Light-particle correlations measured in heavy-ion collisions at GANIL

B.Erazmus, C.Lebrun, C.Ghisalberti, R. Lednicky*, L.Martin†, D.Nouais, J.Pluta, D. Ardouin, J.P. Cussonneau, P. Eudes, F. Guilbault, P. Lautridou, A. Rahmani, T. Reposeur, D. Roy, L. Sézac

Laboratoire SUBATECH, Université de Nantes / Ecole des Mines de Nantes / IN2P3/CNRS, 2 rue de la Houssinière, 44072 Nantes Cedex 03, France

N. Carjan, J. Quebert

Centre d'Etudes Nucléaires de Bordeaux-Gradignan, 33175 Gradignan Cedex, France

M. Lewitowicz, W. Mittig, P. Roussel-Chomaz, A. Chbihi, J. Galin, D. Guerreau, M. Morjean, A. Peghaire

GANIL, BP 5027, 14021 CAEN, France

P. Aguer

Centre de Spectroscopie Nucléaire et de Spectroscopie de Masse, 91405 Orsay, France

R. Siemssen

K. V. I. Zernikelaan 25-9747 AA GRONINGEN, The Netherlands

W. Burzyński, W. Peryt

Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland

H. Dabrowski, P. Stefański

Institut of Nuclear Physics, Kraków, Poland

Abstract : Light-particle correlations were measured at GANIL, using the ORION detector, to select impact parameter with the help of neutron calorimetry, and the magnetic spectrometer SPEG, to measure precisely very small relative momenta. The time delay between two deutrons emitted by an equilibrated source strongly depends on the centrality of the collision. The contribution of both preequilibrium and equilibrium protons is observed for the first time in the same experiment (ORION) and a strong dependence of the correlation function on impact parameter selection and directional cuts is seen. The two-proton correlation function is measured in previously unaccessible region of very small relative momenta 1-10 MeV/c particularly well suited to extract with high accuracy the lifetime value of an equilibrated long-lived source. The Coulomb directional effect in p-p correlations is observed for the first time, giving the additional information about lifetime and kinematic characteristics of the emitter.

*Permanent address: Institut of Physics, Na Slovance 2, 18040 Prague 8, Czech Republic

†Present address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing MI 48824, USA

1. INTRODUCTION

Light-particle correlations at small relative velocities reflect space-time characteristics of the production region due to the effects of quantum statistics (for identical particles) and final state interaction. Usually, these effects are contained in the two-particle wave function if the mutual interaction of two particles only is taken into account . Thus the correlation function of two particles with 4-momenta p_1 and p_2 can be represented as a convolution of the modulus squared of this wave function with the emission probability of noninteracting particles at the space-time points $x_1 = \{t_1, \vec{r}_1\}$ and $x_2 = \{t_2, \vec{r}_2\}$. The latter can be simply described using a gaussian or exponential parametrization or distributions predicted by a model taking into account the dynamics of the reaction.

The two-body approximation is however questionable in the case of heavy-ion reactions when the particles are produced in a strong Coulomb field of residual nuclei. Clearly, the interaction of particles with the emitter cannot itself be a source of correlations but it can modify the shape of the correlation function. At characteristic emission times τ of several hundreds fm/c or higher this complicated three-body problem can be solved in the classical approximation. In fact, the classical trajectory calculations show [1,2] that, despite the one-particle spectra are substantially affected, the effect of residual nucleus on particle correlations is of minor importance though, it is noticeable for particles with different charge-to-mass ratio. The theoretical description of particle correlations can be extended to lower values of τ in the quantum *adiabatic* approach, assuming the relative motion of the two particles much slower than their motion with respect to the Coulomb center [3]. In such an approximation, the two-particle wave function is just multiplied by the usual Coulomb functions describing the independent motion of the two particles in the field of the Coulomb center. The recent quantum calculations show that the effect of residual nucleus on particle correlations at small relative velocities increases with decreasing τ and with the increasing difference in charge-to-mass ratio of the particles. Study of directional dependence of particle correlations can be used to extract the information on the form of the production region and the emission time. The experimental results of two-particle correlations in heavy-ion reactions show a strong dependence of the correlation strength on particle velocity and emission angle. For instance, for p-p correlations this effect was observed in a number of experiments performed generally without centrality selection [4–7], with some exceptions [8,9]. This dependence can be related to the contribution of different production mechanisms characterized by substantially different space and time scales, like preequilibrium and equilibrium emission. In such a situation, to deduce possible dynamic properties of the reaction, the correlation experiment should be substantially selective. We report here the results from an experiment performed at GANIL allowing, besides the angular and velocity cuts, for the centrality selection with the help of neutron calorimetry using the ORION detector.

