SELECTION OF VIOLENT COLLISIONS BY MEANS OF A NEUTRON CALORIMETER FOR INTERFEROMETRY MEASUREMENTS

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1) Introduction.

Many two-particle correlation measurements have been used to study heavy-ion collisions at intermediate energy to get information on the space-time characteristics of the emitting source as well as on the temperature deduced from the population of excited states. The obtained results [1-3] confirmed the relevance of the method but also the dependence of such results on parameters of the collision (impact parameter ...). In this spirit, one can point out two important effects. The first one concerns the preequilibrium emission which can produce two particles in a very short time scale (less than 10^{-22}s). The second one concerns the evaporation from an equilibrated nucleus. In this case the characteristic time gives information on the deexcitation of hot nuclei. Depending on the system and on the angular position of the detectors, one mechanism or the other can be enhanced. For instance the p-p and p-t correlation data [4-7] measured at backward angles with the Ar + Ag system at 39 MeV per nucleon reflect an equilibrium emission from the target-like nucleus.

Improvement in this approach can be obtained by selecting the involved impact parameter interval. An experiment [8] tentatively used the charged particle multiplicity in a limited part of the space as a selection parameter. Its selectivity appeared to be rather poor. In a recent measurement on the $^{36}Ar + ^{45}Sc$ reaction at 80 MeV per nucleon [9] p-p correlations were analysed using the total tranverse energy of charged particles detected in a 4π multidetector as a filter of the violence of the collisions.

The aim of the experiment presented here was to choose experimental conditions to observe mainly light particle correlations coming from heavy equilibrated quasi-projectile nuclei and to sort the events in several intervals of reaction violence. In his report we want to demonstrate that one can use a high efficiency 4π neutron detector as a calorimeter and gain with such an instrument high selectivity on the violence of a collision. (for more details see Ref.10).

2) Neutron multiplicity and prompt pulse charge measured by the ORION detector.

So far, the 4π ORION detector was essentially devoted to the neutron multiplicity measurement, Mn, event by event. Interesting results [11-16] have been reported which show the relevance of the Mn value for selection of the initial excitation energy involved in the reaction.

The neutrons are detected in five tanks surrounding the scattering chamber which are filled with liquid scintillator doped with Gd. The scintillation light generated by the recoiling protons and carbon nuclei of the medium after multiple scattering of the neutrons is collected by means of 30 phototubes surrounding the tank, giving rise to the so-called

QPP signal. Later on, i. e. approximatively 700 ns after the neutron emission, and for several tens of microseconds, the phototubes are fired by γ rays resulting from the radiative capture of the thermalised neutrons by gadolinium nuclei, giving the opportunity to measure the neutron multiplicity Mn for any event (Fig.1). It is the length of the capture process (several tens of μs) which make possible the distinction between the two sources of light. The first one is fast, the second delayed and one is thus able to measure for the same event the integrated charge QPP related to the total kinetic energy of the neutrons (prompt signal) and a quantity, Mn, which is their number (delayed signals). The detector acts as a calorimeter and a multiplicity meter.

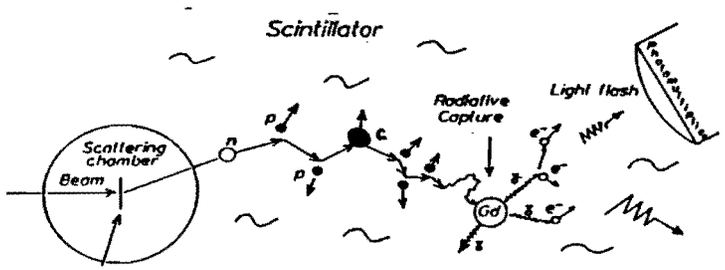

Figure 1: *Neutron detection in Gd loaded scintillator detectors (from ref. 14)..*

Due to the large capture time the Mn measurement imposes a slow counting rate. This limiting factor makes difficult the use of the neutron multiplicity information in interferometry measurements for which good statistics with a reasonable amount of beam are needed. On the contrary, the signal issued from the slowing down of the neutrons being orders of magnitude shorter, appears well suited for faster measurements.

