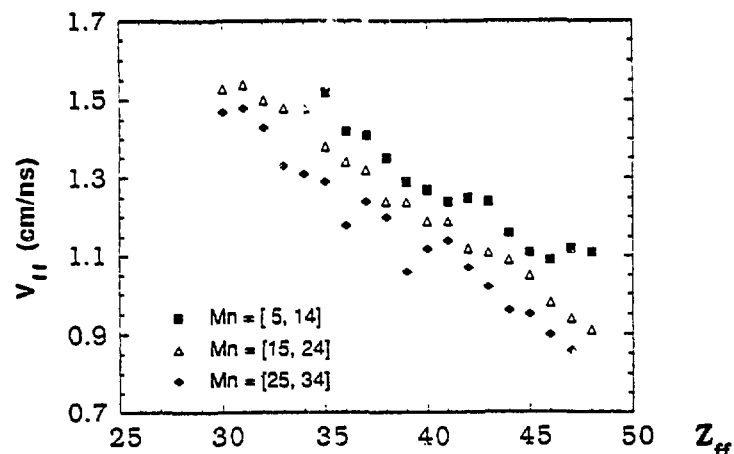


Fig.8 Fission fragment intrinsic velocities as a function of their Z's and for several neutron multiplicity gates.

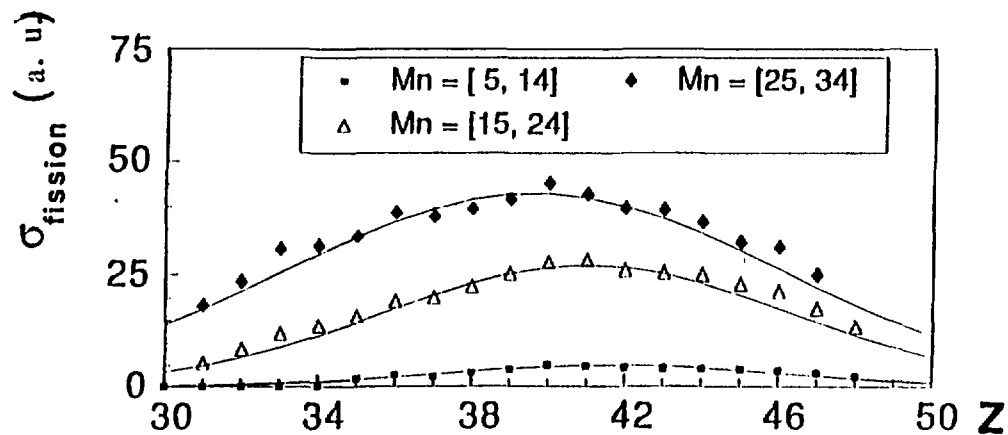


Fig.9 Integrated cross sections of the fission fragments as a function of their Z for several neutron multiplicity gates.

The most intriguing and interesting feature from these data is connected with the spin of the fissioning nuclei. The data reveal that pretty large amounts of spin are present. The finger-print is the existence of "rings" in the invariant cross section picture of fig.6. Why are there "rings" of events and not "disks" (or filled "rings")? In contrast with fusion-like reactions<sup>13</sup>), the velocity vector of the fissioning nucleus is not unique but describes a cone of revolution around the beam axis. Therefore one would expect the tips of the velocity vectors of the fission fragments to be located on spheres that strongly overlap, as suggested on top of fig.10.

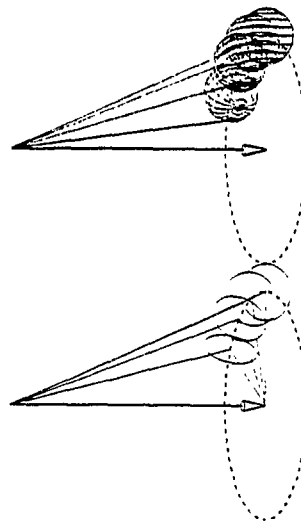


Fig.10 Sketch illustrating the effects of spin on the distribution of the fission fragments as observed in fig.6 (see text).