The experimental resolution often reduces the quality of the measured correlation function, especially in the region of very small relative momenta which is particularly well suited for a precise determination of the lifetime of the equilibrated emitting nucleus. We present here the results of a measurement of the p-p correlation function covering, with a very good precision, an extended range of the relative momenta from 1 to 100 MeV/c. To reach the region of very low relative momenta we have used an original setup based on the magnetic spectrometer SPEG at GANIL.

2. INTERFEROMETRY MEASUREMENTS SELECTED BY NEUTRON CALORIMETRY

In order to measure the centrality of each event we use the neutron calorimetry with the help of ORION detector at GANIL. A ^{93}Nb target was bombarded by a ^{208}Pb beam at 29 MeV per nucleon. This system favours the neutron emission and the reverse kinematics allows to observe in the forward direction the particles emitted by the heavier partner. The beam energy was set to reach high excitation energy with a relatively small amount of preequilibrium particles. Charged particles were detected by 48 CsI detectors covering radial angles between 25 and 80 degrees and spanning 50 degrees in azimuth. This system allowed to measure the proton-proton correlation function with a relative momentum threshold of about 10 MeV/c. For each coincident event a centrality parameter called QP was recorded. It corresponds to the total charge of prompt light pulses induced by the neutron detection in the liquid scintillator loaded with Gadolinium surrounding the reaction chamber. This parameter is well correlated to the neutron multiplicity (measured at low reaction rate) and related to the projectile-like velocity [10]. We define three centrality classes: more peripheral, intermediate and central (Fig. 1). Single events used for the normalisation procedure of correlation functions were recorded for each separated class.

2.1. d-d correlation function

The measured d-d correlation function exibits different shapes when selected by different centrality parameter from peripheral to central collisions. We compared the data with predictions of the classical model describing correlations of sequentially emitted light

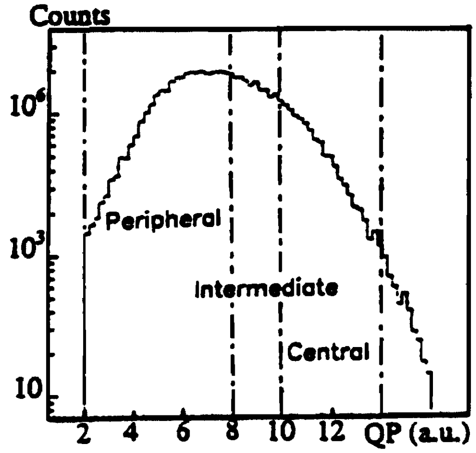

Figure 1. Distribution of all coincident events with respect to the centrality parameter QP determined in the text.

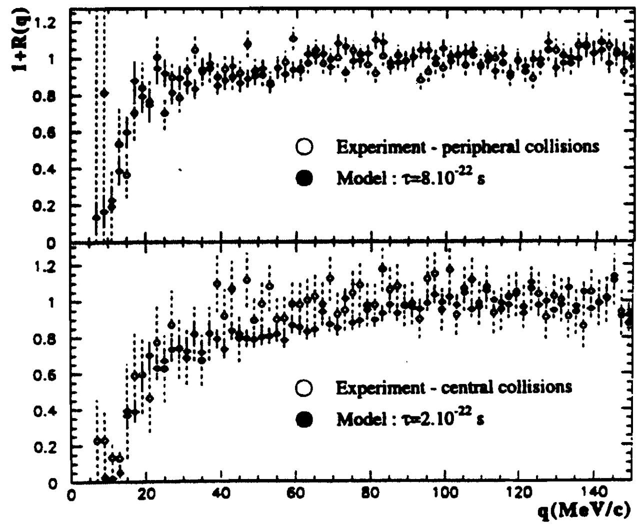

Figure 2. Experimental d-d correlation functions compared with the predictions of the classical model.

particles including three-body Coulomb interaction [1,2]. For these particles, essentially emitted by an equilibrated source, the time delay between two emissions depends on the involved excitation energy. We observe indeed that lifetime value is smaller for central collisions (Fig. 2).