In the present contribution we want to demonstrate the relevance of such an approach, first by studying the correlation between Mn and QPP and then by considering other observables which are known to be very sensitive to the violence of the collision [15].

3) Experimental set up.

The experiment was performed in the scattering chamber of ORION at GANIL. To favour the emission of neutrons we used the ^{208}Pb at 29 MeV per nucleon on a ^{93}Nb target. This beam energy was chosen to allow to reach high excitation energy without large preequilibrium emission. In reverse kinematics one can observe in the forward direction the particles emitted by the heaviest partner and limit the observation of the preequilibrium particles associated with the light partner. Other advantages of reverse kinematics are the possibilities to minimize the energy threshold limitations due to higher momenta of the detected particles and to focuse them in a limited amount of space.

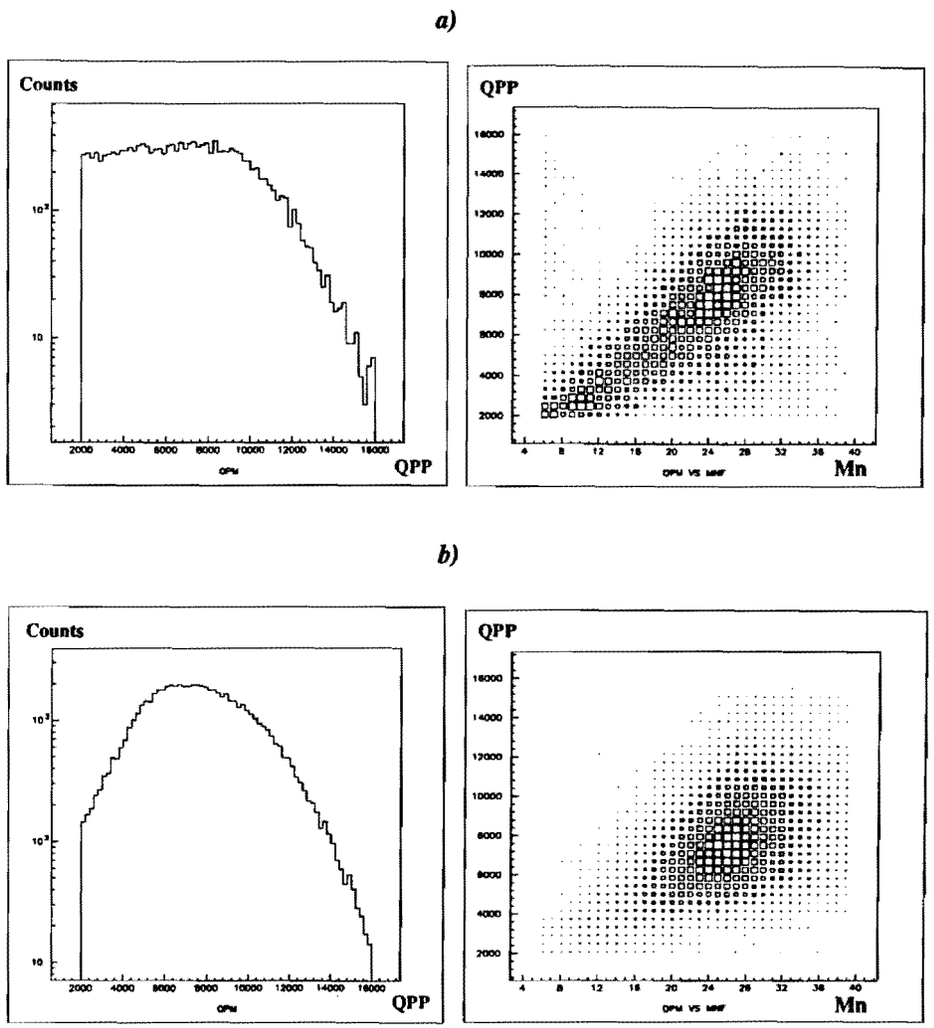

Figure 2: *Correlation plots between QPP and Mn and the projection on the QPP axis for two triggering conditions: a) inclusive data ; b) one of the CsI's as a trigger.*