If it were so, we would observe filled disks instead of open rings in fig.6. The explanation for the existence of rings lies in spin effects. If the fissioning nuclei are spinning around an axis perpendicular to the reaction plane, then the tips of the velocity vectors of the fragments will not be distributed on spheres but essentially focused in the reaction planes like it is sketched on the bottom of fig.10. The existence of rings is unmistakably the signature of spinning nuclei. The "thickness" of the ring must bring combined information on the selectivity in deflection angle of the fissioning nucleus after neutron multiplicity selection and on the spin strength. It can be noted in fig.6 that, with increasing neutron multiplicity, one shifts progressively from a thin ring to a disk. Is it the scattering angle of the fissioning nucleus which gets poorly determined or the spin value which decreases? Evaporation prior to fission is expected to broaden the primary angular location of the fissioning nucleus and to diminish the spin value of the nucleus when undergoing fission.

Both effects should contribute to the filling of the ring. Monte-Carlo simulations are clearly needed to estimate all these effects. Moreover, in a forthcoming experiment, we will try to get more constraints in detecting, in addition to the present observables (one fission fragment and the neutron multiplicity), both the scattered target-like nucleus (to define the reaction plane) and the complementary fission fragment.

To summarize, in the first part of this contribution we have shown that pretty hot nuclei could be obtained in peripheral collisions of Kr+Au. The collisions considered in the chosen example give rise to a nucleus of  $Z=28$  with a kinetic energy of 1600 MeV (i.e. a velocity close to 27 MeV/u to be compared with the 32 MeV/u of the beam). The excitation energy deposited in the non-detected target like-nucleus, deduced from the neutron multiplicity measurements, amounts to 700 MeV ( $T=6$  MeV). In the second part of the contribution, one used the well known properties of fission, and particularly its sensitivity to spin, to show in a qualitative way that pretty high spin values are into play. A more quantitative analysis together with additional measurements are still needed in order to infer precise figures of spin. It can be noted that for the 29 MeV/u Pb+Au reaction  $l_{\max}$  amounts to 1700  $\hbar$ . If we assume that the sticking or rolling conditions can be fulfilled for initial angular momenta of about  $2/3 l_{\max}$ , then a projectile-like (and its target partner) could acquire an intrinsic spin of about 160 $\hbar$ . The behavior of a Pb-like nucleus brought in such an exotic state ( $T=6$  MeV and  $J=160\hbar$ ) is certainly worth to be studied in detail. It is also worth recalling that, when obtained in peripheral collisions, the hot nuclei thus formed do not suffer much initial compression at variance with what happens in more central collisions. There is thus an interesting field to be explored of hot, high spin but uncompressed nuclei<sup>14</sup>).

\* Experiments performed at the GANIL facility

# The data presented in this contribution have been obtained in collaboration with a large number of people listed below. Special tribute should be paid to E. Crema and S. Bresson who have performed the data reduction of the Kr and Pb parts respectively.

**Kr experiment:** E.Crema, S.Bresson, H.Dobre, J.Galin, B.Gatty, D.Guerreau, D.Jacquet, U.Jahnke, B.Lott, M.Morjean, E.Piasecki, J.Pouthas, F.Saint-Laurent, E.Schwinn, A.Sokolov and X.M.Wang.

**Pb experiment:** S.Bresson, R.Bougault, J.Colin, E.Crema, J.Galin, B.Gatty, A.Genoux-Lubain, D.Guerreau, D.Horn, D.Jacquet, U.Jahnke, J.Jastrzebski, A.Kordyasz, C.Le Brun, J.F.Lecolley, B.Lott, M.Louvel, M.Morjean, C.Paulot, E.Piasecki, L.Pienkowski, J.Pouthas, B.Quednau, W.U.Schröder, E.Schwinn, W.Skulski, J.Töke

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