2.2. p-p correlation function

As we already stressed the forward mean position of the proton detectors favoured the detection of the particles emitted by a fast source, especially by the heavy projectile-like partner. On this assumption the expected correlation function obtained without any selection will be of the thermal type. This is confirmed by the experimental result shown on Fig. 3.

However, we should analyse the influence of various cuts and deduce possible concealed contributions to the correlation. To classify experimental events we have used three types of selection: according to the angle ψ, with the assumption of a projectile-like emission, the parallel component of the pair velocity and the centrality parameter QP [12]. A first cut on the parallel pair velocity can favour more or less the involved emitting sources. As shown on Fig. 4-a the correlation function changes from a shape characteristic for preequilibrium particles, with a very strong correlation near 20 MeV/c when the more backward events are selected, to a thermal shape for the more forward events. We can now select events corresponding to the so-called "preequilibrium" part of the previous cut and analyse the centrality effect. Again, very big changes can be observed in Fig. 4-b. More peripheral events give a correlation function strongly peaked at 20 MeV/c while more central ones produce a flat shape. This behaviour confirms the efficiency of the centrality parameter. The decrease of the correlation at 20 MeV/c with the centrality might be interpreted as an increase of the relative weight of thermal protons compared with preequilibrium ones. Finally, it is interesting to observe the directional effect. Fig. 4-c presents the correlation function in more extreme "preequibrium" situation obtained with the more aligned events (ψ less than 40 degrees), compared with two non-aligned cases. In spite of the lack of statistics induced by cumulated cuts, a clear increase of the correlation with the alignment is seen.

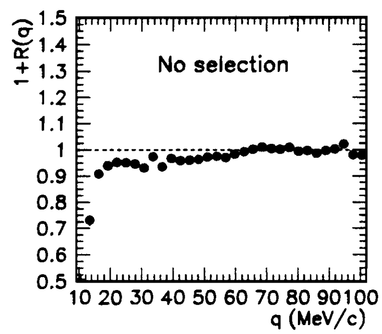

Figure 3. Experimental p-p correlation function obtained without any selection

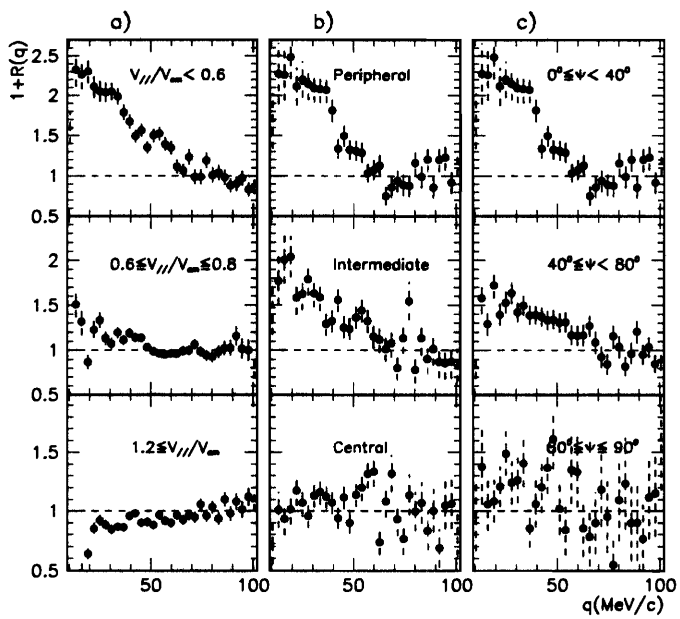

Figure 4. Experimental p-p correlation functions obtained after some selections according to the parallel projected velocity of the pair (a), to the centrality parameter (b) (with aligned events only), and to the aligment (ψ value) (c). Arrows indicate the 20 MeV/c q-value.