The scattering chamber is a cylinder (59 cm in diameter and 120 cm long) with the beam direction as a symmetry axis. Particles were detected by 48 CsI detectors (1.27 cm in diameter). Among them 4 detectors (10 cm long) were put in a plane at 5.5 , 10 , 15 and 20 degrees in the forward direction. At backward angles, 4 other detectors (4.5 cm long) were set at 100, 120, 140 and 160 degrees. The correlator itself was formed with the 40 scintillators (4.5 cm long) left in a compact geometry covering radial angles between 25 and 80 degrees and spanning 50 degrees in azimuth. The minimum relative angle between two detectors was 4.7 degrees.

The energy calibration was obtained by detecting secondary beam of light particles with known magnetic rigidity with the detectors positionned near the beam axis. Those particles were identified from the conventional pulse shape analysis. An algorithm has been developped [17] which can automatically deduce the value of an identification parameter from the slow and fast components of the integrated charge.

In this experiment the trigger was a signal from any of the CsI detectors and all parameters from ORION and CsI's were registered. The single events correspond to the detection by only one CsI detector and their registration was scaled down. The other events are the coincident events. In this report we will focus on the alpha particles detected in the single events.

In order to study the correlation between the neutron multiplicity Mn and the prompt pulse charge QPP a special measurement has been made with a chopped beam (3 successive RF bursts within 300 ns every 70 μs) requiring as triggering conditions the coincidence between a RF signal and the prompt signal from ORION. In this measurement the total reaction cross section is investigated (inclusive data).

Figure 2 shows the correlation plot between the Mn and QPP values. In part a) the data are inclusive and in part b) they are triggered by the CsI. A strong correlation is observed, giving confidence in ORION used as a calorimeter liding to a similar selectivity as used as a multiplicity meter. The strong suppression of events in b) simply reflects that in a Pb-like nucleus charged particle emission arises only if enough excitation energy has been deposited [16].

4) The alpha-particles as probes of the quality of the calorimeter selectivity.

The pattern of light-particle emission is known to constitute a sensitive probe of the properties of heated nuclei (or heated nuclear matter at large) and hence of the violence of the collision. In order to test further the quality of the QPP signal as a filter on impact parameter, the alpha-particle emissions were investigated in detail. Such particles present two advantages as compared to protons: first as composite particles they are thought to be less subject to preequilibrium emission than nucleons, then their larger Coulomb repulsion give them a more visible signature of the nucleus they come from.