To estimate the sensitivity of the p-p correlation function to the space-time parameters of the emitter and to the orientation of the relative momentum, described here only by the angle ψ with the pair velocity in the source rest frame, we have used the model of Lednicky and Lyuboshitz [11] taking into account, besides antisymmetrization, the Coulomb and strong interaction between the two protons. The proton source is supposed to have a radial gaussian shape with a mean radius r and a characteristic emission time τ. Fig. 5 shows the correlation functions obtained for various values of the parameters r and τ and the angle ψ. Fig. 5-c shows the influence of the ψ value on the shape of the correlation function. If the relative momentum vector is perpendicular to the emission direction a clear decrease of the correlation can be observed. In the model this result is induced by the antisymetrization effect. Note that the theoretical predictions assuming a spherically symmetric emission source are incompatible with the range of variation of measured effect (Fig. 4).

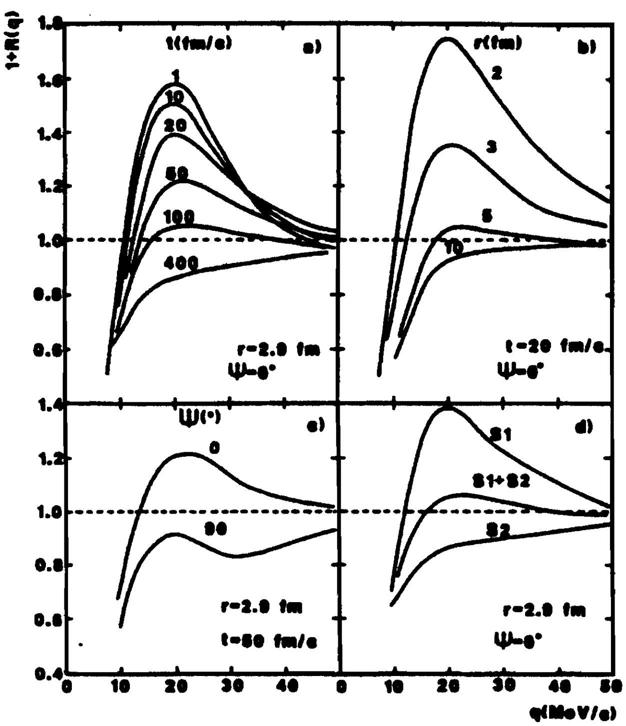

Figure 5. Theoretical p-p correlation functions obtained with different sets of parameters r and τ and the angle ψ. In d) S1 corresponds to τ = 20 fm/c and S2 to τ = 400 fm/c. The result obtained with mixed sources (30%, 70%) is labelled S1+S2.

The plots in Fig. 5 give a clear indication of the possibility to deduce the space-time parameters from the shape of the p-p correlation function provided the proton pairs are emitted by a unique source. However, before using these theoretical predictions to analyse experimental results, we must keep in mind the complexity of the reaction mechanism. Two main effects occur: the first one corresponds to the mixing of impact parameters and the second one - to the dynamical time evolution of the system during the collision. This time can be simply shared in two parts. At the begining of the reaction some nucleons can be emitted without collision or after few collisions. The corresponding proton pairs are called preequilibrium pairs. For them the short time scale will induce a strong correlation near 20 MeV/c. During the second part of the time evolution the system thermalizes and proton pairs are essentially emitted by equilibrated sources. Then the time delay between the emission of the two protons will be large, depending on the involved excitation energy, inducing a flat shape of the correlation function near 20 MeV/c. To illustrate the influence of these dynamical effects the Fig. 5-d gives a shape (S1) corresponding to a preequilibrium source and another one (S2) corresponding to an equilibrated source. On the same figure we show the correlation function corresponding to the p-p pairs emitted by the two mixed sources (S1+S2). In such a case the parameters r and τ, deduced from the global shape, represent average values weighted by the number of pairs emitted by each source. Therefore it is useful to investigate in the same experiment the conditions allowing to observe separately particles from the preequilibrium and thermal emission.

3. TWO-PROTON CORRELATION FUNCTION MEASURED AT VERY SMALL RELATIVE MOMENTA

In the case of equilibrium emission, due to the lifetime effect, the correlation between the emitted particles is strongly attenuated and restricted to the low relative momenta. The region of very small momentum ($q < 10$ MeV/c) allows one to precisely determine the lifetime while the intermediate range (10 MeV/c $< q <$ 30 MeV/c) seems to be well suited to study the relative weight of each effect giving rise to the correlations [13]. However, the experimental resolution often reduces the quality of the measured correlation function in this region implying a weak constraint on the theoretical predictions and thus a limited accuracy of the extracted parameters [2].

We have recently performed a measurement of two-proton coincidences covering, for the first time with a significant amount of statistics, an extended range of relative momenta from 1 to 100 MeV/c. An original setup has been employed to reach the region of very low relative momenta.

During the experiment, performed at the GANIL facility, a 45 MeV/A $^{129}Xe(45^+)$ beam was used to bombard a 1mg/cm^2 ^{48}Ti target. In this reaction, studied in reverse kinematics, we were mainly interested in the detection of the light charge particles coming from the decay of a highly excited projectile-like emitter. The detection setup, centered at $\theta = 25°$ in the laboratory frame, was composed of the magnetic spectrometer SPEG associated with twelve CsI(Tl) scintillators located in the reaction chamber (Fig. 6).

The spectrometer is characterized by a high resolution allowing an accurate determination of the angle and the momentum of the particles as required for a coincidence mea-

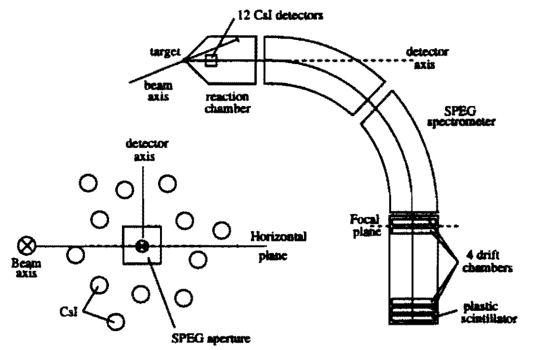

Figure 6. Schematic views of the experimental setup in the horizontal plan (right part) and from the target (left part).

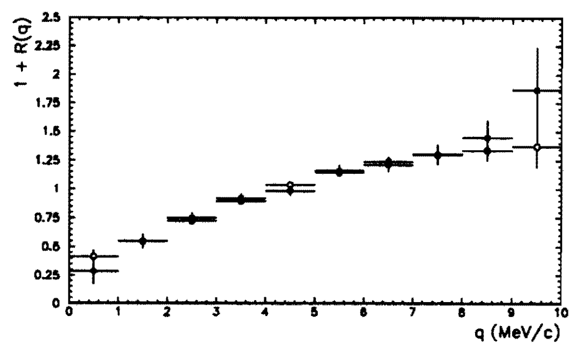

Figure 7. Experimental correlation function (solid circles) measured in SPEG compared to the correlation function (open circles) predicted by the classical model for the mean lifetime $\tau = 3.9\ 10^{-21}$s and convoluted with the response function of the spectrometer.

surement. Moreover, it was used as a trigger of small relative momentum pairs selecting a very narrow region of the angular and energy distribution of the emitted protons (respectively defined by a solid angle of 4.9 msr and a momentum acceptance of $\Delta p/p = 7\%$). The spectrometer's magnetic rigidity was set to detect, on the nominal trajectory, protons with a kinetic energy of 30 MeV. The SPEG detection system, usually devoted to measure heavy residues, was adapted to detect light particles in coincidence [13,14].

The identification of protons was done using the residual energy signal provided by the plastic scintillator and the energy loss signals measured in each chamber. A good separation was obtained between the coincident and the single protons using the $(E, \Delta E)$ matrix. Applying geometrical conditions to the position signals delivered by each drift chamber, a final selection was performed. Then, based on the position measurements, the trajectories of the protons and their initial momenta were calculated.

From the two-proton coincidences measured in the spectrometer, the experimental correlation function was constructed covering the range from 1 to 10 MeV/c. The coincidence spectrum was corrected for a rate of 20% of random proton pairs. The uncorrelated background spectrum was generated from pairs of single protons. The correlation function was finally normalized by setting equal areas of the correlated and uncorrelated spectra. A good resolution, of the order of 1 MeV/c, in the whole range of the relative momenta covered by the spectrometer, results from a good position resolution (estimated at 3 mm) of the drift chambers.