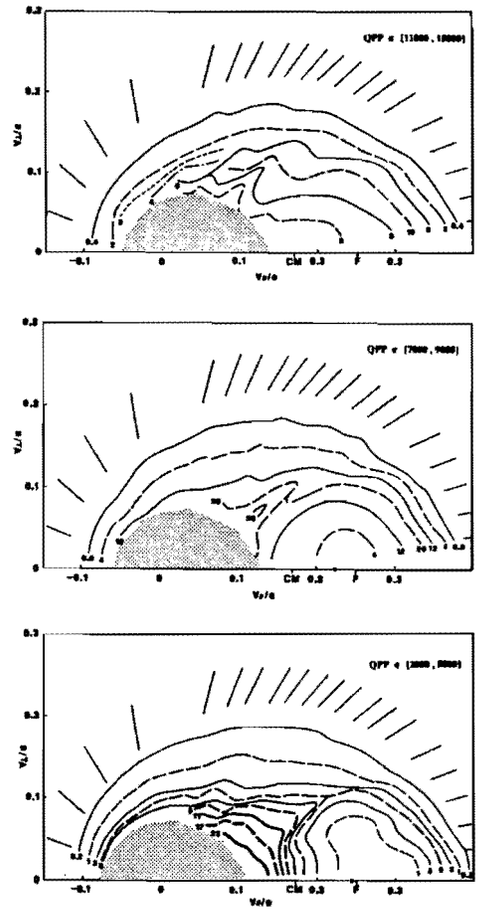

Figure 3: *Invariant cross-section contours for the alpha particles emitted in the $^{208}Pb+^{93}Nb$ reaction and selected in three QPP bins. The solid segments correspond to the angular positions of the CsI detectors.*

The alpha-particle galilean invariant cross sections have been presented as a function of the $v_{//}$ and $v_{\perp}$ components of these particles for three gates in QPP. In Fig. 3 are shown the most central and dissipative collisions (a) and then in more and more peripheral collisions (b and c). It must be stressed that the most peripheral collisions are hindered by the requirement of at least one charged particle in coincidence (Fig. 2).

A clear evolution is shown in the level contours in Fig. 3 when more and more dissipative collisions are considered: the Coulomb ring pattern well shown in c) and even in b) is washed out in a). Distinct sequential emission from projectile-like and target-like nuclei might be masked when, as a function of energy damping, the projectile-like and target-like recoil velocities get closer and closer. The target-like nucleus is accelerated at the expense of the projectile-like which is slowed down and the two Coulomb rings are overlaping in the mid rapidity region smearing the nice pattern shown in 3 c) or 3 b). Alternatively, the observed smearing could be due to the growing contribution of an intermediate velocity source (preequilibrium) which would fill the space between the two previously mentionned contributions.

The evolution of the characteristics of the projectile-like source is clearly shown on the one dimension energy spectra recorded at very small angle. The double bumped structure corresponding to the two kinematical solutions for alpha-particle evaporation is well observed for the less dissipative collisions (small QPP in Fig. 4). A steady shift from 240 MeV to 190 MeV in the location of the high energy bump is clearly observed as expected with higher energy damping and demonstrates the good sensitivity of the QPP trigger. It is worth mentionning that the low enrgy peak (second kinematical solution) suffers from being experimentally truncated at low energy which makes it more and more difficult to see as the energy damping increases. Moreover it overlaps with target-like particle emission.

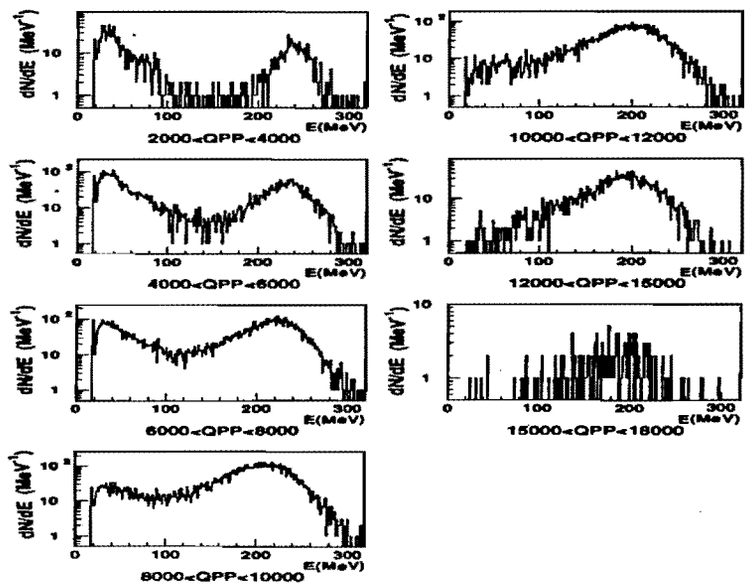

Figure 4: *Alpha particle energy spectra at 5.5° for seven adjacent QPP bins.*

5) Can the QPP data be translated in impact parameter?