In order to extract the space-time dimensions of the emitting source we have compared the experimental correlation function to the predictions of a classical approach [1]. In frame of this model, three-body tridimensional trajectory calculations were performed describing two light charged particles sequentially emitted from a recoiling nucleus. Thus, the value of the mean lifetime of the hot nucleus was extracted taking advantage of the strong sensitivity of the coincidence spectra and the correlation function to the lifetime for very small relative momenta. Whith the help of a χ^2 statistical analysis, the best agreement with experimental data was obtained with the mean lifetime $\tau = (3.90 \pm 0.15)\, 10^{-21}$s (Fig. 7). From this large value one can conclude that the long-range Coulomb interaction is the most important source of the two-proton correlations measured in this experiment.

The information on the shape of the particle source as well as about the emission time can be extracted applying on the correlation function different angular cuts with respect to the pair motion. In case of a sequential equilibrium emission, a quantum model taking into account the quantum statistics and the final state interaction effects predicts a surprising result [11,13]: a strong suppression of the correlation in case of both extreme longitudinal ($\vec{q}||\vec{v}$) and transverse ($\vec{q}\perp\vec{v}$) orientations of the relative momentum and the pair velocity (Fig. 8). The suppression of the transverse configuration, sensitive to the space dimensions of the source, is well known and due to the antisymmetrization of the particle wave function. The effect predicted in the case of the longitudinal correlation function is more unusual and can be attributed to a directional dependence of the Coulomb interaction between the protons. However, the range, over the $\cos\psi$, of these two effects is different: the Coulomb interaction causes a smooth extended suppression while the quantum statistics effect is characterized by a sharp evolution over a reduced region around $\cos\psi = 0$. Thus the experimental observation of the latter effect would be possible with a very good statistics only.

A similar study has been performed in frame of the classical model used to extract the source lifetime [1]. In order to investigate this effect, we have compared the experimental two-proton correlation functions, constructed for three gates of the relative orientation of the vector of momentum difference and the pair velocity, with the predictions of the classical description corrected for the SPEG resolution. The shape of the correlation function obtained for the longitudinal orientation clearly differs from those observed for the transverse and intermediate relative orientations, as expected by the classical approach (Fig. 9). We should emphasize that the suppression for the transverse orientation, due to

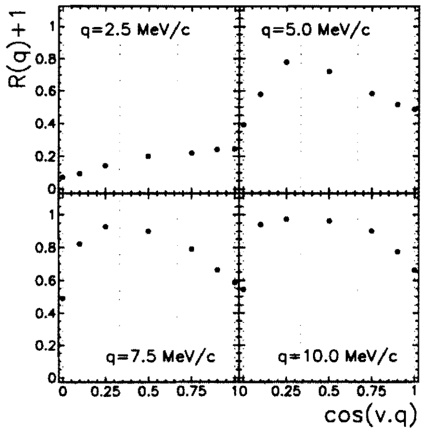

Figure 8. Dependence of the theoretical p-p correlation function on the relative orientation $\hat{v} \cdot \hat{q} = \cos\psi$ between the pair velocity and the relative momentum of the protons predicted by quantum model for the lifetime $\tau = 3.6\ 10^{-21}$s and four different values of the relative momentum.

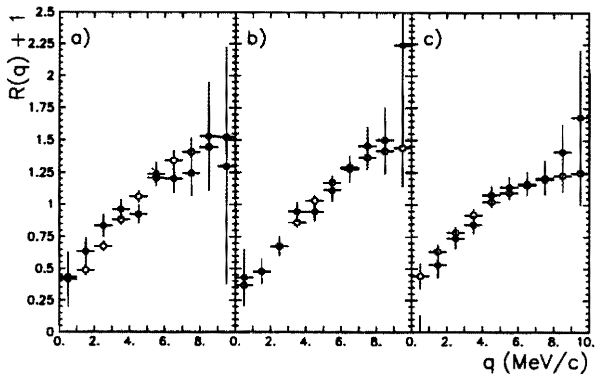

Figure 9. Experimental two-proton correlation function (solid circles) compared to the prediction of the classical model for the lifetime $\tau = 3.9\ 10^{-21}$s and the source velocity $v_s = 0.27c$ (open circles), constructed for three different gates on the relative orientation of the vector of the momentum difference and the pair velocity : $\cos\psi \in (0, 1/3)$ (a), $\cos\psi \in (1/3, 2/3)$ (b), $\cos\psi \in (2/3, 1)$ (c).

the antisymmetrization effects, predicted by the quantum model is washed out. Since the directional effects are the most pronounced when the angular cuts are made in the source rest frame, the particle source velocity v_s acted as a free parameter in this comparison. A fairly good agreement has been found between the experimental and the theoretical correlation functions and a value of the particle source velocity has been deduced : $v_s = (0.27 \pm 0.03)c$ which compares well with the data [16].

This result is the first signature of directional effects in particle correlations in the sequential decay of an excited source in statistical equilibrium.This kind of analysis provides a consistency check on the lifetime value extracted from the angular integrated correlation function and moreover it appears to be a powerful tool to determine the kinematic characteristics of the source.

It should be stressed that the classical approach is valid provided the distance between emitted particles in their c.m.s. r^* is larger than their Bohr radius a, and the relative momentum q is not too close to the classical boundary value $(ar^*/2)^{-1/2}$ [2]. As far as the first condition is concerned, it is satisfied due to the large estimated lifetime τ of 1200 fm/c leading to the characteristic distance $\langle r^* \rangle \doteq v\tau \sim 120$ fm larger than the Bohr radius $a = 58$ fm of the two-proton system. However, as the boundary relative momentum corresponding to $\langle r^* \rangle = 120$ fm is ~ 4 MeV/c, the second condition is certainly not fulfiled in the measured region of very small relative momenta. This is demonstrated in

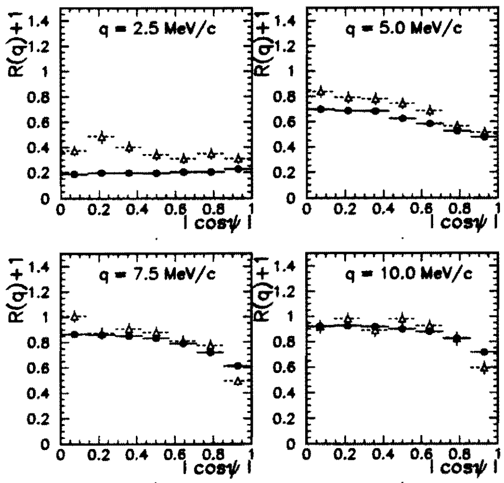

Figure 10. Comparison of the orientation dependence of the theoretical p-p correlation functions predicted by quantum (•) and classical (△) models for lifetime τ = 1080 fm/c, proton pair velocity in the source rest frame v = 0.17c and four different values of the relative momentum. In both models only the Coulomb interaction between the two protons is taken into account.

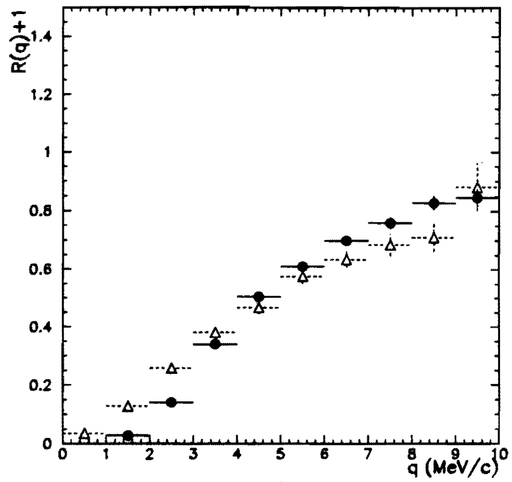

Figure 11. Comparison of the theoretical p-p correlation functions calculated in quantum (•) and classical (△) models for the conditions expected in SPEG experiment: lifetime τ = 1200 fm/c and source velocity v_s = 0.27c (corresponding velocity of proton pairs in the source rest frame v = 0.11c). In both models only the Coulomb interaction between the two protons is taken into account.