By applying the massive transfer model one can tentatively correlate the QPP information with the impact parameter. In this model it is assumed that the heavy partner (the Pb nucleus) captures nucleons from the light one and that the number of captured nucleons is simply function of the overlap between nuclei i. e. depends on impact parameter. This has two major consequences: the more nucleons are captured, the hotter and slower the generated fused nucleus must be. Since the evaporated particles bear in their energy spectra an information on the velocity of their emitter, there is a possibility to connect through the data shown in Fig. 4 (position of the high energy bump) the excitation energy (E*) of the emitter and the impact parameter (b) with QPP. This is shown by the curve in Fig. 5. It must be stressed that such a model becomes very loose for the more central collisions when the two partners start overlapping deeply and might undergo deep inelastic collisions rather than incomplete fusion. Moreover in the tail of the QPP distribution one becomes more and more sensitive to fluctuation effects, which in large part can originate from light collection in ORION. This is the reason why the tail in Fig. 5 is more suggested than really experimentally determined.

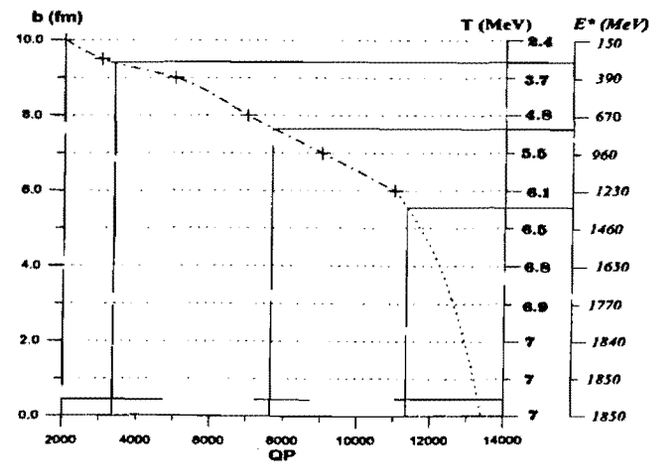

Figure 5: *Relation between the impact parameter and the QPP value as deduced from a massive transfer model. The corresponding temperature and excitation energy values are indicated on the right vertical axis.*

Finally the high energy part of the spectra in Fig. 4 have been fitted by a single Maxwell-Boltzman distribution assuming that these spectra represent pure sequential evaporation from the projectile-like nucleus without any contaminant from other sources.

As it can be seen in Table 1, both the recoil velocity and the slope parameter (temperature) values match reasonably well those deduced from the massive transfer model. Very hot nuclei can be formed in the most dissipative collisions in agreement with what has been observed in Ref. 15 for the similar system, Kr +Au at 32 MeV/nucleon.

It is also shown that one explores temperatures which nearly double from one edge to the other edge of the implied impact parameters. Such a dramatic evolution should definitely show up in the interferometry data when the latter are worked out.

QPP min		2000	4000	6000	8000	10000	12000
	QPP max	4000	6000	8000	10000	12000	15000
$\frac{VR}{c}$	minimisation	0.24	0.24	0.22	0.22	0.20	0.19
	model	0.23	0.23	0.22	0.21	0.20	0.18
T (MeV)	minimisation	3.4	3.7	4.9	5.8	7.2	8.6
	model	3.1	3.7	4.8	5.6	6.1	6.8

Table 1 : *Velocity and temperature values extracted from minimisation procedure and from massive transfer model for six QPP bins.*

6) Summary.

It has been shown that a 4π high efficiency neutron detector could be used as a calorimeter instead of a multiplicity meter in order to select collisions as a function of the reaction violence. As a consequence and due to the fast response of the detector used as a calorimeter, this filter appears to be perfectly suited for exclusive interferometry measurements requiring large statistics.

Then a source analysis has shown that temperatures ranging from 3 to nealy 7 MeV were reached, giving the possibility to address the issue of interferometry measurements over well defined and distinct initial conditions.

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