Figs. 10 and 11 showing a comparison between the classical and quantum calculations, taking into account the Coulomb interaction only between the two protons. We can see that the classical approach overestimates the value of the correlation function for relative momenta smaller than $\sim$ 5 MeV/c. We have checked that this overestimation weakens when increasing the characteristic distance $\langle r^* \rangle$ by doing the calculations at higher pair velocity or longer lifetime τ.

The full three-body calculation has been worked out only recently. Convoluted with the response of the spectrometer, the quantum approach will give a longer lifetime than that extracted from the classical calculation.

Twelve CsI(Tl) scintillators were used during the experiment. Events measured in these detectors will permit to construct the p-p correlation function at higher relative momenta and to undertake a comparative study with the unlike particle correlation functions.

4. CONCLUSIONS

Two exclusive measurements of light-particle correlations were performed at GANIL, using the detector ORION, to select impact parameter with the help of neutron calorimetry, and the magnetic spectrometer SPEG, to measure precisely very small relative momenta. The experimental data are *selective* and *precise* allowing to extract a valuable information about space-time characteristics of the production process in intermediate-energy heavy-ion.

In particular, in ORION experiment:

- a strong impact parameter dependence of particle correlations is observed;
- the two-proton correlation measurements show, for the first time in the same experiment, the contribution of both preequilibrium and equilibrium protons;
- strong directional effects are observed in correlations of p-p pairs selected from preequilibrium events. These effects, in principle, allow to determine the shape and lifetime of the emitter;

and in SPEG experiment:

- the two-proton correlation function is for, the first time, measured in the region of very small relative momenta 1-10 MeV/c, especially suited to extract with high accuracy the lifetime value of an equilibrated long-lived source;
- The directionnal effect in p-p correlations due to the Coulomb interaction is observed for the first time. This effect, besides the additional information about lifetime, allows to determine the kinematic characteristics of the emitting system.

As far as a detailed analysis of experimental correlation data is concerned, it should include the influence of the interaction with the emitting nucleus, increasing with decreasing emission time . Further progress could be achieved when coupling the calculation of the final state interaction effects to a dynamical model (e.g., QMD) describing the space-time evolution of particle production in heavy-ion reactions.

REFERENCES

1. B. Erazmus, N. Carjan and D. Ardouin, *Phys. Rev.* **C44** (1991) 2663.
2. B. Erazmus, L. Martin, R. Lednicky and N. Carjan, *Phys. Rev.* **C49** (1994) 349.
3. R. Lednicky, V.L. Lyuboshitz, B. Erazmus and D. Nouais, submitted to *Phys. Lett.* **B** and *Nucl. Phys.* **A**.
4. J. Pochodzalla et al., *Phys. Rev.* **C35** (1987) 1695.
5. D. Ardouin et al., *Nucl. Phys.* **A495** (1989) 57c.
6. D. Goujdami et al., *Z. Phys.* **A339** (1991) 293.
7. P. Lautridou, Thesis University of Bordeaux 1, France (1989).

8. A. Ferragut, Thesis University of Caen, France (1990).
9. M. A. Lisa et al., *Phys. Rev. Lett.* **70** (1993) 3709.
10. L. Sézac, Thesis University of Grenoble 1, France (1993); C. Ghisalberti et al., Proc. of the XXXI Intern. Winter Meeting on Nucl. Phys. Bormio, Italy (Jan. 1993) 293.
11. R. Lednicky and V.L. Lyuboshitz, *Yad. Fiz.* **35** (1982) 1316 (*Sov. J. Nucl. Phys.* **35** (1982) 770); Proc. Int. Workshop on Particle Correlations and Interferometry in Nuclear Collisions, CORINNE 90, Nantes, France, 1990 (ed. D. Ardouin, World Scientific, 1990) p. 42.
12. C. Ghisalberti et al., Proc. Fifth Int. Conf. on Nucleus Nucleus Collisions, Taormina, Italy, 1994.
13. L. Martin, Thèse de Doctorat, Université de Nantes (1993).
14. L. Martin et al., *Nouvelles du GANIL* **43** (1992) 3; Proc. Fifth Int. Conf. on Nucleus Nucleus Collisions, Taormina, Italy, 1994.
15. W.G. Gong et al., *Phys. Rev.* **C43** (1991) 1804.
16. L.G. Moretto et al., Int. Rep LBL-30930 (1991).